SSCL-SR-1235

Superconducting Super Collider
A Retrospective Summary
1989–1993

Superconducting Super Collider Laboratory*
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PREFACE

In October of 1993, the staff of the SSC Laboratory was shocked to learn that the U.S. Congress had voted to terminate the construction of the project. Because cancellation came while project activities were in full motion, a substantial amount of physical construction was under way and a vast array of technical equipment was being installed, under procurement, or in the final design stage. Throughout the Laboratory, technical and support people felt the need to capture information about what had been accomplished during the ten years of SSC development and, in particular, during the last five years in Texas.

Because of the importance of the intellectual commitment that was invested in the project, it was decided to preserve as much of the information about the status of the accelerator and research facilities as possible. A working group was appointed incorporating machine and detector task leaders to summarize the project status at the end of 1993. This retrospective document results from the efforts of the working group. It includes a broad range of contributed papers, gathered into seven parts. It was quite difficult to assemble this summary information since many members of the Laboratory staff were in the process of coping with an unanticipated career change and the myriad demands both personal and professional that such a change presents. It was not possible to prepare a fully integrated text using the variety of contributions, and it was accepted that the text should reflect perspectives of the individual contributors. Consequently, it was decided that it would be appropriate to identify the individual authors and prepare the document in the form of a proceedings report of the working group.

The text was submitted to the editors who attempted to establish a consistent style of presentation and to keep the material within the overall context of describing the SSC. In addition, considerable help was provided to the editors. Bob Rooney helped to make the material read with clarity and directness. The document was managed by Caprice Adame who kept track of all the parts in her firm manner. She was assisted by Shirley Watson in an early phase and Valerie Kelly later. Other support came from Nita Sage and Dianne Garner. Clean up and page layout of the final report was accomplished in the Laboratory publications office by Sue Weaver, Dee Dee Kennedy, and Tom Coyne. The report was printed at the Laboratory under the supervision of Don Johnson and his associates. A plan for distribution of this report was made by Charlotte Whitney, assisted by Catherine Gannon. The actual mailing of the report was done by numerous volunteers assembled by the Out Placement group of Personnel under the direction of Gary Damiano. A great deal of thanks is due to these individuals from all former members of the SSC Laboratory.

It is gratifying that so many people were interested in contributing to this major, "final," retrospective publication as they left the SSC Laboratory. It is the hope of the editors that this report will serve not only as a useful resource document but also as a reminder of the considerable amount of good work that was done on the SSC project, and of the commitment of the many dedicated individuals who pledged their personal efforts and professional futures to the worthy endeavor of building a new Laboratory.

Editors
Gerald F. Dugan
James R. Sanford

April 1994

LABORATORY OVERVIEW

(R.F. Schwitters)

The Superconducting Super Collider (SSC) Laboratory began in January 1989 when Universities Research Association (URA) entered into a contract with the United States Department of Energy (DOE) to build the SSC and related facilities in Ellis County, Texas, and to operate them for use by the scientific community. In October 1993, Congress ordered the termination of the SSC; by that time about 20 percent of the project had been completed, less than 20 percent of the estimated cost had been expended, and no technical obstacles to the completion of the project had been identified. This report presents a comprehensive technical picture of the SSC and will serve as a resource for those interested in further examination of the detailed design that was accomplished together with other documentation that defines what the SSC was to be.

By the late 1970s, the international physics community had recognized that new experimental tools were required to advance high energy physics beyond the level of theoretical understanding represented by the highly successful Standard Model of particle physics. Based on the successes of the CERN proton-antiproton collider and the Fermilab Tevatron, the High Energy Physics Advisory Panel (HEPAP) to the DOE recommended in 1983 that the United States build a new proton-proton colliding beam facility, the SSC, using superconducting accelerator magnet technology derived from that proven at the Tevatron.

Through a series of summer studies sponsored by the Division of Particles and Fields of the American Physical Society, workshops, and other meetings, a consensus developed that the new device should be capable of colliding beams of protons with energies up to 20 TeV per beam at several intersection regions with luminosities as large as $10^{33} cm^{-2}s^{-1}$. With these parameters, the SSC would be able to carry out experiments to elucidate the mechanisms responsible for electroweak symmetry breaking, the cornerstone of the Standard Model. It would also probe matter and energy at mass scales of 1 TeV/c^2 where entirely new families of particles and related forces are thought to exist. The results of experiments performed at the SSC were considered essential for continued progress in high energy physics; they would also benefit cosmology because the extreme conditions encountered in the SSC's collisions would reproduce on a tiny scale the conditions thought to have prevailed throughout the universe in the first fraction of a second following the big bang.

The task of studying the feasibility of building an SSC and developing a preliminary conceptual design for its construction was carried out by the Central Design Group (CDG), which formed in 1984, drawing on people with accelerator and experimental expertise from laboratories and universities here and abroad. A detailed conceptual design report was completed in 1986. It presented a design of the main collider and associated systems for a generic site. The CDG also produced a cost estimate, a preliminary construction plan, and documentation specifying site requirements. The most critical technical component of the new accelerator would be the set of superconducting magnets required for the collider rings and the high energy booster. In association with other laboratories, the CDG began an R&D program focused on the magnet design chosen for the conceptual design. The body of work carried out by the CDG formed the technical basis for the U.S. government's review of the proposed SSC project, leading ultimately to the decision by President Reagan in 1987 that the United States should undertake its construction.

Shortly after the President's decision, DOE invited the various states to submit proposals to host the SSC. Thirty six proposals from 25 states were reviewed by a National Research Council committee to determine those best qualified for housing the SSC and its associated research center. Seven proposals deemed best qualified were further studied by DOE, and the Ellis County, Texas, site was selected in November 1988.

The new SSC Laboratory began to take shape in February-March 1989 occupying converted warehouses rented for temporary office and laboratory space. Physicists, engineers, technicians, and support staff came to Texas from the CDG, other national laboratories, universities, and other countries, all of them excited by the challenges of building this great instrument and by the promise of its scientific program. Many local people also joined the Laboratory, and it became a center of great interest to the local community and a resource for science education to many schools in the region. The staff, which initially numbered less than a dozen, grew at a rate of about 50 new employees per month during the early period; by the time the SSC was terminated, there were more than 2000 regular employees and many visiting scientists and engineers from around the country and abroad.

The first major technical task of the new Laboratory was to review the Conceptual Design Report of the CDG in light of recent developments in accelerator science and to apply it to the Ellis County site. In parallel, the site, particularly its underground conditions, had to be characterized in much greater detail than had been necessary for site selection in order to carry out cost reduction studies, to prepare detailed designs, and to specify to the State of Texas the precise parcels of land that would have to be acquired. The SSC Laboratory also took responsibility for continuing the superconducting magnet development program.

The Laboratory made extensive use of committees of internationally recognized experts from throughout the world to provide independent external review of work performed by Laboratory staff and advice to the Director on major technical and management decisions. The principal standing committees consulted regularly by the Laboratory were the Scientific Policy Committee (SPC), the Program Advisory Committee (PAC), the Machine Advisory Committee (MAC), and the Underground Technology Advisory Panel (UTAP). UTAP had been formed by the CDG, and in the mid-1980s, it prepared a National Research Council report with recommendations on construction contracting practices for the SSC. During the course of SSC construction, UTAP interacted closely with personnel in the Laboratory's Conventional Construction Division on all aspects of underground work including geotechnical studies, construction approaches, cost trade-off studies, and underground safety. In addition, DOE and URA carried out frequent reviews of SSC activities on both technical and administrative matters.

During the spring of 1989, a special ad hoc committee was formed to review the CDG superconducting magnet R&D program and make recommendations to the newly forming SSC Laboratory on how to proceed with the program. While the committee was generally satisfied with the approach taken, there was concern over quench performance of magnets that had been produced in the program. The committee urged that consideration be given to modifying the design of Collider dipole magnets to provide a greater operating margin against quenches. The Laboratory accepted this advice and began to design a 50 mm aperture magnet as a backup to the primary 40 mm design of the CDG, should a change ultimately be required. (A larger dipole magnet aperture naturally increases the operating margin because the cross-sectional area of superconducting material increases, thus allowing the current density to be reduced.) Subsequent review of the Laboratory's magnet efforts was carried out by the MAC.

By the fall of 1989, several changes had been made to the Collider lattice to simplify the design, accommodate to the actual site, and make use of advances in accelerator design tools since the Conceptual Design Report of 1986. For example, it was recognized that interaction regions could be arranged in pairs with alternative paths ("bypasses"). This concept opened the possibility of operating one pair of detectors while a second pair was being installed or modified in the unused bypass, radiologically isolated from the operating Collider. Beamline magnets could be re-arranged to direct protons for collisions to detectors in the second bypass while the first pair of detectors was available for servicing or modifications. Detectors anticipated for the SSC were very large, and it was determined early in the design process that moving them off beamline for servicing would be impractical and prohibitively expensive. Bypasses gave the possibility of up to eight interaction regions, four of which would be operating at a given time. Actual construction of bypasses was not undertaken, because they would have represented an increase in the scope and cost of the SSC; but provisions for their later introduction could be incorporated at minimal initial expense and disruption to the program. The MAC, SPC, and PAC all endorsed the bypass concept.

A serious design issue arose during 1989 concerning the stability of beams freshly injected into the Collider rings. Advances in computing technology and software made it possible to simulate with greater confidence than was possible during the conceptual design studies the motion of relatively low energy particles stored in a collider ring over large numbers of orbital periods. Beams are most vulnerable to being lost from stable orbits at the injection energy, before acceleration begins due to the effect of imperfections in the dipole field of the Collider bending magnets arising from errors in wire placement during magnet construction and other effects. The magnet imperfections, if large enough, could lead to unstable orbits and unacceptable particle loss. While the new computer studies did not prove the CDG design to be inadequate, they indicated that the design was risky and could lead to machines that would be difficult to commission and operate. Two principal recommendations were developed by Laboratory staff to deal with this concern. The first was to raise the injection energy and, hence, the peak energy of the high energy booster from 1 TeV to 2 TeV; the second was to increase the Collider dipole magnet aperture from 40 mm to 50 mm, thereby reducing the effects of inevitable construction imperfections. As noted previously, the larger aperture would also improve the operating margin of the dipole magnets. These changes would greatly reduce the risk of beam loss during injection, but it was recognized that they would increase costs and change the site footprint.

When it was estimated that effecting these recommendations would entail a potential cost increase of about $1B, the Laboratory faced its most critical technical decision. The MAC met in the fall of 1989 and strongly recommended that the design modifications be incorporated. When the detailed technical analyses were completed, the Laboratory accepted the MAC advice and informed DOE of the proposed design changes. The cost increase associated with the design changes led to consideration of whether the scope of other parts of the project might be modified so that the total project cost as estimated by the CDG and DOE could be maintained.

In late 1989, the Laboratory invited an ad hoc group of physicists familiar with SSC scientific issues to study the consequences of reducing the peak proton beam energy, the performance figure with the greatest leverage on overall cost, as a means of reducing the project's cost. The group strongly urged retention of the 20 TeV peak beam energy so that the complete range of electro-weak symmetry breaking phenomena could be studied; lower energies, the group concluded, would increase the risk of being unable to perform definitive measurements of this crucial process. Other parties, including officials from the State of Texas and members of governing boards of URA also debated the proposed design changes and the question of reducing the peak beam energy. Finally, the Secretary of Energy commissioned a special report by HEPAP in January 1990. The Secretary accepted HEPAP's recommendations that the proton energy not be reduced and that the technical design changes be implemented.

The crucial decisions taken during 1989 and more detailed geotechnical data becoming available from on-site studies permitted determination of the final footprint required for the SSC in October 1989. DOE transmitted the footprint to the State of Texas in March 1990 to begin the formal process of land acquisition by the state.

In late 1989 and early 1990, the basic ground rules for establishing the scientific program of the SSC were developed by the Laboratory in close consultation with the SPC and PAC. Key considerations included developing the best overall initial experimental program based on proposals to the Laboratory from prospective scientific users, evaluated in a manner to ensure fairness. A call for "Expressions of Interest" (EOI) in the initial scientific program of the SSC was issued in early 1990 with a submission deadline of May 1990. The EOIs were meant to provide a picture of scientific demand to gauge user interest and to provide input to accelerator designers in developing final machine requirements. The Laboratory also continued to oversee the highly successful generic detector research and development program begun by DOE and CDG.

Eventually, over 20 EOIs were received spanning a wide range of physics interests, from very large detectors for studying the high-mass phenomena for which the SSC was designed to small experiments designed to study details of known processes that could benefit from the very high beam energy of the SSC. Interest was expressed even in using unique SSC equipment, such as very large cryogenic reservoirs, to perform experiments outside high energy physics. The EOIs also spanned a wide range of number of authors from one-person efforts to huge collaborations. Subsequent action on the Expressions of Interest took place through discussions between proponents and Laboratory staff, follow-on meetings of the PAC, refinement and development of formal proposals to the Laboratory, and sponsorship of workshops to develop plans and ideas. From the outset, the Laboratory and its advisory committees, the SPC and PAC, strongly supported the notion that the initial physics program should be diverse and include smaller experiments in addition to the very large detectors that were known to be needed. But because of the long time needed to build the large detectors, initial attention was concentrated on the large experiments.

Considerable debate occurred on the question of the number of large detectors to be built for the initial round of experiments. The choices were to build two large detectors with overlapping and complementary characteristics, or to build only one general purpose detector while reserving resources for subsequent experiments. A substantial majority of those consulted favored two detectors ready for initial data runs at SSC turn-on, and the Laboratory was following a two-detector policy up to the time the project was terminated. Preliminary approval had been given to the Solenoidal Detector Collaboration, and the Gammas, Electrons, and Muons Collaboration was proceeding satisfactorily toward approval. However, the Laboratory had not made final commitments to construct either detector because of unresolved funding questions. The Laboratory was prepared to go forward with only one of the detectors or with staging the completion of both large detectors, depending upon how funding constraints developed.

A site-specific conceptual design, a basic construction plan, and a detailed cost estimate were presented to DOE in the summer of 1990. Over the next two years, myriad technical issues were resolved as detailed designs progressed and the final geometry of the Collider rings and injector accelerators was set in anticipation of the start of civil construction. The MAC and UTAP met periodically to give crucial advice. The first civil construction on the SSC footprint began in 1991 for the Magnet Development Laboratory and other technical facilities at the N15 site. The final layout of the Collider rings, interaction region halls, and injectors was determined in late 1991. In 1992, the N15 site was occupied by Laboratory personnel. A major technical milestone of assembling and operating a complete half cell of Collider magnets (five dipoles, one quadrupole, and associated "spool pieces") was accomplished in August 1992. Tunnel boring machines began excavating the housing for the Collider rings in early 1993.

After the critical decisions of late 1989 and early 1990, meetings of the MAC (taking place typically two times per year) focused on designs of the low energy accelerators to be used in the injector chain. Here, a principal issue was maintenance of the beam brightness, which is directly related to the ultimate Collider luminosity. It was evident that space charge forces acting on freshly injected protons in the low energy booster were likely to be the limiting factor for beam brightness in the overall injector system. The brightness strongly depends on the energy of protons injected into the low energy booster from the linear accelerator. The MAC recommended raising the proposed design energy of the linear accelerator system from 600 MeV (kinetic energy) to 1000 MeV. In 1992, the Laboratory decided to construct the tunnel for the linear accelerator long enough to provide space for later installation of additional accelerating sections that would permit 1000 MeV operation eventually, but to configure the linear accelerator for initial operations at 600 MeV. Performance studies indicated that the SSC design luminosity could be achieved with the 600 MeV design; the longer tunnel provided relatively inexpensive insurance for the future when higher brightness might be required. The Laboratory also decided to construct a short segment of ancillary tunnel, branching away from the main linear accelerator, that could be used, with no degradation of SSC's scientific program, in conjunction with a possible future proton therapy center for cancer therapy and research.

In 1992, technical issues that required review and advice by the MAC included ramp-rate performance of superconducting magnets and vacuum properties of the Collider beam tube. Tests of SSC dipole magnets indicated erratic ramp-rate dependence of the quench threshold and field quality. This was of concern principally for the high energy booster, which required significantly faster ramping of the current than did the Collider rings. The ramp-rate dependence of the magnets was traced to intra-strand coupling of wires within the superconducting cable from which the magnets were built. The issue of the Collider ring vacuum is very complex and has not been completely resolved to this day. The MAC examined it several times, and considerable effort on the part of Laboratory staff and collaborators from other institutions was devoted to the matter. The Collider vacuum issue had been recognized by the CDG; the new ingredient was the realization that *local* vacuum effects could lead to operational difficulties for the Collider, even if the average vacuum permitted an acceptable beam lifetime. A principal technical question was whether a special liner, placed inside the bore-tube of the magnets, would be required to assure reliable operation. The related question of the quadrupole magnet aperture was resolved in 1993, when it was decided to change the baseline design value of 40 mm to 50 mm, the same as the dipole magnet (the scaling laws for performance of dipoles and quadrupoles are different, meaning that it was not *a priori* evident that the two apertures should be identical).

In 1993, R&D efforts aimed at resolving the remaining technical questions were progressing well and were not affecting the critical path for construction. However, budgetary shortfalls from Administration and Congressional actions necessitated stretching out the schedule, which had the effect of increasing the total estimated cost. Ultimately, Congress determined that the costs were too large to continue.

PART I. ACCELERATORS

PART I. ACCELERATORS

Chapter 1. Introduction

(M. Syphers)

The basic parameters of the Superconducting Super Collider (SSC) were established some ten years before its termination in 1993. In the summer of 1984, a Central Design Group (CDG) was established at Lawrence Berkeley Laboratory to organize the SSC design effort. The CDG developed a design for a generic version of the SSC independent of site.[1] More importantly, it developed a design procedure that could be modified to the conditions of the selected site. During the first 2 to 3 years of experience at the SSC Laboratory, efforts concentrated on tailoring the generic design to the Texas site and fleshing out the injector specifications. A detailed snapshot of the SSC design as of 1990 can be found in the Site-Specific Conceptual Design Report (SCDR).[2]

During the two years before 1993, many advances were made at the SSC Laboratory. The list of the Laboratory's successes included the construction of a Magnet Development Laboratory and a Magnet Test Laboratory; construction and operation of the Accelerator Systems String Test facility; construction of the first cryogenic refrigeration plant; completion of the Linac tunnel; and major advances in the construction of the LEB and MEB tunnels. Underground construction of the main Collider facilities was well under way: approximately 40 miles of the 54-mile tunnel were under contract for construction. Sixteen shafts to tunnel depth had been drilled completely, including three magnet delivery shafts, which were to be used as starting points for tunnel boring drives. Tunneling began in January 1993, and by October 1993, 16 miles of tunnel had been bored. A major laboratory milestone was reached on August 14, 1992 with the successful powering of a complete half-cell, including a string of industrially produced Collider dipole magnets, to full excitation. This crucial test and others conducted at the ASST facility are discussed further elsewhere in this document.

The parameters and requirements of the SSC can be found in the Laboratory Systems Specifications documents (see Tables 1-1. and 1-2.).

Table 1-1. High Level Requirements for the SSC.

SSC Parameters	
Proton Energy (each ring)	20 TeV
Peak Luminosity	$10^{33}cm^{-2}\ sec^{-1}$
No. of Interaction Regions	up to 4 initially
Storage Time (typical)	20 hours
Test Beam Energy	200 GeV
Availability (projection of scheduled time)	80%

Table 1-2. SSC Injector Parameters.

	Collider	HEB	MEB	LEB	Linac
Beam Kinetic Energy	20 TeV	2 TeV	200 GeV	11 GeV	0.6 GeV
Circumference (m)	87120	10800	3960	570	
Superconducting/ Normal	SC	SC	N	N	N
Bunch Spacing (m)	5	5	5	5	
Output Transverse Emitt. (rms,normalized, 10^{-6} m-rad)	1.0π	0.8π	0.7π	0.6π	$<0.3\pi$
Protons/bunch (10^{10})	0.75	1	1	1	
Cycle Time		~4.3 min	~8 sec	0.1 sec	

Proton beams were to be fed into the main Collider synchrotrons from a chain of injector accelerators, which consisted of a linear accelerator, two resistive synchrotrons, and one superconducting synchrotron. During the nominal collider filling scenario, the Linac would accelerate negative hydrogen ions (H^-) to a kinetic energy of 600 MeV. These ions would be charge-exchange injected into the Low Energy Booster (LEB) and bunched into RF buckets. The LEB would then accelerate the proton beam to a momentum of 12 GeV/c. The 12 GeV/c protons would then be fast extracted from the LEB in a single turn, and transferred bucket-to-bucket into the Medium Energy Booster (MEB). Six cycles of the LEB would be accumulated in the MEB before the beam was accelerated to 200 GeV/c momentum. The 200 GeV/c beam would then be fast extracted from the MEB and injected into the High Energy Booster (HEB). Three cycles would be accumulated in the HEB before acceleration to 2000 GeV (2 TeV). The protons would then be fast extracted from the HEB and injected into one of the Collider rings. There would be a change in polarity and beam direction in the HEB on alternate cycles. The process was to be repeated 16 times until both Collider rings were filled with counter-rotating proton beams.

Once the Collider was filled, the proton beam in each ring would be accelerated to an energy of 20 TeV. At this energy, the beams could be brought into collision and focused to a small spot size at the interaction points, where the physics experiments would be performed. In addition to the above scenario, the injector complex could have been used to provide test beams for detector development, calibration, and testing. In this mode of operation, beam would have been slow extracted from the MEB at a momentum of 200 GeV/c (see Figure 1-1).

The final number of bunches in the Collider synchrotrons was to depend in large part on the rise and fall times of the kicker magnets that were used for injection and extraction in the accelerators, and on the ratio of the circumferences of the various injectors. For the SSC design, the Collider would be approximately 90% filled, i.e., 90% of the RF buckets, spaced 5 m apart, would be filled in the Collider (see Figure 1-2).

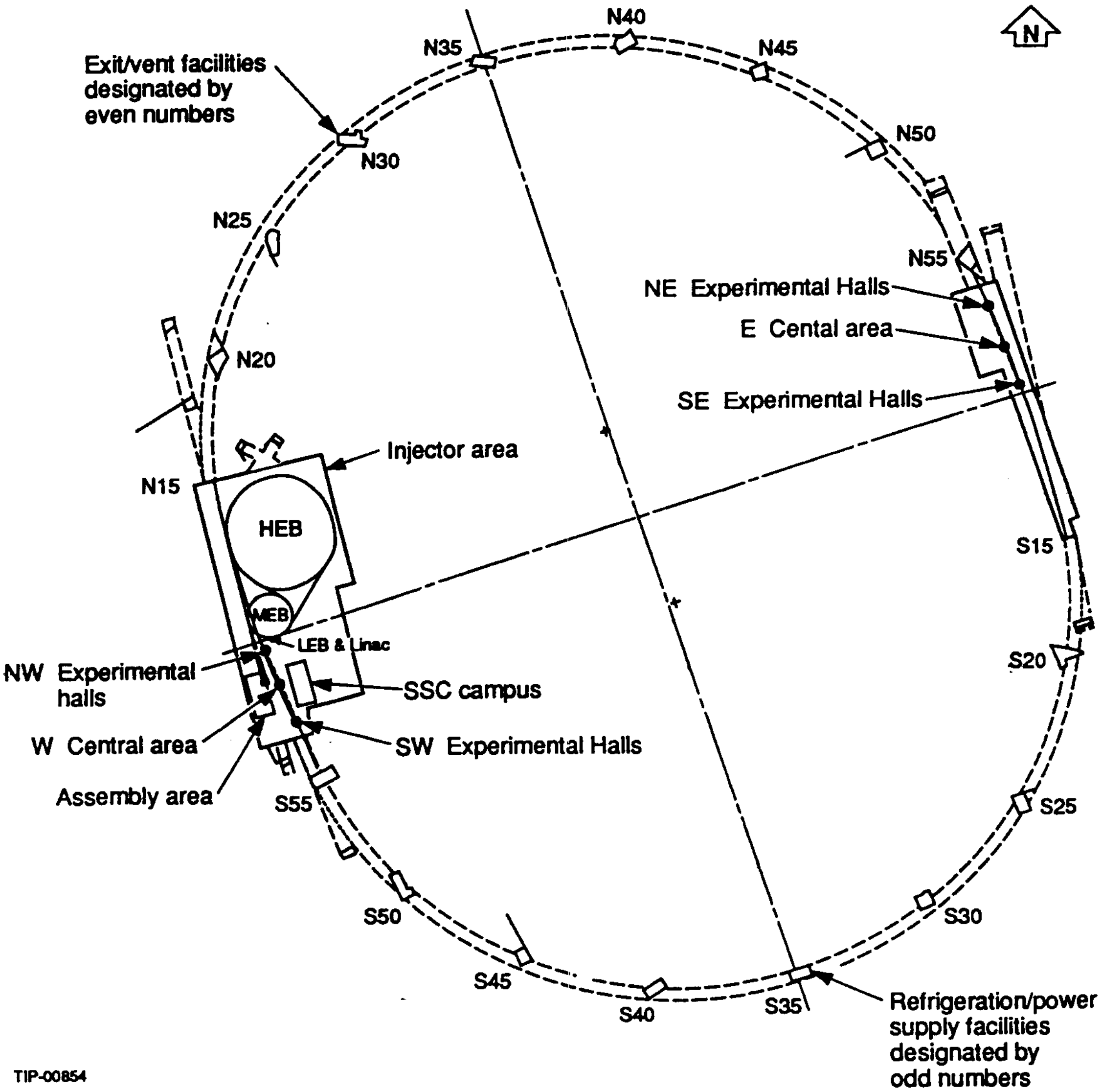
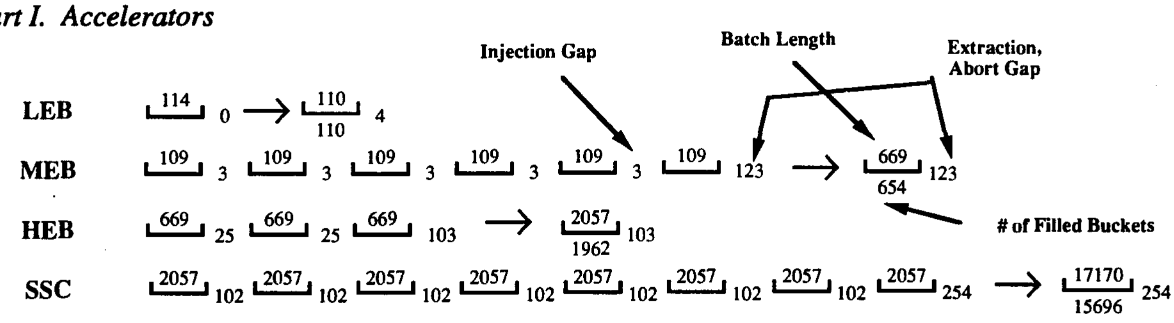


Figure 1-1. Layout of the SSC Accelerators.



$$\eta = 15696/17424 = 90.1\ \%$$

Figure 1-2. Collider Filling Scenario.

The value of the bunch spacing is determined from the desire to have approximately one detected interaction per bunch crossing (η_{int}~1) at the interaction point. This desire is not a strict requirement but arises from judgements related to optimizing detector performance and cost-efficiency. A luminosity of L=10^{33}cm^{-2}sec^{-1}, and an effective proton-proton cross section of σ_{int} = 60 mb, yields a bunch spacing of rougly:

$$S_B = \frac{\eta_{int}\, c}{L\sigma_{int}} \cong \frac{1 \times 3 \times 10^8}{10^{33} \times 60 \times 10^{-27}} = 5 \text{ m}$$

The bunch spacing was always understood to be a parameter which could be varied (in multiples of the RF wavelength) to increase the luminosity if required (subject to constraints imposed by the beam-beam interaction, and at the expense of η_{int}). In the event that the bunch spacing needed to be altered, it was felt that the accelerator circumferences should contain several common factors so that changes in bunch spacing could be made in one accelerator and the bunches naturally transferred to the following accelerators down the chain. The circumferences of the injectors were chosen as indicated in Table 1-3. This allowed, quite naturally, for bunch spacings of 5 m, 10 m, 15 m, and so forth.

Table 1-3. Circumferences of the Injectors.

	Circumference (m)	Circumference/5 m
LEB	570	114=19 $\times$ 3$\times$2
MEB	3960	792=11 $\times 3^2 \times 2^3$
HEB	10800	2160=5 $\times 3^3 \times 2^4$
Collider	87120	17424=$11^2 \times 3^2 \times 2^4$

Following the 1990 SCDR, there were several significant changes to the SSC design. The list that follows is not meant to be exhaustive, but it reflects the general evolution of the designs as more studies were performed and more details of the site became known.

The most significant changes in the injector chain came about in the designs of the LEB and MEB synchrotrons. A new LEB lattice was adopted that had three-fold symmetry and a transition energy above the extraction energy of the machine. This was accomplished by using a novel optical scheme where the dispersion function was kept small through the bending regions of the accelerator. In accommodating this function plus the necessary space for RF, injection, and extraction devices, the LEB circumference was increased from 530 m to 570 m.

Similarly, the MEB lattice was extensively modified after the SCDR design. Previously, the MEB straight sections had been generated by leaving out bending magnets within the normal FODO focusing structure. In the MEB design at time of termination, two forms of matched insertions were used to provide the necessary straight sections. The longer straight sections were used for resonant extraction to the test beams facilities, for extraction to the HEB, to a beam dump, and for RF. The short straight section design accommodated injection. The long straight section optical design provided beam sizes more conducive to resonant extraction.

The circumference of the HEB was also modified. The new HEB design had a circumference of 10,800 m, as opposed to the previous length of 10,890 m. The previous circumference was exactly one eighth that of the main Collider rings, and it made for a longer cogging time during transfers.

A major change to the Collider layout was the introduction of mini-straight sections by omitting roughly 50 dipole magnets per ring in the arcs. Previously, the arcs of the Collider had consisted of 35 km of solid magnets and spool pieces, which left no room for future equipment if ever deemed necessary. The new design not only permitted space for future equipment, it also allowed for a more flexible placement of utilities shafts around the circumference.

In addition to the arcs, the optical layout of the cluster regions was significantly altered after the 1990 design. The interaction region design was much more flexible in its range of tunability, in its range of possible detector free space, and in its correction systems. In addition, the location of the experimental halls for the large detectors was changed. The 1990 plan had the large, major detectors sited on the west side of the ring, near the injectors. Subsequently, it was determined that while the Collider ring itself would be in the Austin Chalk on the west complex, the foundations for these large detector halls would end up in Eagle Ford Shale. It was then decided to move the large detectors to the east side. While the accelerator was to pass through Taylor Marl material on the east, the foundations of the large caverns would be in the Austin Chalk, which was geotechnically preferable.

Chapter 2. Injector Overview

(M. Syphers)

Each of the accelerators in the injector chain had design issues that were particular to its own energy range and performance requirements. Some of the more prominent issues that influenced the design of these machines are discussed below, and further details of the designs will be presented in subsequent sections.

Linac

The Linac injector for the LEB provided a 600 MeV (kinetic energy), 25 mA H^- beam at a 10 Hz pulse rate with normalized rms transverse emittances less than 0.4 π mm-mrad in both planes. The pulse length was 8 msec for three-turn injection of 10^{12} protons into the LEB (collider fill mode), and 35 msec for 16-turn injection of 5×10^{12} protons in the "test beam" mode. The design of the Linac was conventional and made up of several stages of acceleration. A 35 kV ion source and low energy beam transport (LEBT) was followed by a 427 MHz radio frequency quadrupole (RFQ) in which the beam energy was increased to 2.5 MeV. The 2.2 m long RFQ was followed by a drift-tube Linac (DTL), operating at 427.6 MHz. The DTL increased the beam energy to 70 MeV over a distance of 24 m. The four-tank DTL design used permanent magnet quadrupoles in a FODO array with post stabilizers. Each tank had its own 4 MW klystron.

A side-coupled linac, operating at 1282.2 MHz (the 3rd harmonic of the RFQ/DTL frequency) completed the acceleration to 600 MeV. This portion consisted of 72 coupled-cavity sections, each with 16 accelerating cavities, connected into 9 modules of 8 sections each. Each module was powered by a 20 MW klystron. The coupled cell linac (CCL) portion of the Linac was 112.4 m long.

As in all the accelerators in the injector chain, one of the most stringent design requirements of the Linac was the final transverse emittance produced. The 0.4 π mm-mrad emittance requirement for the Linac had been studied extensively with computer simulations and analytical studies, and the results looked very promising. The only hardware that produced beams, the ion source and the RFQ, produced them with the specified emittances. (See Chapter 34 on Ion Source/RFQ.)

LEB/MEB

Two synchrotrons utilizing resistive magnets formed the next part of the injector chain, the Low Energy Booster (LEB) and the Medium Energy Booster (MEB). The basic lattice design constraints for the LEB were a small circumference to minimize space charge effects, adequate azimuthal space for the required hardware, and sufficiently large transition energy to avoid crossing transition and to provide an adequate slip factor at extraction to support cogging procedures. For the MEB, the lattice design had to provide space necessary for injection, two extraction channels for transport to the HEB, RF, and slow resonant extraction devices for transport of protons to the test beams facility. These functions demanded a number of straight sections in the device. As in the LEB, space charge issues came into play in the MEB, predominantly at transition. However, for the MEB, transition was not avoided, though it was designed to be as far away from the injection energy as practical thus reducing the space charge effects. This accelerator was the only circular accelerator at the SSC designed to cross its transition energy.

HEB

The High Energy Booster (HEB) would have been the highest energy accelerator in the world when commissioned. The 2 TeV superconducting accelerator would transport beams in either the clockwise or counter-clockwise directions for acceleration and transport into the two Collider synchrotrons. This would also have been the first superconducting accelerator to operate in a bipolar fashion. The bipolar operation of the superconducting magnets, and the subsequent tuning of the accelerator systems, presented one of the interesting challenges of this particular accelerator.

One of the more important design issues facing the Laboratory was the observed ramp dependence of the field harmonics and the quench level of the superconducting dipole magnets that had been built. The dipole magnets for the Collider were required to ramp to full energy at a modest 4 A/sec. At this rate, magnets built at the time of termination were able to achieve top energy without quenching. However, when ramped at rates corresponding to HEB operation, which was about 15 times higher, several of the magnets that had been built quenched at currents below the operating point and exhibited poor field quality during ramp. The actual quench level depended upon the magnet and appeared to be connected to the interstrand resistance of the cable used. This topic is discussed in further detail in the section on Ramp Rate issues below.

Transfer Lines

The transfer lines, which guided the particle beams from one accelerator to another, were another area of intense design effort, in many cases as demanding as the accelerators themselves. For the SSC design, there were six transfer lines, and eight beam abort and beam dump transport lines. The longest beam transfer line, connecting the MEB to the HEB in the counter-clockwise direction, was 2.3 km in length and contained roughly 100 magnetic elements.

One of the more complicated areas of the entire accelerator complex was the West Utility Region, at the interface of the HEB and the Collider synchrotrons. Here, beams were to be transferred from the HEB in both directions into the upper and lower Collider rings. The plane of the HEB was to be separated vertically from the planes of the two Collider accelerators by about 14 m. (See Figure 2-1.) The array of extraction magnets, beam transport magnets, injection devices, and associated shielding in these two intersecting beamlines made for challenging accelerator design and civil engineering efforts.

The preservation of transverse emittance was perhaps most taxed during the process of transferring beam from one accelerator to another. Injection mismatches, particularly of transverse central trajectories, could dilute beam distributions in phase space. These effects were most damaging at higher energies, where the beam spot sizes were smaller due to adiabatic damping. For instance, a 0.5 mm amplitude mismatch in the transverse trajectory from the HEB into the Collider could generate an increase in the normalized transverse emittance of 0.8π mm-mrad, almost doubling the emittance that would enter the Collider from the HEB. Thus with higher energies, power supply stability, magnet setting accuracies, and injection damping became extremely important.

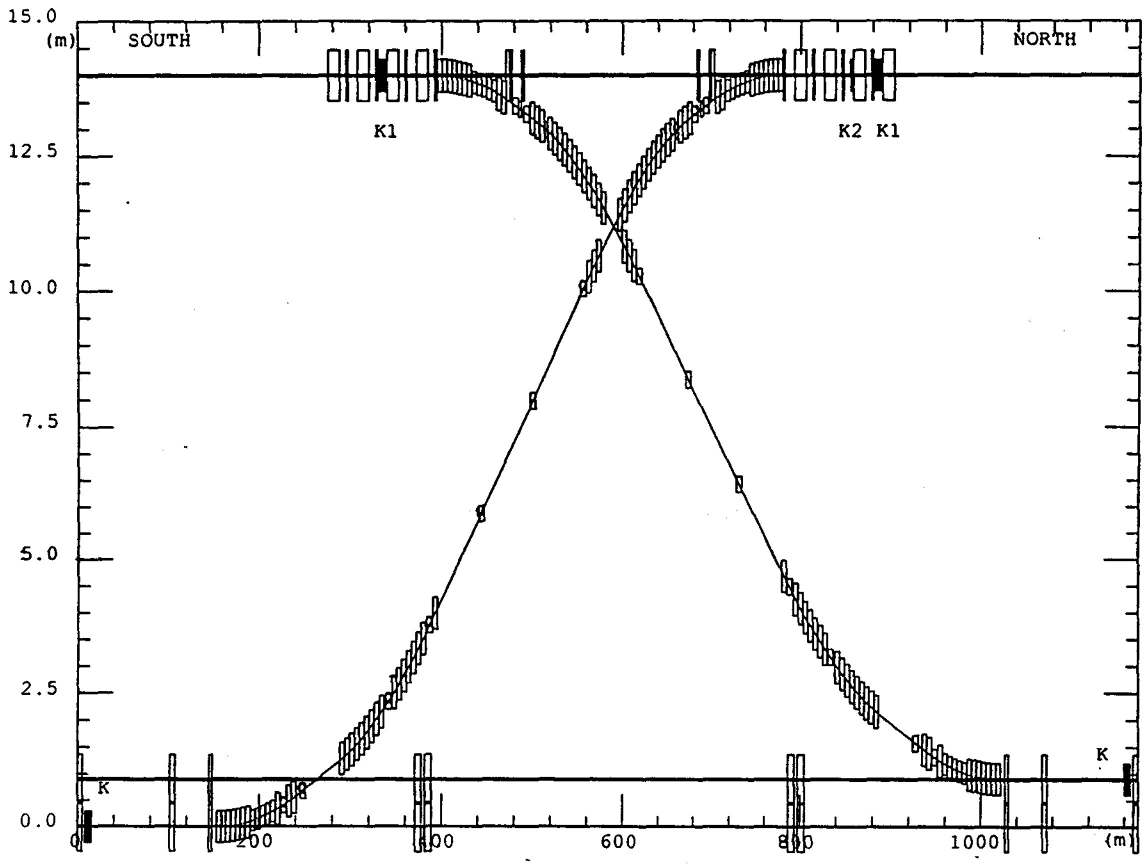


Figure 2-1. HEB Beams Transferred to Collider Rings.

Test Beams

One of the functions of the Medium Energy Booster was to provide 200 GeV proton beams to a test beam area for detector component testing, calibration, and R&D. While test beams from the High Energy Booster were not in the baseline current at the time, the HEB lattice facilitated 2-TeV extracted beams for this purpose, and the aperture requirements were set to accommodate the larger emittance beams that would inevitably have gone with higher intensity operation. The HEB long straight section was aligned with the MEB and Test Beams facilities with this future use in mind. (More details about the Test Beams facilities can be found in the discussion of test beams in Chapter 15.)

Chapter 3. Linear Accelerator

(W. Funk and G. Leifeste)

The SSC Linear Accelerator (Linac)[1-6,43,44,54] was designed to accelerate beams of H^- ions to 600 MeV. Macropulses of 9.6μs duration, 21 mA peak current, were to be stripped on a foil and fill each of the 114 RF buckets of the Low Energy Booster (LEB) with 10^{10} protons in 4 turns. The Linac was to operate at 10 Hz to support the fast-cycling, resonantly driven LEB. In addition, the Linac was to provide longer (35μs) pulses at 25 mA to fill the LEB for Test Beam operation. In fact, test beams were intended to be used for calibration of detector components, and they would require currents much less than those given above. A high current mode of operation was seen as providing the potential for a fixed-target physics program (see Table 3-1).

Table 3-1. Linac Specifications.

Particle	H^-
Output Energy	600 MeV*
Nominal Output Current	25 mA†
Pulse Length	2 - 35 μs
Pulse Repetition Frequency	10 Hz
Output Transverse Emittance (n, rms)	≤ 0.3 π mm-mrad
Output Energy Spread	≤ 100 keV
Basic Radio Frequency	427.617 MHz‡
Scheduled Availability (Collider Filling)	≥ 98.8%

* ability to upgrade to 1 GeV was envisioned
† designed to be able to handle up to 50 mA
‡ 9th harmonic of LEB injection RF - preserves bunch-to-bucket transfer option

Physics and Operational Requirements

(W. Funk and G. Leifeste)

The three main requirements placed upon the Linac that differed notably from those dictating the design of earlier proton Linacs for injection into booster synchrotrons were: low transverse emittance, high availability, and preservation of the bunch-to-bucket LEB injection option. The latter requirement led to the choice of the basic RF frequency; the first requirement led to the choice of output energy. In addition, since space charge forces in the LEB at injection would dominate overall emittance growth during the acceleration process, space was reserved, both in the Linac tunnel and the RF gallery, for additional klystrons and coupled-cavity Linac (CCL) modules to boost the output energy to 1000 MeV.

A study[42,70] carried out for the University of Texas Southwestern Medical Center determined that the Linac would be a suitable source of protons for a radiotherapy facility. Although a final decision was still pending at termination of the project, the Linac was being designed to be capable of providing beams of protons ranging in energy from 70 to 250 MeV. The primary impetus of this was the need to provide a stub-out from which the transfer line to the proton radiotherapy facility could begin, and to provide for adjustable quadrupole magnets in the CCL portion of the Linac.

Overall System Description

(W. Funk and G. Leifeste)

The type of accelerator technology selected for the acceleration of protons and other heavy ions was dictated by the velocity range through which the particles were to be accelerated. The linear accelerator was required to accelerate protons from zero to about 80% of the speed of light; and over this range of velocities, four different technologies would be required for an optimized accelerator design. In addition, three matching sections would be required to accommodate the dramatic differences in longitudinal and transverse beam focusing in the four different accelerating systems, so that the transfers could take place with minimum increase in beam emittance. Finally, a transfer line would take the 600 MeV beam to the LEB. This would include an energy compressor system to reduce the energy spread to the desired level of ± 100 keV. (See Figure 3-1.)

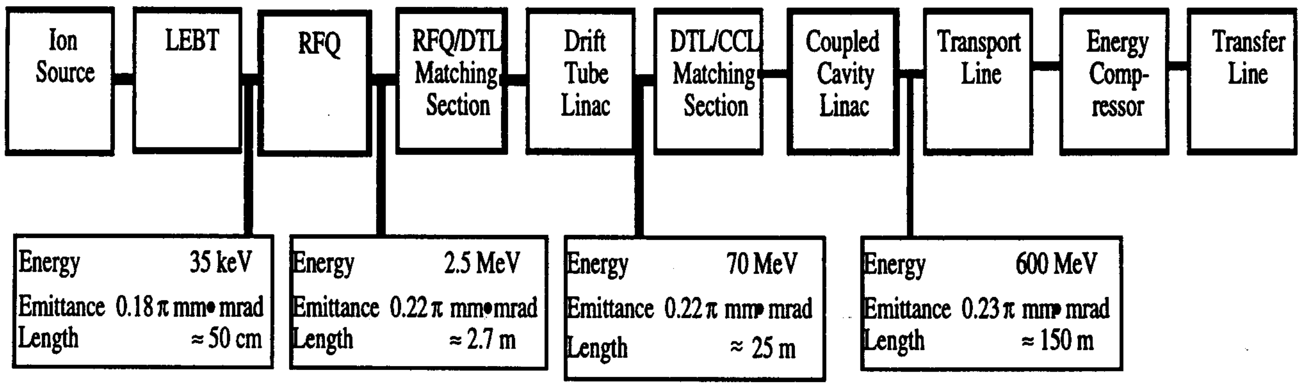


Figure 3-1. Conceptual Layout of Linac.

Ion Sources

(K. Saadatmand)

Two different technologies were investigated for use as the H^- ion source for the SSCL Linac: cesiated surface (magnetron) sources and non-cesiated volume (RF discharge) sources.[8,9] Both were carefully measured on the emittance test stand and both demonstrated normalized, transverse, rms emittances of ≈0.1 π mm mrad, significantly better than the design objective of 0.18 π mm mrad. The results were predicted by an in-house analysis code and confirmed with REANE.[10] In addition, the volume source continued to demonstrate superior operational characteristics with respect to commissioning times and stability. As a result, the volume source was chosen for the SSC Linac.

The volume source chamber was made up of a 10-cm-long by 10-cm-diameter hollow copper cylinder with a back plate at one end and a plasma electrode at the other end. The plasma was confined by the longitudinal line-cusp field produced by rows of water-cooled, samarium-cobalt magnets that surrounded the source chamber and back flange. A pair of water-cooled permanent magnet filter rods placed near the plasma electrode created a narrow region of transverse magnetic field that divided the source chamber into the discharge and extraction regions.

In the discharge region, pulsed RF power was inductively coupled to a mixture of hydrogen gas and electrons (supplied by a hairpin tungsten filament) to ionize and excite the hydrogen gas molecules. RF power coupling was accomplished via a two-turn, ceramic-coated copper antenna connected through an isolation transformer to a network that matched the impedance of the RF amplifier to the plasma. The magnetic field of the filter rods prevented the energetic plasma electrons from entering the extraction region. Cold electrons, positive and negative ions, and vibrationally excited hydrogen molecules drifted across this magnetic field into the extraction region and formed a low-temperature plasma. This cold plasma enhanced the formation of H^- ions by dissociative attachment.[71]

The RF volume source was operated in the pressure range of 15–25 mtorr at 30–50 kW of pulsed RF power (up to 1-ms pulse width). Beam was extracted through 35kV across a single extraction gap. Unavoidably, a high-current electron beam was also extracted. At high powers, the electron-to-H^- ratio could be as high as 50:1, but a ratio as low as 25:1 under nominal operating conditions was achieved. The electrons were separated from the H^- beam by a set of spectrometer magnets placed immediately downstream of the extractor electrode. The separator magnets were housed inside a soft iron envelope (11 and 5 cm long for the R&D and Injector sources, respectively) to prevent fringe fields from penetrating the extraction gap and source (see Figure 3-2).

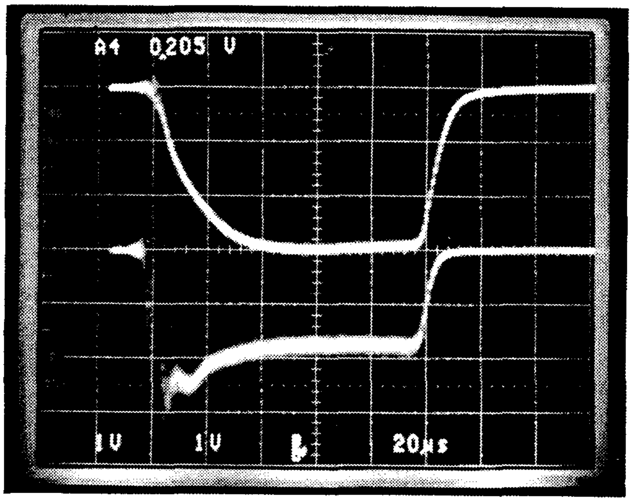


Figure 3-2. Typical H^- Beam Current and Electron Current.

Low Energy Beam Transport Systems

(K. Saadatmand)

The decision to use an electrostatic low energy beam transport (LEBT) was reached early in the program based on the realization that associated electric fields would not allow the buildup of a plasma from the background gas. The process generally took several microseconds to reach equilibrium. Because this was a substantial fraction of the total beam pulse length for collider fill operation and because the optics of the LEBT would be changing as the plasma developed, it was felt that this would have an unacceptable impact on the effective output emittance of the Linac beam. The alternative approach of maintaining a very low background gas pressure in the LEBT was felt to be impractical, because the source/LEBT configuration had to be very compact with minimum access for vacuum pumps, and the gas throughput had to be fairly high.

Einzel lens and Helical ElectroStatic Quadrupole (HESQ) LEBTs were investigated[12-15] on the test stands, but only the Einzel lens system had a detailed characterization. Detailed study of the HESQ concept was under way at the time of termination. A collaboration was established with the low energy beam transport group at the University of Maryland (UMd) for the investigation of a conventional electrostatic quadrupole lens.[11] In support of this activity, the magnetron source was loaned to the UMd group during 1993, when it became clear that staffing levels were not going to reach the point where the Injector Section of the Linac Group could successfully execute both development programs. Although the Einzel lens system was used for all beam tests of the RFQ, a final selection for the SSC Linac had not been made.

Radio Frequency Quadrupole

(D. Raparia)

The four-vane RFQ (see Table 3-2) was designed[16] and constructed by AT Division staff at the Los Alamos National Laboratory (LANL) under contract to the SSCL. A significant design change took place in early 1991, when it was discovered that the higher multipole content of the cavity fields would be sufficient to significantly degrade transmission. The fabrication technology used, in which four quadrants were electroformed into a single RF and vacuum envelope, restricted the design to 1.1 m-long sections. Rather than increase the number of sections from two to three, it was decided to slightly decrease the aperture and create a voltage ramp that would increase the RF power required. Satisfactory characteristics were restored, including essentially zero transverse emittance growth during acceleration, at the additional expense of a 30% increase in the longitudinal emittance and in the focusing strength required in the LEBT. The RFQ was delivered to SSCL during the summer of 1992. In the following nine months, it was installed, commissioned, and tested.

The RFQ end walls were specialized devices, providing vacuum isolation valves and instrumentation in a package occupying minimum length along the beam line for optimum beam handling on both input and output of the RFQ. They were manufactured to SSCL designs by the Kansas City Division of Allied Signal.

Table 3-2. RFQ Specifications.

Frequency		427.617 MHz	
Input Energy		0.035 MeV	
Output Energy		2.5 MeV	
Input Current		30 mA	
Output Current (Accelerated Beam)		≈ 27 mA	
Input Transverse Emittance (n, rms)		≤ 0.20 π mm-mrad	
Output Transverse Emittance (n,rms)		≤ 0.20 π mm-mrad	
Output Longitudinal Emittance (rms)		≈ 0.8×10^{-6} eV–s	
Output Beam Radius (rms)		0.75 mm	
Vane Tip Radius		1.5 - 3.85 mm	
Bore Radius		2.0 - 3.5 mm	
Peak RF Field		36 MV/m (1.8 × $E_{Kilpatrick}$)	
Total RF Power		345 kW	
Structure Power		280 kW	
Length		2.1863 m	
Input Instrumentation:			
Wire Scanner	1	Toroid	1
Faraday Cup	1	Segmented Aperture	1

The RF power amplifier, low level RF controls, and elements of the RF supervisory controls were obtained through a collaboration with LANL.[17] The power amplifier, based on the Ground Test Accelerator (GTA) design, was delivered to SSCL, where it was installed, connected to utilities, and commissioned. It achieved satisfactory performance at the 600 kW level and during RFQ acceptance tests, but subsequently it began to experience problems associated with a rapid deterioration of the cathode output of the tetrode. Replacement tubes experienced positive feedback problems with parasitic modes of the input cavity and, at the time of project cancellation, this problem had still not been solved. It prevented accumulation of much of the potential scientific information that could have been obtained from testing of the RFQ and diagnostic equipment.

Amplifier supervisory controls, based on an Allen-Bradley Programmable Logic Controller, were integrated with the power amplifier and successfully tested. The SSC standard for supervisory controls was to have been based on single-board computers on a VME/VXI bus, and work had begun on developing a replacement supervisory control system which would have been more representative of those required for subsequent Linac modules. The low-level RF control system was based on the In-phase and Quadrature system.[23] It was commissioned at SSCL, tested with a cavity load and a klystron simulator, and integrated with the power amplifier. Supervisory controls for the low-level system were based upon the system developed for GTA.[24]

The RFQ was equipped with beam position monitors, toroids, and wire scanners as part of the permanent instrumentation suite, and a diagnostic cart was assembled that provided, in addition, a longitudinal and transverse emittance measurement capability during commissioning. Vane voltage calibrations were verified by bremsstrahlung end point measurement.

All the RF accelerating cavities, including that of the RFQ, would have had their operating resonant frequency matched to the drive frequency by adjustment of operating temperature. To this end, each was to have been provided with a closed loop cooling/heating system in which the temperature setpoint could be adjusted either manually or automatically on the basis of a resonance error signal derived from the low-level RF control system. This system was tested on the RFQ and worked well.

Because all resonant structures have a relatively long thermal time constant, the ability to respond rapidly to a request to service any of the Linac users would have depended on the accuracy with which the temperature control unit could hold the resonator on tune, and on the difference between the temperature distribution characteristic of an RF driven structure and one heated only through the water system. Experience[18-22] on the RFQ seemed to indicate that the RF system was sufficiently close to resonance when heated only with water that rapid RF turn on would be possible.

Drift Tube Linac Input Matching Section

(M. Haworth)

Matching from the RFQ into the DTL[25-28] was foreseen as one of the operations most critical to preservation of beam transverse emittance. The original Linac plan included (for reliability) two ion source/LEBT/RFQ systems matched into the single DTL in a sophisticated 120° switchyard. During 1991, it was decided that the reliability requirement would not be fully in force until the Collider began operation in 1999. Shortage of internal engineering resources, a growing appreciation of the difficulty of designing and engineering a satisfactory switchyard, and a renewed emphasis on cost led to a decision to abandon dual injectors and revert to a simpler, straight-ahead matching section. This transition replaced a system of 4 bunchers, 3 dipoles, and 14 permanent magnet quadrupoles with a much simpler one consisting of 2 bunchers and 4 variable gradient permanent magnet quadrupoles (see Table 3-3). Detailed design of subsystems and components was well advanced. Commissioning was to have begun in 1993, but it never occurred even though manufacture of components was about 90% complete.

Table 3-3. DTL Input Matching Section Technical Parameters.

Length		600 mm	
Bunchers:			
Number		2	
Type		Double-gap	
Frequency		427.617 MHz	
Peak Voltage (E_0TL)		136/146 kV	
Power required		30 kW	
Quadrupoles:			
Number		4	
Type		Variable Gradient PMQs	
Gradient		30 - 100 T/m	
Bore		24 mm	
Instrumentation:			
Beam Position Monitors	3	Toroids	2
Wire Scanners	2	Slit & Collector	1 set
Segmented Aperture	1	Faraday Cup	1

Drift Tube Linac

(M. Haworth)

The main components of the DTL were being obtained from industry after competitive bid. The four Alvarez tanks were being manufactured by AccSys Technology, Inc.,[29] the klystrons had been constructed, tested, and delivered by Thompson CSF, and the pulse modulator order was placed with Maxwell Laboratories, Inc., Balboa Division. Both the tank and modulator contracts were about 75% complete at the time of termination (see Table 3-4).

The gradient in tank 1 was ramped, and the field everywhere was post-stabilized. The phase of the RF in the last two cells of tanks 1 through 3 and the first two cells of tanks 2 through 4 was adjusted to provide extra longitudinal focusing through the intertank space. This was initially achieved by moving the gap centers, which had the unintended effect of producing a field tilt. Although the tilt could have been corrected using the post stabilizers, an alternative solution was developed that restored field flatness without using up any of the post stabilizer operating range.[30,31]

Table 3-4. DTL Technical Parameters.

Length	Cells	Output Energy	RF	Power Required
Tank 1	4.499 m	56 cells	13.41 MeV	1.187 MW
Tank 2	5.956 m	40 cells	32.84 MeV	2.333 MW
Tank 3	6.063 m	30 cells	51.59 MeV	2.360 MW
Tank 4	6.258 m	26 cells	70.00 MeV	2.387 MW

Peak RF power available		4 MW	
Permanent Magnet Quadrupoles		156 / Sm_2Co_{17}	
Quadrupole Gradient (-0 %, +5 %, sorted)		132.7 T/m	
Quadrupole Bore		18.5 mm	
Design Transverse Emittance (n, rms)			
Input		0.20 π mm-mrad	
Output		0.21 π mm-mrad	
Instrumentation:			
Beam Loss Monitors	3	Beam Position Monitors	6
Toroids	3	Wire Scanners	3
Absorber / Collectors	3	Diagnostic Pods	3

Coupled-Cavity Linac Input Matching Section

(C-G. Yao)

The frequency tripling which occurred at this point in the accelerator made it critical to carefully design the section for minimum emittance growth. Fortunately, the beam energy was 70 MeV, which provided sufficient longitudinal space and beam stiffness for solutions to be reasonably easily implemented. (See Table 3-5.)

Table 3-5. CCL Input Matching Section Technical Parameters.

Length		2.9526 m	
Bunchers:			
Number		2	
Type		CCL sections	
Frequency		1282.851 MHz	
Peak Voltage		1.2 / 1.8 MV	
Power required		426 / 657 kW	
Quadrupoles:			
Number		9	
Type		Electromagnet	
Gradient		40 T/m	
Bore		23 mm	
Instrumentation:			
Beam Position Monitors	3	Toroids	3
Wire Scanners	3	Slit & Collector	1 set
Beam Loss Monitors	3	Bunch Shape Monitor	1
Absorber / Collector	1	Diagnostic Pods	4
Design Output Transverse Emittance (n, rms)		0.21 π mm-mrad	

Coupled-Cavity Linac

(C-G. Yao)

The CCL design was extensively modified during 1991.[33,37,38] (See Table 3-6.)

Table 3-6. Final CCL Technical Parameters.

Frequency	1282.851 MHz
Input Energy	70 MeV
Output Energy	600 MeV
Number of modules / tanks	9 / 72
Peak Surface Field	32 MV/m ($1.0 \times E_{Kilpatrick}$)
Field Gradient (E_0T)	7.2 - 6.55 MV/m
Synchronous Phase	–25°
Amplitude Stability	± 0.5%
Phase Stability	± 0.5°
Magnet Lattice	F0D0
Length	112.41 m
Bore Radius	10.0 mm
First Neighbor Coupling Constant	6 – 7%
Intertank & Intermodule Spaces	
Modules 1 and 2	$7/2\ \beta\lambda$
Modules 3 - 9	$5/2\ \beta\lambda$
Bridge Couplers:	Multi-cell magnetic
Number	63
Coupling Constant	≈ 12%
Transverse Emittance (n, rms)	
Input	0.22 π mm-mrad
Output	≤ 0.25 π mm-mrad

Design for Reduced Emittance Growth

The initial impetus for redesign of the side-coupled Linac was the increased transverse emittance growth in the CCL, associated primarily with frequency tripling and the changes previously mentioned in the RFQ. The mechanism that drove emittance growth was coupling between position in longitudinal phase and the magnitude of the RF defocusing force. The original design had a predicted emittance growth through this mechanism of approximately 30%. After the RFQ change, emittance growth was predicted to be about 50%, which was clearly not compatible with producing a beam within the emittance specification[32] of Table 3-1.

A secondary motivation was provided by the need to minimize costs wherever it was possible to do so without jeopardizing technical performance. This manifested itself in the CCL as an attempt to reduce the number of klystrons. In the original design, the CCL was sub-divided into 10 modules of 6 tanks, each powered by a klystron. The first and last tanks in each module consisted of 20 cells, while the remainder had 22 cells. Space on the beam line provided by the shorter tanks was used to house instrumentation.

Bridge couplers in the original design were 5/2 $\beta\lambda$ long in modules 1 to 5, and 3/2 $\beta\lambda$ long in modules 6 to 10. Intermodular spaces were 9/2 $\beta\lambda$ and 7/2 $\beta\lambda$ in the first five and four modules, respectively. Pulsed quadrupoles between each pair of tanks provided a FODO transport channel. For ease of manufacture, all cells in any given tank were designed for the same value of β. To make optical properties approximately independent of current, the accelerating gradient was ramped from ≈1 MV/m to the equilibrium value of 6.6 MV/m in the first two tanks of module 1.

It was observed that coherent synchrotron motion was the cause of the emittance growth, through the mechanism cited earlier. This occurred even in the case of zero injection phase error because of the ion β variation in a tank designed for constant β. It was further observed that the motion was made more complex by the biperiodicity in longitudinal focusing arising from two different tank lengths. The first part of the solution was, therefore, to reduce the magnitude of the oscillation by reducing the number of cells per tank and increasing the number of tanks per module. Next it was decided to keep the number of accelerating cells in each tank the same, and to eliminate the practice of having longer intermodular spaces in which to install instrumentation. This increased the number of quadrupoles and decreased their spacing, leading to a further reduction in average beam size and in the non-linear r-z coupling leading to emittance growth. This lattice, which became very smooth and regular in all three phase planes, essentially eliminated emittance growth.

The most serious problem arising from these changes was the elimination of extra space between the modules for diagnostics. A special effort on compact quadrupoles, diagnostic boxes, and flanges produced designs for these components that were consistent with available space, as set out in Table 3-6. The diagnostic plan for the CCL was further refined to provide space for diagnostics between each tank, rather than just between each module. Although permanent installation of measuring instruments at each of these locations could be neither justified nor afforded, the ability to concentrate diagnostic elements in critical locations as needed would have provided the flexibility necessary to achieve the ambitious goals for beam quality. The problem of predicting the precise optimum location for a fixed set of instruments was exacerbated by the large transverse phase advance in this design ($60° \leq \sigma_t \leq 80°$).

Design for Fewer Klystrons

In examining the potential for reconfiguring the CCL for fewer RF power modules, several power-saving elements were found. First, the reduction in beam size everywhere allowed a reduction in bore radius, even while the ratio of maximum beam size to bore radius was decreased. This allowed the basic cavity to be redesigned for an improved shunt impedance. Second, other minor cavity geometry changes contributed a few percent increase in shunt efficiency, as well as a small reduction in peak surface electric field. Third, re-evaluation of the ramped gradient section in the first module showed that, while the concept was valid and the match to the CCL was essentially independent of current, the penalty associated with forgoing the option was negligible.

At the same time, however, concern had developed over the potential for difficulties in driving the long assemblies of coupled resonators. It was concluded that the design coupling constant of 5% was certainly too low, and it was raised to 7% in modules 1 to 5, and 6% in modules 6 to 9. This change used up essentially all the power saved, so that the only way to reduce the number of RF stations was to reduce the power margin in the klystrons. Fortunately, the original designers had wisely included a power reserve of approximately 75% over the amount required to establish the fields in the cavities and accelerate beam. By reconfiguring the 10 modules of 6 tanks into 9 modules of 8 shorter tanks driven at slightly higher gradient, it became possible to achieve the same performance with one less klystron, while maintaining a margin for waveguide loss, control, and klystron aging of 63%. At the same time, the design improvement referred to in the preceding paragraph allowed this to be done without increasing the peak surface electric field above $1.0 \times E_{Kilpatrick}$.

Bridge coupler design was also revisited. The "standard" TM_{010} design used at both Los Alamos Meson Proton Facility (LAMPF) and Fermi National Accelerator Laboratory (Fermilab) had proven to be difficult to tune, and would have been challenging in the higher β modules. Several[34-36] alternative design concepts were analyzed numerically and modeled at low power. The final choice of a magnetically-coupled multi-cell design was motivated by its high internal coupling co-efficient, which provided low power flow phase shifts and high group velocities through the couplers, and relative ease of fabrication and tuning.

Although the concern about the number of cells per module[39,40] was first addressed in the context of the improved design, it should be noted that the final design had almost exactly the same number of cells per module as did the original.

Design for International Production: China

The well-known requirement for substantial international contributions to the project led to favorable consideration of a proposal from the Institute for High Energy Physics[41], Academica Sinica, Beijing, (IHEP) for a collaboration in the construction of the CCL. IHEP successfully constructed the Beijing Electron-Positron Collider (BEPC), after which the Linac component is closely modeled on the standard SLAC 2856 MHz traveling wave design. IHEP subsequently provided many other accelerating columns of this design to other institutes around the world. IHEP's lack of direct experience in design, construction, and tuning of side-coupled proton Linacs, however, led to the hosting of several Chinese scientists and engineers over the last year of the project for the purpose of training them in the specialized techniques of assembly, tuning, and testing that had to be applied to the Linacs.

SSCL engineering resources were strained beyond the breaking point in attempting to implement this approach. Fortunately, it was possible to purchase engineering services from the AT Division at Los Alamos, who also proposed and implemented an automated drawing scheme. Although it took some time to set up, the scheme sped up enormously the process of generating the roughly 2000 drawings needed for the CCL. Considerable physics advice was also gratefully received, and, although it was not always incorporated in the final design, it was always valuable in the way it identified and focused attention on important technical issues.

Design for International Production: India

The design effort on compact quadrupoles was carried out, to the prototype stage, using internal SSCL resources. The offer of a contribution from India, however, led to the identification of these quadrupoles, and other magnets in the Linac-LEB transport/transfer lines, as a suitable area for contribution. Accordingly, an engineer from the Indian Center for Advanced Technology in Indore spent several months at the SSCL, and reviewed the magnet designs for physics and manufacturability. Eventually, however, the interim agreement with India lapsed, and it could not be restored before the project was canceled.

Although originally proposed as pulsed magnets to minimize cooling requirements, it was decided to change to DC magnets to economize on power supply and control costs. The new requirement to support provision of beams to the proton therapy facility, however, implied laminated magnets with short time constants. A requirement was imposed that the field in the CCL and transport line quadrupoles be switched between 600 MeV and 70 Mev settings between Linac pulses, because the plan was to drift the lower energy beams through all or part of the CCL without acceleration. Those modules not required for a particular beam energy would still receive a standard RF drive pulse, but it would not arrive at the module coincident with the beam.

Transport Line

(M. Haworth)

The Transport Line[48] was required to guide the H^- beam from the end of the 600 MeV CCL to the beginning of the Transfer Line to the LEB. If it were to be desired at some future date to reduce emittance growth in the LEB by increasing the Linac output energy, the Transport Line would have been removed and replaced with additional CCL modules.

The Transport Line was a FODO array with 90° phase advance. It used quadrupoles with 23 mm aperture diameter, identical to those used in the CCL. Two prototypes were fabricated and field measured, and the measured and calculated field properties compared very well. Industrial production of 106 quadrupoles was to have begun in the summer of 1993. All the magnets had built-in steering coils which were to be selectively energized. Four picture-frame-type steering magnets were provided at the beginning of the line to align the CCL beam onto the optic axis with the help of four position monitors. Diagnostic elements, e.g., position monitors, toroids, wire scanners, were the same as those on the CCL. Wire scanners were to be used to tune the first four matching quadrupoles, which were independently excited. It was planned to use a least-square-fitting technique with deviations in beam sizes from matched values as dependent, and quadrupole currents as independent variables. The nineteen quadrupoles that formed the FODO array were energized using two power supplies. The last two quadrupoles were used for phase space matching. There were three beam alignment systems in each plane, and each system consisted of two steerers and two position monitors.

Transfer Line

(M. Haworth)

The Transfer Line[48,55,56] had a larger cross section, in general, than did the Transport Line. It used quadrupoles with aperture diameter of 75 mm. Industrially produced prototypes of these quadrupoles and steering magnets were available for measurement in late 1993. There were two 8° and one 4° bends on this line. Each 8° bend consisted of two 4° dipole magnets 0.5 m apart. Thus five identical 4° dipoles were being built, each a 1 m-long rectangular magnet. Maximum bending field was restricted to 4 kG at 1 GeV to limit losses due to Lorentz stripping of the

H^- ions in the beamline to 0.1%.[3] Splitting the 8° bends offered another advantage, in that scraped beam was diverted toward H^+ absorbers without experiencing strong edge defocusing effects. Dipole magnets were designed to keep $\Delta B/B$ due to the sextupole component below 1×10^{-4} at 1 cm from the central ray. This eliminated the need for discrete sextupole magnets, which were earlier provided to minimize phase space distortion at the dispersive point at the center of the achromat formed by two 8° bends. A prototype dipole would have been assembled in-house by September 1993. All the magnets were designed for operation up to 1 GeV energy.

The number of cells in the energy compressor cavity was reduced to 11, from the earlier 20, to keep phase shift for the RF drive low at the onset of the beam loading. At the same time, the total power requirement was also kept low. The primary function of this cavity was to reduce the energy spread of the beam, but it also corrected for the energy jitter due to CCL instabilities.

Two scrapers, installed upstream of the first 8° bend, scraped particles very much off in position and angle in each transverse plane. Ray tracing calculations, using TURTLE, showed that most scraped particles (H^+) could be transported to the absorbers without hitting beamline components. Similar results were obtained for the off momentum particles scraped at the center of the achromat. In both case, the particles did not enter the second 4° dipole of the 8° bends. Instead, they came out of the exit edge of the first 4° dipole and traveled straight to the absorber. Beam steering was achieved using a position monitor near every quadrupole cluster and a steerer placed upstream. The last two steerers in each plane allowed near orthogonal control of position and angle at the injection point.

LEB Injection Girder

(M. Haworth)

During injection, four identical bump magnets, excited in series by one power supply, were to bump the circulating beam by 47.2 mm from the LEB closed orbit.[57,58] Each bump magnet had a magnetic length of 0.6 m. A 1.4 m long septum magnet separated the injected beam from the circulating beam. An iron shield between the two magnets minimized the magnetic field interaction. The bump magnets were to have a flattop time of 35 ms. While the rise time was not critical, the fall time was to be as short as possible. The excitation waveform for the septum magnet was a 1.5 ms half sine wave. The magnets were to be made using thin (0.05 mm) laminations in form of a tape wound core. All would have been designed to operate at 4 kG peak field at 1 GeV. Mechanical designs were completed and the prototypes were expected to be supplied by industry in October 1993. The bump magnets required ceramic vacuum chambers to eliminate eddy current effects.

The H^- beam was to be stripped to H^+ with 95% efficiency, using a 200–250 mg/cm^2 thick carbon foil placed midway between bump 2 and bump 3. Over 4% of the incoming beam would have been converted into H^0 while the rest remained as H^-. The H^0 beam traveled undeflected to a beam stop at the exit of bump 4. The H^- beam, bent to the left by bump 3, came out into the air through a thin window to fall on the same beam stop. The intensity of this beam was to be monitored, and an unusual rise would indicate foil rupture. Two position monitors, downstream of bump 4 on the LEB ring, were to be used to align the injected beam. A foil positioning mechanism was provided to hold spare foils and a TV-viewed flag, and to allow changing them without breaking vacuum.

Conventional Facilities

(R. Cutler)

Requirements Committee

In December 1990, a Linac Conventional Construction Requirements Committee was formed, consisting of representatives from Accelerator Systems Division (ASD), Conventional Construction Division (CCD), and Accelerator Design and Operation Division (ADOD) (later to become the Project Management Office [PMO]). This committee was charged with developing the preliminary design requirements for the Linac building and tunnel and with defining the utilities (electric power, LCW, Racks, and cable trays) to be needed.

The committee report[69] was produced in February 1991. The CCD estimate of the cost of the facility exceeded the Baseline Cost Estimate (BCE) by nearly a factor of two.[72] A delay of several months ensued as methods were explored to reduce construction costs. Several cost savings were instituted, including elimination of cranes, ceiling height reductions, building width reductions, tunnel height reductions, tunnel width reductions, reduction of berm radiation shielding, and elimination of windows in the building.

Title I, Title II, and Issue for Bid Drawings; Contract Award and Construction

The design requirements were turned over to Parsons Brinckerhoff/Morrison-Knudsen (PB/MK) and Title I drawings had been developed by July 1991, Title II drawings by January 1992, and Issue for Bid drawings by March 1992. The construction contract was awarded in May 1992, calling for completion one year later. Some problems were encountered with the contractor concerning quality control on floor tolerances and waveguide locations, but these were eventually resolved.

Several changes were made during the progress of the contract. The first was the incorporation of a proton therapy tunnel stub for a future medical facility, which was incorporated into the contract as a change order. A second change was needed to satisfy a new requirement that no LCW could leave technical buildings because of concerns over activation. The requirement necessitated more room in each of the machine buildings to allow for heat exchangers and LCW systems, instead of booster pumps. The three original pump rooms were then combined into one large room.

During the contract period, PB/MK monitored the contractor with oversight by CCD and PMO. A weekly meeting reviewed construction progress and problems. Beneficial Occupancy was achieved in August 1993, about 4 months behind schedule. All building systems were complete, except for a gas supply for the heating system. An award for the LCW pump room was pending at the time of project cancellation.

Utilities

Utilities are defined as electrical power wiring, cable trays, LCW system, equipment racks, and compressed air. At the time of project termination, the contracts for installation of this equipment were on hold while attempts were made to reconcile the serious underestimate of utilities costs in the BCE.

Radiation Safety Problems

In late 1992, a preliminary radiation safety guideline issued by the SSC[73] reduced the allowed radiation exposure to both radiation workers and the general public by a factor of 40 from DOE guidelines and required that all personnel safety systems be passive. The guidelines, coming late in the Linac design cycle, would have had an impact on Linac operations. Additional shielding, not allowed for in the original building design or cost estimate, would have been needed around the source area and around the waveguide penetrations. At the time of termination, additional funds were being requested to make it possible to meet the new radiation guidelines.

Installation

(F. Spinos)

The Linac was uniquely a series of inter-dependent accelerators that would accelerate ions to an energy of 600 Mev. Starting at the Ion Source, each component required a previous component to accomplish acceleration of ions, thus dictating that each component be installed, tested, and commissioned before the next in the series was installed. In general, the installation requirements were labor intensive and required the purchase of fixed price and task order subcontract labor, the purchase of the equipment and the incidental hardware to perform Linac installation, and the purchase of materials and services for some support systems. Installation procurement did not include the purchase of the major machine components, although the tracking of component devices through procurement was an installation effort.

Installation procurements included contracts for equipment rack and cable tray installation, absorber installation, RF wave guide installation contract, building pedestal crane installation, fork and scissor lifts, tools and miscellaneous hardware, a tunnel and gallery mobile reverse booming crane, ion source, DTL, CCL, transport line, transfer line, and other fixed price task order sub-contracts. The Linac mechanical installation was planned to be 12 to 15 man-years of effort including contract, budget, and first line project management, subcontract field supervision, bottoms-up cost estimating, performance tracking, installation data base development, issuing installation process specification, and supporting design engineering.

AC Power Distribution and Electrical Installations

The installation functions included determining the panel loading, cable sizing, cable routing, earth ground schemes, the pulling and terminating of power and ground cables, and purchasing the cables and hardware associated with the 120V/208V/480V AC power installation. At the beneficial occupancy date (BOD), CCD/PB/MK was expected to provide 120V/208V/480V power panels, 120V wall receptacles, and lighting for the above and below ground Linac facilities. Power panels were not included in the construction of the Source Area but were included in the Linac Gallery.

ASD/Mech Installation was expected to bring 120V/208V/480V Power to a Source Area Panel and to distribute the required power to Source Area racks, devices, and equipment. The Group was also expected to distribute 120V/208V/480V power from the CCD provided power panels to the racks, devices, and equipment in the Linac Tunnel and Gallery. As required by ASD/EE and ASD/ME Groups and Linac RF, the Installation Group would provide the labor force for the routing, pulling, and terminating of cables for electronic devices and installing electronic equipment. ASD/EE with support from ASD/ME Utility would provide the Design Engineering and design packages (e.g., materials, parts lists, drawings) required for Installation Labor contracts.

The plan was to let the ASD/Mech Section issue a fixed price service subcontract for distributing 120V AC Power from the power panels to equipment racks in the Source Area, the Linac Gallery, and the Linac Tunnels and tie the racks to the building grounding system. Also, the plan would have subcontracted the distribution of 208V/480V AC power from the CCD power panels for the Linac RF systems and for the installation of a Source Area Power Panel along with the distribution of the Source Area 208V/480V AC power. The contractor would have received design requirements from ASD/EE, Linac RF, and ASD/Mech Groups and have been expected to provide services that would include: hardware and cables; the labor for installing (routing and terminating cables) the designed 120 VAC, 208 VAC, and 480 VAC systems electronic equipment; and the pulling, terminating, and connecting of control cables, signal cables, and power cables to respective electronic devices as required by the ASD/EE, Linac RF, and ASD/Mech Groups. The contract would have been managed as a coordinated effort between ASD/EE and ASD/Mech Sections and the Linac RF Group.

Vacuum Systems

The Source, LEBT, RFQ, Matching Sections, and DTL would have been delivered with vacuum systems (pumps, valves, flanges, isolation valves and vacuum controls) as part of their equipment packages. The CCL would have been delivered with a vacuum manifold as part of a CCL Module assembly. The Linac Transport and Transfer line beam tubes and vacuum system and the CCL vacuum system and equipment were to be designed and provided by ASD/Mech Vacuum Group.

The ASD/Mech Installation Group was to install and assemble the CCL vacuum manifold and the vacuum system and vacuum system controls, vacuum pumps, and isolation systems for the Source, LEBT, RFQ, the Matching Sections, DTL, and CCL. The group would also install the Transport and Transfer Beam Line beam pipe, vacuum system, vacuum system controls, vacuum pumps, and isolation systems.

ASD/Mech Vacuum Group provided technical expertise and consultation to the design of Source, LEBT, RFQ, and DTL vacuum systems. They were also procuring for and providing the specifications for the CCL, Matching Sections, and the Transport and Transfer Beam Line vacuum systems, interface to controls, vacuum pumps, and respective power supplies and gauges.

Mechanical Installation

The ASD/Mech Install Group would have provided a vacuum leak check service with ASNT Certified Technician for all Linac devices, systems, and assemblies that were required to be leak tight. This service would have been on going for subassemblies, completed assemblies, subsystems, and systems during all phases of installation and commissioning. The mechanical installation for Linac by the ASD/Mech Install Group would have included the rigging, anchoring, assembling, welding, and aligning of the Linac devices and equipment shown in Table 3-7.

Table 3-7. Equipment to be Installed for Linac Devices.

Devices	Equipment
Ion Source	vacuum pumps
LEBT	beam tubes
RFQ	klystrons
DTL's	modulators
BPM's	wave guides
Linac Quads	respective support structures in the Linac Gallery & Tunnel
CCL	respective support structures in the Source Area
Matching Sections	respective support structures in the Transport and Transfer beamline

The mechanical installation for Linac also included: the design and procurement of support stands and support equipment for the DTL & CCL; matching Sections, the DTL Inter-Tanks, and all the Transport and Transfer beamline components and devices; the connecting of devices and equipment to the instrument air system and Linac LCW (Low Conductivity Water) cooling water manifolds; the installation of temperature control carts and portable shield walls, as required, to accommodate both installation and commissioning schedules; the installation of cable trays, equipment racks, and instrument air and (LCW) cooling water systems through fixed price subcontracts managed by the ASD/Mech Utilities Group; the installation of the Linac Abort System and Commissioning shield walls; the pre-installation assembling, testing, handling, receiving, warehousing and delivery of major components, supporting devices, and installation hardware; and data entry and daily logging of installation certifications, equipment installation, procedure change and design modifications.

Commissioning Plans

(J. Hurd)

The SSCL Linac was to be commissioned[45,47,49-53] in stages. Each major segment[6] of the Linac was to be installed, RF conditioned,[20] and then commissioned with beam. The stages and components to be commissioned in each section were ion source and low energy transport, RFQ, RFQ-DTL matching section, DTL tank 1, DTL tank 2, DTL tank 3, DTL tank 4 and DTL-CCL matching section, CCL module 1, and CCL modules 2-9, and transports to the LEB.

To successfully meet the brightness requirements, it was considered necessary to quantify and understand each section separately. This could not be done after completion of the Linac, because of the lack of adequate space for diagnostics in the final configuration. Limited diagnostics were imposed by the design requirements and resulting physical space limitations. Much like the GTA accelerator,[59,60,61] each segment had to measured and understood separately after installation.

The basic parameterization of the Linac could be sub-divided as follows: (1) Transmission parameters: losses, activation, and radiation levels; capture; and acceptance mapping.
(2) Transverse parameters: steering, alignment, envelope, match, and transverse emittance.
(3) Longitudinal parameters: RF phase and amplitude, longitudinal match, beam phase and energy, and longitudinal emittance.

Not all characteristics could be measured for all sections. The experiments were tailored to measure the critical beam and machine parameters of each section that could be measured with standard beam instrumentation.

The first parts of the Linac, an Ion Source, LEBT, and RFQ[8,9,12,14,18,20-22] were installed in a lab at the Central Facility (CF) and commissioned. Procedures were developed for submission, review, and approval of experimental plans, recording results, and review. (See Table 3-8.)

Table 3-8. Summary of Linac Machine Studies.

Experiment Title	Lead Experimenter	Date Submitted	Approved / Deferred / Disapproved	Scheduled / Deferred (Date)	Report (Document Control No.)
Rutherford Scattering Beam Energy Measurement	P. Ferrel / G. Arbique	4/22/92	Approved	June 14–18	Complete.
Bunch Shape Scan	J. Hurd	4/22/92	Approved	May 9–10	SSCL-Preprint-374
LEBT Faraday Cup	G. Arbique	4/22/92	Approved	Current	
Experimental Test Plan to Investigate Unexpected Radiation Levels Measured on the Linac Injector on 12-April-93	K. Saadatmand	4/22/92	Approved	April 26–27	Complete
ε_t Measurement I, Using Existing Hardware and Software	K. Saadatmand	4/22/92	Approved	May 3–7	
ε_t Measurement II, Using New Hardware and Software	K. Saadatmand	4/22/92	Approved	July 5–9	
RFQ Entrance Aperture and Faraday Cup.	G. Arbique	5/7/93	Approved	From May 7	
Transverse Emittance as a Function of Time	J. Hurd	6/4/93	Approved	Deferred	
Longitudinal RMS Emittance Using BSM	J. Hurd	6/4/93	Approved	Deferred	
Longitudinal RMS Emittance Using BSM & Spectrometer	J. Hurd	6/4/93	Deferred	Deferred	

To commission the Linac, a special suite of diagnostics was required,[49] in addition to the normal set of diagnostics.[51] Two important diagnostics, the Bunch Shape Monitor[53,62,63] and the new Slit-and-Collector Emittance Measurement Unit were successfully tested. Both units utilized advanced design and were capable of measuring the time dependence of the beam bunch shape and transverse emittance. The new emittance gear utilized a new, low-cost, high speed digitizer designed by SSCL in collaboration with Allied Signal, Kansas City Division,[64] and a new emittance re-analysis code, EMAP,[65] based on the LANL code REANE. Other special diagnostics under development included harps,[66] wire scanners,[67] and absorber collectors.[68] In support of the commissioning effort, simulation and analysis codes were being written.[47,50,67] Of special interest was a new procedure and code developed for setting RF phase and amplitude.[47] Commissioning of the SSCL Linac was planned and well under way at the end of the project. Good results were starting to emerge, advancing the state-of-the art in some cases.

System Safety

(V. Oliphant)

The System Safety engineering and management process was started early in the design of the Linac with the creation and acceptance of a plan describing what was to be evaluated, how it was to be evaluated, and when. The Linac was the first to form a working group composed of a system safety engineer, a systems engineer, and Linac section leaders. The group was to act as a review group for all hazard analyses that were done.

The hazard analysis process involved using the actual design engineers to conduct hazard analyses and safety assessments of their system designs and operations. The concept of delegating detailed hazard analysis tasks to the individuals closest to potential safety problems was first used on the ASST and perfected on the Linac. It proved to be the best method of identifying potential hazards and implementing hazard prevention, elimination, and mitigation methods. Once each analysis was complete, risk assessments were performed and mitigation methods or prudent corrective actions were recommended to minimize risk. The final step in the Linac hazard analysis process was for the working group to review and either approve the analyses or make recommendations on how to make the situation better. This was sometimes an iterative process from which a better design evolved. Preliminary hazard analyses were requested for Linac PDRs, and final hazard analyses were required for CDRs.

A Safety Analysis Report was generated from the detailed hazards analyses. The accuracy of this very important document was verified by all affected personnel in both the Linac and the ASD groups. Once it was verified as accurate, it was approved by the Lab and sent to DOE for concurrence. The next step validated the safety report. A system for hazard tracking (with accountability) was created to complete the closed loop system of Hazard Identification, Risk Assessment, Mitigation, and Tracking to resolution. The system verified that the system hazards had been mitigated and that risks were reduced to an acceptable level. The verification was system safety's input to a readiness review.

The Linac readiness review process[46] was developed as a multilevel, multidisciplinary independent review to demonstrate that the facility, equipment, procedures, and personnel were, in fact, ready to start operations. Readiness was demonstrated through presentations, documentation, and walkthroughs. Once the independent review panel was satisfied, a request was sent through the Laboratory Director to DOE requesting a permit to operate. To make the request process more efficient, a checklist was created that demonstrated accountability by requiring the signatures of the responsible engineer, the machine leader, and the readiness review committee attesting that each requirement had been met. This led to efficient readiness reviews and successful requests for permits to operate. The processes developed for the Linac became benchmarks for the rest of the Lab.

Machine Studies and Operational Safety

(W. Funk)

Continuous improvement in the performance and reliability of the Linac was a major long-term goal. Proposals for improvement would have required validation through experimentation with the Linac itself. The experiments were to be conducted as "machine studies," and the conduct of machine studies required controls. A Machine Studies Management Plan was devised, reviewed, and imposed to ensure quality and timeliness in the studies and to ensure that the safety implications of the proposed experiments were reviewed, new hazards were mitigated, and mitigations of existing hazards were not compromised.

The approach was to develop a series of procedures that retained the maximum amount of flexibility in, and local control of, the ability to plan and conduct machine studies consistent with imperatives of safety and quality. The Machine Studies Management Committee was formed, chaired by the Linac Group Leader, and consisting of the Chief Linac Scientist (appointed by the Linac Group Leader), and the Chief Operator (appointed by the Head of the Accelerator Operations Department). The Linac Group Leader was responsible for day-to-day management and scheduling of the machine studies program. He had overall responsibility for ensuring that the machine studies were well conceived, carefully planned, and carried out in accordance with Laboratory policies and procedures, particularly as regards safety.

It was recognized that any experimental plan could be subject to a requirement for short-notice modification. To provide for this flexibility, the experimental team was required to obtain concurrence from the Chief Operator or his on-duty designate, and another authorized individual, not a member of the team, that all hazard variances had been identified and appropriately mitigated. Individuals who granted this authority were identified and qualified by the Machine Studies Management Committee and approved by the Head of the Accelerator Operations Division.

Quality Assurance

(S. Davis)

From August 16 to September 1, 1993, the QA Office performed an audit in accordance with all sections of the SSCL QA. Linac activities were also evaluated for compliance with the Project Management Plan, the Engineering Management Plan, and the Configuration Management Plan. The Audit Team evaluated activities by reviewing documentation, interviewing personnel, and observing activities, equipment, and facilities. As a result of the evaluation, several opportunities for improvement were identified by the Audit Team for PMO and ASD in the development and implementation of procedures for design control activities, configuration management of hardware and software, and performance of technical reviews.

Chapter 4. Low Energy Booster

(U. Wienands, T. Grimm, J. F. Knox-Seith, N. Li, S. Machida, N. K. Mahale, S. Tollefson, T. Webster, and X. Wu)

The Low Energy Booster (LEB) was to accelerate the Linac beam from 0.6 GeV to 11.1 GeV kinetic energy. Injection into the LEB is accomplished by stripping the H^- beam to H^+ using a carbon stripper foil in the injection straight, thus allowing for the accumulation of 4 turns for Collider operation and up to 20 turns for test beam operation. The LEB cycles at 10 Hz repetition rate to minimize the time spent by the beam at low energy where space-charge tune shift is most severe (up to -0.6). Extraction from the LEB is done with a single-turn extraction system using a set of fast kicker magnets and two magnetic septa. Total circumference of the ring is 570 m. The complete specifications for the machine can be found in Refs. [1] and [2].

Primary concern in the design was the preservation of the transverse beam emittance ($\varepsilon^* \approx 0.4\,\pi$ mm-mrad) to support high-luminosity operation of the Collider. To achieve this despite the substantial space-charge forces at injection, the machine is fast-cycling and transition has been pushed well beyond the extraction energy to prevent the tight bunching of the beam that occurs during transition crossing. Comprehensive LEB documentation is being prepared for publication at the time of termination.[3]

Magnet Lattice

The magnet lattice of the LEB is somewhat innovative. The ring has a three-fold symmetric separated-function FODO lattice, one arc and one straight section making up each triant. Each arc consists of four superperiods, each with three FODO cells, the central one being devoid of bending magnets. It has been shown[4] that such a superperiod will have a γ_t higher than its tune if the phase advance approaches 270 degrees. Dispersion will be fairly high in the empty arc cell, while being low or even negative in the bending cells and in the dipoles, which results in excellent chromatic stability. A slight modulation of the quadrupole strengths is introduced to set γ_t and the phase advance independently and to tune the arcs to be achromatic to 2nd order ($3 \times 2\pi$ phase advance), suppressing dispersion in the straight sections.

The straight sections consist of three FODO cells. Matching to the arcs is achieved by grouping the quadrupoles into four families, thus allowing the match of β_x and β_y, μ_x and μ_y. The straight has non-zero fractional phase advance to set the fractional tune of the ring, also ensuring zero dispersion.

The lattice functions, for one triant calculated using the code DIMAD,[5] are shown in Figure 4-1. The straight sections provide space for injection (S1), extraction (S2), the RF cavities (S3), and a variety of diagnostic and ancillary functions. Extensive tracking and analytic studies have demonstrated that the lattice optics would be extremely stable against chromatic aberration, magnet-to-magnet variations, mistracking of quadrupoles and dipoles, and other imperfections. The predicted dynamic aperture of the lattice with magnet imperfections included is well outside of the physical aperture.

The overall nominal (single-particle) working point of the LEB is $(\nu_x,\nu_y) = (11.65,11.60)$. A comprehensive set of individually controlled trim quadrupoles is provided to make it possible to vary the tune by ±0.5 in either plane independently (allowing for tune split) as well as to control the matching of the straight sections. It is foreseen that high-brightness operation will require adjustment of the working point at injection to (11.85,11.80) to accommodate the space-charge tune shift at injection.

The trim quadrupoles are used to correct half-integer stopbands, in particular the $2\nu_x=23$ resonance, which is not structural but will be crossed by the working point of the high-brightness beam. In addition, a set of 12 skew quadrupoles is being provided in the straight sections to correct linear sum and difference resonances. Third-integer resonances are corrected by suitable excitation of the chromaticity-correction sextupoles in the arcs; 12 additional skew sextupoles are used to correct skew-coupling resonances.

The LEB was about 25% completed at termination. With the exception of the RF cavity, R&D work is nearly completed. The concrete shell of the LEB tunnel is 90% complete, but no buildings have been erected. The energy storage inductors (ESI), which are major components of the Ring Magnet Power Supply (RMPS), are being delivered under Attachment 2 to the Interlaboratory Agreement with Budker Institute of Nuclear Physics (BINP) Novosibirsk, Russia. Prototypes for all LEB magnets have been built both in Russia and in the United States; measurements have been performed at BINP and at SSCL and are being documented in Ref. [3]. A prototype RF cavity has been built and assembled at SSCL and two tuner concepts have been tested: a conduction-cooled tuner designed and built by BINP and a directly cooled tuner designed and built at the SSCL. Prototypes have also been built for beam position monitors, dipole and quadrupole vacuum chambers, clocks for synchronization of the LEB with the MEB, extraction kickers and the quadrupole girders, all of which are described in more detail in the subsections of this chapter.

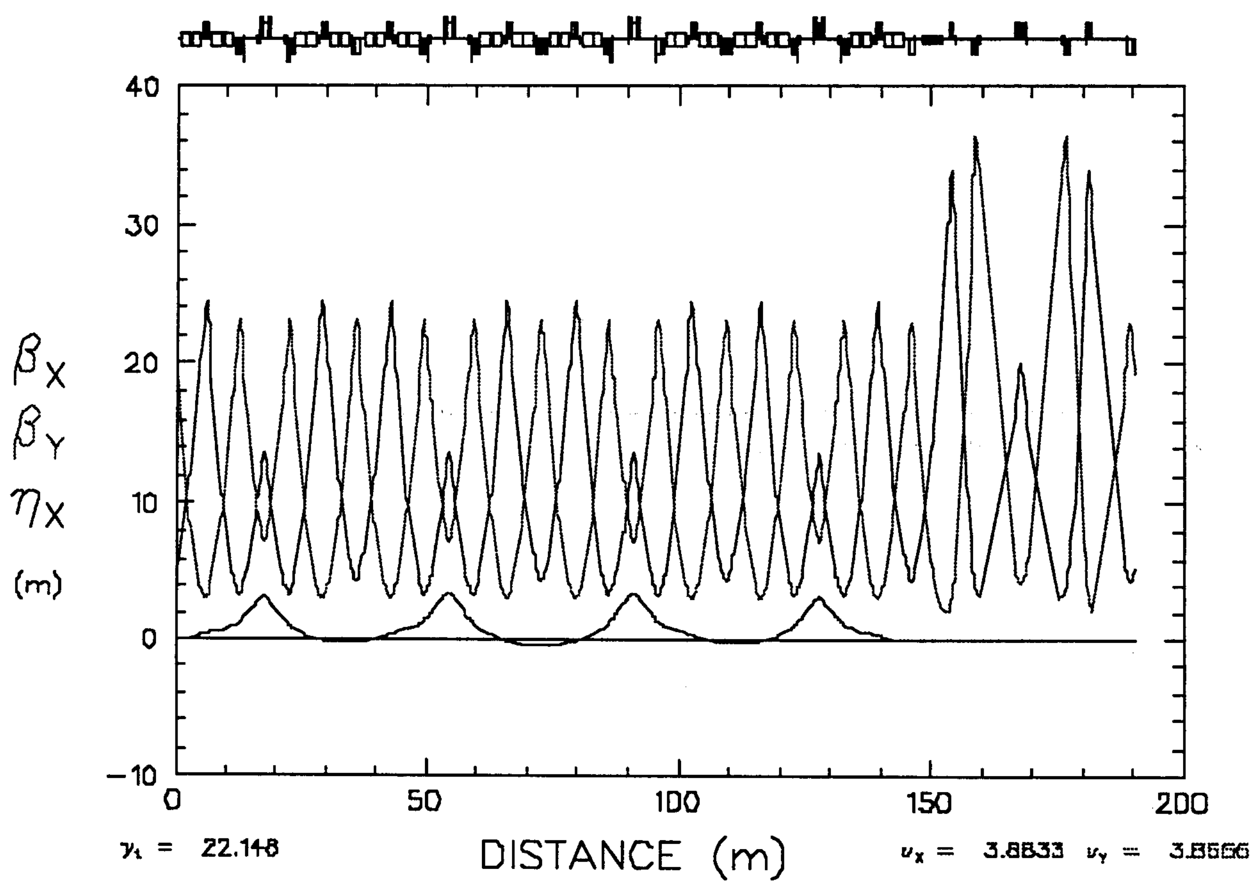


Figure 4-1. Lattice Functions.

Power Systems

Ring Magnet Power System

The LEB Ring Magnet Power Supply (RMPS) supports both a linear ramp at nominally 1/3 Hz repetition rate and a sinusoidal cycle at 10Hz repetition rate. This is done with one power supply design using the Fermilab modification of the "White" circuit. At 10 Hz the LEB ring magnets and the Energy Storage Inductors (ESI) together with the capacitance of 18 mF capacitor banks make up a resonant circuit excited by the power supply. The RMPS is subdivided into 12 such resonant cells. Each cell includes four dipoles and seven or nine quadrupoles and has a Q of about 40. Knife switches are used to disconnect the capacitors for non-resonant operation. The ESI, capacitor banks, and switches will be located on outdoor cement pads located symmetrically around the ring. Three identical power supplies are being used to keep the maximum voltage to ground below 2kV. The topology of the circuit is shown in Ref. [6].

The LEB specifications call for an accuracy of the magnet current of 10^{-4}, cycle-to-cycle. At low frequencies this is maintained by the regulation circuit. Passive filter networks are used in the magnet circuit to reduce noise and ripple levels on the magnet current to the 10^{-5} level. The regulation circuit is implemented digitally using signal processors and a sampling frequency of 1440 Hz. Regulation and interface to the control system is essentially done by the same system. Current information will be obtained using a DC current transducer mounted in the tunnel[7] with an accuracy better than 10^{-5}.

The modified White circuit presents a complex load to the power grid; a correction filter will improve the power factor to acceptable levels. Power distribution to the ring magnets is done using an air cooled copper bus for the supply rail, while the return rail (having fewer segments) is water cooled. All distribution subcomponents will be located on outdoor cement pads located near the three power supply buildings.

Corrector Power System

All 244 LEB corrector magnets are individually excited by a power amplifier controlled by the interface to the control system and powered by bulk power supplies, typically one bulk power supply feeding 8 to 16 amplifiers. Bandwidth requirements are driven by the necessity to apply dynamic corrections varying throughout the 10 Hz LEB cycle; this is required to program a certain variation of the working point, maintain matching of arcs and straight sections at all times, and correct eddy-current effects. The waveform of the magnet current is controlled by an arbitrary function generator loaded by the control system. Grouping of the corrector quadrupoles and sextupoles into families is done by software.

The ESI procurement will completed in April 1994. The design has proceeded to the point that technical specifications required for procurement are 95% complete for the following: AC converter transformers, AC switch gear, harmonic filter/power factor correction, DC power converters, and the DC bus. Preliminary design is 90% complete for the following: converter firing circuits, current and voltage regulation loops, and supervisory control system. Prototypes of these electronic systems are 50% complete. The RMPS control software is in the preliminary requirements definition stage. The corrector power supply was to be acquired in two parts, the power supply assembly and controls interface. The power supply assembly was to be purchased, and a requisition was ready for implementation. The controls interface was to be designed and built by the SSCL. A prototype had been completed at the time of termination.

Magnet System

The magnets confine and bend the proton beam inside the vacuum system. Because of the high cycling frequency, the maximum magnetic fields are moderate, 1.38 T for the dipoles and 0.8 T at the pole tip for the quadrupoles. The two-dimensional design of the magnets aimed to minimize body-field harmonics and maximize magnet efficiency; the design is discussed in Ref. [8]. An empirical approach was adopted for the 3D design of the end packs. To mitigate eddy-current effects at 10 Hz operation, 0.5 mm thin laminations made of high-resistivity silicon steel are used and current paths on the inside have been avoided. All magnets except for the skew sextupole are to be fabricated by BINP under Attachments 1 and 4 to the Interlaboratory Agreement SSC-92-W-11138.

Measurements of the prototype quadrupoles and dipoles have been carried out at the SSC Lab using rotating coil systems with long and short coils specifically designed for the LEB quadrupoles. Additional dipole measurements were carried out with a flat coil system designed and manufactured in house. BINP carried out Hall probe measurements of both dipoles and quadrupoles under DC and AC conditions. Evaluation of these results was still in progress as the Lab shut down.

Main Quadrupoles

All LEB quadrupoles use the same lamination and core design. To simplify fabrication and match the production facilities available at BINP, the laminations are not glued together. Delamination is prevented by a stainless steel rod through each pole tip clamping the core ends. The end packs are made from glued laminations. G10 blocks at each end of the core at the pole tip prevent delamination of the chamfered end packs. The iron core is stacked in quadrants. The lamination has protrusions ("ears") on one edge which are clamped together using rods sitting on the "ears." The four-quadrant design allows straight-forward assembly of the coils onto each quarter core. The brackets to hold the coils to the core in the main quadrupole are made of stainless steel. It has been suggested to slot the material to prevent eddy-current induced heating and magnetic fields.

Three main quadrupole prototypes have been built, one at Lawrence Berkeley Laboratory (LBL) and two at BINP. The LBL prototype has been measured both at LBL and at SSCL. Body field and integrated harmonics are acceptable and reasonably close to predictions. Saturation sets in at about 1% lower field than expected. Agreement between the measurements was generally good, but a skew sextupole absent in the LBL data was found at SSCL. It was attributed to mechanical deformation during transport. A lack of mechanical stability was noted and tracked to metal fatigue in the bolts clamping the quadrants together. The magnet was then used to fine-tune the end packs.

The second prototype was made at BINP and shipped to SSCL. Field harmonics were consistent with those of the LBL prototype, but the saturation field of the Russian steel was about 1% higher than of the U.S. steel. The magnet was then used to re-test the end pack design and to test the end pack design proposed by BINP. The SSC design had slightly better integral uniformity; however, with the BINP end pack, the effective length change with excitation was reduced compared to the SSCL end pack. This improved tracking between quadrupoles and dipoles.

Two prototype trim quadrupoles have been built and measured at SSCL, one each of the low-field and the high-field types. They differ in the coil configuration: the low-field quadrupole has air-cooled coils while the high-field quadrupole is water-cooled. The field quality of the high and low field quadrupole is acceptable. The low field quadrupole exhibits a measurable sextupole component, which is attributed to assembly errors. Because the quadrupole prototypes demonstrated the acceptability of the lamination, the quadrupole lamination die was approved for production.

Main Dipoles

The main dipole is a laminated H magnet using single-core laminations to minimize assembly tolerances and simplify core assembly (at the expense of requiring the disassembly of the vacuum system should a dipole need to be replaced). Angle irons are welded to the core along the magnet on all four corners to provide mechanical stability. Stainless Steel end plates prevent delamination of the end packs. Flat pancake coils are inserted through the center of the magnet. End packs are glued and welded laminations. The vacuum chamber in the dipole is made of Inconel 625 with a single eddy current correction coil. The calculated residual field errors are acceptable. AC measurements, planned for BINP, are in progress and will be documented in a separate report.

Three prototypes have been built, one at the Stanford Linear Accelerator Center (SLAC) and two at BINP; the first was shipped to SSCL for DC measurement, and the other has remained at BINP for DC and AC measurement. The body field transfer function of the BINP prototype was measured both at BINP and at SSCL, with NMR and Hall Probes at the approximate center of the magnet. Agreement between the measurements is reasonable. Some field-distribution measurements taken at BINP indicate that the body field is close to the design uniformity. The integrated field uniformity needs some improvement at injection. The integrated field strength of the dipole is lower than specified and will require operating at higher power supply currents. Tracking differences of the dipole and the quadrupole have been found to go beyond 1%, significantly exceeding expectations, with dipole saturation occurring at significantly higher currents than quadrupole saturation. End pack design adjustment of both quadrupoles and dipoles, as well as the properties of the steel used in the BINP prototypes, might have reduced this to a tolerable level. Work on this issue as well as the field uniformity was being completed as the project terminated.

Corrector Dipoles

The corrector dipole uses the same steel and lamination thickness as the main magnets. The core length is 110 mm. To avoid welding deformation, the core has two solid stainless steel end plates and four studs through the laminations to squeeze the laminations between the end plates. The lamination is C shaped in order to allow installation or removal of the magnet without affecting the vacuum system.

A prototype has been built at SSCL and used for end pack chamfer development. Because of the shortness of the magnet, end fields have significant impact on the integrated field uniformity; the design called for using the "nibble method" for cutting the chamfer. This involves cutting each lamination individually and then assembling the end pack. Field uniformity is slightly outside the specified tolerance, but tracking studies using the measured magnet data lead to the acceptance of the magnet design including chamfer.

Corrector Sextupoles

The core uses two laminated half yokes to reduce the difficulty of general assembly. The lamination uses the same material as the main magnet laminations. The core assembly design has not been decided on, i.e., whether it would use a welded packs configuration or a welded entire core configuration. Two prototypes have been built at SSCL and used for chamfer development. Final measurements using both the Danfysik system and the Field Effects quadrupole measurement system show acceptable integrated field quality.

The skew sextupole is an air-core magnet. The coils are mounted around the vacuum chamber, which supports the whole magnet. The current and number of turns are chosen to allow the magnet to be driven by the same power supply as the skew quadrupole, thus reducing the number of different power supply types.

RF System

RF Program Requirements

The design criteria for the RF program are low space-charge tune shift, maximum beam transmission, and a match of the bunch to the Medium Energy Booster (MEB) at extraction. The voltage at injection is 24 kV, arrived at by maximizing the capture efficiency. With ideal control of the RF, nominal capturing efficiency is 99.7% ; with RF error (noise and jitter) of 10 kV in amplitude and 1° in phase, however, the losses are about 2.5% as estimated by simulations using the code ESME. The maximum voltage in the cycle is 765 kV and the maximum synchronous phase angle is 61.25 degrees, which provides for a bucket area of .054 eV-s at the critical point in the program. The voltage at extraction is chosen to be 80 kV, which is a compromise between conflicting requirements for matching to the MEB and stable operation of the RF cavities. It might have been necessary to increase the voltage if multipactoring and beam loading compensation requires it. The LEB bunches can be dynamically matched to the MEB buckets by introducing a phase jump in the last millisecond before extraction, thus shearing the LEB bunches. Alternatively injection into the MEB can proceed with a mismatch, diluting the longitudinal emittance. The RF frequency changes from 47.514 MHz to 59.776 MHz.

Injection into the LEB, in collider mode, is to be accomplished in four turns using adiabatic capture. About 9 Linac microbunches are captured each turn in each of the LEB buckets. The rms spread of the microbunch is about 100 KeV with a jitter of 75 KeV. Ninety five percent bunch area at extraction is 0.025 eV-s. The bunch height and length at extraction will depend on whether the bunch is matched to the MEB bucket. If matched, the RMS dimensions would be 2.16 MeV and 20 cm; if not matched, 3.0 MeV and 14 cm. In the test-beam mode, 20 turns will be accumulated. The longitudinal parameters of the bunch are similar to the collider mode; however, the transverse emittance is larger. Also the beam loss will increase to about 5%. At the higher current, beam-loading issues in the RF cavities are expected to become more important and therefore would require compensation.

RF System

The RF system is required to produce a peak voltage of 765 kV and tune with the beam from 47.514 to 59.776 MHz in 50 ms. Ferrite biasing is used to tune the cavities due to the fast tuning rate. The limited lattice slot length of 22.4 meters (total) and the system cost scaling with the number of stations require maximum voltage on each gap with the goal of reaching 130 kV peak voltage per station. This requires 8 cavities in the ring with sufficient margins to be able to operate with two cavities disabled. Because use of the Fermilab Booster cavity was precluded by these requirements, a perpendicularly biased YIG ferrite, $\lambda/4$ coaxial cavity was chosen based on the LANL development of such a cavity in the 1980s.[10, 11] Tuning is achieved by a coaxial ferrite-loaded tuner. Since the cavity has to support the rapid 10Hz cycling rate, the tuner housing is slotted to reduce eddy currents.

Differing in the means by which cooling is achieved, a prototype cavity and two tuner concepts have been built and tested extensively. The first tuner to be tested was designed and built at BINP using BeO discs sandwiched between the ferrite rings to transport the heat to a cooling jacket. The whole ferrite pack was glued together and into the tuner shell using an epoxy compound. Tests at SSCL demonstrated sufficient bandwidth and tuning range but higher than expected power loss and temperatures, and the tuner failed during a high-power test.[12] The tuner has since been rebuilt at BINP.

The other tuner, designed and built in house, uses direct cooling of the ferrite by immersion in the cooling liquid, either LCW or FC77. To contain the coolant the slotted tuner walls are sealed with an epoxy composite. Tests of this tuner at high power and over extended periods (24 hr) were successful up to about 100 kV, but arcing was experienced at gap voltages of 130 kV. Bandwidth of the tuner was more than 2 kHz. The tests have demonstrated that the concept of the cavity is capable of providing RF voltage at or close to the level required. However, at the same time major mechanical issues have been uncovered that are for the most part rooted in the slotting of the tuner. An alternative prototype, without a slotted tuner, has been designed with an expected bandwidth of 50-100 Hz. The prototype had not yet been assembled or tested as the project shut down.

The RF control system is based on a VXI/VME architecture. The RF control loops are: beam phase, voltage amplitude, tuner bias, RF feedback, radial position, and synchronization.[13] The control system can also counter-phase the cavities. Coupled bunch instabilities, driven mainly by the cavities' higher order modes, are stabilized by a broadband passive damper on each cavity.[14] To maximize availability and flexibility, each of the stations is controlled individually, with a supervisory system providing the interface to the LEB control system.

Vacuum System

The vacuum system consists of vacuum chambers, pumps and monitor/control equipment. The vacuum system must provide an operating pressure no greater than 1×10^{-7} Torr, without interfering with any other accelerator systems.

The LEB ring is divided into 20 vacuum sectors each approximately 25 meters long. Thirty l/s ion pumps are spaced about every 6 meters. Injection and extraction regions require extra pumping depending on the design of kicker and septum magnets. RF regions get one 120 l/s ion pump per cavity. Vacuum chambers were designed to use the simplest and most economical method which reduces eddy current effects to acceptable levels. Other components were chosen to achieve requirements listed in the LEB 3B specs[2] and to achieve mechanical tolerances within the given space.

Bellows, Flanges, Seals, Gauges, Pumps, and Controls

A prototype of the shielded bellows has been built to design, and other minor design changes are required. Flanges and seals will be off-the-shelf items. The flange design, utilizing chain clamping, was chosen because of limitations on space and access. Gauges, pumps, and controls will be off-the-shelf designs, with slight modification of the pumps.

Vacuum Chambers

In the drift section there is no issue involving eddy currents here, because there are no magnets. This allows use of a simple stainless steel tube. The design was completed, but no prototype had been built as the Project closed. In the quadrupole, analysis shows that a thin-walled Inconel 625 tube reduces eddy currents sufficiently. The chamber is circular in cross-section through the quadrupole, trim quadrupole, and sextupole magnets. It has an elliptical section for the orbit correcting dipole. The beam position monitor is welded into the pipe at the end of the main quadrupole magnet. With this design for the vacuum pipe and the magnets, the pipe must be inserted into the quadrupole and sextupole magnets before the flanges are welded on the ends. The orbit corrector can slide onto the vacuum pipe from the side without opening the vacuum. A prototype was built, and was checked out mechanically. Measurements planned for BINP included confirmation of eddy current effects in this vacuum chamber. A tube identical to the vacuum chamber segment inside the quadrupole had been shipped to BINP, but the measurements had not yet been made.

Dipole

Analytic results show that field effects due to eddy currents in a simple Inconel 625 tube in the dipole would be too large. Three solutions were considered: carbon fiber tubing, ceramic tubing, or inconel tubing with correction coils. Carbon fiber tubing was rejected because of cost and technical difficulties with the reliability of metallic liners. Ceramic tubing was rejected because the walls would be too thick and the cost would have been very high. Inconel 625 tubing alone has eddy current effects exceeding the requirements by a factor of five. Correction coils mounted on the vacuum chamber, driven by a yoke winding, were used at Brookhaven National Laboratory (BNL) on the AGS booster.[15] A similar scheme was analyzed for the vacuum chamber and magnet and found to be adequate. A single correction coil per quadrant can bring the field back within specification. (See Figure 4-2.) Because these coils are driven by the same flux change that drives the eddy currents in the vacuum chamber, they track the eddy currents and do not require any separate power supplies. Optimum correction coil placement was found using a code written by Ross Schlueter at LBL. The result was tested using PE2D. The actual coil position was then pushed out and down toward the midplane because of difficulties in inserting the assembly into the magnet. This was again tested using PE2D and found to be acceptable (see Figure 4-2).

A prototype dipole vacuum chamber was built with the corrector coils mounted as described and tested mechanically and electrically. The prototype was then shipped to BINP for testing in the AC driven dipole magnet. The tests had not yet been carried out at the time of termination.

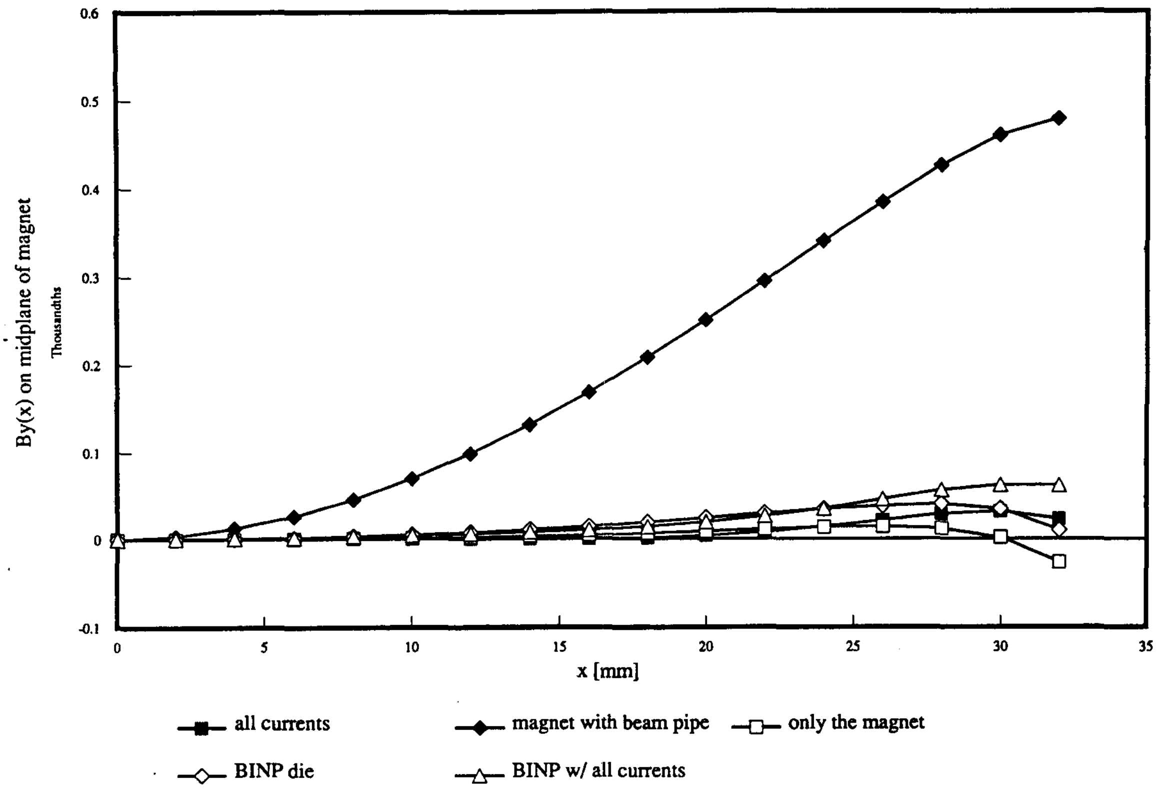


Figure 4-2. Field Distribution in Dipole.

Extraction System

The LEB extraction system has been designed to extract a 12 GeV/c proton beam from the LEB in both the collider fill mode and the test beam mode; the normalized transverse beam emittance (rms) in these modes being 0.6π mm-mrad and 4.0π mm-mrad, respectively.[16] It is a single-turn, vertical extraction system that provides the same extracted central orbit at the septum magnets for all possible working points; the LEB can be operated with tunes ranging from 10.9 to 11.9 in both horizontal and vertical planes. It fits into the LEB S2 straight section and has no effect on the three-fold symmetry of the LEB lattice. The system consists of a fast kicker, 2 septum magnets, and 5 bump magnets. Once the proton beam reaches the final momentum of 12 GeV/c, the bump magnets are powered to steer the circulating beam slowly towards the septum. Then the fast kicker deflects the beam across the septum where it receives additional deflection to leave the machine. Each of the 5 bump magnets has its own independent power supply so their magnetic fields can be independently adjusted to generate an adequate vertical displacement at the septum for all possible LEB working points. Once the kicker magnet is turned on, the same extracted central orbit will be achieved regardless of where the LEB is operated. The maximum deflection angle required for the bump magnets is about 5.0 mrad, corresponding to a maximum integrated strength of 0.18 T-m. To minimize the kicker strength and achieve the bending required to extract the 12 GeV/c proton beam, two septum magnets are used in the system. The first has a thin septum of 3 mm and provides a moderate deflection angle of 5 mrad; the second has a 7 mm septum and deflects the proton beam by 50 mrad. The required integrated strengths are 0.2 T-m and 2.0 T-m, respectively. Special shielding is used to prevent leakage of the magnetic field outside the septa that otherwise would cause emittance growth on the last few hundreds turns prior to powering the kicker. The deflection angle of the kicker magnet is 1.5 mrad at an integrated strength of 600 G-m. The kicker is made up of eight modules to achieve a rise-time of 80 ns.

Utilities

The LEB infrastructure/utilities consist of several elements including electrical power, low conductivity water (LCW), potable water, communications, natural gas, drainage, and roads. The LEB complex will receive 12.47 kV electrical service from the west complex substation via two independent interfaces, one to the Ring Magnet Power System (RMPS), and one for the LEB technical systems. Power will be routed to the tunnel from the surface buildings through an extensive network of conduits and cable trays.

For cooling technical systems, the LEB S1 pump room will receive pond water from the MEB pond via 16-inch supply and return trunk lines. The 12-inch LCW lines will be routed from a centralized pump room located adjacent to the S2 building into the LEB tunnel. LCW is piped through the tunnel to each surface building with double containment on sections between the tunnel and buildings. Each building is also provided with curbing for containment of LCW in case of accidental release. Secondary 6-inch LCW supply and return lines run inside the tunnel between the S2 and S3-RF buildings specifically for cooling of RF technical systems.

There can be no direct interface to potable water except for fire hydrants, which are placed around the LEB site and supplied by two 12-inch water mains from the west complex. The LEB complex will interface with the Lab-wide Global Controls Communication System. There will be a T1 class interface to the Lab-wide telephone system at the S3-RF building. Natural gas, to be used as the source of heating is to be supplied by the west complex natural gas system. Both internal and external drainage/sump systems will be provided with a centralized collection point located near the S3 access building.

The LEB road network will be provided (two primary roads) capable of meeting transportation requirements for the delivery, installation, and removal of all LEB systems. Primary access to the LEB, for technical systems delivery, is the main delivery shaft, located across from the S3-RF building. The other access shaft is located across from the A2 building and used for personnel egress.

Conventional Construction

The LEB and Transfer Tunnels were constructed by the cut-and-cover construction method. The LEB Tunnel is 12 ft wide × 10 ft high approximately 1,870 ft long reinforced box-culvert type structure. The LEB/MEB Transfer Tunnel is 8 ft wide × 8 ft high and approximately 382 ft long. Approximately 63 ft of the 8 ft × 8 ft Linac/LEB Transfer Tunnel is included in the LEB construction contract. There is also a 3 ft to 3-1/2 ft wide × 10 ft high approximately 40 ft long tunnel to the Emergency Egress structure; and a 6 ft wide × 10 ft high approximately 50 ft long tunnel to the Installation and Service Access Building. The tunnels are covered by berms for radiation shielding. There were to be eight surface facilities totaling approximately 14,000 square feet. The surface facilities were to be constructed of prefabricated building materials.

The LEB conventional construction included the following systems: roads, parking, storm drainage, potable water for fire protection, cooling pond water, natural gas, sanitary sewer connection for tunnel drainage; mechanical system to include HVAC; electrical system to include lighting, distribution for conventional systems, grounding, fire alarm and lightning protection; and fire protection as required by the FPDA.

The LEB tunnel shell was approximately 90% complete with all but three of the floor slabs completed. LEB Tunnel backfill to grade was 20% complete. The LEB/MEB Transfer Tunnel has been completed and backfilled, and 20% of the berm is in place. The S3 Access and A2 Access/Egress concrete structure shells have been completed to grade and the foundation for the A2 Arc Power Supply Facility is in place. Infrastructure items are complete to the point indicated by the following percentages: roads, 75%; storm drainage, 75%; potable water, 100%; cooling pond water, 75%; natural gas, 10%; and communication and electrical ductbanks, 99%.

Beam Instrumentation and Commissioning

Diagnostics

Beam position monitors

Beam position monitors (BPMs)[17], ninety in all, are to be located next to each quadrupole. Spatial constraints require their placement at the upstream end of the adjacent quad in some locations and at the downstream end in others. A single design suitable for nestling inside either end of the quad coil overhang, with signal feed throughs at the outside end for accessibility, is desirable. Electrical non-directionality is required and it is satisfied by selection of a shorted stripline pick-up design. Four electrodes, each 15 cm in length and subtending a 70 degree angle on an 8 cm diameter, are incorporated into each pick-up to allow two plane observation. Pick-up design had been completed as of shutdown.

Beams of three distinct bunching structures are intended to be observed. Residual 428 Mhz bunching from the Linac remains for the first few LEB turns (especially if the injected pulse length is limited to one LEB turn or less). Linac-style BPM electronics will be provided at a few LEB locations for beam position observation during the early phase of the LEB cycle. For machine commissioning and diagnostics, observation of un-bunched beam filling less than the full LEB circumference will be necessary. Again, electronics suitable for this purpose will be provided at a few locations around the machine. In normal operation, beam filling the LEB circumference is bunched by the LEB RF after only a small number of turns. All ninety BPMs will be equipped with electronics to process the available 47–60 MZ signals to produce turn-by-turn position information. Software will process the position data and adjust dipole corrector magnets to establish the desired closed orbit at injection and during acceleration. BPM electronics design is well into the prototype stage.

Profile monitors

To facilitate beam profile and emittance measurements, there will be three profile monitors, one horizontal and one vertical in a straight section, and another horizontal at an arc location. Ionization profile monitor type devices are planned. The LEB beam size (2 mm rms) requires small collector electrodes for the desired resolution. Two modes of monitor operation are planned: one with fast sampling time but limited resolution, and another with a slower data rate but enhanced resolution.

Beam current monitors.

Three types of beam current monitors are included: one video bandwidth transformer for injection current measurement, one DC transformer for beam intensity measurement throughout the acceleration cycle, and two multi-gigahertz wall current monitors for phase, bunch length, and longitudinal bunch shape measurement.

Beam loss monitors

Ninety beam loss monitors will be uniformly distributed around the ring to provide information on magnitude and location of beam losses. Additional monitors can be placed in areas of special interest, e.g., injection and extraction regions. Ion chambers of the Tevatron style or solid state devices are under consideration as detectors.

Wire scanners, viewer screen, particle catchers, diagnostic kickers, and dampers

Wire scanners are planned for the injection section to measure injected beam position, angle, and profile. A remotely removable fluorescent screen, monitored by camera, will be included at the injection stripping foil location to monitor beam position on the foil. Charge collecting devices, dubbed "particle catchers," are to be available in the injection section to provide signals from the stripping process. An electron catcher, enveloping the stripping foil, will provide a signal useful for monitoring stripping foil integrity and measuring the relative timing of injection and the orbit bump decay. Slightly downstream, a device to intercept and provide a signal from unstripped H^- ions will monitor injection stripping efficiency and serve as an indicator of foil failure. Diagnostic kickers are provided to impart an impulse stimulation to the beam for tune measurement and other diagnostic purposes.

Beam Commissioning

A commissioning task force was formed in late 1992 whose main goals were: (1) to establish a commissioning scenario, (2) to examine diagnostics specifications, (3) to develop specifications for high level software, (4) to simulate the commissioning, and (5) to identify specific issues.

An outline of the commissioning scenario was proposed and refined which includes: matching injection field strength to the energy of the Linac beam; diagnosis of mismatch between LEB RF frequency and bending field strength; achieving the first turn in the LEB; establishing the closed orbit; RF commissioning without acceleration; commissioning of feedback loops; RF commissioning with acceleration; measurement of tune; measurement of lattice functions; measurement of phase advance section by section and diagnosis and correction of local matching; measurement of momentum compaction factor; and synchronization to the MEB when γ_t is far from the design value.

As examples, Figs. 4-3. and 4-4. show the rms emittance evolution in the horizontal and vertical planes, respectively. There are no space charge effects included, but the tracking errors between dipoles and quadrupoles push the transverse tune down during a cycle. The emittance jump at about 17 msec is caused by the coupling resonance $4\upsilon_x + 2\upsilon_y = 354$. Simulations of the commissioning procedure were performed using the hypercube computer, including orbit correction, and transverse and longitudinal tune measurement. Simulations with space charge effects demonstrated the relation between asymptotic emittance and the residual closed-orbit excursion. Bandwidth requirements were estimated for each data flow to ensure compatibility with the diagnostics and the control system.

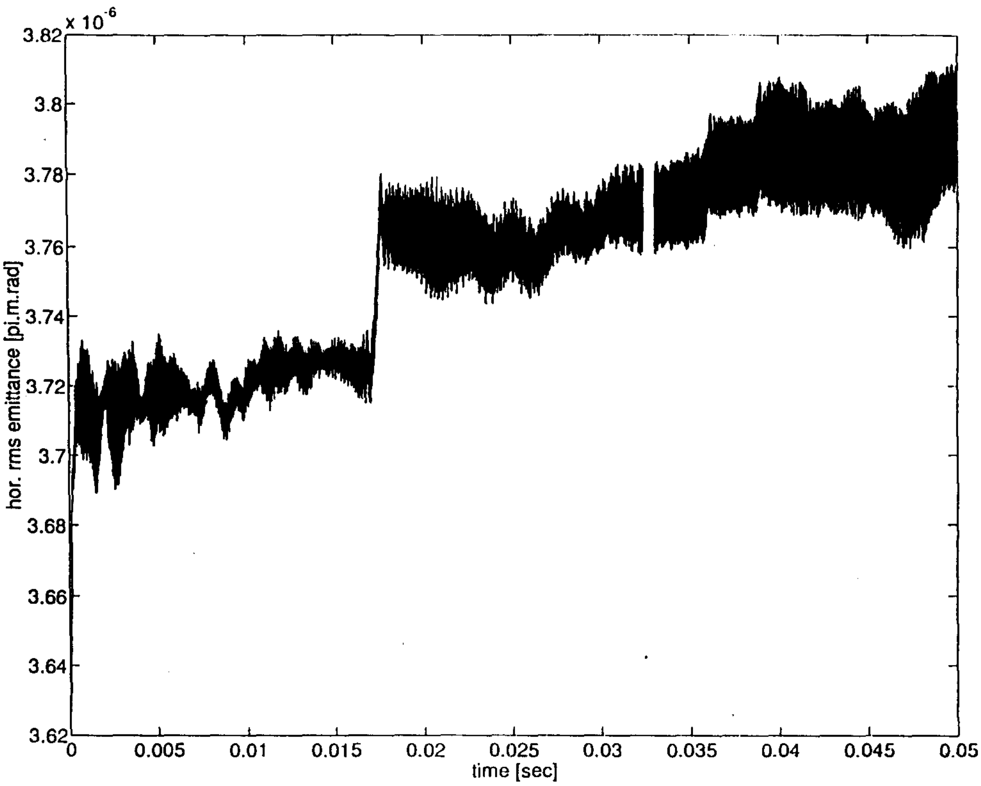


Figure 4-3. Evolution of Horizontal Beam Emittance during the LEB Cycle.

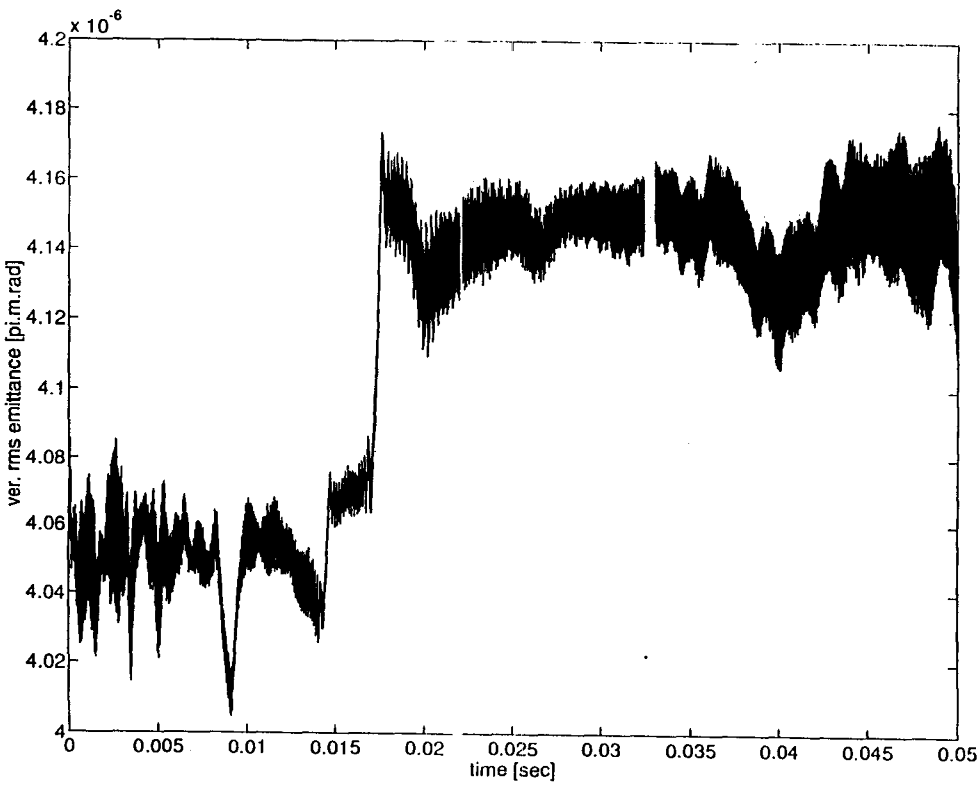


Figure 4-4. Evolution of Vertical Beam Emittance during the LEB Cycle.

Chapter 5. Medium Energy Booster

(R. Gerig, B. Platt, S. Chen, E. Lincke, J. Palkovic, N. Mao, Y.X. Huang, K. Bertsche, J. Matz)

The Medium Energy Booster (MEB) is the third of the SSC accelerators and the largest of the resistive magnet synchrotrons. The choices of circumference and the dynamic range over which the beam is accelerated are part of the global choices made in determining the parameters of all of the SSC machines. The top momentum of 200 GeV/c is determined by the Collider top momentum of 20 TeV/c and the constraint that both the Collider and the HEB are limited to a dynamic range of 10. Because of choices in circumference and cost tradeoffs, the MEB achieved this momentum by pushing the field as high as possible in resistive magnets while maintaining field quality sufficient for very low loss slow extraction. The injection energy of the MEB is limited by the acceptable dynamic range of resistive magnets, which sets the injection field at approximately 1 kilogauss corresponding to about 12 GeV/c. Details of the primary requirements for the MEB are contained in the MEB 3A[1] and 3B[2] documents. With the circumference and the momentum range constrained, the considerations relevant to the lattice design for the MEB are: the transition energy, the optimal FODO cell parameters, and the number of insertions.

Lattice Design

Choice of Transition Energy

There was considerable interest early in the design of the MEB in avoiding transition crossing. The primary concern for doing so was the tight transverse emittance budget imposed on all the machines. No other machine has accelerated a very small emittance beam through transition. Thus there was uncertainty as to the effect of transition crossing on the transverse emittance. There are two ways to avoid transition crossing: placing it below the injection energy, or placing it above the extraction energy. If the MEB were to have a transition energy below injection energy, the dispersion function would have to be unusually large (some of the conceptual designs had dispersion functions in the 10 to 16 meter range). The amplitude function would also be larger. This choice would place tighter requirements on the field quality of the magnets and would certainly result in a smaller dynamic aperture. The other choice is to place the transition energy above the extraction energy. The transition energy (often characterized as γ_t where $\gamma \equiv E/E_o$) is derived from the quantity $1/\alpha_p{}^2$, where α_p is the momentum compaction function. Placing γ_t above the extraction energy is difficult because the momentum compaction function must be made extremely close to zero. It is, however, possible to make the momentum compaction function negative, which results in an imaginary γ_t $(i\gamma_t)$. The manner in which this is done is to make the dispersion function negative in the dipoles. There have been a number of creative suggestions as to how to do this. The decision to use a standard FODO lattice was based on lack of extensive experience or simulation of the $i\gamma_t$ lattice, more complicated zero dispersion insertions for the $i\gamma_t$ lattice, and the belief that the $i\gamma_t$ lattice would involve either an increase in circumference or a reduction in peak momentum.

FODO Cell Design

Once the standard FODO lattice was decided on, other choices were based on the desired value of γ_t. The SCDR MEB lattice had a γ_t of about 15, which was judged to be too close to injection. A γ_t of 24 was chosen for the revised lattice. The cell length was based on the choice of the maximum value of the amplitude function, the desire to have an even number of dipoles per half cell (useful when the cell phase advance is around 90°), and the maximum practical length of resistive magnets (about 6 meters). The quadrupoles were centered in the available space, a decision that aids in the design of symmetric insertions and provides more space for correctors at larger beta functions. Furthermore, because most special purpose devices are needed where the horizontal amplitude function is large, the space at horizontally focusing quadrupoles was made greater than the space at vertically focusing quadrupoles.

Insertion Design

Because of the number of transfers associated with the MEB, a relatively large number of insertions were needed. There are five transfers (one for injection, two for extractions to the HEB, one for test beam, and one for beam abort), and because of the layout of the site, only two of these could be opposite each other. Therefore a total of eight insertions had to be included. Each insertion reduces the packing factor of the ring, thereby pushing up either the magnetic field or the circumference. The circumference was considered to be constrained at 3960 meters, and efforts were being made to keep the field at or below 1.8 Tesla. This motivated the design of very efficient (i.e., least amount of drift space) insertions. For this reason, two different designs were chosen. One was designed for the injection transfer; it employed the standard FODO quadrupole spacing, and used missing dipoles to allow space for the transfer line magnets, the kicker slot, and dispersion matching.

The second insertion is used at locations where 200 GeV/c beam transfers occur. The standard inter-quad spacing does not allow sufficient room for the transfers to occur. Therefore a long straight insertion was designed. The design considerations were: a free drift space of about 25 meters for beam transfer; a zero dispersion in the straight section, and a drift space approximately 90° upstream of the long straight for inclusion of kickers or electrostatic septa.

Transverse Dynamics

Dynamic Aperture Requirements

Among the sources of nonlinearity in the MEB lattice are the chromaticity sextupoles and the main magnet (dipole and quadrupole) errors. The effects of these nonlinearities on the dynamic aperture have been investigated. The chromaticity correction sextupoles drive the normal third order integer resonances, as well as the fourth order difference resonance of $2\nu_x - 2\nu_y = 0$. The location of the sextupoles was arranged to minimize all the harmonics of the driving terms. With this sextupole distribution and no other errors, the dynamic aperture (determined by single particle survival after tracking 1024 turns) and the linear aperture (smear < 0.064 and variation of tunes with amplitude < 0.006) of the lattice are larger than 2100π mm-mrad and 600π mm-mrad, respectively.

To reduce the linear coupling resonance, especially the fourth order difference resonance of $2\nu_x - 2\nu_y = 0$, the horizontal and vertical tunes were split by an integer. This greatly reduced the coupling between horizontal and vertical motions, and therefore significantly increased the linear and dynamic aperture. The MEB lattice was simulated at injection energy with field errors in all dipoles and quadruples (both systematic and random), alignment errors in all elements, and synchrotron oscillations. The error specifications were taken from the MEB 3B document.[2] Base tunes of ν_x=25.430 and ν_y=24.455 were used in all the simulations. Under these conditions, the dynamic aperture and linear aperture of the MEB lattice were $150\pi \pm 5\pi$ mm-mrad and $90\pi \pm 5\pi$ mm-mrad, respectively. For long turn tracking (38000 turns, corresponding to the injection time) the linear aperture was still larger than 90 π mm-mrad, which is beyond the MEB required transverse acceptance of 40 π mm-mrad. At extraction energy the linear aperture was ~1000 π mm-mrad.

Closed Orbit and Amplitude Function Errors

Closed orbit deviations caused by alignment and field errors corresponding to the specifications in the MEB 3B document can be in excess of 20 mm. A total of 112 horizontal and 106 vertical correction dipoles with corresponding Beam Position Monitors are used for closed orbit correction. At injection energy, correction to better than 1 mm is attainable. At extraction energy, full aperture correction is not possible. Studies using the limited corrector strengths indicate that the high field orbits can be controlled to rms deviations of several millimeters.[3] Where unreasonable peaks occur, quadrupole realignment may be needed. At high field extraction locations, the need for high field dipole bump magnets was anticipated.

Because of the presence of random gradient errors and sextupole misalignment errors, the lattice amplitude functions around the ring are different from that of the "ideal" lattice. The maximum deviation of the amplitude function ($\Delta B/B$) is about 15%. The primary cause of the deviation is the random strength variations in the quadrupoles ($\Delta GL/GL$).

Correction Schemes

The linear coupling of the MEB is due mainly to skew quadrupole errors. For global decoupling correction, four families of skew quadrupole correctors (a total of 8) are needed to reduce the bandwidths of the difference resonance of $\nu_x-\nu_y=1$ and the sum resonance of $\nu_x+\nu_y=50$. Another technique for decoupling is to use the four families of skew quadrupoles to minimize four independent coupling matrix elements in the one-turn matrix at a selected location which is used in the TEAPOT simulations code. The two methods of using four families are nearly equivalent. The maximum eigenangle and the minimum tune separation after decoupling are 8° and 0.0006, respectively, as compared with the uncorrected values of 45° and 0.013.

Resonance correction was considered for the following resonance lines: the third order normal structure resonances of $3\nu_x=76$, $\nu_x+2\nu_y=74$, the third order skew resonances of $3\nu_y=73$, $\nu_y+2\nu_x=75$, and the second order resonances of $2\nu_x=51$, $2\nu_y=49$. The resonance corrections were to be done by adding additional correctors. The approach was based on a vector analysis of driving terms with a sine and cosine component.[4] The correction schemes do not have any impact on chromaticity or tune values. Therefore two orthogonal pairs (wired in the opposite polarity) are needed to correct each resonance line. There are a total of 8 normal correction sextupoles, 8 skew correction sextupoles, and 8 correction quadrupoles.

The correction system was of sufficient strength to correct for all the errors specified in the 3B document. Additionally, the variation in $\Delta B/B$ was significantly reduced from 15% to 8% after the correction of the half-integer resonances.[5]

Emittance Preservation

To achieve the luminosity goal of the Collider, a very stringent transverse emittance budget has been imposed on the MEB. It is 0.6 π mm-mrad at injection and 0.7 π mm-mrad at extraction (normalized rms). The total growth allowance is about 17%. In the design study, care has been taken to consider the following major sources that might cause the emittance to grow.

<u>Space charge tune shift</u>

By the Laslett formula, the maximum tune shift in MEB is 0.083 at injection.[6] The shift may cause the beam to cross lower-order resonances, which could produce an emittance growth and particle loss. The suggested fractional operating point, therefore, has been moved on the tune diagram from (0.42, 0.38) to (0.43, 0.46) to avoid crossing third-order resonances. A simulation study showed that the emittance growth could be reduced from 10% to less than 1%.[7]

<u>Decoherence effect</u>

In the MEB, injection errors (0.7 mm in horizontal plane and 1.0 mm in vertical plane) come from the LEB extraction system, the MEB injection kicker and other elements in the beam transfer line. Because of the tune spread in the beam caused by the residual chromaticity and other nonlinear effects, the emittance will be diluted up to 20% and 85% in horizontal and vertical planes, respectively, after 300 turns.[7] A damper is needed to suppress the injection errors within 50 turns to limit the dilution within tolerable level (< 1%).

<u>Coherent instabilities & impedance requirements</u>

The coherent instabilities in the MEB could be classified in three categories: single bunch, coupled bunch, and resistive-wall instabilities. In some case, the instabilities may lead to the emittance growth and even beam loss. Precautions have been taken to cure this problem. Many efforts have been made to reduce the MEB broadband impedance including shielded bellows and screened pump ports. As a result, the MEB broadband impedance is expected to be less than 1.65 MOhm/m. It is much lower than the threshold value of the single bunch instability, which is 36 MOhm/m at injection.[8]

The coupled bunch instability is caused mainly by the high-frequency impedance of the RF cavity. The growth time of the instability is around 1 second, which is not tolerable considering that the beam will circulate in the ring for 5 seconds. A higher order mode (HOM) damping scheme is therefore proposed. With a few major high-mode impedance peaks damped by a factor of 10, the growth time could be increased to about 20 seconds.

As a type of multiple bunch instability, the resistive-wall instability could be triggered in many different modes. For the MEB, the lowest mode has a frequency of 41 kHz, with a growth time of 2.5 ms. The highest mode frequency is just half of the RF frequency, which is about 30 MHz. To suppress the instability, a feedback system with the following parameters is suggested.[9] Bandwidth: 30 kHZ - 30 MHz; deflection: 3.2 mrad/turn, at Pinj = 12 GeV/c; damping period: 50 turns; acceptance: 2 mm; and peak power: 700 W.

Transition crossing

Special attention has been paid to MEB transition crossing, when the beam will suffer from a non-adiabatic dynamic process. The bunch becomes very narrow, leading to an increase of the bunching factor from 8.1 at injection to 65 just after transition. However, because the beam dispersion spot size is large compared with the B spot size at that time, the Laslett tune shift basically keeps the same value as at injection. The simulation also indicates no emittance growth from this effect.[10]

One concern is the head-tail instability around transition. As the phase slip factor approaches zero, less Landau damping is provided. A large shift in coherent mode frequency due to chromaticity will certainly occur; a strong coupling of m=0 mode to the resistive part of the broadband impedance can be expected. To overcome this problem, a chromaticity jump is suggested. By changing the sign of the chromaticity as the beam crosses transition, the frequency shift could be guided in the right direction to avoid the instability.

Longitudinal Dynamics

Choice of Parameters

The MEB is required to accelerate a train of ~ 670 proton bunches from a momentum of 12 GeV/c to 200 GeV/c. Given the momentum curve, an RF voltage curve was chosen that gave a bucket area proportional to the momentum. The initial and final bucket areas are then chosen. Given the voltage curve, the phase curve is determined, along with the required number of cavities. The ring voltage at injection is set by the requirement to match the RF bucket height of the MEB to that of the LEB at injection. With the longitudinal emittance of ~ 0.4 eV-s coming out of the LEB, the initial voltage is constrained by the allowable space-charge tune shift.

Instability Threshold

Longitudinal beam stability in the MEB[11] was analyzed by looking at single bunch and multiple bunch stability separately. Calculations of the MEB impedance budget predict a longitudinal coupling impedance $|Z_{\parallel}(\omega)/n|$ of $\cong 1\Omega$, which is somewhat arbitrarily multiplied by 2 to give a conservative estimate of the machine's coupling impedance. With the expected longitudinal parameters of the beam in the MEB, it does not appear that the beam will be anywhere near the stability boundary in the complex impedance plane. Longitudinal multiple-bunch instabilities are caused, as in the transverse case, primarily by HOMs in the RF cavities. Growth of the instabilities must be controlled with HOM dampers.

Transition Crossing

The emphasis in the approach to transition crossing was to maintain control of the beam. To this end, a "duck under" transition crossing scheme in which the RF cavities are divided into two sets was chosen.[12] The RF phasors of the two sets of cavities form an opening angle, with the net phasor aligned with the beam phasor as the beam goes through transition (for a period of ≈ 10 ms centered around transition). This allows the radial position feedback system to continue operating as the beam passes through transition. Another advantage to this scheme is the ease of adding an RF harmonic to implement a "flattop" crossing scheme.

Power System

The ring magnet power supplies are very similar in design to the power supplies in the other machines. Voltage considerations determined that eight power supplies (of 2000 volts each) were needed on the dipole bus, and one 2000 volt supply was needed on each quadrupole bus.

Argument for Three Separate Buses in MEB

Of the synchrotrons at the SSC Laboratory, the MEB is the only one that has three separate buses for the main magnets. In the other machines, the dipoles and quadrupoles are wired in series on the same bus. The MEB utilizes separate buses for the dipoles and for each quadrupole type (focusing and defocusing). The reason for this in the MEB is as follows. To accommodate the dipoles and quadrupoles wired in series, they must track each other very accurately. That is, the ratio of field to gradient must remain very nearly constant, or the machine tune will vary as a function of the dipole field. The MEB has the largest dynamic range of any of the machines, and the resistive dipoles begin to saturate near the top field. It is difficult to design a quadrupole that will saturate in the same manner as the dipole; therefore high field tune correction would be needed. An additional motivation for the tune correction quadrupoles is the requirement that the machine be tunable over a certain range (±1 unit). These quadrupoles would be required at most main quadrupole locations, and would be sufficiently large to cause an increase in the circumference of the machine. They would require substantial power supplies and current distribution systems. The cost that one would pay for the three bus system is in the additional solid copper bus used for the quadrupoles, and in the more sophisticated current control and regulation system to provide tune tracking. Trade off studies for high energy resistive machines have commonly resulted in a three bus system as opposed to lower energy, rapid cycling resistive synchrotrons, or superconducting machines, which are less prone to saturation effects and can better utilize a series configuration.

Correction Element Power Supplies

There are two basic types of correction element power supplies used in the MEB. One type is for individually powered magnets such as correction dipoles and resonance correcting quadrupoles and sextupoles. These were to be commercially available supplies with controls specified by SSCL. The power supply specifications were very similar to one type of LEB correction magnet power supply, and a common design was anticipated for that reason.

The other type of correction element power supply is for the chromaticity correcting sextupoles. There are two families of these magnets, and therefore two circuits are needed, each supplying current to about 82 magnets. It had not yet been determined how many supplies would be needed on each circuit. Care had been taken in the design of the MEB dipoles to avoid the situation in which a four quadrant supply would be needed.

Magnet System

Dipoles

The MEB main dipoles are the single most expensive item in the MEB ring. They are also the costliest part of the ring to operate, so it was necessary to minimize both the immediate capital cost and long-term operational costs for these magnets.[13] The initial capital cost increases with the amount of copper and steel (and hence the magnet size), and the long-term operational cost decreases as the amount of copper (and hence the steel and size of the magnet) increases. Therefore the overall size of the magnet is a compromise among the conflicting goals of: (1) keeping the magnet narrow to minimize tunnel width and hence civil construction costs, (2) minimizing the amount of steel and copper used to keep initial capital costs at a minimum, (3) making the cross-sectional area of the coils large to minimize long-term power consumption costs, and (4) providing a substantial steel yoke for the magnet. The last goal provides enough steel in the yoke both to keep the magnetic efficiency high and to minimize steel saturation and remnant field harmonics at injection. The final design compromise was biased slightly in favor of a larger magnet with more steel by the desire to keep its construction simple. It was decided to keep coils out of the gap region and off the midplane, and to use simple pancake coils. This meant that a polebump with sensitive construction tolerance would not be necessary, and field quality would not be sensitive to precise positioning of the coils. The number of coil turns per pole was determined by the desire to put the peak operating current near 5 kA so that the power supplies would be similiar in design to supplies used for other accelerators.

The magnet design and mechanical drawings passed a Preliminary Design Review (PDR)[14] in April 1991, and the first model prototype was completed at Fermilab in May 1993. The model was tested at Fermilab where it performed according to design after three iterations of the endpack.[15] Moscow Radio Technical Institute (MRTI) in Moscow, Russia, was selected as the manufacturer. They have the steel, copper and tooling necessary for the construction of three prototypes. Completion was still expected in early 1994 as the project closed down.

Quadrupoles

Design considerations for the MEB main quadrupole were that it be able to operate with the same power supplies as the main dipole (and thus a similar peak operating current), and that it be of simple construction to avoid sensitive construction tolerances. This was achieved using a symmetric core and a racetrack coil design. The poletip is the standard truncated hyperbola shape with a radius large enough to accommodate the MEB beampipe. Special polebumps were not required to achieve the desired field quality in the good field region. The width of backleg is the result of conflicting requirements to keep it wide to prevent steel saturation and maintain high efficiency, and to keep it narrow to provide space in both the injection beamlines from the LEB and extraction beamlines to the HEB, where these quadrupoles get in the way of transfer-line magnets. The magnet design and associated mechanical drawings passed a PDR[16] in April 1991, and MRTI in Moscow, Russia was selected as the manufacturer. The first model prototype was under construction in Russia with completion also expected in early 1994.

Correction Magnets

The chromaticity sextupole magnet[17] design was very straightforward; the primary consideration being ease and simplicity of construction. Water cooled racetrack coils are used; they can easily slide onto the poletips. The horizontal and vertical dipole correctors[18,19] contain the poletip adjustments necessary to get the integrated BL desired. In addition, they had the requirement that they be able to operate DC at peak current of 15 A without damage, in case a magnet should be accidentally left on at peak current. The trim and skew quadrupole corrector[20,21] design was chosen identical to the LEB main quadrupole, because this magnet design already existed, and it more than met the design requirements. The harmonic and skew sextupole correctors[22,23] were also designed for ease and simplicity of construction.

Other miscellaneous magnets for the MEB include high field correctors to be used in conjunction with the kickers at extraction lines[24] to bump the beam out of the ring. These were likely to be a very short version (0.5 m) of the MEB main dipole. Also, there are several octupoles to be used for slow extraction. They had not yet been designed at shutdown, but again, besides meeting the integrated field requirements, the primary consideration would have been ease and simplicity of construction.

The magnetic design and mechanical drawings for the chromaticity sextupole, the horizontal and vertical dipole correctors, and the trim and skew quadrupoles had been completed, and each had passed a PDR. The magnetic design and mechanical drawings for the harmonic and skew sextupole correctors had also been completed but had not yet passed a PDR. Prototypes of the chromaticity sextupole, the horizontal and vertical correctors, and the trim and skew quadrupoles had been completed at SSCL and have undergone testing as the project ended. IHEP in Beijing, China, and Shanghai Motor Works in Shanghai, China, were identified as the manufacturers of the chromaticity sextupole and the horizontal and vertical dipole correctors. They also had completed prototypes and were in the process of testing them. Budker Institute of Nuclear Physics in Novosibirsk, Russia was identified as the manufacturer of the trim and skew quadrupoles. Prototypes had been built and tested and were awaiting a Critical Design Review (CDR) at project's close.

RF System

Choice of RF Cavity Design

A $\lambda/4$ (quarter-wave) cavity design was chosen for the MEB after a detailed analysis of five different designs. The $\lambda/4$ cavity was chosen based on mechanical considerations, the ease of implementing fast feedback, the ability to use HOM dampers designed for the LEB cavity, and the ability to achieve the required gap voltage of 170 kV without multipactoring.

Tuner Considerations

The tuner mechanical design was incomplete. A change to the tuner power supply design was necessitated by the fast slewing rate required by the "duck under" transition crossing scheme.

Higher Order Mode Dampers

To limit the growth rate of the various longitudinal coupled-bunch modes to 4 e-foldings, the HOMs need to be damped.[11] Several schemes have been devised for doing this, including a simple resistive shunt added to the tube section of the cavity at a null of the fundamental.

Instrumentation

Some of the most important diagnostics for the MEB are the beam position monitors (BPMs), which couple to the electromagnetic field of the beam to measure position of the beam centroid. They are located at positions of large β, because it is here that beam position is most affected by errors in quadrupoles or correctors. Thus there is one BPM per half cell in the FODO lattices. Dedicated BPMs are used to provide feedback signals for control of the RF and beam damping systems.

The BPM pickups consist of pairs of 50-ohm electrical striplines which are shorted at one end and supply signal to a 50-ohm line at the other end. Their conceptual design has been completed and is somewhat novel. Each pickup has an outer vacuum enclosure with an oval cross-section, slightly larger than the beam pipe. The actual striplines lie on the beam pipe outline and are either two curved electrodes for horizontal pickup or two flat electrodes for vertical pickup. The ends of the vacuum enclosure are tapered (1:4) for beam impedance considerations. The striplines are tapered at the output end to provide constant signal impedance, and not tapered at the shorted end. Because of the wide dynamic range of beam currents in the MEB, log ratio signal processing is a good choice. A prototype of a log ratio BPM electronics module for the Linac has been completed, and preliminary specifications have been written for the MEB module.

Beam loss monitors (BLMs) are essentially radiation detectors located at positions of large β. They are most sensitive to the beam periphery, thus they complement the BPM position information and also give information about beam focusing. A detector prototype has been completed. A prototype BLM electronics module for the Linac has been completed, and preliminary specifications have been written for the MEB module.

There are two devices to measure beam current. The DC current transformer (DCCT) is a magnetic amplifier with DC response to measure average beam current. The fast current transformer (FCT) has no DC response, but it has a larger bandwidth and is sensitive to current fluctuations within individual batches. The wall current monitor is somewhat similar to the beam current monitors, but it has a very high bandwidth and is able to provide longitudinal beam profile information of individual bunches. Prototypes have been completed for Linac-specific devices, and preliminary specifications have been written for the MEB devices.

Transverse beam profile information is obtained from flying wires, which are located at positions of large β, and at both large and small dispersion points. They are envisioned as rotary devices similar to those at Fermilab, and they were in the preliminary specification stage. For tune-up when beam would be dumped on the first turn, four multiwire beam profile monitors are located at succeeding positions of large and small β. The electronics for a single channel has been prototyped; the mechanical assembly has been specified and a prototype was in progress.

A wire scanner (essentially a very slow flying wire) is used to measure the transverse profile of the slowly-spilled beam for test beam operation. A beam damper system is necessary to damp transverse beam oscillations because of injection errors or transverse instabilities. A transverse kicker in each transverse plane is used to study transverse beam dynamics and to adjust tune. The physics parameters for the wire scanner, beam dampers, and kickers have been specified, but no further work has been done on them as the project ended.

Other Systems

Utilities

The MEB low conductivity water (LCW) system was decentralized with a deionizing plant at each of the eight surface buildings. The original design utilizing a central plant at the MEB cooling pond was abandoned when the costs associated with containment of LCW spills, as mandated by Environment, Safety, and Health (ES&H) regulations, were considered. The current design has pond water distributed from a central pumping location to heat exchangers at each building. Each octant of the ring was independent in normal operation; that is, LCW from a surface building only circulates in the associated ring octant. In the event of pump failure, flow in the affected octant could be made up by opening normally closed valves to the adjacent sectors.

The compressed air system was required to operate vacuum gate valves, the beam plug in the LEB to MEB (LM) transfer line, and possibly some beam diagnostic instruments. It was envisioned as a centralized system with a single compressor pressurizing a small diameter tube with accumulators placed periodically around the ring to provide capacity. The transfer lines and LEB would have been served by the same system. It was expected that vendors would supply the cable trays and equipment racks. Specifications were intended to be global across all machines and to conform to standard product specifications from manufacturers. A PDRR was held in October 1993.[25]

Magnet Stands

Design work had concentrated on the dipole and quadrupole magnet stands. Special magnet designs had not progressed to the point where stand design could have begun. Because corrector stands were relatively simple and inexpensive, they received lower priority. Two designs had been considered for the dipole and quadrupole magnets: a six-strut system, and a jack- and- roller system designed for the Main Injector dipole magnets at Fermilab. Analysis of the six-strut system showed that it would easily meet the alignment and load requirements for both magnet types. The Fermilab design was shown by prototype testing to be acceptable also. Based on the much lower unit cost of the Fermilab stand and the development cost savings that could be realized by simply copying that design, this stand was chosen as the primary candidate for the dipole magnets. Although more robust than necessary for the smaller quadrupole magnets, the same design was chosen for them as well based on the development cost savings that could be realized.

Vacuum System

The vacuum requirement was determined by the emittance growth allowable from residual gas scattering. With an average ion pump spacing constrained by slot requirements to eight meters, the maximum allowable outgassing rate of the stainless steel beampipe was extremely low. The problem had been overcome with a system design in which getter pumps were added at each pump location (approximately 430), and the number of ion pumps was reduced to approximately 125. The result was higher pumping efficiency with reduced system cost. The MEB vacuum system passed PDR in August 1993.[26]

Abort System

The abort system includes the extraction magnets, transport line, and beam absorber. The system design included the number, sizes and strengths of the kicker,[27] septum and C magnets. The extraction magnets were in the preliminary design stages but had not been reviewed. The choice between independent power supplies and driving the magnets from the dipole or quad buses remained to be made. The transport line lattice had been established, and it used only preexisting steering magnet designs. Considerable study had been performed to develop a beam absorber that would not require water cooling to reduce system cost and maintenance requirements and improve radiation safety. The beam absorber preliminary design used a graphite target that met the criteria under the beam abort scenarios that had been expected.

LEB to MEB Transfer Line

Design Philosophy and Matchings

The LEB to MEB beam transfer line[28] was to transport a 12 GeV/c proton beam from the LEB to the MEB. The transfer line must accommodate a range of LEB tunes and various errors in the two boosters. Therefore, the design of the transfer line must consider the basic optical problems, including beam centroid matching, β function matching, and dispersion function matching.

The beam is extracted from the LEB vertically and injected into the MEB through a vertical Lambertson magnet and a horizontal kicker[29] so as to reduce the required kicker strengths. Vertical extraction is followed by ten vertical dipoles in the transfer line, which accommodates the different elevations of the two boosters and makes vertical dispersion (D_y) matching easy. The two horizontal dipoles introduced in the transfer line are for matching to the non-zero horizontal dispersion (D_x) in the MEB.

The β functions along the transfer line have a maximum value of 103 m. The transfer line has a low sensitivity to errors in these magnets. The β matching is performed by a matching section within the dispersion-free region. Analysis shows that this section can complete the matching for 20% β variation of the LEB and 10% β variation of the MEB. If the horizontal or vertical dispersion functions of these two boosters vary from the design specifications, dispersion matching can be regained by adjusting the gradients of one or two pairs of quadrupoles in a FODO section in an orthogonal way. A gradient adjustment of about 5% is needed for a LEB horizontal dispersion variation of ΔD_x=0.1 m. As a consequence, the transfer line has a high flexibility to match different conditions.

Error Effects and Corrections

The magnet misalignments and field errors in the transfer line may cause beam centroid, β function, and dispersion function mismatchings. The tolerances are constrained mainly by two factors: limited magnet apertures and the allowed emittance growth. The latter is more stringent, because the allowed emittance growth is only a few percent. If an emittance growth of less than 1% is required, the centroid mismatching Δx_{eq} at the MEB injection point should not exceed 0.1 mm.

The centroid mismatching caused by transient field errors is severe. If the related errors are 1×10^{-2} for kickers, (1-2) $\times 10^{-3}$ for extraction septum magnets and 1×10^{-4} for the other dipoles of the transfer line itself, the centroid mismatching is Δy_{eq}=1.0 mm, corresponding to an emittance growth of about 80%.[30] Therefore an injection damping system in the MEB is needed to correct the effect. The centroid mismatching because of systematic errors, such as dipole rotations and field setting errors, quadrupole transverse displacements, and so on, can be corrected by a scheme consisting of dipole correctors and beam position monitors. The β function and dispersion function mismatchings caused by the allowable rms quadrupole gradient errors of 1×10^{-3} will lead to an emittance growth of less than 1%.

LEB Beam Dump Line

The LEB dump line transports the beam from the LEB to the absorber during the LEB commissioning. This line separates from the transfer line upstream of the four paired vertical dipoles. So, besides the beamplug, there is another safety critical device (consisting of the four dipoles) preventing the unwanted beam from entering the MEB tunnel. The dump line itself consists of two dipoles and one quadrupole. The two dipoles separate the dumped beam from the transfer line in the horizontal plane, and the quadrupole focuses the dumped beam horizontally and makes it have a circular spot on the absorber.

Chapter 6. High Energy Booster

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Top Level Requirements

The primary function of the High Energy Booster (HEB) accelerator is to furnish a proton beam at a momentum of 2.0 TeV/c to the two Collider rings of the SSC. The MEB-HEB transfer line injects proton bunches into the HEB accelerator at 200 GeV/c alternately in clockwise (CW) and counterclockwise (CCW) directions. The beam will be injected, accelerated, and extracted from the machine in 131 seconds. The clockwise beam will be injected into the top ring of the Collider, and the counter-clockwise beam will be injected into the bottom ring. The HEB machine will operate in bipolar mode to accommodate the two beam directions . The HEB magnet cycle is shown in Figure 6-1. The HEB has two aborts: one for each direction of the beam. The HEB machine parameters are shown in Table 6-1. The HEB machine lay out, shown in Figure 6-2, has 6 arc sections (radius 1001.32 m), 2 long straight sections (490 m each), and 4 short straight sections (232 m each) for a total circumference of 10.8 km. The 2 north straight sections are used for the two beam aborts. The machine is divided into 8 sectors. The center point of each is identified as H10 through H80, starting from the center of the west straight section and moving clockwise. The 2 south short straight sections (at H60 for CCW and H80 for CW) are used for injection into the HEB. The west long straight section (at H10) houses the RF accelerating cavities and the extraction lines.

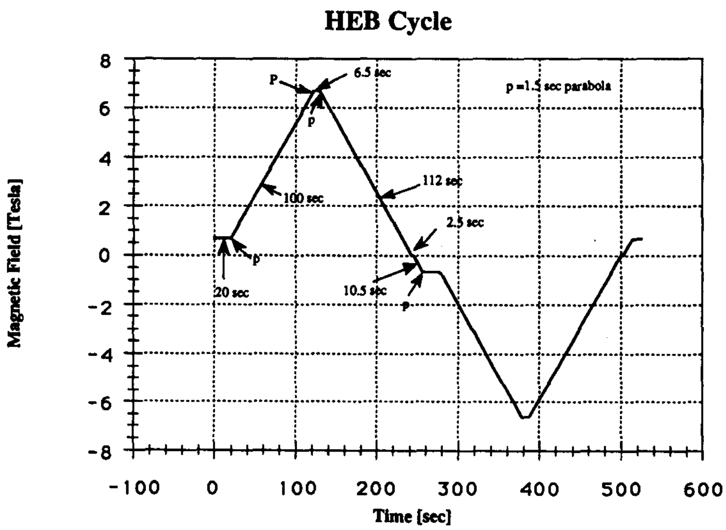

Figure 6-1. HEB Ramp Bipolar Cycle.

Table 6-1. HEB Parameters.

Injection Momentum	200 GeV/c
Final Momentum at transfer to Collider	2 TeV/c
Number of protons/bunch (test beam capability)	10^{10} (5×10^{10})
Harmonic number	2160
Bunch spacing	5 m
RMS 1 σ bunch length at Injection/transfer	0.3 / 0.054 m
Beam Current	89 mA
Output Transverse emittance	0.8π mm mrad
Longitudinal emittance at injection/transfer	0.1 / 0.66 eV sec
Arc FODO half-cell length (2 dipole + 1 quad)	32.5 m
Phase advance per cell; Horizontal/vertical	89.77 / 91.267 degree
Max / min beta function in FODO cell	111 / 19 m
Max / min dispersion function in FODO cell	2.17 / 1.04 m
Total spot size at injection/transfer	0.65 / 0.22 mm
Number of superperiods	2
Horizontal / vertical tune	39.425/38.415
Tune correction range	±2
Synchrotron tune at injection / transfer	0.0001 / 0.0005
MEB Injection	3 fills per injection into HEB
Bipolar operation	8 cycles (515 sec) per collider fill (both rings)
Ring circumference	10.8 km
Tunnel Diameter	14 ft
Tunnel depth from surface	~ 50 m
Tunnel height above Collider	14 m
Shafts	H20 for magnet equipment access, N130, 135 for personnel & equipment
Buildings	N130-135 for kickers equipment, H10RF for RF and local control; H20 & H60 for refrigeration and power supplies
Installed Power	12.47 kV: 29 MVA 4.16 kV: 12 MVA 480 V: 28.5 MVA

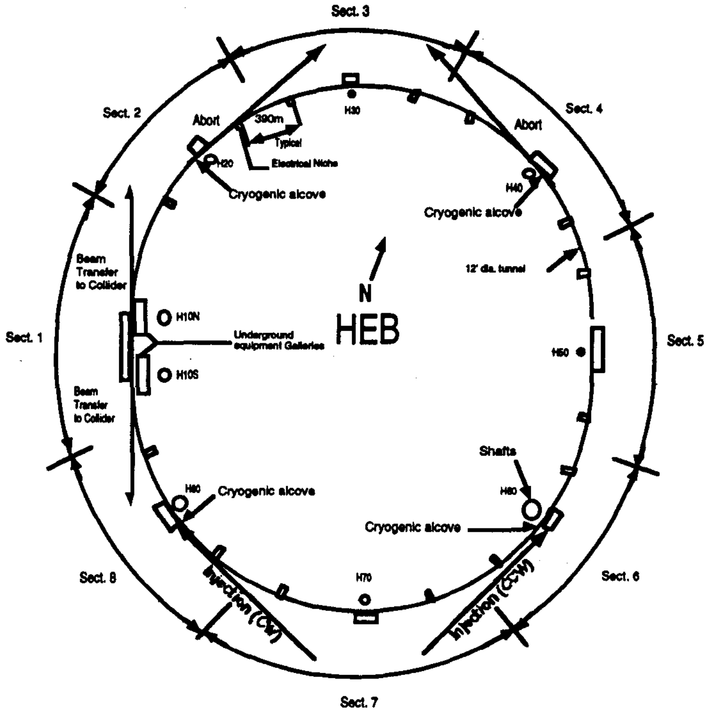

Figure 6-2. HEB Ring Layout.

Lattice Description

The arc section of the HEB is designed to have 256 long half cells, each 32.5 m long containing 2 dipoles and a quadrupole (see Table 6-1 for details). The later high Q lattice design, which is a revision of a previous design,[1] gives arc sections that are almost unit matrices for the lattice functions. The various straight sections are shown in Figure 6-2. The long straight sections (388.35 m), which are designed for beam transfer to the Collider ring and resonant extraction of test beams, consist of a central field free region (121 m) where the horizontal beta function is made large to allow extraction, as well as field free regions (81 m and 33 m) on either end. The short straight sections (230.825 m), designed for injection of MEB beam into HEB and abort, consist of a central (96 m) field free region and a 53 m field free region on each end. The straight sections are connected to the arcs by dispersion suppresser cells. Long-term tracking studies indicate a dynamic aperture of about 8.0 mm for the total machine at injection.

Correction Requirements

The corrector requirements[2] are based on consideration of multipole errors, alignment tolerances and machine parameters (see Table 6-2). The dipole correction provides for a capability of correcting closed orbit distortion of up to 60 mm (4.5 σ). The system of quadrupole correctors includes correctors near every main quad to correct for tracking errors due to dipole saturation, correctors every half cell in the arcs to allow a tune change of 2 units, and 16 quads near the straight sections to provide 2ν resonance correction. A system of 16 skew quad correctors placed near the long straight sections in 8 circuits control $\nu_x \pm \nu_y$ resonances. The sextupole correctors (located next to focusing and defocusing quads in 2 circuits) correct for natural chromaticity and the sextupole components (maximum of 1.5 units per dipole) in the dipoles. The $3\nu_x$ resonance correction system consists of 16 sextupole correctors divided into 2 groups each 90 degrees apart near two opposite short straight sections next to focusing quads. The $3\nu_y$ correction system has 4 skew sextupoles placed in the long straight sections next to the QS2 quads.

Table 6-2. HEB Corrector Magnets.

Type	Number	Location	Max. Strength	Max. Ramp Rate
Dipole			0.7 Tm	0.07 Tm/s
Horizontal steering	160	F quad†		
Vertical steering	156	D quad†		
Quadrupole			0.25 Tm	0.025 Tm/s
Tracking	86	Disp supp & SS		
Tuning and tracking	208	F&D quad		
Tracking, β measurement	6	F&D quad		
Resonance correction	16	LSS		
Skew quadrupole			0.25 Tm	0.025 Tm/s
Resonance Correction	16	F&D quad in LSS		
Sextupole			0.05 Tm	0.0025 Tm/s
Chromaticity	104	F quad		
Chromaticity	128	D quad		
Resonance	16	F quad in SSS		
Skew sextupole	4	QS2 quad	0.05 Tm	0.0025 Tm/s

† Some are placed in the straight section

Longitudinal Beam Dynamics

Detailed studies on longitudinal beam dynamics[3] for the HEB were carried out. The following assumptions were made for arriving at the dynamic variables and system specifications. Ninety-five percent of the extracted MEB beam is assumed to lie within a range of longitudinal emittance of 0.1 to 0.33 eV-s. The HEB longitudinal emittance at extraction is assumed to be 0.66 eV-s, a value chosen to minimize problems posed by intrabeam scattering,[4] beam instability and too large an RF voltage. It is assumed that the increase in the longitudinal emittance would be obtained by varying the RF voltage at twice the synchrotron frequency during acceleration·

The bucket area to 95% beam area ratio is assumed to be six. The HEB magnet ramp shown in Figure 6-1 is assumed. An RF system at 60 MHz frequency is chosen. After injection and acceleration, the bunches will be rotated so that the aspect ratio of the ellipse matches that of the Collider at beam transfer.

The following are the highlights of the results on the longitudinal dynamics studies. Stable and feasible ramp functions were obtained for the RF phase and voltage, with only a 2% growth in longitudinal emittance occurring in the simulations. The synchrotron frequency at flat top is 2 Hz and the flat top of 6.5 seconds is very short (only 13 synchrotron periods). Therefore only non adiabatic longitudinal phase space manipulations can be carried out for cogging.[5] ESME studies indicate that the bunch rotation scheme will work well. There may be some beam loading problems at injection, which can be mitigated by an appropriate arrangement for the RF system.

MEB-HEB injection lines

Two transfer lines transport 200 GeV proton beams from the unipolar MEB to the bipolar HEB.[6] The main parameters of these lines are listed in Table 6-3. The geometry of the two machines is such that the CW line does not contain any major horizontal bends. Because the extraction and injection sections are dispersionless and the expected $\delta p/p=5 \times 10^{-5}$, the issue of horizontal dispersion matching is not important. The extraction and injection sections of the two lines are quite similar to each other. Extraction utilizes five horizontal kickers at 0.93 T-m/kicker to produce a beam separation of 31.7 mm from the MEB design orbit followed by Lambertsons and a C-magnet. Injection into the HEB also uses two Lambertsons and a C-magnet and six kickers with 0.5 mrad total kick. Collimators are placed in the downstream warm region to protect the superconducting elements from damage in the event of kicker misfires.

The main body of the CW line consists of two vertical bend centers each of which is individually achromatic. In the CW line the beam is matched into a 90° FODO array of 31.6 m half-cell length. In the CCW line the beam is similarly matched into a 90° FODO transport section following the extraction Lambertsons. This line, however, also includes an 80 mrad horizontal bend. All achromatic bends are imbedded in the 90° FODOs and, therefore, allow for control of the dispersion vectors with two pairs of corrector quads. Potential sources of emittance dilution were studied and it was found that the only significant contribution would come from jitter in the kickers (0.09π mm mrad per 1% stability), Lambertsons, and the first and last group of dipoles (0.12π mm mrad per 100 ppm).

Table 6-3. Parameters for Transfer Lines.

PARAMETER	CW LINE	CCW LINE	STRENGTH		[LENGTH]
Length (m)	850	2200	-		
Dipoles	6	22	7	T.m	[5 m]
Quadrupoles	26	53	41	T.m/m	[1.5 m]
Symmetric Lambertsons	2	2	6.1	T.m	[5.5 m]
Asymmetric Lambertsons	2	2	5.2	T.m	[4.7 m]
C-magnets	2	2	3.4	T.m	[2.7 m]
Extraction Kickers	5	5	0.09	T.m	[1.43 m]
Injection Kickers	6	6	0.052	T.m	[1 m]
Trim Dipoles	28	54	0.3	T.m	[1 m]
Trim Quadrupoles	4	8	6	T.m/m	[0.5 m]
BPMs	34	59	–		[0.25 m]
BLMs	23	50	–		–
X and Y Profile Monitors	6	6	–		–

Abort and extraction

The HEB requires a full aperture beam abort over a dynamic energy range of 200 GeV to 2 TeV for the CW and CCW beams.[7] The HEB abort and extraction parameters are given in Table 6-4. The maximum stored beam energy of 6.55 MJ in the superconducting HEB imposes the full aperture requirement. The aborts consist of two major parts: (1) the abort channel, common to the HEB ring, at the H20 and H40 utility straight sections, and (2) the absorbers, which lie in galleries on a line tangent to the HEB ring.

Table 6-4. HEB Abort and Extraction.

Beam Power: Collider Injection (upgrade)	192 GW (960 GW)
Beam Stored Energy: Collider Injection (upgrade)	6.55 MJ (32.75 MJ)
Proton Energy range	0.2 to 2 TeV
Number of protons	1×10^{14} @ 5×10^{10}/bunch (Max)
Number of protons per year	1.8×10^{19} @ 5×10^{10}/bunch (Max)
Abort kicker rise time	Within abort gap time = 1.7 μs
Flat top	one circumference for full beam =36.1μs
Abort control	Manual & Automatic
Kicker prefire / misfire	The abort system will abort beam with a 10 mm offset from the closed orbit with any one kicker misfiring or prefiring.
Delay time	Beam is aborted within three turns from when any of the permits is removed or from when an abort condition is detected
Muon vector	The muon vector after the backstop shall fall within the stratified fee site boundaries

When the HEB beam has to be aborted, the abort kicker magnets are triggered and fired with a rise time of 1.7 μs, synchronously at the beginning of the abort gap. Abort is triggered in case of high beam loss, large (> 3 mm) betatron oscillations due to kicker misfires, large transverse injection errors, or other technical reasons, such as vacuum leaks, refrigeration plant failure, or quench detection. The kickers move the aborted beam vertically into the field region of the Lambertson magnets. The field of the Lambertsons is such that the beam is bent horizontally "out of" the HEB ring. The kicker magnet wave form has a 20% droop, such that vertical "painting" of the beam across 50 mm takes place at the face of the graphite beam absorber ≈ 400 m downstream of the utility straight sections.

The location of the HEB absorber relative to the ring is determined as a compromise between two opposing constraints. The first constraint, which arises from muon radiation considerations, would require a design that would place the absorber far from site boundary, or close to the HEB ring. A 2 TeV muon vector is defined as a 10 mrem/year isodose contour, assuming that the aborted beam is attenuated only through natural earth shield (i.e., Austin Chalk) and the aborted beam is absorbed in a graphite and steel absorber. This vector has a length[8] of 1625 m. On this basis, the HEB absorber is tentatively placed some 1900 m from the site boundary. The second constraint, which arises from the beam dump temperature rise (ΔT) consideration, requires a design that would place the absorber far from the HEB ring, to allow the natural beam spot to become larger and, consequently, the energy deposition and ΔT to become smaller. The compromise between the two constraints is achieved by allowing the "natural droop" of the kicker flat top to be as large as 20%, which still allows the beam to fit through Lambertson magnets and results in the beam "painting" a 50 mm vertical stripe on the face of the graphite absorber core. This restricts the graphite core to a maximum temperature of ≈ 900°C (1,100°C with a single kicker misfire[7]). The absorber also protects the environment from ground water activation by using an iron shield surrounding the graphite core.

Superconducting Magnets

Five different types of superconducting magnets are required for the HEB (see Table 6-5).

Table 6-5. Integrated Field Strength Requirements.

	Design Point @ 6650 A	
Magnet ** Designator	∫BdL @ 2 TeV/c (Tesla-Meter)	∫GdL @ 2 TeV/c (Tesla)
HDM (U &L)	81.869 ± .08*	
HQM (F & D)		298.68 ± 1.0*
HQM1		168.38 ± 0.56*
HQM2		210.55 ± 0.7*
HQM4		624.71 ± 2.05*

** Quads and dipoles operate in series at 6650 A.

Dipoles

The HEB is designed to have 512 dipoles. The magnets are specified[1] to have a field integral of 81.869 ± 0.08 T-m at 6650 A, an aperture of 50 mm, and a slot length of 13.171 m (including interconnect length). The general requirements for the HEB dipole and higher multipoles under ramp conditions, the heat leak budgets, and the operating pressures are given in an SSC report.[2]

The HEB dipole magnet[9] (HDM) is a superconducting cold iron magnet with a two layer coil insulated for high quench voltages and equipped with quench heaters. The coils are held against azimuthal and radial forces, in a structure consisting of nonmagnetic collar laminations, iron yoke laminations (which also confine flux and enhance the central field), and a cylindrical shell (which also acts as the He vessel and withstands a quench pressure of about 14 atm). The end turns are held by specially shaped end parts that bear against a structural end plate to withstand longitudinal forces. The cold mass is supported in the cryostat by 4 Fiberglass Reinforced Plastic (FRP) support posts. The cold mass is shielded against thermal radiation by two shields, one at 80 K and one at 20 K. In addition, loosely wrapped multi layer insulation prevents heat leaks by radiation. The assembly is contained in an iron vacuum vessel. Because the maximum radiation dose for the magnet coils has been estimated at 100 MRad, conventional materials can be used for the magnet. The construction of the dipole is essentially similar to the Collider Dipole Magnet except for the o.d. of the vacuum vessel (787.4 mm), length (13.171 m), sagitta (18.8 mm), and an additional LHe line for return.

The magnet has to operate with the fast ramp cycles (62 A/s) of the HEB. Under such conditions, AC losses[10] from hysterisis and eddy currents in cable, cable strands, and components of the magnet create additional heat. In addition, eddy currents cause undesirable multipole field harmonics in the magnet. R&D focused on these issues has indicated that ramp sensitivity due to strand coupling by low interstrand resistance is an issue to be resolved. This is discussed separately in a SSC document and later in this report.[11]

Three model magnets based on an SSC design, were built and tested to prove that the design was basically sound. Design changes required to improve performance were identified. Westinghouse Electric, subcontractors for the development of HDM, were in the process of carrying out design activities on a full length prototype when the SSC project was terminated.

Quadrupole

The HEB requires 4 different quadrupoles (see Table 6-5). The arc quadrupole has an aperture of 50 mm, a gradient of 185 T/m at 6650 A, and a slot length of 2.483 m. The general rmultipole requirements, the heat leak budget, and the operating pressures are given the in HEB 3B specs.[2]

The quadrupole[12] is, in concept, similar to the dipole except that because there are four pairs of coils for four poles, the collar configuration is different. The detailed design however has significant differences. The inner and outer layers of the coil are wound from a single length of cable without a splice. The collared coil is held in the iron yoke cavity with a sliding contact. The shell over the yoke and the He vessel are different parts. The design would be adapted for the HQM1, HQM2 and HQM4 quads required for the straight section (see Table 6-5). The detailed design of the HEB quadrupole magnet cold mass and tooling are complete, and the program had entered the fabrication phase when the SSC project was terminated. No cryostat design effort had been initiated.

Correction Magnets

As stated above, there are close to 900 superconducting correction magnets in the HEB ring. They have lower strength requirements compared to the Collider. The planned design[13] uses superconducting strands wound into a coil, insulated and clamped into an iron cavity. The cross sections of the magnets have not been finalized, but one option is to retain the same cross section as for the Collider and adjust the length.

Spools

The functions of the standard spool in the arc are cryogenic control, quench control, corrector magnet support, vacuum isolation, power delivery, and beam position monitor support. About half the arc spools also have recoolers to reduce the temperature of the liquid helium. The transfer spools provide most of the functions of the standard spool, in addition to their principal function of transferring cryogens and main power busses around the warm regions. In addition there are special spools: feed spools to provide connection to power supplies and the cryogenic plant, end spools for turn around, and isolation spools to provide isolation of cryogenic sectors for maintenance, warm up, and cool down. The special spools may be left or right handed. There are 271 standard and recooler spools and 71 special spools.

One option for the spool is to use a design similar[14] to that of the Collider, and the other is to combine the quadrupole and the spool functions into a combination spool, thereby reducing one interconnect per spool, reducing the number of supports, and saving time on alignment in the tunnel. A study of the latter option indicated that it might be attractive and a preliminary concept had been created for that option.

Power Systems

The main magnets are powered by four main ring power supplies, each rated to 7000 A and 1000 V (corresponding to a maximum ramp rate of 71 A/s). The ripple and regulation requirement are fixed at 100 ppm at 7000 A. The load is distributed equally between upper and lower buses to optimize performance and minimize quench voltage. Eight dump resistors are connected to the bus to bring down the current in the superconducting string with a 36-second exponential decay time constant.

The dipole correction magnets are powered individually by 316 supplies. The arc tuning quads are powered in six circuits. Two additional quad supplies are used in the straight section, ten quad supplies are used for dispersion correction and one power supply each is used for beta function measurement and half integer resonance correction. Two families of sextupole correctors are powered by two supplies. Four other supplies power skew quads, and three supplies power skew sextupoles. The power supplies are rated for 10 A/s with a maximum voltage of 25 V and current of 100 A.

Quench Protection System

The Quench Protection System (QPS) for the HEB is envisioned to be similar to that of the Collider and will be adapted to the HEB cell. The electrical power circuits and cryogenic circuits begin and end together to minimize quench propagation from one magnet section to another. The quench protection system, when a quench is detected, will abort the beam and fire the quench heaters in the dipole(s) of that half cell to distribute the stored energy. An SCR is fired to bypass the cell, and all other elements are brought down with a 36-second exponential decay time constant using 8 dump resistors. The quench heaters (10 to 18 ohms) will use $\leq$400 Joules per cell and are powered by a capacitor bank discharge.

RF System

The philosophy for the RF system is to use a common design with the MEB. Six MEB type cavities (+ 2 for redundancy) would be used to get an RF voltage of up to 1.6 MV. To carry out the bunch rotation at flat top, the voltage reduction requirement would be met by running the cavities with counter phases, so that individual cavity voltages would remain high. The spare cavities would be shorted to reduce the ring impedance. The low level RF, driver, amplifier, and feedback systems would be similar to the MEB system. The tuning range required for the HEB machine is much smaller than that for the MEB, and therefore the tuner would be simpler (a plunger at the cavity end).

Vacuum

There are three distinct vacuum systems; the cryogenically pumped insulating vacuum, the cold beam tube, and the warm beam tube in the six straight sections. The cold beam tube is designed to operate below 1×10^{-6} Pa. Thirty l/s ion pumps are placed every cell (90 meters) to pump non-condensable gases. Gauges are place every two cells. A warm sector valve is at each end of a cryo-loop to keep the warm-up or cool down time at an acceptable level and to meet the component replacement time defined in the HEB 3A specification.

The warm beam tube also operates at 1×10^{-6} Pa. Every warm-to-cold transition has a gate valve. Thirty l/s ion pumps are placed approximately every 10 meters. The beam tube itself is designed to provide high vacuum (1.2×10^{-6} Pa average, including warm regions), minimize parasitic beam heating, and withstand fluid pressure and quench forces. The beam tube is to be made of stainless steel with an i.d. of 41.4 mm and a thickness of 1.5 mm to 2.1 mm.

The insulating spaces around the cryogenic components (magnets, spool pieces, and transfer lines) are evacuated ($<1.3 \times 10^{-4}$ Pa) to minimize the heat load on the cold mass. A vacuum barrier in the SPXA spool piece separates the insulating vacuum system into 65 m sections with individual pressure monitoring (Cold Cathode and Pirani gauges) in each section. Portable turbomolecular pumps will be used for the initial pumpdown. Cryopumping by the cold surfaces will be the principal means of maintaining the insulating vacuum after cool down; there are no installed pumps.

Each dipole, quadrupole, and spool-piece cryostat has a sealed pump-out port located near one end of the cryostat. In addition each cryostat has a pressure relief valve or disc to guard against over-pressure in the cryostat if accumulated frozen gases pressurize it during warm up, or if a cryogenic line ruptures.

Instrumentation

The HEB cells have one vertical or horizontal beam position monitor in each spool and one beam loss monitor near a spool piece. There will be a multiwire beam profile monitor (four for each direction) for horizontal and vertical profiles. Schottky monitors, TV flags, flying wire profile monitors, and synchrotron radiation profile monitors were to be considered as supplemental equipment for the beam diagnostics. There were narrow band global dampers for transverse beam oscillations in both planes because of injection errors and resistive wall instabilities, and wide band transverse dampers whose bandwidth had not yet determined.

Utilities

Low Conductivity Water is required for cooling warm magnets in the straight sections, RF cavities and sources, kickers, power supplies, collimators, and power buses. At the surface 650 GPM (gallons per minute) and in tunnel 756 GPM (total of 1406 GPM) flow is required to meet a maximum temperature rise of 30°C at the outlet. In addition, there are compressed air and water requirements.

Conventional Facilities

Technical facility requirements for the HEB are given in HEB Design requirements document [15] (Level 3B technical requirements specification). The Title I submittal was expected to be delivered at the end of October 1993.

The HEB conventional facilities were to consist of a 10.8 km ring tunnel with two abort tunnels, and parts of the MEB to HEB transfer line tunnel (approx. 1100 ft). The tunnel cross section is 14 ft in diameter and was to be constructed primarily by rock tunnel boring machines.

The HEB tunnel is on Laboratory land. It was to be about 150 to 175 feet below the surface and lay totally in the Austin Chalk. The HEB is tilted to be parallel with the Collider rings. The HEB west straight section is 14 m directly above the Collider ring. At tunnel level, 30 niches were to be spaced approximately 390 meters apart with the exact location defined in the lattice. Alcoves were at each straight section to house cryogenic equipment and to allow for placement and service of the feed, isolation, and end spools. Small holes in the tunnel wall house the quench protection bypass switch equipment near every other spool piece. Local alcoves were planned in the tunnel at H20 and H40 to provide space for the abort kickers and to transition smoothly into the abort line with a rigging aisle. Abort beam absorber galleries are located at the end of the abort tunnel, at H20 and H40. Scraper and collimator shielding alcoves were located primarily in the H50 straight section.

Shafts and associated surface buildings were to be located at H10 (RF), H20 , H40, H50, H60 and H80. Originally planned shafts at H30 and H70 had been deleted because it was determined that they would not be needed for the energy extraction system. In addition there were two shafts in the H10 (west and long) straight section that are common use shafts with the Collider (N130 and N135 shafts) and were in the Collider west utility civil construction package. Cryogenics plants were to be located at H20 and H60. The single HEB magnet delivery shaft was planned to be located in the H20 straight section.

Chapter 7. Collider Overview

(M. Syphers)

General Remarks and Parameters List

A subset of the primary parameters of the Collider synchrotrons is shown in Table 7-1. For a further overview of the history of the Collider design development, the interested reader is referred to the bibliography items.[1-5]

Table 7-1. Collider Parameters.

	1993	1990 SCDR	1986 CDR	UNITS
Injection Energy	2.0	2.0	1.0	TeV
Circumference	87120	87120	82944	m
Cell length	90	90	96	m
Cell phase advance	90	90	60	deg
Dipole Coil Diameter	50	50	40	mm
Dipole Field	6.79	6.60	6.60	T
Quad Coil Diameter	50	40	40	mm
Quad Field	194	206	212	T/m
β^*	0.5	0.5	0.5	m
Crossing angle	<150	<150	<150	μrad

The Collider consists of two 35 km arcs connected by two "cluster" regions. The clusters contain interaction regions for the major detectors and utility regions for beam injection, RF system, beam scrapers, etc. Each arc contains 196 standard FODO cells, with nominally 5 dipole magnets per half cell. Space has been provided in the arcs by occasionally omitting one 15 m dipole magnet in a half cell. This occurs in 26 locations per arc, the detailed pattern being determined by the requirements of dispersion matching plus appropriate phase advance between the straight sections for various useful applications. These small perturbations to the general magnet arrangement also more easily allowed for the placement of all Collider utility shafts on the more favorable land properties being offered by the State of Texas.

There are two "utility regions" on each side (east and west) of the ring that have long straight sections to be used for various accelerator functions such as injection, acceleration, and extraction. The region on the west is used for this purpose. The east region is equivalent to the one on the west optically, but it does not provide any other functions to the machine. It was envisioned that the east utility region could have been used for beam scraping, high-energy beam extraction, or perhaps as another interaction region. The locations around the circumference where the two counter-rotating proton beams were to be brought into collisions are called the interaction regions (IRs). The Collider has provisions for up to four such locations initially, two on the east side and two on the west side.

Lattice Layout

Arcs

The geometrical layout of the Collider arcs was made final in March 1992, when it was officially decided to go forward with a new design in which 26 dipole magnets were left out of each arc of the Collider to provide space for future uses. Such uses could include beam scrapers, beam dampers, correction magnets, polarization preserving devices (e.g., Siberian snakes), and other beam diagnostic devices. The change raised the field of the main bending magnets by 1.27%, while assuming the same magnetic length for the magnets. The dipole magnet operational margin was planned to be restored by a modest increase in refrigeration. A schematic layout of the free spaces in the Collider is presented in Figure 7-1. Table 7-2 shows some of the relevant parameter changes introduced by the new design. More details of the Collider arc lattice can be found in the literature.[7]

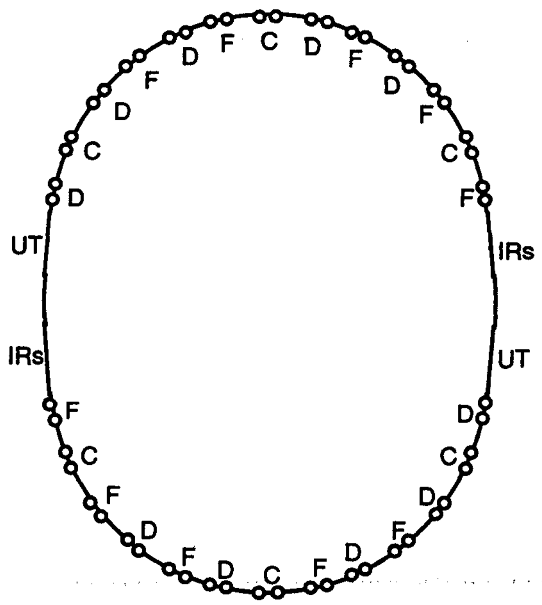

Figure 7-1. Schematic Layout of the Free Space in the Collider.

Table 7-2. Changes of Relevant Parameters for One Ring.

	1992	1990
15 m free spaces (arc)	26	0
2.5 m free spaces (arc)	26	34
15 m spaces (cluster)	2	0
2.5 m spaces (cluster)	0	2
Long Dipoles (15 m)	3972	3978
Short Dipoles (13 m)	196	252
Standard Quads	848	832
Dispersion Suppresser Quads	40	60
Bend Field Increase	1.27%	0
Max. Dispersion in arc		
Top Ring	2.26 m	1.87 m
Bottom Ring	2.26 m	1.81 m
Max. Dispersion in ring		
Top Ring	2.85 m	1.87 m
Bottom Ring	2.85 m	1.81 m

Utility Region

One of the more complicated areas of the Collider is the West Utility straight section, where numerous facilities are located that are crucial to the operation of the accelerator. It is in this 1.35 km region where beam is injected from the High Energy Booster (HEB). Here also RF systems are located for accelerating the beam, scrapers are located for removing the beam halo, and beam is extracted toward the beam dump after a store or because of a triggered abort. Systems for both the CW and CCW traveling proton beams are located in this one straight section. Other functions could be performed here, such as special beam diagnosis and damping of beam oscillations (both transverse and longitudinal). The optical properties of the region have been refined since the 1990 design to improve many of the above operations.

Interaction Regions (IRs)

Much design work has taken place during the last two years in the project with regard to the interaction regions in an effort to decide on the required magnet development necessary to meet the needs of the IRs, and to be as flexible as possible for detector requirements as they unfold. The basic principle of the IR system is that of a telescope. The beam from the arc is brought to a fixed "intermediate" focus using a series of six individually powered quadrupoles. The fixed focal length triplet quadrupoles just in front of the interaction point then focus the beam to its final spot size. Various values of the amplitude function at the interaction point (referred to as β^*) are obtained by tuning the beam parameters at the intermediate focus using the six quadrupoles, essentially moving the focal plane of the secondary lens.

It was decided that the triplet quadrupole magnets would be of 5 cm bore operating at approximately 190 T/m gradients. With this aperture and field, it is felt that a maximum amplitude function of $\beta = 9$ km within these magnets would be acceptable. This is the maximum produced for $\beta^* = 0.5$ m and with detector free space (IP to first quadrupole) of $L^* = 20$ m. Keeping the maximum $\beta = 9$ km as a constraint, this optical system in principle could be used for various values of L^* ranging from 20 m up to at least 90 m with a corresponding reduction in luminosity. In each instance, the triplet quadrupoles would need to have different lengths to regenerate the intermediate focus, but the remainder of the IR design would be unchanged. The system is also designed to keep the maximum amplitude function throughout the region minimized for the injection optics; its maximum is similar to that in the utility region, under 700 m. If, at some later date, larger aperture triplet quadrupoles with gradients similar to the current design could be produced and installed, then the tuning quadrupoles could be adjusted to produce lower β^*. For $L^* = 20$ m, the current design can provide $\beta^* = 0.25$ m. For this case, the maximum β increases to roughly 18 km. In addition, by increasing L^*, the same basic IR design can be used to replace the previous "medium beta" design of the SCDR. This can reduce the number of types of length of magnets necessary in the initial construction phase of the project. As of project closing, the two large low-β^* detectors were to be located on the east side of the Collider, where their foundations would be in the stable Austin chalk. It was envisioned that smaller experimental halls would be located on the west complex.

Special Issues

There were many interesting challenges facing the design of the SSC main synchrotrons. Some of the more prominent outstanding issues that were being investigated as the project ended are discussed below. Further details can be found in other chapters of the report.

Quad Aperture and Mid-cell Correctors

In the early investigations of the SSC design, it was known that for a 1 TeV injection energy and with 4 cm main dipole magnets, correction magnets located next to the quadrupoles would not be enough. The earlier designs used correction coils mounted directly inside the dipole magnets ("bore tube correctors") and, later (in the SCDR), "mid-cell" correctors, which were separate correction magnets mounted in a 50 cm space (the "mid-cell slot") between the second and third dipole magnets in a half cell. Intensive numerical studies showed that at the injection energy of 2 TeV, and with 5 cm dipole magnets, the need for mid-cell correction magnets was reduced. In the SCDR design, these spaces still contained skew quadrupole, octupole, and decapole correctors. A new skew quadrupole correction scheme was later adopted, along with a change in the vertical tune by one unit, which alleviated the need for the mid-cell skew quads. Furthermore, tracking studies indicated that there was little to be gained in accelerator performance with the mid-cell octupole and decapole correctors as long as the dipole magnet specifications were met. At the same time, it was realized that the quadrupole magnet required a 5 cm aperture, similar to that of the dipole magnet. A change in aperture from 4 to 5 cm for the quadrupole meant that the gradient would be lowered in the magnet, thus requiring a longer quadrupole magnet to achieve the same focusing properties. To provide the required additional length, the mid-cell correctors were deleted and the 50 cm mid-cell slot length was allocated to the new quadrupole.

Synchrotron Radiation - Related Issues

R&D was in progress on a liner design for the Collider magnet beam tube. Two issues were at play here: intercepting the synchrotron light at a higher temperature using a liner, thereby reducing the refrigeration power necessary from the cryogenic system; and providing space for a distributed pumping system (liner) to pump gases photodesorbed from the beam tube walls due to synchrotron radiation. The vacuum requirement without distributed pumping was barely met by the baseline design, and increased intensity (either to meet the baseline luminosity, or to upgrade the luminosity) may have been pushing the limits of acceptable accelerator performance. The temperature of the liner was tending toward 4 K, primarily because of the additional cost and complexity of higher temperature systems. The issue is discussed in more detail in the chapter on Collider Cold Bore Tube Vacuum.

Energy Deposition Issues

At the nominal luminosity, 320 Watts from the reactions taking place at the interaction points would be directed toward the IR quadrupoles, which were at 4 K or colder, requiring detailed calculations of energy deposition in these devices, as well as the deposition in scrapers and collimators. Another challenge was the beam dump system, which had to handle the transport and disposition of the 400 MJ of stored energy in each beam.

Chapter 8. Collider Arcs and Utility Sections

(R. Meinke, D. Johnson, Y. Cai, N. Mokhov, W. Nexsen, D. Plant, B. Parker, R. Richardson, S. Saritepe, J. Tompkins, E. Tsyganov, and W. Turner)

The conceptual design of the SSC Collider is described in the Site-Specific Conceptual Design Report (SCDR), published in July 1990. When the SCDR was written, neither the accelerator nor the technical support systems were worked out in sufficient detail. Several modifications of the magnet lattice were necessary to assure that the access points to the tunnel were located on land offered by Texas. The arc lattice was fully occupied by magnets and no room existed for future implementation of other components. The magnet correction system was overly conservative and included octupole and decapole components at the end of cells and in mid-cell positions, which were later found to be unnecessary. The decoupling system described in the SCDR was found to be fully inappropriate and required a complete redesign.

In the SCDR design, the aperture of the main dipole magnets had already been increased from 40 mm to 50 mm, but the main arc quadrupoles and all correction elements had been left with an aperture of 40 mm. This decision caused significant problems. To have a uniform beam pipe throughout the machine, the beam pipe was specified to have a small inner diameter of 33 mm which was barely sufficient for the operation of the machine. The beam tube vacuum of the Collider was not sufficiently well understood when the SCDR was published. It was recognized that photo desorption of hydrogen and carbon-oxides could have significant impact on the luminosity lifetime of the Collider, but the existing data were too sparse to justify or to rule out the necessity of a synchrotron radiation intercept, or liner.

The West Utility of the Collider required major design work to guarantee that accelerator requirements would be met. The injection lines were changed from a superconducting to a normal conducting version because the superconducting version was found to be too costly. The beam abort system required major improvements to accommodate the extreme energy densities of the Collider beams.

Radiation safety issues related to beam loss and energy deposition from the beam halo had not been worked out in sufficient detail in the SCDR. The geometric layout of the access shafts had to be changed to keep the radiation levels from beam loss within allowable limits. Large numbers of collimators had to be introduced in the West Utility and in the vicinity of the interaction regions, to protect the accelerator components and to keep background in the experimental halls at acceptable levels. Also, the beam scraper system required substantial design work to meet the Collider requirements.

The design of the Collider West Utility (WU) Straight at termination of the project provided space and favorable lattice functions for (1) keeping the beam well focused; (2) injection and tune up from the HEB; (3) RF cavities and longitudinal dampers that capture, accelerate and control the injected bunches; (4) scraping and collimating unwanted halo particles; (5) special beam instrumentation and active damping systems; and (6) safely diverting circulating beam to external backstops in both nominal and upset conditions. The Collider East Utility (EU) had the same superconducting quadrupole layout as the WU but without the corresponding warm drift regions. Without these regions, the EU did not accommodate WU functions other than keeping the beam well matched and focused.

Dispersion suppresser (DS) sections are located on either side of the WU and EU insertions as well as outside the East and West Interaction Regions. The DS sections cancel the natural dispersion found in the arcs and thereby eliminate momentum dependence in the utility straight sections, and momentum dependence of the spot size at the interaction points. Future upgrades considered for the EU for momentum scraping and crystal extraction would have required reintroduction of dispersion into the EU.[1]

The transition from a DS section to an IR is accommodated by a short transition to IR (TI) sections. The TI sections provide space for skew quadrupoles for machine decoupling, and they are potential take off/return points for a bypass around the IR. Finally, short arc like sections, denoted transition to utility (TU), provide the bend needed to separate muon vectors from the utility straight sections and IRs.

Performance of the Collider

The expected performance of the Collider had been improved substantially since the SCDR. The primary improvements came from a combination of intentional changes and changes or additions made possible because of a more in depth examination of various problems. Many of the changes have already been mentioned. One of the two major changes was the addition of empty spaces throughout the arcs. In the lattice at shutdown, 13 pairs of dipoles were removed, in a dispersion-pairing scheme, in each arc. This was done both in order to accommodate the required locations for feed and isolation spools, and to insert empty spaces into the arcs. In the SCDR design, the arcs were essentially a solid cryopipe from one cluster to the other. The ability to insert any special device, especially a warm device, did not exist. The missing-magnet holes were arranged around the arc to correspond to F-quadrupole positions, D-quadrupole positions, and some center half-cell positions. These would then be available for the future insertion of such devices as warm collimators, feedback pickups and kickers, special correctors, etc. Experience at the Tevatron had shown that empty places within the lattice would be invaluable in the eventual operation of a large superconducting accelerator.

The other major change from the SCDR lattice was the increase in quadrupole aperture from 40 to 50 mm coil winding diameter. The change allowed the beampipe to be a uniform 42 mm i.d., and also improved somewhat the dynamic aperture because of the improved quadrupole field. It was also found that the mid-cell correctors could be totally eliminated, which greatly simplified the dipole interconnect structure and eliminated the costly mid-cell spool. The mid-cell slot was also eliminated, providing additional slot length for the 50 mm quadrupole. The corrector strengths were also lowered, and the overall correction schemes became considerably simpler. A significant improvement was made in the coupling correction scheme. The basic tune splitting between the two planes was incorporated into the general quadrupole corrector design, and the quadrupole to dipole tracking was adjusted so that the transfer function crossover point was at approximately 4000 amps, thus minimizing the total quadrupole corrector strength needed.

Details of the dispersion suppresser cells were improved. The total number of different quadrupoles was reduced, and detailed consideration was given to tuning and correction of the dispersion suppressers relative to the arcs and the cluster regions. These changes did not result in obvious differences, but many details of the machine's performance would have been greatly improved.

All the design details of the utility and Interaction regions were essentially redone. The IR design was improved, although the basic concept was essentially the same as that in the SCDR. This will be discussed in detail in further chapters. The Utility design, in the SCDR, was purely a conceptual design. In the several years before termination, that design was replaced with a real, engineering design. Some details of the lattice, such as making the quad pairs more cost effective, were changed, but the primary changes were to implement realistic, detailed engineering designs for the injection, abort, RF, collimator, and scraper systems.

Lattice and Correction Systems

Lattice

The latest Collider lattice was revision 2.0 lattice, which included the aperture change of the main quadrupole magnets. This lattice has been stored in the lattice database. In addition to the aperture change of the quadrupole magnets, many improvements were made to the correction system in the Rev2 lattice. In fact, this lattice would be the first to contain not just the main magnets, but also the complete correction system including the interaction regions (see Rev2 lattice references in Chapter 35).

More changes were considered as part of the value engineering process. The strength of the dipole corrector was reduced from 3.0 Tesla-meter to 1.75 Tesla-meter, and skew quadrupole correctors were moved back to the regular spool locations. Many spools were eliminated as a result, and the changes reduced the cost of the correction systems significantly.

A series of updates to the SCDR utility lattice reduced the number of special quadrupoles, reduced the injection kicker and abort kicker field strengths, simplified the IR correction scheme, and provided more detailed component layout information.[1-5] The four special quadrupole types, QU1-QU4, in the SCDR lattice were reduced to two types (QU1=QU2=existing IR quad, QU3 and QU4 special) in the Rev1 lattice.[5] With the planned advent of 50 mm arc (Q) and dispersion suppresser quadrupoles (QS, QS1), a further reduction in the number of special quadrupole types was made to a single special quadrupole type (QU1=QU2=QS, QU4=Q, QU3 special). Associated with these changes, the β-maxima were reduced 40% across the central utility region, QU1-QU4, and the product $K\beta L$ was reduced 32% for better focusing with less total focusing strength. A smaller $K\beta L$ for the Rev2 lattice implied less sensitivity to errors and should have yielded a better dynamic aperture.

The total abort kicker field strength was minimized by a polarity flip of QU1/QU2. Favorable injection matching conditions were maintained, and total injection kicker field strength was minimized by providing $\pi/2$ phase advance from the last injection Lambertson magnet. Also, an additional lattice constraint was imposed on the utility transfer matrix: the overall matrix was made equivalent to an odd number of half cells. This made the utility region transparent to IR corrections, which were made symmetrically in the north and south arcs.

Virtual survey markers were added for niches, shafts, gallery, tunnel transitions, half cell boundaries, RF, instrumentation, damping system, cryogenic cross connects, and interface points to the abort and injection systems. The EU & WU were optimized to reduce the number of special spools and empty cryostat lengths.

Correction Schemes

Only a conceptual correction scheme was presented in the SCDR. As the design evolved, the number of correctors and the necessary field strengths changed. The strength of the dipole corrector was increased from 2.50 T-m to 3.00 T-m. The additional margin was added to compensate for misalignment of quadrupole magnets because of slow ground motion in the tunnel. (This value was later reduced to 1.75 T-M as a result of the value engineering effort.)

The strength of beam separation and crossing angle dipoles was decreased from 15 T-m to 3.00 T-m reflecting the change in the optics of interaction region design. The residual dispersion created by the crossing angle dipoles was compensated by pairs of skew quadrupole and trim quadrupole correctors outside the interaction regions rather than by dipole correctors inside the interaction regions. The strength of the trim quadrupole corrector was increased from 0.53 T-m (at 1.0 cm) to 0.65 T-m to allow for increased saturation of the main dipole magnets, which operate at a higher field.

The strength of the sextupole correctors was increased, largely because of an additional requirement of correcting the second order chromaticities generated by the triplet quadrupole magnets inside the interaction regions. The sextupole correctors in the dispersion suppressers were deleted because their impact on the linear aperture was less than one sigma at the 2.0 TeV injection energy. The total number of sextupole correctors was reduced.

The skew quadrupole correctors were removed from their mid-cell locations to the missing dipole locations in arcs. The decoupling system was designed to be used for either global or local decoupling. Octupole and decapole correctors were deleted from the design. Based on the then current specification of main dipole magnets, those correctors were not needed. Without such correctors, the main dipole specification would still provide a factor of 2–4 in margin on systematic b_3 and b_4. As a result of this change, mid-cell slots were deleted from the lattice

Beam Behavior – Dynamic Aperture

Since the time of the SCDR, the estimated dynamic aperture of the Collider had increased. The increase was the result of more extensive calculations, as well as the result of some changes made to the magnets and the Collider lattice design. The most striking new result concerning the dynamic aperture was the discovery that it had a finite limit. At the time of the SCDR, tracking studies had been carried out for approximately 10^6 turns. The dynamic aperture was observed to shrink linearly with the log of the number of turns. It appeared that the aperture for injection, lasting some 10^7 turns, would be very close to zero. This led to serious concerns about the ability to inject the full beam. Subsequent studies have showed that the aperture was, in fact, well behaved and it reached a lower, non-zero limit, during the injection period. The aperture was found to be approximately 4.3 ± 0.2 mm at 10^7 turns, or 11.3 ± 0.5 sigma at injection. This aperture was for a machine made only of arcs and normal cells. The Interaction and Utility Regions were not included in these calculations, but handled separately with the understanding that they would have to be very well corrected locally. During the time since the SCDR, much work went into redesigning the IRs and the Utility Regions, with the result that the aperture, which was limited by these regions, improved. More will be said on this subject in sections below.

The major change made to the Collider that affected the dynamic aperture was the increase of the quadrupole magnet aperture from 40 mm to 50 mm. The change had the effect of increasing the dynamic aperture by approximately 0.3 mm at injection, if one simply scaled the acceptable quadrupole multipoles by the appropriate radius ratio. Conversely, for a given dynamic aperture, the multipole requirements for the quadrupoles could be relaxed. An optimization study for the quadrupole specification was under way at the time of project termination.

Also under consideration at termination was the reduction of the value of the injection energy into the Collider. Because of the improved dynamic aperture resulting from the increased quadrupole aperture, the possibility existed to lower the injection energy from 2 TeV. Shown in Figure 8-1 is a graph of the calculated dynamic aperture versus injection energy for several different simulations. The curve labeled "SSCTRK @ 10^5," was known at the time of the SCDR, shows a sharp falloff below 1.5 TeV. This was found to be due to the tune of the machine and the fact that the machine was being driven into a half-integer resonance. Further studies showed a very smooth dependence of dynamic aperture on energy. All of these curves are for a 50 mm quadrupole. It was felt that the possibility of reducing the injection energy to around 1.5 TeV should be seriously considered, and such a recommendation would most probably have been made had the work continued.

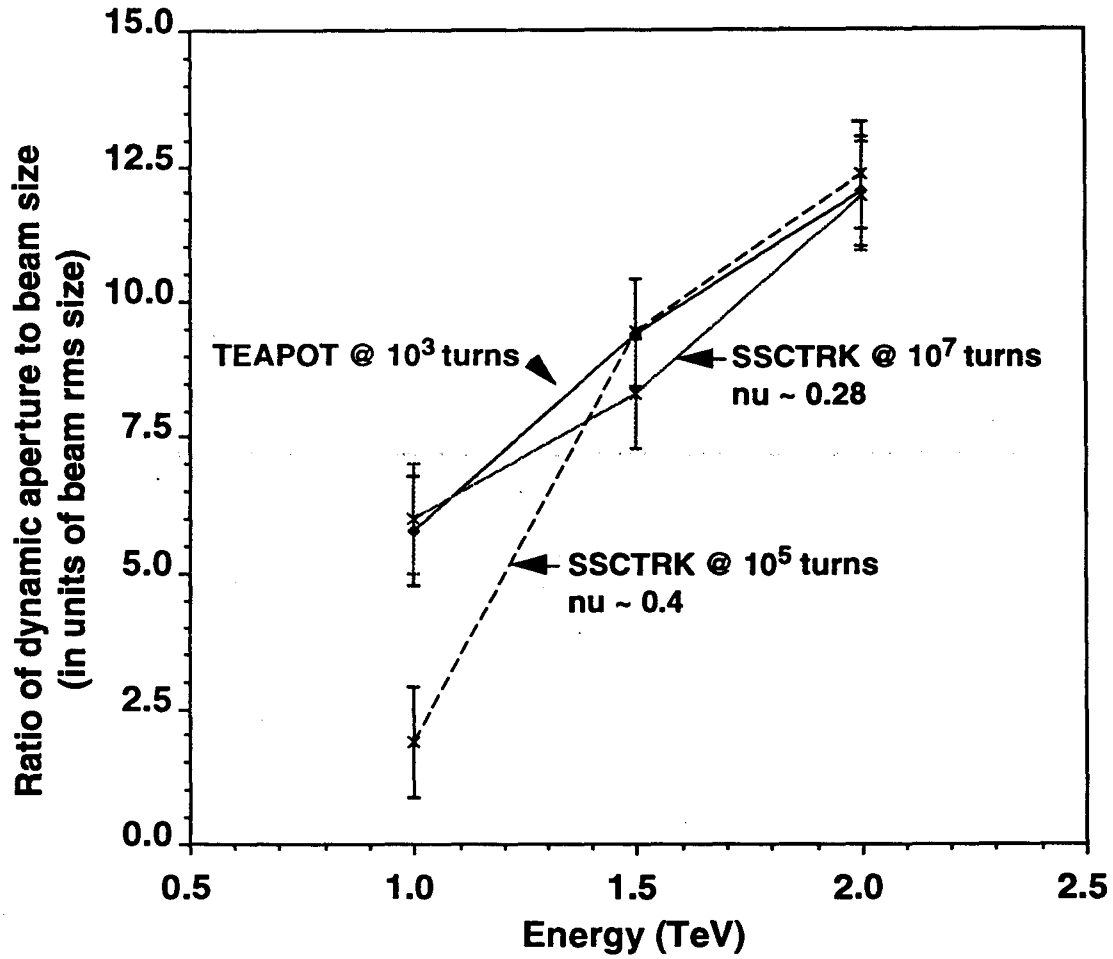

Figure 8-1. Graph of Calculated Dynamic Aperture versus Injection Energy.

Beam Loss Handling

Comprehensive studies were performed on beam induced energy deposition and radiation effects in the arc, utility straight and interaction regions, in access shafts, electronics niches, backstops, beam lines, and the general environment.[1–18] The design of all related systems current at termination were based on full-scale simulations with MARS12 and STRUCT Monte Carlo codes. The main accomplishments are described below.

An overall Collider beam loss model was developed and used in designing a scraper/collimation system. The system minimized the irradiation of the superconducting magnets, maintained favorable background conditions in the interaction regions, and reduced the impact of radiation on equipment, personnel, and the general environment.[1-3,15-17] Detailed consideration was given to the beam failure modes: unsynchronized abort, injection and abort kicker prefires and misfires, and accidental loss of the entire beam, which involved energy desposition in the extreme hydrodynamic regime. These considerations were the basis for the design of the appropriate protectors.[4-6, 16, 18]

The beam abort system design was modified to incorporate allowance for most failures. One feature of the system was the absence of beam pipe along the last third of the beam abort line.[16] Specifications were established for radiation resistance for all component materials to be used in the radiation environment: magnets, interconnects, beam instrumentation devices, fiber optic cables, electronics, transformers, and conventional construction structures.[15, 16] The beam loss monitor system was redesigned.[7]

The Collider access shafts were redesigned to conform to regulatory requirements. Features of the new design included a hammerhead scheme incorporation, shielding walls in the adits on a case-by-case basis, plugs in delivery shafts, and service building considerations.[8,9] Cinder blocks and cooling water were proposed as an optimal cost-effective shielding for the electronics niches. Radioactivation was estimated for accelerator components, cooling water, and air.[15,16]

Accelerator-experiment interface issues in the interaction regions were studied. They included: protection of the low-beta quadrupole triplet against radiation from the interaction points and from the rest of the machine; and reduction of radiation and background levels in SDC and GEM detectors, in experimental halls, and on the surface.[10-14]

Collider Beam Loss Model

This model was based on the following postulates. The expected operational beam loss rate in the Collider arcs at 20 TeV for 1.3×10^{14} protons per beam would be the sum of four sources: (1) interactions (nuclear and Coulomb) with the residual gas (H2, CO, CO2): $5 \times 10^{3} m^{-1}s^{-1}$; (2) fast protons from IRs: $1 \times 10^{3} m^{-1}s^{-1}$; (3) tails from scrapers and collimators: $3 \times 10^{2} m^{-1}s^{-1}$; and (4) RF noise, and collective beam-beam interactions: $2 \times 10^{3} m^{-1}s^{-1}$. The total rate was: $8.3 \times 10^{3} p\ m^{-1}s^{-1}$ which made the operational beam loss density in the arcs about $1 \times 10^{4} pm^{-1}s^{-1}$ (corresponding to 0.44 Watts per 15 m dipole).

Beam Collimation System

The beam collimation system for each of the Collider rings consists of scrapers, coupled with a thin scattering target, and a set of collimators. Functionally, a long resistive bending magnet is required downstream of the scrapers, therefore a pair of scrapers (horizontal and vertical) would be situated in front of the Lambertson magnet of the abort system in the West Utility. A few collimators have to be installed in the West Utility downstream of the Lambertson. Other collimators are positioned in the East Interaction Region. Graphite shadow collimators have to be installed in some locations to protect components in failure.

As a part of the beam collimation system, a pair of scrapers (horizontal and vertical) was incorporated into the middle of the West Utility of each Collider ring (see Table 8-1).

Table 8-1. Maximum Scraping Rate on Scrapers for 250 Fills per Year.

Energy (TeV)	Rate (p/s)	Duration	Annual (p/yr)	Cycle Stage
2	1.3×10^{12}	0.1-1 s	3.25×10^{14}	Injection and beginning of acceleration
20	3.0×10^{9}	15 min	6.75×10^{14}	Beginning of flattop before collisions
20	4.0×10^{8}	24 hrs	8.64×10^{15}	Collisions

Scrapers and collimators have movable jaws controlled by high-precision motors and are surrounded with radiation shielding made of steel. Tungsten targets, 1-mm thick, are used to deflect halo particles deeper into the scraper front face. Scraper jaws are made of copper, and collimator jaws, of steel. The cooling system is designed to maintain a uniform temperature over the scraper jaws sufficient to sustain the flatness of the surface to within 0.005 mm. The essential part of the beam collimation system is a horizontal dogleg structure, which provides a complete interception of neutral and low-energy charged particles from the scrapers. The horizontal dogleg is created by two superconducting dipoles and a set of warm magnets including symmetric and asymmetric Lambertsons and resistive magnets. To provide a fine tuning of the beam on the scrapers, eight dipole correctors are used. A high-precision feedback system would have been used to control scraping intensity.

It was planned that scraper jaws would be positioned at 6 σ from the beam axis for the first 15 minutes and pulled back to 10 σ position for the rest of the store. The most recent simulations suggested that the dynamic aperture of the Collider at the top energy was equal to about 12 σ, and the lifetime of the particles with increased betatron amplitudes (12 to 20 σ) varied from 2 to 50 turns. The lifetime was lower than one turn at amplitudes greater than 20 σ. Therefore, collimator jaws would have been installed between 16 and 20 σ from the circulating beam axis to protect superconducting magnets from irradiation. A set of collimators was required in the Interaction Region to protect the final focus triplet and vertical bending magnets. The details are discussed in the chapter below on Interaction Regions.

Injection/Abort System

The beam can be lost in the Collider because of various failures, such as abort and injection kicker misfire and prefire, unsynchronized abort, and timing errors. This results in the irradiation of accelerator components, quenching of superconducting magnets, and overheating or even melting and destruction of the machine components.

The abort kicker magnet system consists of 24 pulsed magnets with a risetime of about 2 μs. Normally this system is triggered during the 3 μs abort gap in the circulating beam to divert the beam to a massive graphite absorber. If one or more of the kickers prefire or misfire, some fraction of the beam would hit the collimators and cause overheating of the collimator jaws. To decrease the overheating of collimators, it was proposed to compensate a prefired kicker by another with opposite magnetic field (antikicker). In this case, beam abort could be delayed until the abort gap. The Lambertson septum is protected with graphite shadows.

An injection kicker prefire or misfire results in a coherent betatron oscillation of part of the Collider injected or circulating beam. To eliminate the problem it is necessary to increase the number of injection kickers from 5 to 6 modules. Injection kicker timing errors could also cause losses of circulating and/or injected beam. Beam could melt the second and third superconducting dipoles downstream of the injection kicker. The problem is resolved with an appropriately placed two-jaw sacrificial collimator consisting of 3 m-long graphite jaws followed by 1 m-long steel jaws.

Material Specifications With Respect To Radiation

The radiation dose estimates for components in the arcs were based on an expected operational beam loss rate of 10^4 protons per meter per second in each of the rings for 6000 hours per year over 25 years of the machine lifetime. Beam loss levels in the utility straight sections, interaction regions, and dispersion suppression regions could exceed the above level by about a factor of 6. For the low-beta triplet quadrupoles, the levels are even higher. Dose estimates for the arcs, shown in Table 8-2, included in Ref. [15], assume a 50 mm aperture dipole, 40 mm-aperture quadrupole, spool piece, and 33 mm i.d. beam pipe.

Table 8-2. 25 Year Maximum Radiation Dose to Collider Arc Magnets.

Element	Radial Location (mm)	Dose (Mrad)	3B Spec (Mrad)
CDM inner coil i.d.	25	260	1000
CDM outer coil o.d.	50	36	
CQM or SPR inner coil i.d.	20	690	1000
CQM or SPR outer coil o.d.	45	17.3	
Beam pipe	16.5	1380	1400
Support post CQM (CDM)	180	1 (0.3)	
Cryostat o.d.	350	0.28	0.5
Interconnect	105	9	15

If uncertainties in the calculational model and variations of the dose level along the magnet string were taken into account, the accepted specifications for materials to be used in the innermost regions of CQMs and SPRs did not look too excessive. But requirements could be brought down for outer coils and for dipoles. Special consideration was required for WU, IRs, and dispersion suppression magnets.

The increase of the quad and spool piece coil aperture up to 50 mm would decrease peak dose levels in the inner coils of these components up to a factor of two. The peak dose at the beam pipe is almost independent of its i.d. enlargement (33 mm to 40.9 mm). If the misalignment of the inner coil in one magnet with respect to one in an adjacent magnet was less than 1 mm, a mitigation of the radiation requirements on the quadrupole and spool piece could be considered.

Magnets

Dipoles

In this section, the development of the prototype dipole magnets constructed for the Accelerator Systems String Test (ASST) is discussed. The design of these magnets formed the basis for the designs of the Collider and HEB dipoles. Short (or "model") magnets were constructed and tested as part of the vendor programs, but the termination of the SSC occurred before full-length dipoles designed and built at the magnet vendors could be tested.

The Collider dipole magnet design used a two-layer, cos θ-style coil surrounded by stainless steel collars and a cold iron yoke. The operating parameters included a temperature of 4.25 K and a peak field of 6.7 T. Early prototypes were nearly 17 m in length with a coil aperture (inner diameter) of 40 mm. The 40 mm dipole design had been developed to the point where stable quench performance at currents in the range of 6700 to 6900 amps was achieved. The basic design features of the 40 mm dipoles have been described in detail in previous reports.

The decision to increase the aperture of the Collider dipole magnets to 50 mm, based on machine physics considerations, was made in January 1990. A 50 mm design team ("50 mm task force") was assembled from the magnet experts in the SSC magnet collaboration (SSCL, Fermilab, BNL, and LBL), and the 50 mm design was developed, based largely on the design concepts that had evolved in the 40 mm program. The 50 mm magnet program at its inception was confronted with the need to meet a major Laboratory milestone: the Accelerator Systems String Test, the first systems level test of Collider magnets in the anticipated machine configuration of a half-cell. To meet the string test milestone, a "fast track" approach was employed that caused decisions on component design and tooling to be taken simultaneously. The baseline magnet production was to occur at Fermilab; a backup production effort was sited at Brookhaven.

The 50 mm task force decided to pursue two slightly different design approaches at the two laboratories. The Fermilab design incorporated a change in the orientation of the split in the iron yoke (the split was moved from the horizontal to the vertical) along with a slight horizontal oversizing (an interference fit) of the collars to maintain constant contact between the yoke and the collared coil assembly at the midplane. The support of the coil in the end regions, and the method of forming the splice between the inner and outer coil assemblies were also changed. The Brookhaven design more closely followed the 40 mm dipole design, retaining the horizontal yoke split direction and the coil end and splice design. In both cases, the same geometric cross section (arrangement of conductors) was employed to determine the magnetic field.

In the 50 mm aperture design, the features of the magnet were largely a scaling up in size from those in the 40 mm dipoles. A key component of the magnet was the superconducting cable made of NbTi (47% by weight). The 50 mm program decided to use the same superconducting strand that was developed in the 40 mm program and to achieve the required increase in cable width by increasing the number of strands. If the same strand design was used, the processes developed by the conductor vendors could remain constant, and additional conductor development (and significantly increased schedule risk) could be avoided. The only developments required were a cable geometry that met the design requirements and a change in the design of the cabling machines to accommodate more strands.

The magnet designs were carried out by the staffs at Fermilab and BNL in conjunction with the design team at SSCL. During this period, development contracts for the Collider dipole magnet were signed with General Dynamics as the leader and Westinghouse as the follower, and the vendors integrated their staffs into the production effort: General Dynamics at Fermilab and Westinghouse at BNL. At each of the laboratories, the first magnet was fabricated by the laboratory staff while the second magnet was jointly assembled by the laboratory staff and vendor personnel (a "technology transfer" magnet); subsequent magnets were fabricated by the vendor personnel alone. The program worked well with a high degree of cooperation among the laboratories and industry.

Nine ASST magnets were produced at Fermilab and seven were produced at BNL:

At Fermilab	At BNL	
DCA311	DCA207	Laboratory
DCA312	DCA208	Technology Transfer
DCA313	DCA209	Vendor
DCA314	DCA210	
DCA315	DCA211	
DCA316	DCA212	
DCA317	DCA213	
DCA318		
DCA319		
DCA320		Post - ASST Fermilab
DCA321		R&D magnets
DCA322		
DCA323		

All 16 of these magnets underwent cold testing at Fermilab or BNL during the period from November 1991 through July 1992. The last two magnets fabricated at BNL used an all kapton/polyimide adhesive insulation scheme rather than the baseline kapton plus fiberglass impregnated epoxy system. Following the completion of the ASST magnets, four additional R&D 50 mm dipoles —DCA320-DCA323—employing variations in the conductor insulation scheme, were fabricated and tested at Fermilab. These post-ASST magnets used all polyimide (either kapton or apical) conductor insulation and an epoxy adhesive.

Comments on design issues

The mechanical stability of the cold mass largely determines quench performance. It had been determined in the 40 mm program that the stainless steel collars surrounding the coil were not stiff enough to support it against the radial component of the Lorentz force. At full field, the collars would deflect on the order of 50 to 100 microns at the midplane. It was also determined that a small clearance (~250μm in the early design) between the collared coil assembly and the iron yokes led to erratic axial motion during excitation and a build up of force between the coil end and the end plates following successive excitations. The initial solution in the 40 mm program was to constrain the collared coil assembly in both the radial and axial directions by the insertion of shims between the collars and the yoke and to replace 19 mm-thick, split end plates with one piece, 38 mm-thick end plates. The shims ensured contact between the collars and the yoke during assembly, cool down, and during magnet excitation; the stiffer end plates reduced the axial motion allowed the coil to less than 20μm. The first shimmed magnets displayed greatly improved quench performance, and the 40 mm design was then altered to provide a "line fit" between the collars and the yoke, where the outer radius of the (warm, unloaded) collars was equal to the inner radius of the iron yokes. This collared coil-yoke interface was dubbed the "line fit" design.

The line fit design subsequently evolved. A salient feature of the collared coil assembly is a small but systematic increase in size along the vertical diameter (the direction in which the collaring force is applied and the coil is compressed) after collaring. The distortion was dubbed "vertical ovality." In the initial, round design of the line fit collars, the ovality was typically 250 to 300μm on the diameter. The vertical distortion led to a natural interference fit with the yokes. Because the yoke cavity was designed to fit a round collar geometry, the vertical elongation results in a gap between the yoke halves. To complete the cold mass, the yoke blocks have to be pressed together and the outer stainless steel shell then welded around them. Weld shrinkage provides the force necessary to pull the yoke halves closed and, as a result, increases the compressive load on the coils.

As discussed above, the 50 mm prototypes developed at Fermilab and BNL employed different approaches to the collared coil-yoke interface. The BNL version continued with the horizontally split yoke and an "anti-ovalized" collar design in which the positions of the keyways, which were used to lock the upper and lower collars together, were relocated to reduce the net distortion on the vertical diameter. In the BNL design, the interference was in the vertical direction while the horizontal size of the collared coil remained essentially unchanged, being equal to that of the inner diameter of the yoke. However, the differing thermal coefficients of the iron yoke and the stainless steel collars resulted in a gap, on the order of 50 μm, at the midplane following cool down. During magnet excitation, the Lorentz forces moved the coil down and radially outward so that it was possible (depending on the size of the vertical interference) for the collared coil to lose contact with the yoke at the pole before it had been pushed outward into contact with the yoke at the midplane. The design of the anti-ovalized collars at BNL was to account for these effects.

The Fermilab approach was to utilize a vertical yoke split and build in a positive interference of the collars (by small changes in the collar outer radius) with the iron yoke at the midplane. As with the horizontal yoke split design, the welding of the stainless steel outer shell onto the collared coil closed the gap between the yoke halves and ensured contact between the collars and yoke during all phases of magnet excitation. The key feature of the Fermilab design was that the interference occured at the midplane where the resultant of the Lorentz forces acted. The collared coil was in constant contact with the yoke, and the yoke and stainless steel outer skin provided a system of large effective stiffness, supporting the collars against the Lorentz force.

In the Fermilab vertical yoke split design, the outer stainless steel shell played a more important structural role than in the horizontally split BNL version. The shell had to react the Lorentz force along the horizontal diameter because the yoke blocks did not provide any direct support in that direction. The shell tension had to exceed the Lorentz force to keep the yoke gap closed and the coil supported. Calculations indicated that the 4.95 mm-thick shell would keep the yoke gap closed up to a field of 10T, which was well beyond the normal operating regime.

The two approaches to the yoke-collar interface resulted in subtle differences in the yoke adjacent to the collars and in the coil cross section. In the horizontally split yoke, the notch that accommodates the collars was at the pole, while that for the vertically split yoke was at the midplane. In addition, the pole in the outer layer of the Fermilab version of the cross section was 250 μm smaller than in the BNL design. It should also be noted that the Fermilab yoke design incorporated an additional hole in the laminations near the rectangular bus slot.

Quench performance

The requirements for the Collider dipole magnets include no quenches below the operating current and no more than two quenches 5% above the operating current. All the ASST magnets performed well in training, exhibiting stable quench plateaus at currents above 7200 A with few or no training quenches. Magnets DCA313, 314, and 317 all exhibited an initial quench significantly below the Collider operating current; however, subsequent quenches were at or near the short sample limit†. The origin of these three quenches was determined to be near a mechanical feature in the lead end region of the magnet. The quenches were localized at a point near the boundary between the end clamp assembly and the collared portion of the coil. The support for the conductor in this region involved several pieces; the assembly procedure for the region was modified in subsequent magnets and no recurrence of this type of quenching was observed. Two other magnets had initial quenches near or slightly below the operating current: DCA316 and DCA211. In all cases, following a thermal cycle to room temperature and re-cooling to 4.35 K, the magnets returned to their plateau currents with almost no discernible re-training.

† A conductor's short sample limit is determined by tests of a "short sample" of the cable in a special test dewar setup. The short sample limit corresponds to a resistivity of 1×10^{-14} Ωm as measured in I-V tests. For SSC cable, the short sample current, I_{SS}, is defined at 4.2 K and 7 T for the inner conductor and 4.2 K and 5.6 T for the outer.

The quench performance of the ASST dipoles was strikingly successful: the first dipoles exhibited excellent quench behavior as did the subsequent prototypes. The immediate success of these prototypes indicated a maturation of both the design and fabrication processes. In addition to quench testing at 4.35 K, most of the ASST magnets were also tested at lower temperatures, typically 3.85 K and 3.5 K. Because the Lorentz force is proportional to the current squared, the lower temperature tests occurred at force levels of more than 45% and 60% above those of the normal operating current. Nearly all the ASST dipoles reached their short sample limits with one or a few quenches at 3.85 K, and most performed as well at 3.5 K. The stable behavior at higher currents was indicative of a robust mechanical design.

The possibility existed that certain magnets in the Collider lattice might need to be operated at "superfluid" temperatures (below 1.9 K for 4 atm Helium). Low temperature tests were performed for one of the post-ASST magnets, DCA322, down to 1.8 K. The results were quite surprising: although the magnet had displayed more training than previous 50 mm dipoles at 4.35 K, and had not reached its short sample limit at 3.0 and 2.5 K, it quenched at currents of nearly 10 kA in superfluid and twice ramped to the limit of the power supply without quenching.

<u>Ramp rate sensitivity</u>

The early ASST dipoles showed a sensitivity to ramp rate (*dI/dt*) that had not been observed in the 40 mm magnet program. It was first noted as a depression of the quench current plateau relative to that expected from short sample predictions. The effect was studied by ramping all magnets to quench over a range of ramp rates.

Examination of the data revealed an interesting pattern: at least two distinct classes of quench current versus ramp rate behavior could be identified. The first class (called "*Type A* " magnets) of ramp rate dependence included magnets in which the quench current at low ramp rates was only slightly lowered, but the current dropped precipitously at high ramp rates (above 50 A/sec). The second class of magnets (*"Type B"*) demonstrated nearly opposite behavior, with the quench currents dropping dramatically at ramp rates up to about 50 A/sec and then only gradually at higher ramp rates. There were also a few magnets that displayed significantly less sensitivity to the ramp rate. The Type A magnets could be explained by models of the coil that have very low interstrand resistance and generate large eddy currents when ramped. The Type B magnets were not as easily explained; detailed models of the superconducting cable behavior were being developed at shutdown. In both cases, the contact resistance between strands in the cable was considered to be a critical variable.

The Type A magnets also exhibited anomalous behavior in their multipole measurements, which was demonstrated to be caused by eddy currents. The anomalous behavior included hysteresis (up ramp versus down ramp differences) in unallowed multipoles and reversal of the sense of the hysteresis loop in some of the allowed multipoles.

The 4 A/sec ramp rate for Collider operation did not present a quench current problem in the face of the data. The HEB, however, must operate at ramp rates of 62 A/sec, and the observed ramp rate sensitivity—both Type A and Type B would be of concern. The quench data taken at 4 A/sec demonstrated plateaus well above the operating current, which satisfied the Collider "margin" requirement of 10%. Studies of the down ramp behavior (ramping the magnet down from the operating current level at rates of 200 A/sec to 300 A/sec, which could occur during Collider operation) indicated that there was sufficient margin to avoid quenching.

The issue of AC losses/ramp rate sensitivity in superconducting magnets had been dealt with at previous accelerators by controlling the surface of the conductor strands: the Tevatron coated alternate strands with either a resistive or a conductive coating; HERA employed conductive coatings; at IHEP/UNK, a resistive coating was developed by controlled oxidation during cable fabrication. These and other methods were under investigation for the SSCL cable at time of termination, primarily for application in the HEB dipoles.

Magnetic field measurements

All the prototype ASST dipoles were studied in a series of warm and cold measurements of the field harmonics. The cold measurements included fixed current, axial scans, dynamic measurements during ramping at fixed locations, and "time decay" measurements at injection current, also at fixed locations. Measurements were also performed of the field strength, or transfer function, and the field angle. The fixed current, axial scans yielded information on the field quality due to conductor geometry and were most representative of the reproducibility in the manufacturing process. In this section, primarily field quality and warm to cold multipole correlations are discussed. The agreement between data and the calculated field properties that depended on the iron yoke (e.g, saturation effects) was quite good, and the models accurately reproduced the persistent magnetization current contribution.

All magnets fell within the "3T + |T systematic|" acceptance limits. In most cases, the clustering of magnet multipole values was quite small with respect to the limits: the random variation (σ_{rms}) was much smaller than that allowed by the specifications. The reproducibility of the field, in both warm and cold measurements, as evidenced by the small random variation, was another indication of the uniformity and control of the coil and cold mass fabrication processes and the quality of the measurements.

The average over all magnets, or systematic value, of each multipole was near zero for most multipoles: the higher order terms were very small, but there were several terms that had distinctly non-zero averages, and these merited further discussion. Those outside the range allowed by the specifications included a_2, b_2, b_4, b_6, and b_8. These multipoles fell into two types: skew terms which were un-allowed multipoles, and normal terms which were allowed by the coil symmetry.

The skew quadrupole term, a_1, arose from a top-bottom asymmetry in the cold mass (typically arising from a mismatch in size of the upper and lower coils or an asymmetry of the collared coil within the iron yoke). A small displacement of the midplane could introduce a significant a_1 term; the sensitivity was on the order of one *"unit"* (10^{-4} B_0) for a 25 μm displacement. The specifications placed a stringent requirement on the systematic (average) value of a_1 – .04 units—but allowed a large random variation of 1.25 units. The average value of a_1 warm was slightly above the specification value, while the cold measurement was slightly below the limit. In both cases, the statistical uncertainty dominates and the value is consistent with the specifications.

The skew sextupole term, a_2, arose from a more complicated asymmetry in the coil—both left-right and top-bottom differences. During the magnet fabrication process, systematic measurements were made of the coil sizes along their length. The measured values for each coil would be combined and used with analytic calculations to predict the resultant field deviations, a_1 and a_2, along the length of the magnet. The correlations appeared to be quite good at the level of a few tenths of a unit.

The clear correlation between the coil size measurements and the skew terms indicated a predictability (and hence, a means for control) of the magnetic field from geometric quantities. The sources of the non-zero skew terms could be traced directly to quantities measured during the fabrication of the magnet and thus could form the basis for process control techniques to monitor and correct the production. At the level of $\leq .001$inches in coil size variation and $\leq .1$ units of the field, deviations were still largely systematic (not random) in nature and could be addressed in the manufacturing process.

The non-zero allowed terms had several origins; b_2, b_4 and b_6 had contributions from persistent currents in the superconductor. The persistent current contribution was largest in b_2; its effect decreased rapidly in the higher order allowed multipoles b_4, b_6, b_8. . . The average value of b_2 for the ASST magnets was slightly beyond the Collider specification limit of 2 units at low field and well beyond the high field limit of 0.8 units. The value of the geometric component of b_2 is sensitive to the pole angle and thus to the size of the pole shim used to correct for the systematic coil azimuthal size variation. In the ASST magnets, the cross section was not tuned to the final cable size and thus both the Fermilab and BNL designs had sizable b_2 components. This value could be controlled by small changes in the magnetic design, and it was corrected in the coil cross section of the General Dynamics magnets.

The terms b_4 and b_6, which are allowed by the coil symmetry, arose from changes in the "as built" conductor positions from those in the design. Because they were allowed terms, the shifts could be moved in the next iteration of the coil design by appropriate changes in the conductor placement and wedge dimensions. The higher order term, b_8, was designed to have a value of roughly .05 unit for use as an internal "reference" point in determining the magnetic center. It was subsequently determined that this value was too large for Collider operation, and it was to be reduced in size in the iteration of the cross section design. The measured value of b_8 was in good agreement with that predicted.

In sum, the departures from the specifications were understood from either the coil size variation or from effects in the allowed terms, which could be corrected by iteration of the cross section design. The very small rms variation of the allowed multipoles meant that relatively few magnets had to be measured to determine corrections necessary to iterate the design. The only significant issue was the extremely stringent limit on the systematic values for a_1 and a_2, which were connected with the strength of correction elements and were being actively discussed at time of termination.

Magnetic measurements - warm-cold correlations

Plans for the Collider dipole production called for cold testing of roughly 10% of the total magnet population.† In this approach to testing, it was important that warm measurements accurately predicted the cold multipole content of the magnets. To determine whether this was the case, the ASST test program included measurements before, during, and after each cold test. The average values of multipoles measured at ± 10 A were compared to those measured at 2000 A when the magnet was cold: the correlation coefficient of the warm and cold values was determined for each multipole as well as the warm-cold difference.

† The overall average of 10% was dictated by fiscal constraints and was thus determined by the number of cold test stands available. During the early pre-production and low rate production phases of the dipole program, all magnets were to be tested until the test stand capacity of the SSCL and the vendors was reached.

Clear warm to cold correlations existed for all multipoles; the random errors in the warm measurements dominated the overall error.* Even in cases where the correlation coefficient was substantially less than one, the average value of the warm-cold difference was very close to zero (except for an expected magnetization current contribution in the cold measurements of allowed multipoles), and the width of the distribution was quite small. The salient fact in examining the warm-cold data was that, excluding magnetization effects, the average difference was roughly zero: *there was no appreciable change in multipole value from warm to cold.* (Note: this applied to the Fermilab version of the ASST magnets; the BNL magnets displayed a warm-cold shift in b_2 and b_4 that could not be explained by persistent current effects.) The stability of the multipoles indicated that there was no systematic distortion of the coil geometry due to the cool down, and it lent some confidence to the scheme, which depended on warm measurements alone as the primary indicator of magnet quality.

<u>Summary</u>

The ASST dipoles represented a significant achievement and a joint success of the SSCL, the national laboratories in the magnet R&D collaboration (BNL, Fermilab, and LBL), and the industrial partners (General Dynamics and Westinghouse). The new 50 mm aperture dipole was brought from design to successful tests of prototypes. In total, 20 full-length prototype magnets were tested in little over one year—nearly as many prototypes as had been produced and tested during the entire 40 mm program. Two design variants were pursued: the mainstream design developed at Fermilab and a backup program at BNL. Both versions of the 50 mm dipole performed extremely well in performance tests.

The quench performance of these prototypes was very good: there was only a small amount of initial training and almost no re-training following a thermal cycle. The prototypes also performed well at lower temperature, again displaying very little training in most cases at test temperatures of 3.85 and 3.5 K. Quench protection studies indicated that the inner coils were "self protecting," while the outer coils (with smaller conductor cross sectional area) required active protection to limit quench temperatures to less than the allowed limit of 400 K.

The magnetic field quality of the ASST dipoles was very good. The random variations in the multipoles was much smaller than those allowed by the Collider specifications. A small number of multipoles had systematic values outside the specification limits; however, these could be identified as due to early compromises in the design of the magnetic cross section beacuse of schedule or understood in terms of coil size variation. Only the extremely restrictive limit on the skew quadrupole (a_1) appeared to be difficult to attain; the other values beyond the systematic limit were in allowed multipoles and hence could be corrected in an iteration of the cross section design.

* The random error in the warm measurements was determined to have a significant contribution from the high impedance input to the DVM. A low noise pre-amplifier had been designed and tested, resulting in decreases in the random noise contribution by a factor of from 4 to 10 for the different multipole components. This pre-amplifier was in routine use with the measurement systems at time of shutdown.

The saturation and magnetization components of the fields were in good agreement with calculations. Comparisons of the warm and cold magnetic field properties displayed strong correlations in all multipoles, indicating little change in coil geometry and lending further credence to the plan of establishing magnetic field quality by warm measurements for most of the magnets produced.

The observation of significant eddy-current-related effects in several of the magnets led to an expansion of the test program to understand these phenomena. The eddy current effects included a strong sensitivity to ramp rate and eddy current contributions to the multipoles. The effects were found to be related to a lower than expected inter-strand resistance in the cables in the magnets, and investigations were under way to determine the best approach to increasing and controlling the inter-strand resistance as the project ended.

The ASST dipole program developed a new design, integrated industrial teams into the production effort, and produced 20 prototype dipoles, all of which displayed excellent electrical and mechanical performance. All the major goals of the ASST program were met, and while field quality was not a primary goal in the initial magnets, the results indicated that the requirements of the Collider would be met. Programs were under way at the vendors to address issues raised by the tests: iterations of the cross section design at General Dynamics were to result in improved field quality, and studies of the cable treatment at Westinghouse were to determine the approach to the AC loss effects, which were germane to the HEB magnets.

Quadrupoles

The Collider quadrupole magnet was a cos 2θ design surrounded by stainless steel collars and a cold iron yoke. The SCDR operational design gradient was 215 T/m at 6500 A with an aperture of 40 mm. Several incompatibilities between the 50 mm CDM and the 40 mm CQM were discovered after the SCDR. A change request was issued in the summer of 1993 for a 50 mm aperture CQM. This discussion summarizes the 40 mm and 50 mm programs; but, because no final 50 mm design had been completed for the CQM, only the HQM and IR quadrupoles will be summarized.

<u>The 40 mm CQM LBL design</u>

The LBL 40 mm "QCE/QCC" series 40 mm quadrupole program consisted of four 1.0 m and six full length (5.0 m) cold masses, which were part of the ASST program. Designed, built, and tested at LBL over the period 1989 to 1992, the design gradient was 215 T/m at an operational current of 6500 A. The cross section consisted of inner and outer coils both of which use 30 strand 1.8:1 copper to superconductor ratio conductor. There are 8 turns on the inner coil and 13 on the outer. The coils were wound and cured separately and eventually spliced together outside the yoke after skin welding. The collars consisted of a four piece design, initially made from aluminum and later changed to Nitronic 40. Compressed (azimuthal direction) coil sizes were measured, and shim thicknesses were determined from these. When placed at the pole, the shims produced the target prestress (40 Mpa). Separate shims were used for inner and outer coils. Collaring was performed horizontally in 6 inch (150 mm) increments. The collaring keys were not staggered. The collars were designed to be self supporting, so that no additional support was required from the yoke. The yoke material provides a field enhancement of 8% and showed very small (0.01%) saturation at full gradient. Various collar yoke interfaces (sliding, clamped, partially clamped) were tried during assembly. Various end load configurations were also tried during assembly; typically a 5000 lb (22 kN) end load was used.

Early models showed a significant amount of training and retraining. The collar-yoke interface did not seem to affect the performance. Cutting an early model into cross sections ("cookies") showed that the pole shims moved radially outward during collaring, leaving one or two strands of the inner pole turn conductor essentially unsupported. This was rectified for QSC405/QCC405, and quench performance was significantly improved. A detailed discussion of the LBL design can be found in Ref. [1].

Babcock and Wilcox/ Siemens 40 mm design

The B&W/Siemens program[2] consisted of three 1.0 m and five full-length (5.0 m) cold masses, which used essentially the same cross section as the LBL design: the differences were in the HERA-style cold mass mechanics and manufacturing as described below. The "coil-on-coil" technique used an internal ramp between inner and outer coils and a "fishbone" spacer which bound the inner and outer coil together. The inner coil was wound and cured before the outer coil was wound on top of it (the inner coil was cured "twice"). The collars were a two-piece design made from Nitronic 40. Alternate pairs of collars were rotated 90 degrees, and the pole stress was distributed axially using "pole sheets" (essentially thick pole shims) of N40. A single shim was used at the pole to produce the correct prestress. The coils were collared vertically and the collaring keys were staggered. The collar yoke interface slid via extended collaring keys which fitted into slots in the yoke. The outer diameter of the yoke was reduced by approximately 20 mm over the LBL design, which saved material and weight without affecting the transfer function. No end load was used on the full-length cold masses.

Test performance showed a dramatic improvement in quench performance. The last of the full length versions showed no training. Ramp rate dependence of quench current in both the LBL and B&W/Siemens models is essentially non-existent.

Saclay 50 mm design

The Saclay 50 mm quadrupole magnet was designed for the HEB.[3] The magnet evolved from a version of the HERA cold mass mechanics and had a gradient of 186.5 T/m at 6550 A. The design utilized 25 turns (inner 8, 3, outer 14) of 36 strand cable with a copper to superconductor ratio of 1.8:1. The strand was 0.6477 mm in diameter. The magnetic design had two conductor blocks in the inner layer and one conductor block in the outer layer. The pole face of the inner and outer layers were made coplanar by curing in a pole piece to the outer coil, which resembled a large wedge.

The cold mass mechanics were the same as those described for the Babcock and Wilcox/ Siemens 40 mm design except that the collaring keys had sliding strips to minimize the contact pressure on the keys. The keys were located at 45°, 135°, 225°, and 315°, extending into yoke slots that provided the sliding yoke collar interface. The inertia tube was implemented to reduce twist associated with standard magnet stainless steel shells, and it had the additional benefit of decoupling the ASME constraints from the shell related welding stresses.

The Saclay program originally contained three 1.6 meter prototypes. As of the writing of this report, no model or prototypes had been completed.

IR 50 mm design

The SSCL designed Interaction Region (IR) quadrupole magnet had unique dipole magnet cold mass mechanics employing the line-to-line fit philosophy developed at BNL.[4] The turns were supported at the poles by brass pole laminations, which had sickle shaped tabs extending from 45° to the midplane. The stainless steel collars appeared to be hoop collars except for the sickle tab inserts. The magnet cross-section had 27 turns of 36 strand cable, 11 turns in the inner layer and 16 turns in the outer layer (inner 8, 3 outer 13, 3). This configuration produced 193.8 T/m at 6714 A. The magnet was constructed with a coil-on-coil winding and curing process, and the inter-coil spacer was solid G-11 rather than a fishbone configuration.

Six model magnets were planned in two lots, and four had been completed. QSE101 and QSE102 were lot 1 magnets using the ASST glass-epoxy insulation and Nitronic-40 collars.[5] Good quench performance was achieved with typically 2 to 3 training quenches to plateau and little or no re-training. Limited magnetic measurements were performed, and only the warm measurements were considered accurate. The conclusion was that the harmonics were within the three sigma limit, but there was some concern about the breaking of quadrupole symmetry. At time of termination, QSE104 was completed but untested and QSE105 was near completion. The two magnets were lot 2 magnets that had a 3PM insulation scheme and high-manganese steel collars. The 3PM was employed to meet the IR radiation requirements and to provide better coil dimensions. The high-manganese collars were selected to maintain the line-to-line fit at cold temperatures, which was required for quadrupole symmetry.

Conclusions

The IR and HQM quadrupole magnets were considered inadequate as a design for the 50 mm CQM because of a lack of field gradient strength to meet lattice requirements; about 25 cm of additional slot length would have been needed. The primary CQM contractor, Babcocks and Wilcox, performed a trade study for a 50 mm CQM design and produced a magnetic cross-section (inner 9, 2 outer 16) similar to the HQM except for two additional turns in the outer coil.[6] The design required a higher keystone cable to make the turns more radial near the pole. This configuration produced 204.4 T/m at 6714 A. The cold mass mechanics was planned to be identical to the Babcocks and Wilcox 40 mm program.

Just before the project termination, a proposal had been made to combine all 50 mm quadrupole programs. A small lattice change (a reduction of the CDM slot length by 5 cm) would have allowed an adequate slot length for both the HQM and IR style quadrupole magnets.

The IR quadrupole program was innovative in that the design could implement dipole style collaring techniques, which were considered to be easier in a production environment. The dipole collaring techniques were more appropriate for the longer magnets in the IR region. The IR quadrupole had more risk associated with field quality because there were more high tolerance parts involved in maintaining quadrupole symmetry, and there were a more complex line-to-line fit mechanics which had to be maintained at 4.2 K. There was a lack of information for reaching a final conclusion on the field quality performance because of program termination.

The Saclay/HERA cold mass mechanics magnets had a proven track record in field quality performance, and they were preferred by the accelerator physicists to lower harmonic error risks. The vertical stack collaring may have represented a more complex manufacturing process, which could have had cost implications in a high production environment.

Correctors

The SCDR listed preliminary requirements for correctors and outlined several candidate fabrication techniques. Considerable evolution in requirements and design were expected. Corrector magnet packages, including a dipole, quadrupole, sextupole, octupole, and decapole were to occupy the spool pieces. Octupoles, decapoles, and skew quadrupoles were to occupy some mid-cell positions.

As the design evolved, several changes in field strength requirements were made. The dipole corrector magnetic field strength was increased from 2.5 T-m to 3.0 T-m (and later reduced during the value engineering effort). The quadrupole corrector magnetic field strength was increased from 0.53 T-m to 0.65 T-m at a radius of 1 cm. Half of the sextupole corrector magnets were increased from 0.21 T-m to 0.23 T-m at 1 cm, and the other half were increased from 0.13 T-m to 0.15 T-m at 1 cm. A detailed description of all these changes can be found in the SSCL Change Request, "Collider Arc Corrector Magnets - BCE to 3B Specifications." Additional description can be found in SSCL Change Request, "Increased aperture for quadrupoles and spool pieces from 4 cm to 5 cm." After evaluation of all potential technologies, it was decided to investigate those that would optimize production processes while reducing costs and saving time.

One of the choices involved a process called Jellyroll technology, an off-shoot of techniques used at BNL to develop the SSCL distributed correction coil designs. A similar technique was then being used on RHIC corrector magnets. Initial development of the technology took place at the Texas Accelerator Center (TAC) using super ferric designs with stressed skins. TAC built eleven quadrupoles and two dipoles. Five of the last six quadrupoles had acceptable initial training performance. It was decided that the technology offered enough significant advantages to continue into an industrialization program.

LBL also worked on early corrector development for the SSCL. Their focus was on air core potted random wind magnets, similar to those built for the Tevatron, but without nesting of elements and with a goal of much higher performance. Early work surveyed insulation systems and developed techniques using Kapton wrap insulation. The potted magnets were successful, but owing to packing fraction limitations and large (20 mil) wire diameter, the short magnets were not suitable for the SSCL. However, LBL had made many advancements in winding and processing for random wind magnets. They also explored magnets with hot (high Jc) wire with some success, and high packing density (ordered wind) coils with not much success. At LBL they had successfully made sextupoles and quadrupoles with their baseline design and were beginning work on magnets with smaller wire diameter. This work was transferred to the SSCL with promises to continue as a backup method, but it was later abandoned.

In the industrialization program, SSCL called for "ordered wind" technique as one of three options (the others being Jelly Roll and Direct Wire) offered for development. Initially, ordered wind was described as a high density potted coil. Concurrent with the start of the industrialization program, SSCL invented a non-potted ordered wind technique using Kapton insulated wire suitable for superferric magnets. The vendor was later given both potted random wind and SSCL-style ordered wind/superferric magnets as options. They chose to work on the latter as part of phase I industrialization.

A third technique chosen to be investigated was called "direct wire" technology, an amalgamation of processes from several areas of expertise. It was loosely modeled after beam tube mounted coils used in HERA. In theory, the preferred technique would use automated techniques similar to those used in jellyroll coils, with a high coil packing density like the ordered technique. Although the technology was in its infancy, it was chosen as one of the options for industrialization.

A developmental specification was produced to assemble what was at the time the best understanding of the corrector magnet requirements and the technologies of direct, ordered, and jellyroll technologies. This specification was the basis of the Phase I industrialization program. Magnets were built at both SSCL and the contractors. Detailed results of both the early Laboratory R & D and the Phase I industrialization prototypes can be found in a summary presented at the first Collider corrector magnet Preliminary Design Review Report (PDRR) September 25, 1992.

Late in October 1992, the decision was made to build corrector magnets with a clear bore aperture of 5 cm. Previous jellyroll and ordered wound magnets had a clear bore aperture of 3.5 cm, just large enough to fit over the beam tube. In-house prototypes had been built with 4.0 cm clear bore apertures, and Phase II industrialization was planned to incorporate 4.0 cm design magnets. The change required considerable re-design effort. Because the Jellyroll technology possessed the lowest conductor packing density, the larger aperture required Jellyroll magnet lengths that no longer fitted in the spool piece. The costs of coils produced with this technology also continued to rise and it was therefore decided to drop the Jellyroll technology and move into Phase II industrialization with 5 cm aperture magnet prototypes.

Contracts were issued for the Phase II industrialization program with the Babcock & Wilcox Co., Everson Electric, and Martin Marietta Corp. Magnet prototypes built by the latter two vendors were to use ordered wound technology, and the first was to use direct wire technology. The Phase II program was never completed. Two ordered wound full length dipoles were built by Everson, and four ordered wound full length quadrupoles and sextupoles were built by the Martin Marietta Corporation. Not all these magnets were tested, however. The Phase II ordered wound magnets that were tested met their minimum acceptance criteria. Six direct wire sextupole magnets were built by Babcock & Wilcox Corporation. Only about half of them had been tested to date as the project ended.

During this period, a Phase I industrially built corrector magnet package composed of a dipole, quadrupole, and sextupole magnet of each technology type was assembled into an ASST spool piece and installed in the string test. It was found that in this environment, all correctors met or exceeded the operational requirements. SSCL also built a full package of direct wire magnets that was to be installed in the first Martin Marietta preproduction spool piece. The spool remained incomplete and untested at time of shut down.

Studies were made of the production designs of the corrector package. At termination, it was believed that ordered wind technology would yield the most efficient use of superconductor for the dipole magnet, and that the direct wire process would offer the most efficient use of superconductor for other magnet types. During the value engineering effort, it was determined that reducing the required strength and number of dipole correctors would make profound changes possible in the overall corrector magnet design and configuration.

Spool Pieces

The spool pieces in the Collider arc, utility, and IR region were the primary interface between the Collider magnets and the support systems. The spool piece supported the basic requirements of the machine and provided for cryogenic conditioning (recooler and temperature measurement), electrical power, quench protection, corrector magnets, and beam position monitoring systems.

The initial design requirements used for the spools was established in the SCDR.[1] There were 29 variations of the spool design planned for the Collider arc and utility regions. The spool requirements are defined in the Level 3B specification for the arc sections and utility regions. (See Refs. [2] and [3].) At project termination, the spool effort was concentrated on industrialization, conceptual design requirement definition, and testing. A summary of the spool program status then current can be found in Refs. [4] and [5].

Industrialization Program

The objectives of the program were to produce production spool piece designs and to develop a capability for manufacturing and delivering production spool pieces at the rates required to meet the Collider installation schedule. The production designs had to meet the established performance requirements through design reviews, analyses, and testing through the production prototype phase. (See Refs. [6-15].) References [7] and [13] guided the development and implementation of the industrialization activities for the Collider standard arc spool pieces, which constituted most of the spool pieces to be produced. They also included nearly all the basic components that were included in the various spool piece configurations. The results of the Collider standard spool piece industrialization activities would have had a direct impact on the designs and unit costs of all other spool pieces in the Collider and HEB.

Under the process defined by Refs. [7] and [13], two standard spool piece subcontractors, Martin Marietta and Westinghouse, were selected to develop production designs, prototypes, and pre-production units on a competitive basis. A selection down to one subcontractor was to occur subsequent to the formal Production Readiness Reviews. The selection process was to be based on firm, fixed-price proposals to provide production spool pieces that met all performance requirements.

Both subcontractors and the SSCL Spool Piece Group participated in a common Preliminary Design Requirements Review (PDRR) during November 1992. The performance requirements baseline was established (see Ref. [16]) from the PDRR. Preliminary Design Reviews were conducted at each contractor's site in February 1993. Both PDRs were considered successful, and the contractors were authorized to complete detailed design and fabrication of prototype hardware. Each contractor completed approximately half of its related activities before being stopped. Both contractors submitted prototype hardware test plans and were preparing for Prototype Test Plan Reviews at the time of project termination.

Spool Prototype and Hardware R & D Status

The spool hardware R & D program addressed components, subsystem integration, and product improvement. Component development was in progress on cryogenic valves, electrical connectors, the vacuum barrier, relief valves, and other components. The early spool prototypes were completed as the Laboratory shut down.

A decision to increase the clear corrector magnet aperture diameter from 40 mm to 50 mm was made in 1991. A 50 mm aperture feed spool (SPRF), recooler spool (SPRA), and an end spool (SPRE) were constructed in support of the ASST milestone. (See Ref. [17] for construction and design details.) A second prototype 50 mm aperture SPRA was constructed in support of a full-cell string test by Meyer Tool.

Spool Testing

The test plan was established in the SCDR. Significant impact on the program budget and schedule would have occurred if increased testing of the spool components had been required. A major problem was encountered with the spool R & D efforts that resulted from a lack of testing facilities and infrastructure in the early phases of the program. Data required for design iterations were difficult to obtain in a timely manner. Two spool test stands were designed and were under construction when work on the Collider was stopped. The test stands were to be used for the testing and design verification of the industrially fabricated prototype spools. The test stands were designed to establish warm to cold correlation of the corrector magnet package with respect to the spool fiducialization and the BPM, to evaluate recooler efficiency, and to conduct power tests on the bypass leads and quench stoppers.

Testing was attempted on two of the early 40 mm prototype SPRAs on the 40 mm String Test conducted at Fermilab. The 40 mm aperture SPRA constructed by Meyer Tool had several problems associated with the electrical systems and the super-insulation, which was packed too tightly. The electrical problems included a bus to ground hipot failure and several missing silicon diodes used for monitoring temperature. Because of the hipot failure, the 40 mm Meyer SPRA was replaced with an SPRA constructed at SSCL. The SSCL SPRA was integrated but failed a critical high pressure check. Schedule priorities associated with the ASST caused the Fermilab string test to be abandoned, and no operational data were collected on the 40 mm SPRAs. (Ref. [18].)

The ASST Phase I SPR that was constructed by CVI was tested on one of the single magnet test stands at BNL. The results of the testing at BNL are summarized in Ref. [19]. The CVI SPRA was installed into the ASST along with the SPRF and the SPRE. Several operational problems were encountered on the spools that were integrated into the string test. The connectors that were used on the spools limited the operational voltage of the string because of the lower breakdown voltage due to the low ionization potential of helium. The connectors were replaced after the completion of Run 1 using connectors with higher voltage integrity in a helium environment (see Ref. [20]). Heat leak measurements of the magnets and the spools were evaluated. Results from the heat leak measurements are in Refs. [21] and [22]. Results from the recooler testing that was conducted on the string is reported in Ref. [23]. Results from electrical tests conducted on the spools is reported in Refs. [24], [25], and [26].

When the ASST was expanded to test a full-cell prototype of the Collider, the second 50 mm prototype SPRA constructed by Meyer Tool was installed. Again, problems associated with high voltage integrity were encountered when the SPRA was tested in a pressurized helium environment (see Ref. [27]). A series of heat leak measurements were conducted, and they are documented in Ref. [28]. Tests results from the Corrector Element Power Leads that were conducted as part of the corrector magnet testing are summarized in Ref. [29].

Spool Summary

Most of the research and development efforts for the spool were complete as the project ended. There was some activity associated with possible implementation of high temperature superconducting corrector power leads and with the recooler design. Other areas where development work had yet to be completed included shields, thermal welds, post, and recooler designs. Other improvements to the spool configuration came as a result of the value engineering exercise that was under way when the Collider project was canceled. (See Refs. [5], [30], and [31].)

Manufacturing and operational experience along with cost and changed project requirements were focusing product improvement efforts. As the cost of the spool became a significant driver, all spool component designs were being reviewed jointly by the Spool Group and the spool vendors to meet the project objectives. A Spool Piece Final Report details the initial component development efforts, the manufacturing lessons learned, a summary of the operational events, and the ongoing component development prior to termination.

Power and Quench Protection System

Before the value engineering (VE) effort, the Collider power system design, with the exception of the utility straight warm magnet power, had undergone only minor changes from the SCDR. A major reconfiguration was proposed and preliminary cost comparisons were delivered as a result of the VE exercise (see the discussion below). The corrector power system design also did not change radically from the SCDR before the VE results were obtained. Some changes in bus configuration showed potential cost savings. The quench protection system (QPS) design for the main magnets was virtually unchanged in basic configuration, but the VE teams were considering revisiting the cold diode option. QPS for the corrector systems was still in the early conceptual stage, but preliminary, low cost solutions were being reviewed.

Ring Magnet Power System

The Ring Magnet Power System (RMPS) issues studied over the two years before shut down were the following: (1) power supply ripple, beam coupling, filter requirements, and filter design; (2) magnet energy dump system requirements and design; (3) QPS requirements including diode leakage current and design options; (4) total output current deviation requirements; (5) RMS current deviation requirements around a ten sector ring system; (6) design of the current transductor, regulation, and control; and (7) utility straight magnet power system requirements and design. Other activities in the ASD groups involved level 5 and lower design tasks of standard systems such as rectifier/transformer, AC switch gear, harmonic filter, thyrister assemblies and 12 pulse power converters, firing circuitry and local control electronics, and DC bus system.

<u>*Power supply ripple and beam coupling*</u>

Power supply ripple was an issue that had caused major difficulties in accelerator operation at other laboratories. Thyrister power converters generate very intense 60 Hz harmonics and the residual effects of those harmonics at the betatron frequency must be heavily filtered to minimize excitation of betatron oscillations leading to transverse emittance growth. Superconducting magnet strings are especially susceptible to ripple perturbations because of the propagation of waves in transmission line modes. The problem is recognized as one of the most difficult to analyze, owing to the very small level of the perturbation and the slow growth rate over millions of turns in the Collider. Significant progress was made in modeling the Collider ring power circuit, but only crude models of the beam coupling mechanism were used. A better understanding of dominant beam coupling processes will be crucial to the success of future storage ring programs.

Energy dump system.

The design of this system was refined many times since the SCDR. Trade-offs between peak voltage to ground limits and MIIT limits resulted in a compromise system using nonlinear resistors (iron or steel in the first analysis) to reduce the peaks at a slight MIIT penalty. Mechanical breakers replaced SCRs for opening switches on the dumps and yielded cost and reliability advantages. Full scale circuit models enabled very important insight into the requirements for switch phasing, damping of transients, expectation levels for QPS transient values, and precise circuit resistance tailoring.

QPS system

Quench propagation studies of the 50 mm CDM and CQM magnets showed that no special requirements beyond the SCDR design approach were needed. Studies showed that heater activation delay must not exceed 250 ms. Analysis also showed that the nominal beam tube design could easily withstand the Lorentz and gas dynamic forces of the quench. Tube liner concepts, however, had to be carefully analyzed for integrity during a quench. Before the VE effort, a CCB action was initiated to remove the magnet voltage tap feed throughs and route all voltage tap lines through the magnets and spools. The action would have resulted in a cost saving as well as potential reliability and signal-to-noise advantages.

Current regulation system

Preliminary requirements were developed for total output deviation of the main bus current from program ideal for the bandwidth of 0–10 Hz. Higher frequency components were covered in the ripple specifications. Conceptual design studies were completed for the transductor and regulation system. Several design problems associated with locking the ten sectors were identified. The SCDR had no details for this system, but the VE team suggested solutions.

Utility straight magnet power system

The SCDR called for the connection of all warm magnets in this region to the main bus, but because of the high resistance of this string, the idea was not workable. A completely new design was developed based upon a 2000 A power supply for each ring.

Value engineering results

The RMPS value engineering team proposed eliminating the independent sector power systems and connecting everything in series for each ring. Hence, the differential current transductors would go away, along with the very complex control system required to I-lock the individual sectors. A simple system of shorting straps was devised to allow independent sector operation for commissioning and maintenance. The main change in operation would be a requirement to dump an entire ring after a quench of any magnet in the ring. The cost savings of this and other less dramatic changes were on the order of $15 to 20 million with an expected substantial improvement in reliability.

Corrector Magnet Power System

The basic approach of the Corrector Magnet Power System (CMPS) did not change from the SCDR. However, several small evolutionary changes did take place, mostly in response to changes in corrector magnet distribution scenarios and circuit parameters. Top level requirements for individual dipole supplies and series family supplies had settled to stable values. Because of under staffing in the ASD Corrector Power Group, very little Level 4 and below design work had been done.

Analysis showed individual corrector dipoles to be self protecting. Series families required some type of QPS consisting of a bypass on each magnet, a quench monitoring and control system, and an energy dump system. Bypass elements could be inexpensive back-to-back diode stacks, SCRs, triacs, or even relays. No requirements or preliminary designs were developed for the other elements.

The CMPS value engineering team did an exhaustive review of options for modifying or eliminating corrector magnets and power supplies (see the discussion of the VE corrector magnet group in this document). Schemes for using different combinations of main bus power and trim supplies on the main magnets were studied. All were marginal or more expensive than the baseline system. However, savings on the $15-million level were realized by using mostly superconducting rather than warm bus, which reduced copper cost and supply power requirements.

Connection Pieces

The maximum length of an accelerator lattice component was set by the size of the magnet delivery shafts at approximately 15 m. To assemble the Collider, individual connection components have to be delivered to the correct tunnel position and then connected together. There are three classes of special lattice components that provide for this function. They are interconnects, empty cryostats, and the cryogenic bypass. The connection components must provide for transferring all the various functional interfaces required for the operation of the accelerator from one active element to the adjoining one. Examples of these interfaces are insulating vacuum, thermal shields, liquid and gaseous helium, liquid and gaseous nitrogen, power, quench heaters and instrumentation, beam, and mechanical. A complete description of the interfaces and the requirements is presented in Refs. [1] and [2].

Interconnects

The interconnect region is the space between any two individual beamline components that are connected together to form the Collider. Each lattice component was assigned a designated slot length which included its physical length and the length of the interconnect. Owing to the large number of interconnection points, a standard interconnect design was mandated and deviations from the design were to be accepted only when justified by technical requirements.[2] The standard interconnect configuration was defined by the Collider dipole geometry. The key technical requirements follow from the operating parameters of the cryogenic system and the availability of the machine.[3,4] The basic interconnect design had been tested at the ASST in both half and full cell magnet strings. No failures had been encountered during testing operations.

Each interconnect contains eight (8) bellows to provide for thermally induced length changes. There were more than 80,000 bellows in the Collider; each bellows represents a single point failure location that could halt machine operations. Extensive engineering efforts had gone into the bellows design and testing, and tests were conducted by the Laboratory and by General Dynamics. Details of the specific component tests and the results can be found in Refs. [11] and [12].

Empty Cryostats

Empty Cryostats (ECs), which provide drift spaces in the Collider lattice, will be located throughout the entire machine.[8] The ECs are functionally similar to a Collider dipole magnet except that no magnetic field is produced. They are used to support the beam tube and to carry cryogens, the superconducting power bus and instrumentation leads between the widely-spaced magnets of the IRs. They have stiff cold mass and thermal shields inside an insulating-vacuum cryostat, which have a standard Collider magnet interface. The empty cryostats do not contain active elements but serve only to extend the functional interfaces from one active component to another. In this sense, they are basically extended length standard interconnects. ECs interface to other components through the standard interconnect. Empty cryostats are required in several different lengths, depending on location in the lattice.

In FY93, a working group was organized to develop a specification for the standard 15 m empty cryostat for the Collider and HEB.[5] A conceptual design based on the accepted specification was developed by this group with additional engineering support. The results of the effort were presented at the Empty Cryostat Conceptual Design Review, held in September 1993.[6] The report of the design review panel is presented in Ref. [7]. An Empty Cryostat Final Report describes the final concept as well as the tools used for the design and analysis.

Cryogenic Bypass

The cryogenic bypass provides a system for transporting the cryogenic and power interfaces around areas where a warm beam tube is required in the Collider, predominantly in the west utility and interaction regions. The basic requirements for the bypass are given in Ref. [8], and further details on the bypass operational requirements are contained in Ref. [9]. Sections of the cryogenic bypass, with a maximum length of 15 m are connected by a special interconnect. A working group was established in FY93 to develop the level 4 specification for a 15 m bypass cryostat. The resulting specification is Ref. [10]. A conceptual design integrating the piping for both rings into a single vessel was to be developed, but the effort terminated with the project.

Cryogenics

The Collider cryogenic system provides for the Collider superconducting magnet coils operating at a temperature of 4.35 K max. Because of the temperature differences of up to 0.25 K along the Collider cell and allowing for recooler ΔT's, the temperature of the supercritical helium entering the cell needs to be 4.0 K nominal.[1, 2] The heat load from magnet cryostats, spool pieces, and other cryogenic equipment of the Collider sector requires a nominal 36g/s helium liquefaction, and 5400 W, 10000 W, and 65000 W refrigeration at 4 K, 20 K, and 80 K, respectively. The 4 K heat load contains both static and dynamic components.

The half cell heat load measurements performed at the Accelerator Systems String Test (ASST) facility suggested[3] that the heat load in the 50 mm aperture 15 m-long dipole cryostats was well within the budget at 80 K, and very close to meeting the budget at 20 K. The static heat load of 4 K strongly depended on the position within the string, with a minimum in the innermost dipole. The average for the three inner dipoles was 1.4 W/dipole, larger than the 0.36 W/dipole static heat load budget. It was likely that some of the excessive heat at 4 K entered the string via the spool pieces, so that the heat load at 4 K was found to be well above the budget. The calculated component of the dynamic heat load due to the beam gas losses was revised upward to 0.028 W/m from the value 0.0086 W/m cited in the SCDR.

The refrigeration for the heat load at 4 K and 20 K is provided by the helium cooling system[4, 5] while the refrigeration for the heat load at 84 K is provided by the nitrogen cooling system.[6] The Collider helium cooling system includes 10 identical helium liquefier/refrigerator plants located at the surface, 10 cold compressor boxes, distribution boxes located in the tunnel, and the spool pieces. The helium liquefier/refrigerator plant consists of a 20 bar compressor system including a dehydration skid, 300 K-80 K cold box, 80 K-4 K cold box, surface distribution box, GHe storage, LHe dewars, and LN_2 dewar. The 300 K-80 K cold box contains dual full-size heat exchanger cores, a nitrogen boiler, and dual 80 K adsorber beds. The 80 K-4 K cold box contains turboexpanders, heat exchangers, a 20 K bed, and a buffer volume. The surface distribution box contains a 4 K precooler and a 20 K heat exchanger.

In the maximum capacity operating mode, the helium plant has the capacity for 45g/s liquefaction and 6750 W and 15000 W refrigeration at 4 K and 20 K, respectively. The minimum design efficiency of the refrigeration system is 28% of the Carnot cycle efficiency. The helium plant capacity exceeding the actual sector heat load is reserved for redundancy. In case of a single plant capacity reduction from a component failure, additional liquefaction was to be transferred from the neighboring helium plants.

The cold compressor box interfaces with the surface distribution box, the surface nitrogen system, the tunnel distribution box, and the nitrogen subcooler box. The cold compressor in this box maintains the pressure in the helium gas return lines of the Collider strings low enough to keep the boiling temperature in the helium recoolers at 3.90 K-3.95 K. From/to the underground distribution box, the streams of cryogens are transferred to/from the four strings of the sector, including magnets, empty cryostats, spool pieces, bypasses, and other equipment. Each Collider sector contains 24,629 kg of helium.

For the 80 K cooling system, two possible sources of liquid nitrogen have been considered: remote air separation plant, and air separation plants directly connected to the Collider nitrogen system. During normal operation with a liquid nitrogen consumption of 4784 g/s, 19 truckloads/day from a remote plant would have been needed (~1000 truckloads for the Collider cooldown). Alternative systems with one, two, and ten directly connected plants have been studied,[6] projecting return of the capital investment in 3.5 to 4.8 years of operation.[7] Each Collider sector contains 34,862 kg of nitrogen. Around the Collider site, nitrogen is transported in the magnet cryostat and spool piece piping.[8] Various recooling schemes based on compact and continuous recoolers had been studied.[6] Pumps are necessary to deliver the liquid to the surface and to distribute it in case of transient upset operating conditions.

The cryogenic system has to operate in numerous modes: normal, utility, special, and maximum & minimum capacity, needed for the Collider normal and emergency operation, cooldown, warm up, maintenance, and repair.[9] The normal operating modes include standby, normal operation, assist, and quench & recovery modes. The aim of the utility modes was to transfer the Collider from the warm state to the cold standby state, and vice versa, and to enable maintenance and repairs in sections without warming up the whole sector.

The Collider cooldown, beginning with sector purification, takes three steps: cooldown from 300 K to 80 K (~22 days), cooldown to 20 K (~11 days), and cooldown to 5 K and fill with helium (12-15 hours). The three steps bring the Collider into standby cold status. In the normal operating mode, current could then be ramped through the magnets. If a superconducting magnet quenches, heat is deposited into the helium. Quench valves are opened to relieve pressure from the cold mass to the 20 K line, and full refrigeration power is used to return to normal operating conditions. The smallest part of the Collider that can be separately repaired is a section (six cells). Prior to repair, it has to be emptied, isolated from the string (24 cells), and warmed up. After repair, the section has to be cleaned up, cooled down, and re-connected to the rest of the string.

Three helium liquefier/refrigerator plants, with 22g/s liquefaction and 2200 W refrigeration at 4.5 K each, similar to the Collider/HEB plant, had been built at the N15 site[10, 11]: the ASST-A, N15-B, and MTL plants. The ASST-A plant was successfully tested at full power in full refrigeration, full liquefaction, and refrigeration/liquefaction modes of operation. The 550 W ASST-B plant[12] and the ASST-A plant supported operations during the ASST testing Runs 1 & 2, and the ASST testing Run 3, respectively. While reliability of both systems was excellent, their availability was limited because of the large number of power outages experienced at the N15 site during the run periods. The spool piece helium recoolers tested at the ASST facility exceeded[13] the performance specified in Ref. [14]. The typical helium peak pressure due to the 50 mm aperture magnet quenching at operating current was 1.28 MPa.[15]

Behavior of several cryogenic components and systems had been extensively simulated using mathematical models.[16] An essential input for the cryogenic system resulted from the following: (1) the cooldown and warm-up simulations of the Collider ring,[17] (2) the helium venting model for the Collider half cell,[18] (3) the dynamic model for the beam tube vacuum effects on the cryogenic system,[19] (4) the simulation of the various cooling schemes and heat interception systems, (5) the simulation of the cryostat insulating vacuum break, and (6) the thermal optimization of the He cooled power leads.[20] Catastrophic events, such as quenching of all magnets in a sector, failure of the quench valves to open, and a break in the insulating vacuum, were simulated to establish performance requirements for the quench and relief valve system, loads on the cell piping, magnet and spool piece posts, and the half cell vacuum barriers.[21]

Diagnostics

Beam diagnostic needs were outlined in the SCDR[1] but evolved in some areas. Beam instrumentation requirements for the Collider arcs and utility sections had been covered in the appropriate 3B specifications.[2,3] Design and development effort by the ASD Beam Instrumentation department had concentrated on the beam position monitors (BPM) and the beam loss monitors (BLM), because the large number required would have necessitated early production. Of the remaining diagnostics, only a few of each were required per ring. For this reason, work on them had been postponed to later years. Of these diagnostics, only three appeared to need an appreciable development effort to meet the requirements. They were a beam size monitor, BPMs with sub-micron resolution to be used as detectors for the transverse damping system, and a Schottky noise system.

Beam Position and Loss Monitors

The BPM design had progressed to the prototype stage with no major problems. A change from the SCDR approach was the decision to build most of the BPMs as single plane detectors, thus simplifying the design and improving reliability by eliminating four feed throughs, two of which had to operate at LHe temperatures. (In the SCDR the BPMs were to be two plane devices, but as a cost saving measure only one plane was to be instrumented.) A logarithmic amplifier circuit for beam position signal processing had been developed. This signal processing method promised major advantages in terms of cost and dynamic range over those suggested in the SCDR. There had been some problems in meeting requirements that signal cables connecting the BPM to the outside of the cryostat be able to withstand a large radiation dosage (10 MGray) over the life of the Collider. The dosage, which was the value expected at the beam tube wall, had been interpreted as being the requirement for the BPM cables because it was not appreciated how fast the radiation field would drop with radius. The closest the cables could come to the beam tube center was a radius of 6 to 7 cm, and at this distance, simulations as the project ended indicated that the expected lifetime dose would be ~0.07 MGray. At this level no special cable should have been required.

The beam loss monitors design had not progressed as far, because it was not required as soon as the BPMs. The baseline approach was to use ion chambers similar to those used on the Tevatron, but solid state detectors were being investigated because of their potentially higher sensitivity.

Beam Size Measurement

The SCDR suggested the use of flying wires and synchrotron radiation (SR) imaging for determining the beam profile. The purpose of the SR imaging was to provide a continuous non-interfering monitor of the beam profile; however, a closer examination showed that because of the small size of the beam and the high energy, the image would suffer from a large amount of diffraction broadening, which would reduce the sensitivity of the measurement to an unacceptable level. This realization led to a survey of known minimal interference beam size measurement techniques that might possibly be used on the Collider.[4] It was concluded that of the approaches that appeared to be feasible, all required at least some development for SSCL usage, and that the development of an electron beam probe offered the best promise. The electron beam probe was preferred because of its promise for furnishing a non-interfering measurement of both transverse and longitudinal profiles of individual bunches. The technique had extreme flexibility, allowing measurements over a wide range of beam parameters.

Special Instrumentation

A wideband damping system required a small number of BPMs with sub-micron resolution. Development of BPMs with these capabilities would have been necessary and appeared to be within reach.[5] Resolution requirements could be relaxed if gain and bandwidth requirements could be decreased. The consensus as the project ended was that this decrease was possible. A Schottky "noise" system would have been required mainly for passive measurements of the accelerator tune. The sensor was a high sensitivity BPM working in the frequency domain to measure the betatron side band frequencies of sub-micron amplitude incoherent beam fluctuations. The Schottky detector might be used as a sensor for an active tune control system, which would probably have been required to compensate for tune change during ramping and beta squeezing owing to the decay of long-term persistent currents.[6]

RF and Longitudinal Feedback Systems

Requirements and RF System Choice

To assure proper Collider operation, the RF system was required to provide 20 MV peak RF voltage for each ring at 360 MHz RF frequency, a basic requirement that remained unchanged. However, significant problems existed in the baseline RF system design. The five-cell normal conducting cavities described in the SCDR might not have been able to perform the specified Collider functions for the following reasons: (1) difficulties in damping the higher order cavity modes (HOMs); (2) risk involved in operating RF windows that had to handle about 200 kW power; and (3) reliability issues that related to availability of the RF power sources.

In the situation of the Collider, the RF system performance was assessed according to its capability for handling transient beam loading, the RF power requirement, and damping of the HOMs. Optimization of system performance, reliability, construction, and operational costs led to the choice of a superconducting single-cell RF cavity system for the Collider rings.[1]

System Layout

In each Collider ring, the peak RF voltage of 20 MV was to be provided by 10 Niobium cavities similar in shape to the Large Hadron Collider (LHC) design.[2,3] Two such cavities would be put in one cryostat (cryo module). Each cryo module is fed by its own RF power amplifier, which is a 200 kW klystron. The operating temperature of these cavities is 4.3 K. The RF power stations is located on the surface, allowing easy access during Collider operations. The klystrons and cavities are connected with WR 2300 waveguide, and power splitting is done in the tunnel with 3 dB hybrids. Each cryostat is 2.1 m long. The separation of the adjacent cryostats is 5.4 m, and the cavities for the top and bottom rings are staggered. This leads to a required lattice space of 70 m in the West Utility straight section.

RF Cavity

The dimension of the Collider cavity was scaled from the LHC design. To minimize the overall RF power requirement, the cavity will be loaded from 3×10^9 to 6×10^5 for half-detuned cavities, and the required power for each cavity will be 43 kW, which is sufficient to correct injection errors as well.

HOM Damping

HOMs in a superconducting cavity fell into several frequency ranges and therefore could be dealt with as groups. The first group of dangerous modes (TE_{111}, TM_{110}) were at about 1.4 times the fundamental mode, and the second group (TM_{011}, TM_{111}, TM_{020}) at about 2 times the fundamental frequency. HOM couplers that could damp these modes effectively had been developed at CERN.[4] HOM damper design for the Collider cavities was expected to be similar.

RF Cavity Control

The tuner design for the Collider cavities was expected to be close to that for the LEP cavities in which thermal expansion of support bars is used for slow tuning, and a magnetostrictive device made of Ni is used for fast tuning.[5] The tuning range is 50 kHz for the slow tuner and 2 kHz for the fast tuner. In addition to the traditional control loops such as RF phase, amplitude, and tuning loops, a fast RF feedback loop developed at CERN and a feed-forward system, were also to be built around the cavity to handle high beam loading and reduce coupled-bunch instabilities caused by the fundamental cavity mode. The gain of the fast RF loop should have been about 50.

Refrigeration and Liquefaction Loads

The maximum dynamic RF loss is 388 W for two rings. The cryostat for the Collider cavities is expected to have a length close to 3 m for tuning purposes, and standby losses should have been able to achieve 5 W/m. Distribution losses are estimated to be 300 W, which would have become less if the RF cryogenic system was attached to the N15 cryoplant. These contributions add up to a total refrigeration load of about 940 W. A 1.4 kW cryogenic system is sufficient with 50% safety margin. Liquefaction load could have been determined only after a cryostat design was in place.

Longitudinal Bunch-by-Bunch Feedback System

To address all the possible unstable coherent modes of the beam, the longitudinal feedback system requires a bandwidth of 30 MHz, one half of the bunch frequency. The center frequency was chosen to be 555 MHz. The required peak voltage would be 1kV assuming 2° phase error detected by the pickup. The drastically reduced voltage requirement compared to the one previously derived in the SCDR was due to use of superconducting single-cell cavities. In this case the most unstable dipole mode has a growth time of about 37 seconds after passive damping of HOMs.

As the project closed, there was no specific design for the kicker electrode. A good candidate was the quarter-wavelength coaxial structure developed at LBL for the ALS and SLAC/LBL B-factory projects.[6] Such a device has a much wider bandwidth than needed at 555 MHz center frequency. Therefore, several units could have been connected in series to reduce the power requirement significantly. An appropriate choice (and a nearly optimal one as far as cost was concerned) was a four-electrode kicker for each Collider ring. The kicker array provides a bandwidth of about 100 MHz. The required power is 700 Watts and is to be delivered by one solid-state power amplifier. More detailed study on issues such as beam loading and unwanted modes was still required at shutdown.

Transverse Feedback System

Beam damping was given only a cursory treatment in the SCDR. An active damping system would have been necessary to control the emittance growth that occurred when an amplitude dependent tune spread caused initially coherent beam betatron oscillations to decohere. These coherent oscillations could result from injection errors, multibunch instabilities, or other mechanisms such as ground vibration, coolant flow, and power supply ripple. A number of proposed designs had been proposed for damping systems, but a final selection had not been made. The SSCL had collected significant experience in evaluating requirements for the transverse and longitudinal dampers. In addition to the general requirements on power, bandwidth, and gain, specific attention was given to the analysis of the effects of noise and vibrations on emittance growth.

Beam-Beam Decoherence

The beam-beam effect is the major source of nonlinearities in high energy Colliders. Such a nonlinearity imposes certain limits on the Collider luminosity due to beam instability. Strongly non linear beam-beam forces excite high order mode resonances, causing particles to diffuse into the tails of the transverse distributions and to be lost. The tune spread generated by beam-beam interactions causes fast decoherence of the betatron oscillations and, therefore, imposes more stringent requirements on any feedback system.

Physics of the head-on beam-beam effect was studied during the SSC design by computer simulation. It was found that the decoherence time due to a beam-beam tune spread for two interaction regions was around 0.1 second, about six times shorter than a theoretical estimate made previously. Schemes for suppressing the beam-beam effect were proposed for the SSC and could now possibly be incorporated in the LHC design. Some residual tune spread is needed to Landau damp higher order mode transverse multibunch instabilities due to resistive wall impedance.

Instabilities Control

Transverse instabilities owing to HOM of the RF-system, if they imposed problems, could be controlled by a bunch-by-bunch feedback system (wide bandwidth), which has two BPM's and two kickers. Injection errors and transverse instabilities due to resistive wall impedance (fundamental modes) could be controlled in two turns by a low frequency bandwidth (batch-by-batch) feedback system, which uses two BPM's and one kicker with a different correction scheme. Higher order mode resistive wall instabilities are controlled using Landau damping due to tune spread within the bunch.

Final parameters of the transverse feedback system for the Collider were not yet defined at termination time. The narrow bandwidth system mentioned above would probably have required a damping time less than 10 ms, feedback gain of about 0.05, and bandwidth about 500 kHz. The wideband system might not have been necessary if the cavity HOM were suppressed. Interference between a longitudinal damping system and a transverse damping system was studied but not completed.

Abort/Extraction System

While the fundamental SCDR approach to the Collider abort system remained for the most part unchanged, extensive detailed modifications were found to be needed to make the abort system work and to keep costs under control.[1,2] For the Collider abort system, a fixed horizontal dogleg in the Collider lattice deflects the beam outward using resistive dipoles near the start of the long WU central drift, deflects the beam inward using Lambertson magnets near the utility center, and completes the dogleg using resistive dipoles near the end of the drift. In the SCDR, all resistive dipoles and Lambertson magnets were included on the main Collider bus; unfortunately, the voltage drop across such a string of magnets far exceeded that available from a ring magnet power supply. The problem was solved by replacing the bending outward resistive dipole strings at the ends by a 13 m-CDM powered in reverse polarity, and by putting the Lambertson magnets on an independent power bus. Unlike the SCDR, the CDMs would give a sufficient bend for the abort beamline to clear downstream cryostats.

Beam Backstop

Protons are sent down the abort beamline straight to the backstop after being kicked into the field-free region of the Lambertson magnets. The previous design used only symmetric Lambertson magnets ,which would have required very large horizontal apertures. The problem was solved via a layout of symmetric and asymmetric Lambertsons and resistive dipole magnets for the required bending.[1] A late refinement involved adjusting the length and number of asymmetric Lambertsons so that the magnets for the two rings would line up with each other and could then use common supports. The Lambertson and dipole magnets share a common bus in series with two sets of quadrupole magnets in the abort beamline.[1]

Beam Painting Schemes

The abort beamline "blowup" quadrupoles are needed to avoid damage to the backstop. They do this by magnifying a beam sweeping pattern (painting) generated by fast kicker magnets during a beam abort, and then spreading the full beam intensity over a large backstop core volume. The SCDR painting scheme, involving two sets of oscillating kicker magnets moving the beamspot in a spiral pattern, was susceptible to failure.[3] The problem was solved by using the natural droop of the abort kickers to slowly pan the beamspot vertically, while fast kickers move the beamspot horizontally for a resulting raster scan. The polarities, strengths, and positions of the blowup quadrupoles had recently been optimized to give the maximum painting benefit while keeping to reasonable quadrupole apertures and parameters. Hydrodynamic calculations and simulations of this process performed at LANL suggested that with such a raster scheme, catastrophic "hole boring behavior" could be avoided even if the horizontal painter kicker magnets misfired. Studies were made to optimize the backstop shielding and cooling scheme and associated requirements and to reduce the amount of large diameter beampipe required to transport the beam to the backstop.[4,5]

Bent Crystal Extraction

During the SSC design studies, much work on crystal extraction had been done. The work addressed the issues of control of flux onto the crystal, channeling physics, radiation damage, and beam/crystal interface (e.g., step size onto crystal). Extensive computer simulation and theoretical analysis of the process had been done, including use of the two crystal scheme, RF amplitude and phase noise induced diffusion, and resonant excitation of synchrotron beam oscillation. Design of a crystal extraction facility in the east utility straight had been formulated.

HEB to Collider Transfer Lines

The system is composed of the HEB extraction system, two beam transfer lines, and the Collider injection system.

Change from Superconducting to Resistive Lines

The SCDR postulated the use of superconducting lines. It assumed Tevetron-style superconducting magnets and did not contain all the equipment necessary for a working line. In addition, it did not address problems related to superconducting magnet quenching and the protection of the superconducting elements from kicker misfires and prefires.

A change from superconducting magnets to resistive magnets was undertaken to make the 2 TeV lines operationally reliable and affordable. The main difficulty with the change was that the resistive design had to maintain a reasonable, flexible lattice in a very confined space, while keeping requirements on various components, especially the resistive magnets, within practical technical and budget limits.

A compact resistive lattice has developed after a very wide range of investigations, which significantly improved beam-line optics flexibility and should have been reliable.[1,2] The cost of this design was to be roughly the same as the baseline cost estimate. The resistive line design also made the implementation of beam collimation possible.

A study of transfer line error analysis and beam position correction was done, which was very important to retaining the small beam transverse emittance from the HEB during the transfer process and laid the foundation for detailed technical system specifications The study made use of a software code that had been developed during the process.[3] General progress had been made for all aspects of the engineering design, especially for various[4,5] resistive magnets with high field requirements and very tight spatial restrictions.[6]

HEB Extraction

A special consideration of the 2 TeV beam transfer system design was the reliability and safety issues associated with the huge amount of beam energy(6.5 MJ) of the extracted HEB beam batch. In the original design, HEB extraction kicker misfires could cause superconducting magnet quenching and even irreparable damage by the mis-steered beam. Two changes were made for the HEB extraction channel from the SCDR design. One was extraction kicker segmentation. Single kicker integrated field was reduced from 0.328 Tm to 0.167 Tm. By carefully locating kicker positions, defining proper extraction orbit displacement, and adopting a DC extraction orbit bump scheme, the total number of extraction kickers became essentially the same as called for in the SCDR design.

The extraction aperture (characterized by the aperture of the last superconducting quadrupole from the HEB and that of Lambertson septum magnet at beginning of the transfer line) was examined and specified carefully to leave space for mis-steered beam caused by kicker misfiring, and to mitigate superconducting quadrupole quenching caused by beam halo. Technical design efforts in Lambertson magnet design were made as well to ease the aperture problems.[6]

Collider Injection

Similar work has been done for the Collider injection.[4,7] No DC bump scheme is planned at this stage. A significant change from the SCDR design is the Collider quadrupole polarities. The injection scheme had the first Collider quadrupole seen by the injected beam horizontally focusing. This is necessary to reduce the injection aperture requirement on these quadrupoles.

A collimator is planned for each of the transfer lines to protect Collider components from the misfire of two HEB extraction kicker magnets. Similar devices were to be located after the Collider injection kickers, to prevent Collider magnet damage from injection kicker timing errors.[7, 8] Simulations of beam energy deposition were done for various beam mis-steering scenarios to establish extraction and injection aperture clearances, and to determine location and technical requirements for the collimators.

Controls

The control system design for the Collider was in a fluid state at the time of project termination. In the CDR[1] there is a description of the early global control system. The SCDR[2] also concentrated on global controls issues with more emphasis on communications. Papers[3,4,5] published by members of the ASD/Controls Department elaborated the communications aspects of the control system. Timing issues were also addressed in unpublished reports.[6,7] At termination there was a draft version of the "Global Controls Level 3B Specifications" (E10-000043). Level 3B specification documents for the Collider - E10-000027 (Arc Specification) and E10-000073 (Utility Specification) - contain short descriptions of the Collider control system. The controls section of E10-000073 was greatly expanded from August to September of 1993. This report summarizes the specifications contained in that new version.[8]

Equipment Control and Monitoring

All ramped devices would be controlled by programmable function generators. They have to be capable of producing the output waveform from either a mathematical function or from a table by interpolation. Table (program) switching could be achieved via clock events. All function generators would be loaded from a single application program. In addition, there would be a separate software to examine the cards individually.

The operator must have the ability to step or scan one or two independent parameters while measuring or calculating many others. Therefore a general controls package is needed to step magnets, klystrons, feed-back loops, timing parameters, etc. The parsing functionality, which is the ability to step through a time-bump, must also be provided.

Other important points required for equipment control are: a device name database; device status information; global data and local data interfaces; a clock event interface; readback; card locator software; kicker and pulsed magnet controls; an alarm handling system; and a global ADC compare and restore program.

Timing and Synchronization

Timing issues are discussed in documents listed in Refs. [6] and [7]. To summarize briefly, there would be four clocks coordinating the Collider activities. The Global Clock (GCLK) timing would be used where absolute times and delays are required. The Power Line Clock (PCLK) would generate ticks at a harmonic of 720 Hz and track the frequency variations in the site AC power. Two beam synchronized clocks (one for the clockwise beam - TCLK, one for the counterclockwise beam - BCLK) are needed to coordinate the devices involved in beam transfer.

Beam Instrumentation Controls

Beam instrumentation electronics would reside in VME/VXI crates. There would be a small number of GPIB instruments. The control system would provide the following functionalities: (a) parameter setting, (b) operational mode setting, and (c) enable/disable.

In data acquisition, the emphasis is on block data transfers. BPM and BLM data are obtained in arrays from the buffers on request. Buffers (located in niches, one for each BPM or BLM) would be 64 KByte circular buffers holding the last few seconds of orbits. The abort trigger would freeze the buffers. Each record in the buffer has to contain the turn number. The data array (BPM or BLM readings from around the ring forming a one turn orbit) would contain the timestamp as the header. A processor would continuously calculate the average of the last

128 turns, and the result would be sent to the sector computer at 1 Hz rate. These values would be stored in the sector computer and used to correct slow drifts in the closed orbit. A special data acquisition mode where positive data for 1024 turns from all BPMs are analyzed within 1 min is absolutely necessary. This functionality would be used to perform (a) local decoupling of the Collider, (b) harmonic analysis, and (c) BPM calibration.

Miscellaneous

A central issue in the operation of the Collider is orbit control. A comprehensive application program that combines an online model with correction algorithms has to exist. Orbit control involves orbit smoothing, saving good orbits, i.e., settings of all correctors—dipole, quadrupole, sextupole—as one orbit, correction of slow drift, and correction as a reaction to corrector failures.

Another important operational issue is the control of tune, chromaticity, and coupling, especially during transitional states, such as ramp and squeeze. Initially, open loop controls would be established to control the parameters. Compensation tables would be developed based on operational experience. However, for most of the processes the time scale is seconds. In the open-loop framework, it is very impractical to establish 1-second interval breakpoints. Therefore closed-loop controls were to be established for the parameters tune, chromaticity, and coupling in the second phase of the commissioning.

Other operational issues pertaining to controls can be listed as follows: (a) Beam Permit System, (b) Sequencer, (c) Data Logger, (d) Shot Analysis Program, (e) Correlation Plot Functionality, (f) File Sharing (g) Data Sharing among application programs, and (h) Expert Systems.

Beam Tube Vacuum

The cold (4.2 K) bore tube in the Collider arcs comprises 70.6 km, or 81%, of the 87.12 km circumference of each ring and would have been the primary element of the Collider beam tube vacuum system. The bore tube is the interface between LHe in the magnet cryostats and beam tube vacuum. The new feature of the Collider compared to the earlier superconducting proton storage rings (Tevatron at Fermilab, HERA at DESY) was the presence of a significant flux of synchrotron radiation. At design beam current 72 mA, magnetic field 6.7 T, and beam energy 20 TeV, the synchrotron radiation parameters are 10^{16} photons/m/sec, critical energy 284 eV and radiated power 0.140 W/m. The synchrotron radiation strikes the wall at ~2 mrad angle of incidence where it desorbs gas (primarily H_2, CO, CO_2, CH_4) and contributes a significant heat load (18 kW for both Collider rings compared to 4.2 K plant capacity of 65 kW). The approach taken in the CDR[1] and SCDR[2] was to absorb the radiation at 4.2 K and allow for the heat load in the design of the refrigeration plant. If desirable, the possibility of operation at upgraded beam current was to be accommodated with increased refrigeration capacity, to be added after some period of initial operation. The challenge then was to understand the vacuum implications of the gas desorbed by the synchrotron radiation. The quality of the beam tube vacuum averaged over the Collider circumference was specified by setting the minimum required vacuum limited luminosity lifetime due to beam gas scattering equal to 150 hours. This set upper bounds on the average density of the various gas species: 3×10^8 H_2/cm^3, 3.3×10^7 CO/cm^3, etc.

In the CDG era 1984 to 1989, two sequences of photodesorption experiments were performed at electron synchrotron light sources: the first with 4.2 K beam tubes at the BNL

NSLS UV ring,[3] and the second with 4.2 K open samples at the Wisconsin SRC.[4] This work led to the conclusion, as stated in the SCDR, that "the effect of gas desorption by synchrotron light for the Collider beam tube vacuum will at worst be manageable by slight periodic warmings of the beam tube and most probably will be of no consequence."[5] Beam tube warm ups that are too frequent would be disruptive of the physics program; however, a range of acceptable beam tube warm up frequencies was not addressed in the SCDR. The viewpoint expressed in the SCDR was that the photodesorption coefficients would decrease with continued exposure to synchrotron radiation, and eventually the time between required beam tube warm ups would become very long. The beam tube was specified to be stainless steel electroplated with 100 microns of Cu on the inside surface with residual resistivity ratio RRR = 30 at 4.2 K and B=6.7 T. In this concept the beam tube, or first surface facing the circulating proton beam, is identical with the bore tube of the superconducting magnets. Vacuum pumping is provided by cryosorption on the 4.2 K inside surface of the bore tube. Sufficiently small parasitic heating and resistive wall instability growth rate are assured by the Cu coating.

There were shortcomings in the Collider vacuum analysis as presented in the SCDR: the 4.2 K photodesorption data of the CDG era only extended to the equivalent of approximately one day of Collider operation, and no model was developed for predicting the Collider beam tube gas density. As a consequence it was not possible to quantitatively predict the long-term behavior of the Collider beam tube vacuum. In addition it also came to be appreciated that there was a local limit on vacuum density imposed by the maximum beam gas scattered power that could be absorbed in the magnet cryostats before leading to a runaway increase in beam tube vacuum pressure and/or a magnet quench. The maximum beam gas power deposition was estimated to be 0.6 W/m.[6] The corresponding upper bounds on local gas density were: 4×10^{10} H_2/cm^3, 4.3×10^9 CO/cm^3, etc. Although the limits exceeded the average bounds, they could occur locally without any noticeable effect on the luminosity lifetime. Hydrogen presents a particular problem because its saturated isotherm density at 4.2 K ($\sim 2 \times 10^{12}$ H_2/cm^3) is greater than the local limit by a factor of fifty. Accumulation of a monolayer of physisorbed H_2 anywhere in the beam tube must therefore be avoided. The time to accumulate a monolayer sets an upper bound on the beam tube warm up interval. Indeed, the warm up interval could even be significantly shorter than the H_2 monolayer formation time owing to the unknown desorption coefficients of physisorbed molecules. As a consequence of this local beam gas density limit, the effective overall conditioning of the beam tube is only as good as the least conditioned piece. Each time a segment of the beam tube were to be replaced or exposed to atmosphere, the conditioning process would have to be restarted. Under these conditions, it may be very difficult in practice to achieve the very long intervals between beam tube warm ups envisioned in the SCDR. These ideas are described in Ref. [7].

The realization of these difficulties initiated a re-examination of the Collider beam tube vacuum beginning in the second half of 1990, leading to a report issued in August 1991 which contains a collection of memos and vugraphs by the people involved in the early stages of the re-examination.[8] The report also contains some of the first considerations of a liner for the Collider beam tube vacuum system. The liner is a coaxial perforated tube inserted inside the magnet bore tube. Photodesorbed gases are pumped through the perforations and adsorbed behind the liner out of view of the synchrotron radiation. Cryosorber material added behind the liner greatly increases the absorption capacity compared to a bare metal surface. In this way the liner concept solves the two problems of a simple beam tube: desorption of physisorbed gas, and the increase in the H_2 isotherm pressure near one monolayer surface coverage on a bare metal surface. In April 1991, a research and development program was initiated to acquire the understanding needed on the Collider vacuum and liner issues.[9] This led to new startups of experimental activity and a prototype liner design effort that were still in progress when the SSC was terminated; the status of these activities is briefly described in the following paragraphs. More details are given in Chapter 30.

At the time of termination of the SSC, a 4.2 K beam tube photodesorption experiment had been completed at the VEPP2M electron storage ring at BINP, in Russia under collaborative contract with the SSCL. The experiment measured desorption of 3.4 monolayers of H_2 from an electroplated Cu beam tube in the equivalent of ten days of Collider operation at design intensity.[10] Photodesorption of this magnitude would favor a liner type of distributed pump option for the cold beam tube vacuum system unless some way could be found to reduce the inventory of photodesorbable H_2. As the SSC was terminated, a follow-on 4.2 K photodesorption experiment was being planned for the equivalent of one year's photon flux in the Collider (~2×10^{23} photons/m). This experiment would have provided definitive information on the long-term lost operation time due to beam tube warmups, if a simple electrodeposited Cu beam tube rather than the liner option were used. This information would then have served as a baseline for comparison with other possible materials or beam tube preparation methods, and for choosing between the simple beam tube and liner options.

A design study of an 80 K prototype liner system, designed for a test in the ASST was completed in April 1993.[11] When the study was initiated in June 1992, the results of the later BINP experiments had not yet been obtained, and extrapolation of existing 4.2 K desorption coefficient data favored an 80 K liner temperature over 20 K or 4.2 K. This temperature was required to meet the vacuum luminosity requirement while maintaining low enough impedance of the pumping holes to meet beam stability requirements. Since June 1992, new experimental data had indicated that the 80 K design was conservative and that 20 K and 4.2 K temperature liner options could also meet vacuum luminosity and impedance requirements. The 4.2 K liner option offered some advantages: it did not require an external high pressure GHe loop to regulate its temperature, and did not have the potential for a serious thermal short to 4.2 K. Absence of the GHe loop had the advantages of reducing the radial space requirement, engineering complexity, and cost of a liner. Because of these advantages, the liner design effort was being reoriented toward a 4.2 K system. A requirements document for a 4.2 K liner system was being prepared for formal management approval as the SSC was terminated, and preparation was subsequently halted. An advantage of an 80 K/20 K liner over a 4.2 K liner was that the Collider beam intensity could be decoupled from the 4.2 K refrigeration capacity. However, a management decision was made at the SSCL to provide enough 4.2 K refrigeration capacity for the baseline beam intensity, and to provide for future upgraded beam intensity (if required) by future increases in the refrigeration capacity. In this case, the issue of liner or no liner was to be decided solely on the basis of the vacuum issue.

At the time of the SCDR, the warm tube portion, comprising the remaining 16.5 km or 19% of the Collider beam tube, was not well enough known to specify its detailed vacuum design. Since then, considerable progress was made in the designs of the utility and interaction regions, so that detailed vacuum designs could be done. The warm beam tube vacuum did not present fundamental problems of the magnitude of photodesorption in a cryosorbing beam tube. However, the many specialized components in these regions could lead to complexity, tight space requirements and access problems. The vacuum system for the GEM and SDC detectors had also been designed.[12] Non-accessibility in portions of the GEM beam pipe required development of lumped NEG pumps similar to schemes employed on electron storage rings. The detailed design of the utility region vacuum system had not yet begun when the SSC was terminated.

Database/Modeling

A database and graphical user interface was built to support the design of the SSC Collider machine. The beamline components of the Collider were stored in the database along with location data about the machine. The major engineering systems that support the beam optics were also described in the database. These systems included the electrical systems (main magnet and corrector magnet power supplies), cryogenics, quench protection, beam instrumentation, and vacuum.

A graphical user interface, which displays icons of the components along the beamline, allows the user to traverse along the circumference of the Collider, click on an icon, and display information about the component. The paper, "Accelerator Design Using Databases and Graphical User Interfaces," SSCL-620 describes the database and associated graphical user interface.

Configuration modeling, with associated 3D graphics, was used extensively for the design of the West Utility Region of the Collider, the shaft locations, and standard niche areas. The effort supplemented various design submittals in these complex regions of the Collider. The models depicted underground structures, beamlines, cryogenics, and supports to the extent that information was available. The models documented the level of design and highlighted areas requiring additional effort. Physical interferences between equipment and structures were diagnosed and eliminated during the creation of database models of these complex regions. From the 3D models, three computer generated video animations were created as part of the design review process. They are available from the SSCL Video Library as "West Utility Straight - *date*," West Utility Straight - *date*," and "N45 - *date*."

Conventional Construction and Utilities

Collider Tunnel Shaft and Construction Status

West Complex area (Linac excepted)

Other than the N-15 sites, there is only one shaft in the west complex. This is the Exploratory shaft which is nominally 250 ft deep and 14 ft in diameter. There is, at the 160 ft level, a horizontal adit nominally 40 ft long. There is a waste water treatment plant on site with a capacity of 12,000 gal/day; potable water (installed by Buena Vista-Bethel special utilities district); and a fire protection water system that can supply a maximum demand of 2,000 gal/min. for 2 hours. The system has a storage capacity of 1 million gallons. There are 177,400 ft^2 of building structures including: Magnet Test Lab (54,000 ft^2), MTL refrigerator building (3,900 ft^2), Magnet Development Lab (72,500 ft^2), ASST building (14,000 ft^2), N15 service building (12,300 ft^2), ASST compressor building (12,400 ft^2), and the MTL compressor building (8,300 ft^2).

N15 Service area

The magnet shaft at N15 is approximately 30 × 60 × 224 ft deep. The utility shaft has a nominal 18 ft diameter and is 220 ft deep. The personnel shaft is nominally 21 ft in diameter × 229 ft deep. The tunnel between N-15 and N20 is concrete lined, 14 ft i.d. and 14,700 ft in length. This section of tunnel has unistrut mounted lighting. There were 25 KV lines to N15 with 20 MW of power. The N-15 service building is at the utility shaft location.

N20 Service area

The ventilation shaft is nominally 15 ft in diameter × 167 ft deep. This has a short connecting tunnel/adit from the shaft to the running tunnel. The tunnel from N-20 to N-25 is concrete lined, 14 ft i.d. and 16,500 ft in length. This section of tunnel has unistrut mounted lighting.

N25 Service area

There are two shafts in the "hammerhead" configuration. The personnel shaft is nominally 21 ft in diameter and the utility shaft is 18 ft in diameter. The shafts are 134 ft in depth. The unlined tunnel to N-30 is approximately 17,000 ft long. This section of tunnel has unistrut mounted lighting.

N30 Service area

There is a ventilation shaft nominally 15 ft in diameter. This is in the "half hammerhead" configuration. This shaft is 175 ft deep. There are approximately 17,000 ft of unlined tunnel to the N-35 service area. This section of tunnel has unistrut mounted lighting.

N35 Service area

There are two shafts in the "hammerhead" configuration. The personnel shaft is nominally 21 ft in diameter, and the utility shaft 18 ft in diameter; the shafts are 198 ft in depth. Only the TBM starter tunnel went beyond this point toward N-40, approximately 600 ft.

N40 Service area

There is a magnet delivery shaft and a ventilation shaft at this site. The magnet delivery shaft was 108 ft deep. The ventilation shaft is 103 ft deep. The tunnel is completed from this location to N45, approximately 14,256 ft. It is an unlined tunnel with unistrut mounted lighting.

N45 Service area

There are two shafts in the "hammerhead" configuration. The personnel shaft is nominally 21 ft in diameter, and the utility shaft was 18 ft in diameter: the shafts are 165 ft in depth. The unlined tunnel was not complete through to N50 and its length is approximately 5,000 ft.

N50 Service area

There is one ventilation shaft at this site in the "half hammerhead" configuration approximately 162 ft deep.

N55 Service area

The N-55 site magnet, utility, and personal shafts are partially completed as the project ended.

East Complex area

Site preparation was done, and pads were cut for IR8 and IR5. On IR5, foundation work was complete, and some steel work was done. The north-south road was completed.

S15, S20 Service areas

Undeveloped

S25, S35, S55 Service areas

Site work partially completed.

S30 Service area

The ventilator shaft is complete. The shaft is 15 ft in diameter and 194 ft deep.

S40 Service area

Magnet and ventilator shafts are complete; the depth is approximately 143 ft for ventilator and 147 ft for magnet shaft.

S45 Service area

Utility and personnel shafts are partially complete.

S50 Service area

The ventilation shaft is partially complete.

Chapter 9. Collider Interaction Regions

(R. Steining)

Organization for Construction

The construction management plan for the interaction regions was made to respond to a number of special circumstances. Among them were (1) that the designs of the detectors in the East regions were incomplete with many outstanding unresolved problems; (2) that no specifications for the West regions existed, because no experiments had been approved; (3) that the interaction regions contained small quantities of many types of superconducting magnets with special requirements not used elsewhere in the cold machines; and (4) that the development of the designs for the individual regions required a mechanism for coordinating construction project activities with experimental group activities.

The systems engineering approach, which had been imported to the SSC from defense industries, seemed to be inappropriate when applied to the interaction regions. Although the formal systems engineering approach provided a systematic method for the preparation and modification of specifications, the paperwork and manpower overhead it demanded was enormous. A large overhead may be justifiable in the case of components manufactured in quantities of thousands where mistakes are multiplied by large factors. When the production quantities are small, the approach is not economical. Small mistakes made in small production runs are more easily corrected than prevented. Furthermore, the formal systems engineering approach is a slow process. Because some interaction region requirements were being established by the experimental groups as the interaction regions were being constructed, a more responsive method of construction management was needed at the SSCL.

The approach chosen for the interaction regions was to form an integrated design, manufacturing, and experimental user interface group. Since all interests were represented in the integrated group, it was possible to make cost optimizations efficiently. Concise technical specifications were produced and carefully documented. The specifications were changed only after careful review by the various interests represented in the group. From time to time, the SSC parameters committee reviewed the designs.

Another feature that made the integrated group approach more feasible was the intention that many of the special purpose superconducting magnets (and other components) would be manufactured at the MDL facility on site. There was constant communication between the design efforts and the manufacturing efforts. Members of the manufacturing effort at all levels took part in discussions whenever appropriate. Finally, because it was intended that the MDL facility would become the continuing facility for magnet production and repair once the SSC began to operate, it was appropriate to manage the facility during construction in a manner that would ease the transition to maintenance and repair once construction was completed.

Overview of the IR design

The design of the Collider called for four dispersion free long straight sections where interactions could be achieved. Two of these straight sections were located on the east side of the Collider, and two were located on the west side. The two straight sections on each side of the Collider were separated by a 40 milliradian region of bending called the hinge. The purpose of the hinge bending was to direct the cone of muons produced at one interaction point away from the detector at the other interaction point.

The top level requirements for the Collider specified a luminosity of $10^{33}cm^{-2}sec^{-1}$ at 20 TeV. A detector free space of 20 m on either side of the interaction point was initially required. The luminosity requirement could be achieved with an interaction point beta value of approximately 0.5 m.

Two large detectors, GEM and SDC, had been approved, and both were designed for maximum luminosity (GEM in principle for 10x the design luminosity). The detectors were to occupy interaction points 5 and 8 located on the east side of the Collider. No experiments had been approved for the interaction points on the west side of the Collider. It was anticipated that the west side experiments would have more modest luminosity requirements and larger detector-free space requirements.

The Design Process

Because the east interaction regions were the principal focus of the SSC experimental program, most of the design effort was directed at them. It was anticipated that the west regions could be built by modification of the east region designs and, it was hoped, with suitable rearrangements of accelerator components. The design of the east interaction regions resulted from a competitive process in which two significantly different designs known as *A* and *B* were developed in parallel and evaluated. In their final forms, both *A* and *B* met the basic SSC requirement of a 20 m free space for detectors, a tuning range of the beta function at the interaction point of from 0.5 to 8.0 m, and a vertical separation of 0.9 m between the Collider beam lines. After passing an accelerator physics review, designs *A* and *B* were submitted to the CCD, ASD and MSD divisions for cost, schedule, and engineering review. No significant differences in engineering difficulty or technical risk were identified by the divisions, but significant differences were found in the cost. Costs identified by ASD and MSD indicated that design *B* would cost 6.8 million dollars more to construct than design *A*. Although CCD costs were not estimated, design *B* was identified as more costly and it was abandoned. There were, however, several features of design *B* that were less costly, and design *A* was modified to incorporate them. The final version of design *A* called *The Preferred Design*,[1] was adopted for the interaction regions.

Principal features of the Preferred Design

The general layout of an IR is shown schematically in Figure 9-1. The principal features of the preferred IR design are summarized below.

The length of each IR was 1890 m. With the given magnet parameters in the SSC Collider, this length was enough to provide an adequate focusing of the beam at the IP. The beta function could be reduced from 300 m at the entrance of the IR to 0.25 m at the IP. The optics was antisymmetric about the IP, and the latter was located in the middle of the IR. This ensured that both proton beams experienced identical sequence of the focusing strengths in the IR. Each half an IR was built of two major focusing modules: (1) a 541 m final focus section, which covered the region from the IP to a secondary focal point (SF); and (2) a 409 m tuning section from the SF to the exit of the IR, which provided a two-step focusing of the beam at the IP and allowed almost independent adjustment of each section.

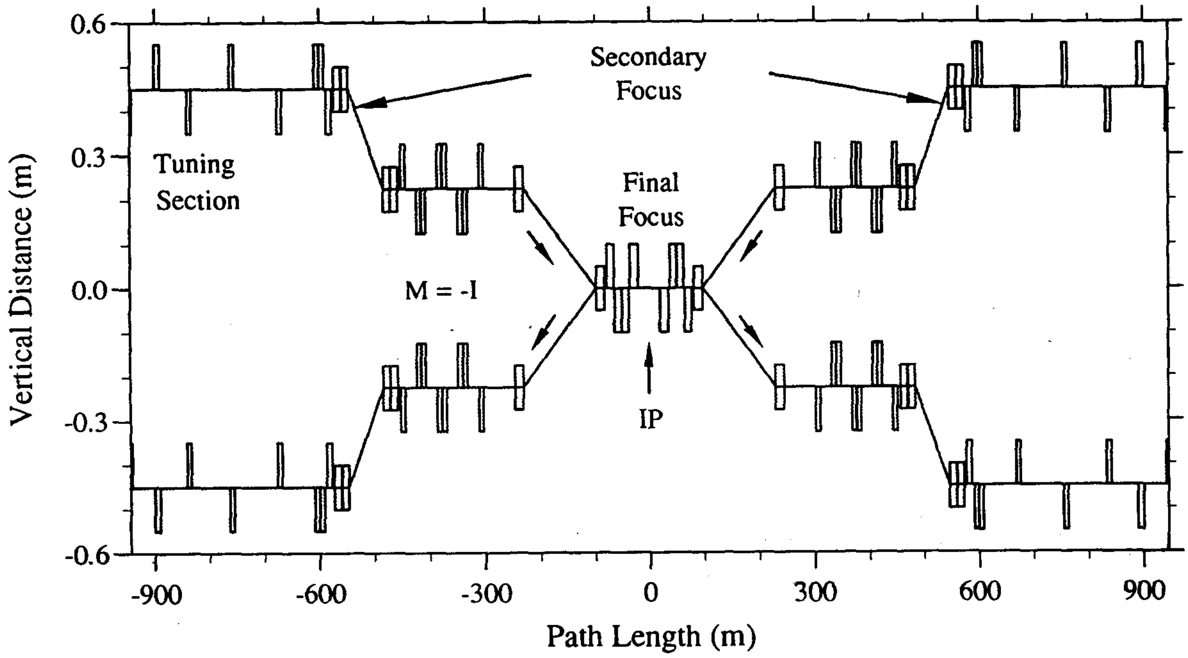

Figure 9-1. General Layout of the Interaction Region.

The final focus section had a fixed transfer matrix from IP to SF with 360 degrees of phase advance. It included the final focus triplet quadrupoles, the M = –1 section, and a set of vertical bending magnets that brought the beams into collision at the IP. The advantages of 360 degrees phase advance across the final focus section were that (1) this phase advance did not depend on β^*, and (2) there was a constant linear transformation of beta function and of beam size from the SF to the IP. The optics of this section acted on the beam as a telescope and created at the SF a magnified image of the beam at the IP. The magnification factor for the beam size was 4.6 and 7.5 in two planes, respectively. An M = –1 section was inserted between the two pairs of vertical dipoles to cancel the vertical dispersion at the IP. The advantages of such a correction scheme were that (1) it provided a local compensation of the dispersion, (2) it did not depend on β^*, and (3) the M = –1 section could be placed anywhere between the two pairs of dipoles. The section was moved as far as possible from the IP to provide the most space for the detector, and to minimize the beta function within this section at collision conditions.

The secondary focus could be useful for beam diagnostics, and protection collimators could be placed here to intercept particles that might otherwise strike the sensitive inner regions of the detector. The final focus triplet quadrupoles were common for both beams. They had constant gradients during variation of β^* (called beta squeeze). The advantages of this were that: (1) the squeeze could be done independently for each ring, and (2) additional eddy current field errors in the quadrupoles were not introduced during the squeeze. The tuning section included six variable gradient quadrupoles to provide the beta squeeze from injection to collision IR optics. The nominal range of variation of β^* was from 7 m at injection to 0.5 m at collision. It was possible to reduce β^* to 0.25 m if a larger triplet bore was provided.

The optics of the tuning section was optimized to (1) minimize the total value of GL-integral over the tuning quadrupoles, (2) minimize the range of variation of the tuning gradients (currents), (3) avoid any reversal of polarity in the tuning quadrupoles, (4) minimize the beta peak values within the tuning section during the beta squeeze, and (5) reduce the number of different types of tuning quadrupoles. To minimize the rate of change of current and the rate of change of chromaticity during the beta squeeze, an exponential dependence of β^* on time was chosen: β^* (t) = 6.8 exp (-t/20.36) + 0.2 The duration of the beta squeeze was chosen to be 100 seconds which was almost the least time consistent with magnet specifications for maximum allowed value of |dI/dt|; it was also the duration used at Fermilab. The IR transfer matrix was kept constant and matched to the outside regions in any optical configuration within the range of β^* values. This kept the rest of the machine unaffected during the beta squeeze. The phase advance across each half an IR had a constant and specific value during variation of the β^*. It provided an optimum phase advance (90 degrees × integer) between the triplet, the main source of the beam perturbation in the IR, and the IR local sextupole and quadrupole correctors distributed in the outside regular cells.

There was enough free space between IP and SF to allow the total space for the detector to vary from 41 m to 180 m. This was achieved by a simple change of configuration of the final focus quadrupoles, with no effect on the configuration of the tuning section (except for a slight change in the range of tuning gradients). There was an optimum phase advance between the two IPs in the cluster ((90+180 × integer) degrees), which provided compensation of the chromatic beta beat and associated second order chromatic tune shift induced by the final focus triplets. This also provided compensation of the systematic gradient errors in the identical IRs. The whole cluster had a unit transfer matrix that was thus matched to any periodical outside lattice and, because of that, did not amplify any systematic field errors in the arcs. The IR quadrupoles had 5 cm bore and maximum gradient of 191 T/m. The 5 cm bore vertical dipoles were identical to the horizontal dipoles in the arcs. Only the dipoles BV1c located next to the triplets needed the larger aperture of 8.7 cm to provide enough space for the separated beams.

A detailed description of the optical design of the interaction regions can be found in Refs. [2], [4], [7], and [14]. The local correction systems for the IR are described in Refs. [3], [4], [5], [6], [8], and [9].

IR Accelerator/Experiment Interface Issues

Activities related to detector and accelerator interface issues increased in 1992 after SDC and GEM produced conceptual design studies and the accelerator group produced a feasible basic optics design.

Radiation Backgrounds

The major subject was luminosity-induced backgrounds, their impacts on configuration and design, and possible solutions. At a luminosity of $L = 10^{33}\text{cm}^{-2}\text{s}^{-1}$ the total interaction rate was 10^8 s^{-1}, with most of the secondary particles being emitted at small angles to the beams. This background was too high for the quadrupoles close to the interaction point, so that collimators and shielding were needed. Some of the low-energy secondary particles scattered into the small angle portions of the detectors, and the neutron rates were much too high (factor of 100-1000 too high). As a result, a large amount of radiation modeling was done by the groups to determine possible solutions.

By the summer of 1993, the outlines of solutions for both SDC and GEM were clear, at least from a radiation physics perspective. A collimator with approximately 25 mm diameter was needed close to the QL1 quadrupoles to protect them from the luminosity-induced particles.

Given the state of knowledge then current, the radiation damage lifetime of the quadrupoles would have been a few years at $L=10^{33}$ $cm^{-2}s^{-1}$. The collimators and the quadrupoles in the detector halls had to be well shielded (~1 m of iron and concrete) to prevent low-energy particles from being scattered back into the detectors. More shielding had to be added at small angles inside the detectors.

For SDC the proposed solution required changing L* to 25 m. For GEM the corresponding value of L* was 34.5 m. The larger distance in the case of GEM was due to a desire to axially move certain portions of the detector relatively easily for repairs during the initial operation. The peak luminosity decrease would have been ~7% for SDC and 20% for GEM owing to the increases in L*. Engineering design work on the implications of these solutions started in the summer of 1993, but it had not progressed very far before project termination.

Parametric predictions were made of the beam-gas background rates in the detectors. At $10^{33}cm^{-2}s^{-1}$ luminosity, the beam-gas rates were small compared to those from the interactions (less than 10% at hydrogen pressures of 10^{-8} torr). No calculations had yet been made for various other sources of backgrounds (injection mode, emittance growth and low-beta quadrupoles, beam perturbations, etc.). Some significant modeling was performed on feasible, and useful, locations of various scrapers and collimators in the whole Collider, but much more remained to be done. The inner tracking chambers of SDC were very sensitive to beam losses: radiation damage problems might have been severe.

Quadrupole Supports

Another problem strongly coupled to the background one was that of mechanical supports for the low-beta quadrupoles, which started nominally at 20 m (actually 25 m and 34.5 m) from the interaction point and were 7 m high for SDC and 13 m high for GEM. The supports were a major task because of the sensitivity of the quadrupoles to vibrations related to the large beam beta-values (up to 9 km) in these quadrupoles, the height of the supports above the floor, and the large mass of shielding (several thousand tons) that had to surround the quadrupoles. The shielding, supports, and quadrupoles had to be removable to permit major changes and major repairs for SDC and GEM. A conceptual design was initiated, using LLNL's resources for finite element analyses, but it had not progressed very far before project termination.

Neutral Beam Dumps

The "neutral beams" emitted from the interaction points during collisions were significant in the Collider. At $L=10^{33}cm^{-2}s^{-1}$, the predicted power was approximately 70 W in each direction, and it was very tightly peaked along each beam. A neutral beam dump was needed beyond the first bending magnet (BV1C) to catch the neutral particles. Initial estimates required an iron cylinder of approximately 3 m in length and 1 m in radius to absorb the neutral beam and keep the ground water induced activity below the proposed levels. Both proton beams had to traverse the dump, and it was expected that the dump would have appreciable radioactivity induced in its central region. Some experimenters showed interest in using part of this neutral beam as a luminosity monitor.

Accelerator/Experiment Radiation Studies

(N. Mokhov)

Comprehensive studies were performed on beam induced energy deposition, radiation effects, and particle background in the interaction regions.[16-21] The newest version of DTUJET93 code was used to simulate 20 × 20 TeV pp-interactions. Hadronic and electromagnetic cascades along with neutron transport down to 0.5 eV in the IR and detector components, tunnels, and experimental halls were simulated with MARS12 Monte Carlo code. The latest lattice and magnet parameters (including overall 3-D geometry, materials, and magnetic field maps), all important SDC and GEM detector details in the near-beam region, and tunnel and experimental hall geometry and materials had been taken into account. Full-scale calculations and optimizations were performed for ±20.5, 25, 35, and 90 m detector free spaces.

The main issues were as follows: A fixed aperture collimator was required on each side of the interaction point (IP) just in front of the first low-β quadrupole to protect the final focus triplet from the intense radiation from the IP. As a result of optimization studies, a 3-meter long steel collimator with a 25 mm diameter aperture was chosen. The collimator was surrounded with 0.75 m thick steel shielding (for protection of ground water), followed by about 1-meter thick concrete shielding. The shielding extended from the forward calorimeter to the first quadrupole, and it protected the detector against low energy neutrons. The collimator significantly reduced the peak energy deposition in quadrupoles (to about 10 times less than quench limit), accumulated dose (~ 200 Mrad/yr), and heat load to QL1 cryo system (~30 Watts). The neutron and photon flux in the detector from hadronic showers in the collimators was a weak function of the collimator location for a 20 to 35-m region.

A full-scale simulation was performed to study hadron, muon, and low energy neutron fluxes at SDC and GEM detectors due to beam-gas interactions in the IRs and local beam loss at collimators and in the beta-peak region. In most cases, this contribution did not exceed a few percentage points. To protect the final focus triplet quadrupoles, vertical splitter dipoles, and other IR components against radiation from the interaction points and from the rest of the machine, a set of additional collimators was needed. The set for the East IRs at termination consisted of 10 collimators with movable jaws. Optimal jaw position was 20 σ from the circulating beam axis. The collimators intercepted high energy protons (mainly diffractive) produced in beam interactions all around the machine and secondaries produced in beam-gas interactions. Collimators positioned downstream of the common vertical magnets intercepted most of the secondaries from the IP. A collimator was also placed in the middle of the hinge region at a non-zero dispersion point.

About 25% of the energy in 20 × 20 TeV pp-collisions was carried by neutrals (mainly neutrons and gammas) and had to be absorbed in the straight forward direction downstream of the IP. The appropriate beam dumps had been designed and positioned at about 182 meters on each side of the IPs. The appropriate shielding in and above the experimental halls, in access shafts, and around all the collimators and neutral beam dumps had been designed to satisfy the SSC radiation control requirements on prompt and residual radiation (ground water, air, and coolants).

Superconducting Magnets for the IRs

Requirements

The requirements can be set forth most efficiently in the two following tables.

Table 9-1. Quadrupole Inventory for 4 Interaction Regions and 2 Hinges.

Quad	N	Lm	Ls	G	Db	Di	Do	W	Comment
CQM	24	5.350	6.240	201.0	40.9	50.0	276.2	4.31	
QS1	8	6.312	7.202	201.0	40.9	50.0	276.2	5.02	
QL-4,-9	32	10.200	11.090	193.8	40.9	50.0	276.2	7.86	
QL-5,-6,-8	64	8.000	8.890	193.8	40.9	50.0	276.2	6.25	
QL-7	16	8.600	9.490	193.8	40.9	50.0	276.2	6.69	
QL-3	8	13.172	14.062	193.8	40.9	50.0	276.2	10.04	
QL-2	16	11.855	12.745	193.8	40.9	50.0	276.2	9.08	
QL-1	8	15.565	16.455	193.8	40.9	50.0	276.2	11.79	
QV	128	8.000	8.890	193.8	40.9	50.0	276.2	6.25	2-in-1
Total	304	2,598.5	2,869.0						

Table 9-2. Dipole Inventory for 4 Interaction Regions and 2 Hinges.

Bend	N	Lm	Ls	B	Db	Di	Do	W	Comment
B	80	14.928	15.815	6.790	40.9	50.0	339.7	18.45	
BS, BV-2	96	12.440	13.330	6.790	40.9	50.0	339.7	15.49	32 BV-2 2-in-1
BV-1	16	14.928	15.815	6.790	40.9	50.0	339.7	18.45	2-in-1
BV-1c	8	15.838	16.725	6.400	70.0	87.0	482.7	30.66	
Total	200	2,754.0	2,931.7						

Key:
- N = Number of magnets
- Lm = Magnetic length (m)
- Ls = Slot length (m)
- G = Max. Gradient (T/m)
- B = Max. field strength (T)
- Db = Beam-tube bore dia. (mm)
- Di = Coil inner dia. (mm)
- Do = Cold-mass outer dia. (mm)
- W = Weight (tonne)

Weight of 2-in-1=twice W

Development Program

QSE Program

The QSE program objectives were to produce short model magnets, 50 mm bore, of high field quality to meet the IR quadrupole field gradient listed above, with a coil insulation system that would withstand a total radiation dose of 10^7 Gray. QSE-101 through -103 were built, and QSE-101 and -102 were tested and the results were reported. QSE-104 was at an advanced stage of assembly. The coils for QSE-105 had been wound. There were no unresolved technical issues relating to the QSEs at project's end.

QCE Program

The QCE program was directed at producing a developmental 50 mm bore, 15 m long quadrupole magnet, with the radiation resistance, field quality, and heat-removal capability required of an IR quad, e.g., QL-1. Its Design Review is documented. The cold-mass design of QCE-101 was complete, had been reviewed, and was documented. Two of the four coils had been wound.

QL-9 Program

The QL-9 program was a follow-on to QCE-101, to produce a prototype, tunnel-ready quadrupole, as a demonstration of manufacturing capability at MDL, and to allow an assessment of the field quality for the quadrupole series QL-9 through QL-4. Both magnet and tooling design were begun, but no cryostat design had started.

BV-1c Program

BV-1c was the beam-separating 87 mm bore dipole at each end of the single-beam-tube section of an Interaction Region. It was a unique, large-bore dipole. The magnet and tooling design was only about half done.

2-in-1 Cryostats

A minimal amount of work had been done on the 2-in-1 region of the Interaction Regions (where the beam separation was 45 cm, and two magnet cold-masses were mounted, one above the other, in a single cryostat). The cold masses, whether dipole or quadrupole, were to be standard 50 mm bore Collider units. Thus the design requirement was to produce a support system within a large cryostat.

Power Supplies

The power system for the IR comprised several subsystems. The systems most studied were the power bus and the power converter systems. The overall control system to coordinate the power converters had not yet been studied as the project ended. The power bus for the IR was envisioned to be constructed of 500 MCM and 1000 MCM cables. Paralleling of cables was to be the method for supplying the higher current magnets. Estimated cable power losses were calculated for both surface and subsurface installation.

The power converters for the IR ranged in current from 300 A to 7000 A. For the magnet configuration chosen, the following converters were needed: 8 each @ 7000 amps, 40 each @ 2000 amps, and 28 each @ 300 amps. The voltage requirements for these power supplies was on the order of 5 to 10 volts. These values were chosen to minimize bus power and thus tunnel heating.

The power configuration for the IR was different from other Collider power systems. In the IR region, the focusing quads were powered by the main sector bus with the above power supplies connected in parallel with the magnets. By shunting current of the proper sign through the magnets, currents were derived for the desired beta function, which allowed for a much smaller dynamic power supply current range and hence smaller currents. Magnet QL8 was the exception, requiring a full 6000 amp dynamic range. This quad was fed by its own resistive bus.

Ground Motion

Ground-motion spectra drop sharply as frequency increases, so that micro-seismic and man-made ground motion are usually not important for small accelerators with large revolution frequencies. The Collider had a low revolution frequency (3.4 kHz), a large number of revolutions (10^8), and very little damping (because the effects of synchrotron radiation are small), so that ground motion frequencies as low as 1 kHz could resonantly excite betatron oscillations of the beams and increase the beam emittance.

Predictions of allowable ground-motion[22–34] and measurements (1993) made at a depth of 67 m in the exploratory shaft near IR1 are compared in Figure 9-2. The measurements have two conditions: "quiet" and "noisy." Quiet spectra were obtained when no construction activities were occurring on the SSC site (e.g., nights, weekends, holidays), and noisy spectra when construction activities were in progress (e.g., TBM's operating, active vehicular traffic). The model assumed 20 TeV energy, $\beta^* = 0.5$ m, and two interaction points, and it required the emittance growth to be less than 20% in 20 hours ($dE/dt < 2.8 \times 10^{-12}$ m/s). The model was sensitive to the fractional part of the tune; tunes of 0.28 and 0.4 are shown. Rigid body quadrupoles with no dynamic amplification due to supports was assumed.

An important issue in the ground motion studies was mechanical resonance of the magnet supports. If such a resonance was located in the frequency region where the magnet could resonate with the beam, the deleterious effects of the ground motion would be amplified. On the other hand, the relevant wavelengths were sufficiently short that some averaging occurred over the length of a long SSC magnet. The design of the magnet supports was to take these considerations into account, but analytical work on these aspects had not been completed as the project ended. The tentative conclusions were that this issue was amenable to solution provided that "quiet" ground-motion conditions were achieved.

Unresolved issues included tolerance, power supply, magnet, and cryogenic matters. Radiation and operational issues also surfaced. The optical & tolerance issues were: (1) The good field aperture of the final focus triplet was barely acceptable. The aperture could be increased through the use of correction coils, but a strategy for doing this had not been developed. At low values of β^* the off axis motion of the beam through the final focus quadrupoles introduced coupling that was too strong to be corrected outside of the final focus region. The need to correct individual final focus quadrupoles for sextupole errors had been identified. (2) Orbit correction methods which took into account the simultaneous presence of two beams in the final focus region were not established. (3) It was clear that tuning the Collider to a β^* configuration would be a difficult operation. An operational simulation of the process which took into account the expected errors in quadrupole gradients was planned but not completed.

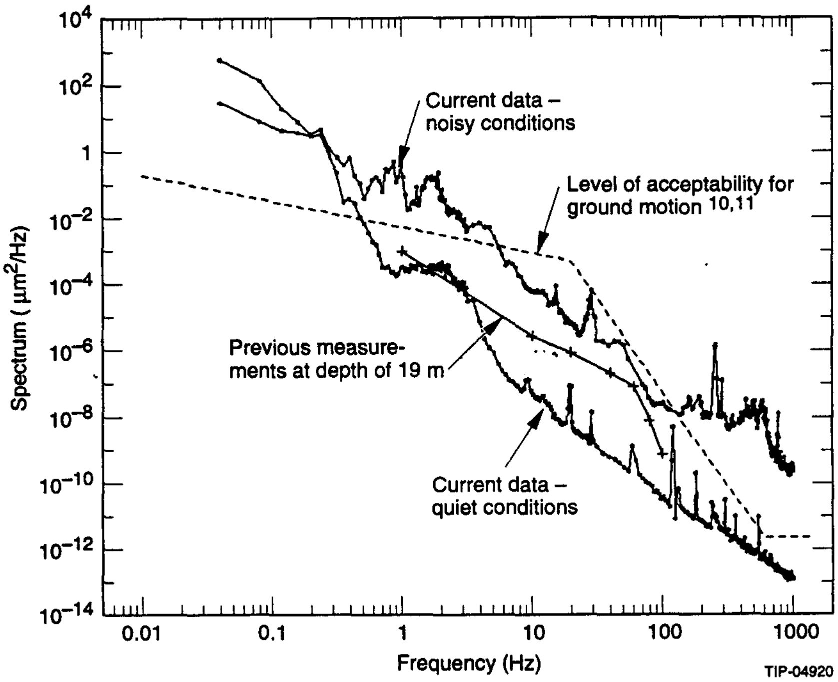

Figure 9-2. Ground Motion.

Power supply issues included: The beta squeeze was to be made by adjusting the current in six quadrupoles in the zoom section of each beam on each side of each IR. Adjustable power for accomplishing the squeeze was to be provided by shunting current from the main ring bus around zoom section quadrupoles with active two quadrant power supplies. Work to establish that the main power supply was stable in this configuration was started but not finished. Magnet, cryogenic, and mechanical issues were: (1) The specifications called for a remote positioning (and rotating) system for the final focus quadrupoles. The mechanical implications for accomplishing this in a superconducting magnet system were not fully evaluated. (2) A practical design for a two-in-one cryostat/magnet was never completed; and (3) The refrigerator capacity assigned to the interaction regions was inadequate, and the inadequacy was driving excessively tight heat load tolerances for IR components.

Radiation and background issues were: (1) A practical design for the neutral beam dump was not completed. (2) The large energy deposition in the final focus quadrupoles imposed unique cooling requirements on the magnets. Tests were still needed to establish the adequacy of the magnet design. (3) Detector backgrounds and their relationship to collimator arrangements were not investigated in sufficient depth. An evaluation of the sensitivity of the detector trigger system to various types of background had not been made. Operational issues included: The implications of having to remove some of the final focus quadrupoles to gain access to the detectors were not fully appreciated. The configuration for the IR halls was adopted without sufficient consideration of its impact on accelerator operations. The issue was complicated by the later understanding that vast amounts of shielding would have to be placed around the final focus quadrupoles.

Chapter 10. Global Accelerator Systems

(T. Elioff)

Global Systems included specific construction items in the accelerator chain that were common to all the machines, such as control systems, intermachine communications, common installation requirements, and overall radiation monitoring. In the construction phase, one of the responsibilities of the Global Systems staff was to ensure that future accelerator operations would not compromised by design features or design changes. Following the construction phase, the responsibilities extended into conducting the operational readiness reviews prior to permission for beam turn-on in any of the accelerators. Through the management of pre-operations tasks, a timely transition from construction to operations was to be assured. Once a machine was deemed fully operational, it was to move under the auspices of a separate division organization that was being established.

To perform these functions, the Global Systems Department was organized around specific groups: the West Site Operations Office, the East Site Operations Office (just being formed), the Global Controls Machine Group, the Civil Infrastructure Machine Group (under consideration), the Global Simulations Group, the Machine Simulations Group, the Radiation Monitoring and Shielding Group, the Machine Installation Group, and the Machine Alignment Group.

The site offices acted as liaison among the various machine and detector groups and the organizations performing the civil and infrastructure construction on the site. These offices had responsibilities for monitoring construction activities. They also performed ES&H functions on the site for the Project Management Office and provided liaison with the support personnel responsible for building and infrastructure maintenance. It was expected that many of the Accelerator Operations Division activities would grow near to and out of the site offices.

Global Machine Controls Group

The missions of the Global Machine Controls Group are summarized in the following nine activities: (1) Review the appropriate global controls schedules and budgets; (2) Provide global controls specifications (level 3A) to the appropriate groups in ASD, namely, Controls (both beam related and process controls), Personnel Access Safety System (PASS), and Beam Instrumentation; (3) Review interface requirements for the Energy Monitoring and Control System (EMCS), Supervisory Control and Data Acquisition (SCADA), and Emergency systems for CCD with regard to their impact on the availability of data to a central control area; (4) Specify and review interface requirements for the detector and test beam systems with regard to their impact on the availability of data to a central control area; (5) Develop machine operational strategies that would affect global machine specifications, such as inter-machine synchronization, power requirements, etc.; (6) Develop a global systems definition for the functionality and interaction of the machine components; (7) Specify global database requirements and machine component naming conventions; (8) Specify and coordinate control room activities; and (9) Develop guidelines and procedures for control and monitoring applications programs.

Naming Conventions

The Device Naming Committee was created to devise a standard mnemonic way to refer to the equipment in the various accelerators making up the SSC accelerator chain. Members of the committee reflected several of the diverse viewpoints of those building the accelerator complex, including members of the various machine groups, the installation team, the controls department, the lattice database group, and project management. The Committee met regularly, inviting members from other machine groups and accelerator systems departments to assemble a naming scheme that would address their respective needs and concerns. A document[1] was produced and programs written to transform the lattice databases into lists of names, which were used for communications with installation contractors, for entry into the Collider component database, and for general drawing identification.

Machine Physics Design Support

The Accelerator Physics Group concentrated their efforts in four areas: Beam Optics (mainly for the Collider), Beam Dynamics (for all five accelerators), Code Development, and support of Task Forces. The Accelerator Physics Group also supported the Liner Design Task Force, the Impedance Committee, and the Error and Emittance Committee. The Beam Optics efforts were focused on four subjects: lattice design for missing magnets in the Collider arcs, IR optics, chromaticity correction, and decoupling.

Beam Dynamics studies for each machine included long-term tracking studies and longitudinal dynamics. Noise effects from a variety of sources such as power supply ripple, RF noise, and ground motion were studied. Impedance calculations were performed, and variable bunch spacing was studied. Machine parameter spread sheets were produced. Magnetic field studies were undertaken, and feed back systems were modeled. Synchrotron radiation studies were ongoing, and bent crystal extraction was explored. Beam dynamics codes were tested in machine experiments at the Indiana University Cyclotron Facility (IUCF). Code development work continued on several fronts. Improvements were made on SYNCH and TEAPOT. New codes under development were ZLIB, BPERM, and a 1-D diffusion code. Support was also provided for object oriented C++ programming.

Machine Simulation

There were four basic machine simulation tasks. These were: (1) Simulation of accelerator performance and the performance of design trade-off studies, as requested by the machine leaders, (2) Development and maintenance of computer codes and resources necessary to perform simulation calculations, (3) Generation of high-level beam control code to optimize performance of the operating accelerator chain, and (4) Development and maintenance of the lattice database.

The simulation performance task concentrated on the Collider and interaction region design efforts. Notable achievements included simulation of decoupling operations, studies of steering corrector failures and strength reduction options, and simulations of effects of higher order multipole fields on dynamic aperture. Strong chromatic effects in the interaction region were modeled along with their correction procedures. The computer code used to do these studies was TEAPOT and its derivatives. The code was extended to run on other platforms, and new functionality was added. A real time simulator code was developed that ran on the massively parallel hypercube system and incorporated real time control hardware and software modules.

Several high-level beam control code modules were written for the LEB. They included closed orbit correction modules, first turn procedures, and tune adjustment modules. They were developed using the real time simulator mentioned above. The SSC Lattice database maintained an historical and precise description of each accelerator design in the SSC complex. The design work itself was performed by the physicists in the various machine groups. Whenever a major design or design change was approved, the lattice description would be handed to lattice database personnel for entry into the database system. The system was maintained in a commercial relational database management system. The structural definition of the table in the lattice database as well as the principal application codes that accessed the database are documented in the Loosely Associated Modules for Beam Design and Analysis (LAMBDA) collaboration software package.

Shielding and Radiation Effects Studies

During the project's final year, significant progress was made on the Radiation Control Manual. Additional work proceeded on the Review and Self-Assessment Program and the As Low as Reasonably Achievable (ALARA) Policies. Design Requirements for Shielding and Access were studied with major emphasis on the Linac. Specifications for several categories of monitoring equipment were created, and an associated training program was been established.

Control Center Facilities

The SSC Conceptual Design Report of March 1986 envisioned a central campus area for key laboratory functions. A central laboratory building within the campus was to house most of the professional and administrative staff. It was planned that this building would also house the main control center for the entire accelerator complex. The SCDR of July 1990 continued with this concept, projecting a 23,000 sq ft operations center that would be an integral part of the campus buildings. The control center was to be in close proximity to the offices, laboratories, and shop facilities of the campus. A visitors' gallery and display area were also planned for the center. It was expected that the central campus facilities would be constructed on a timely basis, not only to provide for overall staffing needs, but also to assure the availability of control facilities for all accelerators.

The acquisition of the Central Facility building in Waxahachie in 1991 provided interim offices for 1000 people as well as shop, assembly, and storage facilities. The immediate need for the central campus facilities was diminished, and schedule delays of more than three years were anticipated for the campus. As a result, the Laboratory was without a plan for providing a control center for operation of the accelerators on a timely basis consistent with start-up activities. Schedules in FY92 projected pre-operations for the Linac in FY95; therefore, associated Linac control facilities would be needed in early FY94. The proposed alternative was to provide temporary facilities that would be marginally adequate and would involve additional costs. Plans for a temporary control room for the Linac were made in FY91 and FY92. The temporary facility was to provide for the control room, associated infrastructure, and office/workspace for operators and technicians. In the final plan, this was accomplished by one 18 ft × 60 ft and two 28 ft × 60 ft prefabricated modules.

In early FY93, the Laboratory Director specified that the main control room building should house not only the controls for the accelerator systems, but also those for the detectors and for all emergency response needs. This arrangement was to have the advantage of facilitating information exchange by direct, face-to-face contact of all appropriate personnel when decisions affecting running modes or emergency situations were to be made. While a central campus area was still envisioned, its location was no longer tied to the Linac or any other accelerator.

Moshe Safdie and Associates were engaged by the SSCL Director to provide a new conceptual design for the campus and to investigate various feasible locations. In December 1992, Safdie presented three siting options, each of which would be anchored on the accelerator operations center. All three located the campus south of the Injector, along the stream that runs south from the LEB. One site was south of the Linac, in close proximity to the Test Beam Facility and IR1. The second was south of this, just north of the Industrial Road. The third site was south of the Industrial Road on the west side of the stream, which would be dammed to form a cascade of lakes in that location. Given the constraints involved in the proximity of IR1 and the extension of the Test Beams in the first two siting arrangements, there seemed to be a consensus favoring the third site.

There was general agreement that construction of the control facility with reference to an identified site for the campus would serve to focus the design of the campus. A decision on the site for the campus was needed before the end of January 1993 to allow the control facility to go ahead at least in time for commissioning the LEB. The schedule for an operational control facility was October 1994, which was determined by the schedule for testing the LEB power supplies.

While M. Safdie and Associates were developing the siting options and an overall plan[2] for the campus, a number of task forces were set up to address the needs of the accelerator controls group, the SDC and GEM detector groups, and other functions such as emergency response. The task forces, with coordination by CCD, provided the general specifications of the control center. Consistent with the CDR and SCDR concepts, the SSC Control Center would be a 24-hour/day staffed operations complex that would house monitoring and control functions for the injection accelerators, test beams, the Collider, and the experimental detector systems. It would also be the operations control center for the cryogenic plants and other associated technical systems required by the accelerators and the detectors, and for access control to all the technical facilities.

The facility would serve as the nerve center for the monitoring and control of all conventional systems (power, water, communications, etc.) of the Laboratory as well as those specific to the accelerator complex. Since it would be occupied 24 hours/day, the center would be the primary office and dispatch point for emergency services including fire-protection, security, and radiation control. The center would also be the coordination point for repair and/or maintenance of technical components and associated facilities. An analysis of the manpower requirements for all the functions of accelerator operations, detector operations, and other monitoring and service functions indicated that the center would house a staff of ~150 people during day-shift operations.

The results of the above studies were incorporated into a draft Design Requirements Document.[3] The control center building required about 30,000 sq ft of floor space. The conceptual layout of the main control room called for a large circular control panel similar to that of the ZGS at ANL. One hemisphere was allocated to the accelerators, while the other was divided in half and assigned to each major detector. The control area could be viewed from an above visitor's gallery that was also to house a museum/demonstration area. A very important consideration in the design of the building was that it should allow for possible future expansion. A sketch illustrating the control center requirements is provided in Figure 10-1.

The preliminary cost estimate[4] was about $6.75M which included a large allowance for conventional cooling necessitated by "open" designs for the building with large window expanses based on the architectural language specified. The M. Safdie design placed the building on a bridge in the middle of a lake. Among the issues to be addressed before final decisions about the design and location were made were: access required for operations in terms of personnel, vehicles, or technical infrastructure, and the costs of possible future expansion. A final decision on the design and location was never made.

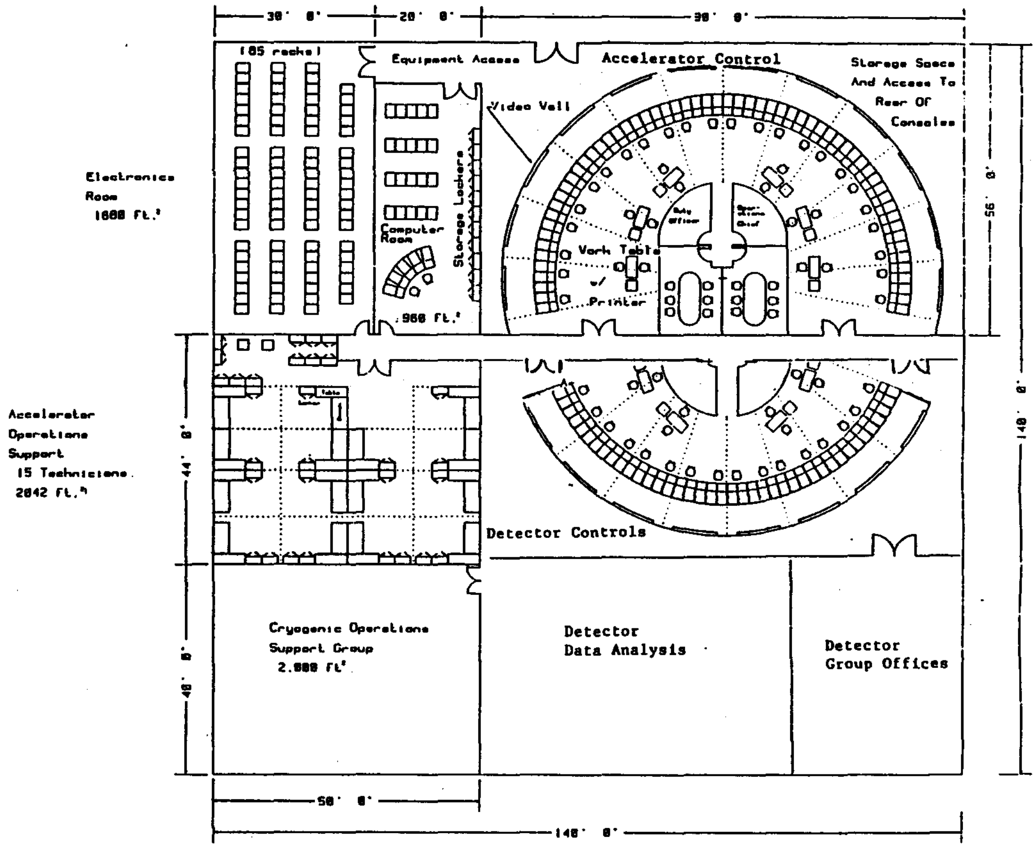

Figure 10-1. SSC Control Center.

Chapter 11. Component Installation

(F. Spinos and B. Kling)

Baseline Installation

Experience at various national laboratories provided precedent for installation planning. Baselines were established that assumed that each separate discipline within the Lab would design, develop, procure materials, and subcontract for the installation labor required to augment the Lab staff in the physical installation effort. The budgets were thus estimated and disseminated throughout the various groups at the SSCL.

Installation Program, Revised

The installation approach was revised as it became clear that the effort was sufficiently large, in both effort and dollar value, to represent a significant part of the program. SSCL determined that cooperation with industry would be the key to a successful program and that only major corporations would have the depth of technical skills, financial resources, and facilities to manage a program of the scope and complexity of the SSC installation.

There were three compelling reasons for selecting only major industrial organizations. First, the varied resource pool would be resident in the selected organizations. Skills ranging from program management to warehouse control would be required, and the availability of large numbers of experienced personnel in each skill category would be especially important. Second, there would not be time for the selected subcontractor to hire, train, and develop a task team from the open market from the point of contract award to the beginning of critical path activity. The third reason was the ability of the subcontractor to fund both the costs of a major proposal and the initial start up costs. The definition of a major subcontractor was never intended as a barrier to companies of lesser size. Specific instructions were provided to the bidders that defined the goals as they applied to small, disadvantaged businesses as well as minority and women owned businesses. Teaming with other small or medium sized businesses was also encouraged.

Implementation of the Solicitation

The Commerce Business Daily notice was posted late in 1991, inviting industrial contractors to participate in the installation program. Approximately 40 industrial concerns attended the bidder's conference. The program included all the installation activities for the Linac, LEB, MEB, HEB, and the Collider, even though some of the ring configurations were not yet fully defined. The solicitation indicated that the SSCL would award two to four study subcontract awards of five hundred thousand dollars each, during which the subcontractors would receive a thorough technology transfer.

Initial Subcontractor Selection

Four proposals were received in answer to the solicitation. Three were accepted by the SSCL based on evaluation criteria scoring. The selected subcontractors were: Bechtel International Corporation, Brown and Root Corporation, and Martin Marietta Corporation. Subtier contractors to the three prime subcontractors noted above included General Dynamics, Westinghouse, Lockheed, Science Applications International, Belding, University of Texas at El Paso, and FATA Automation.

Phase I Report/Presentation

After four months of work by each subcontractor, a fifth and final month was devoted to the preparation of the final subcontractor reports and presentations to SSCL and DOE personnel. The purpose of the presentation was to provide each subcontractor with the opportunity to describe its preferred installation process. However, each subcontractor had reservations about divulging all of its program developments for fear that the information would be of use to its competition. Those reservations resulted in presentations that gave the impression that the propositions were not well thought out, when in reality the missing information was intentionally omitted. Evaluations of all three subcontractors presentations were essentially the same, ranging from poor to barely acceptable. There were, however, some bright spots in each of the presentations and reports, and each report contained at least one item that was well addressed.

Bridge Task Activity

Soon after the end of the Phase I work, it became obvious that there would be some delay in the issuance of the second phase solicitation for the actual installation of the components. This led to the implementation of a "Bridge Task" program, which was designed to refine further the specifics of the installation program. The refinements provided ongoing funded tasks for the subcontractors to amplify the requirements of specific technical systems. The tasks assigned were: (1) the further development of data bases; (2) a more specific set of requirements for the tunnel transportation system; (3) preparation of cable definitions; (4) a specific plan for receiving and handling materials being received from overseas suppliers; and (5) the design of a magnet stand for the MEB dipole magnets.

The formal reports and presentations that were scheduled at the end of a two-month performance period were given to the SSCL, DOE, and the other two installation subcontractors. This resulted in a further leveling of the competitive field because considerably more detail was included in each bridge task. The results of the bridge tasks were incorporated into the Phase II Installation Solicitation that was to be released for bid in the first quarter of 1993.

Additional Bridge Task Definition

The SSCL Installation group continued the planning for the installation task under the assumption that the program delays would require that certain of the installations be accomplished without the assistance of the prospective subcontractors. The Laboratory chose to subcontract additional tasks to the prospective installation subcontractors rather than staffing the jobs with SSCL employees.

Aside from the obvious goal of accomplishing specific required tasks, the additional bridge tasks permitted a continuance of involvement of key individuals from each of the subcontractors and prevented a full stoppage of work on their part because of limitations of funds. All three Phase I installation subcontractors agreed to participate in the additional bridge tasks as a group rather than be assigned individual tasks. Each felt that it would be better served by participating in all the activities rather than being restricted in scope.

Solicitation Preparation

The Request for Proposal had been in the modification stage for some months. The amount of detail had grown, which permitted the solicitation to be more definitive and provide a better evaluation of the proposals to be accomplished by the review team. In late October 1993, however, the program came to a close with project termination.

Significant Accomplishments

The design of the Collider required that the counter rotating beam lines be placed one above the other. Additional requirements of the Collider 3B specification, E10-000027, specified six degrees of freedom for each of the magnets and spools with a tight alignment tolerance. A support system was designed that met all the 3B specification requirements. An additional feature of the support system was the adaptability to remote alignment adjustment. At project close, studies were in progress to use the remote adjustment capability to eliminate the need for corrector magnets.

Utilization of 3D Graphics for Complex Installations

Underground installations are unique in that the dimensions of the underground chambers have very large tolerances, generally in inches. In the case of accelerators within a tunnel, the tunnel centerline and the beam line centerline are independent, which accentuates the difficulty in placing components. Three-dimensional computer graphics that incorporate an interference check capability were used to model the Collider tunnel niches. Civil construction drawing files were electronically transferred as a basis for the 3D views. Two-dimensional mechanical drawings of components were then placed within the civil drawings using the cartesian coordinates for each part. An engineering report described the process along with lists of found interferences.

Definition of an Integrated Tunnel Communications System

Both the CDR[1] and the Collider 3B[2] specification required a tunnel communication system for safety monitoring during the installation phase. The installation subcontractor[3] was tasked with evaluation and cost estimation for such a communication[4] system. Tunnel personnel communications was to be accomplished utilizing a RF radiating cable system providing continuous broad band RF transmission. The minimum system design[5] was to provide for voice frequency communications using multi-site repeater/base station technology for the hand-held personal/portable radio user, and wireless data communication technology using radio frequency base stations.

Development of an Installation Relational Data Base

The subcontractor was charged with the task of implementing a system of graphical representations already in place for the Collider arc sections for the remaining machines elements starting with the Linac. The resulting system would be in a relational database[6] format that would interact with elements of the SSCL database system already in use at the time. In addition to this database, an optical fiber and component interface pull list[7] was to be developed. The software selected to perform this function was SETROUTE by Bechtel Corporation.
Definition of a Tunnel Transport System

Logistical support within the various tunnels during the installation phase relied heavily on the mobility of crews and associated hardware. A subcontractor[8] study for an installation transport systems identified conceptually those piece of hardware required for each machine element and provided analyses for types of power systems.

Chapter 12. Controls

(D. Gurd)

Control System requirements and issues related to the SSC complex of accelerators are not inherently different from those of other large accelerator laboratories, although some special problems result from the large number of control points involved (> 400,000),[1] the large distances between the various components (up to approximately 100 km), and the very high reliability required (98.6% availability for the global control system).[2]

Requirements can be reduced to two broad categories: equipment control and beam control. Equipment control is primarily of interest to equipment engineers and operators during commissioning and maintenance periods, and is intended to facilitate these operations. The view of the accelerator provided is of equipment and of subsystems. Performance of equipment, modules and components is reported to the control system user in engineering terms—volts, amperes, flows, temperatures, etc. Faults are identified and diagnoses suggested. Equipment control frequently requires some degree of local control (in proximity to the equipment). Equipment control provides the necessary underlying infrastructure on which is built beam control.

Beam control is the view of the accelerator appropriate for commissioning, improving and monitoring the quality of the beam for accelerator physicists and operators during commissioning, development, and routine operation. The view of the accelerator is reported in high level accelerator physics terms such as tune, chromaticity, emittance, etc. "Knobs" may also be required to adjust these higher level abstractions. Beam control must generally be done from a central location (the main control room) in order to provide the necessary global views. Beam control is derived from equipment control, and the higher level concepts may be thought of as "virtual devices."

A primary role of the global accelerator control system is integrational. The system has first to integrate the various technical subsystems (cryogenics, power systems, RF, vacuum, timing, beam instrumentation, etc.) into operating accelerators; and then to integrate the chain of six accelerators into a smoothly operating single facility. High level requirements for the Global Accelerator Control System are given in the Global Accelerator Controls Specification Level 3B[(3)] and the Global Control System Requirements Specification Level 4[(3)] both of which exist only in draft form.

Organization

The Accelerator Controls Department was responsible for the design, implementation, installation, and commissioning of all control systems for each of the accelerators in the chain making up the SSC. This included the global hardware, software and communications infrastructure as well as interfaces to beam instrumentation, timing, magnet power (main ring magnets, correctors, kickers), and RF systems. It did not include any control system related to detectors; or to the process control systems for buildings, energy management, HVAC, or industrial water systems.

The Specification Tree was organized by machine, with a control system element for each accelerator of the SSC chain. In addition, it included a branch under Global Accelerator Systems which was uneuphemistically called GACS - Global Accelerator Control Systems, intended to cover systems common to all machines. However, in order to optimize the use of individual skills and to insure standard practice across all machines, the Controls Department was organized by discipline. There were five groups: Application Software and Integration, System Software, Front-End Electronics, Communications, and Process Control.

As a result of this organization, the Controls Department operated as a mini-matrix within the larger matrix-like laboratory organization, with responsible liaison people assigned to each machine, and multidisciplinary teams selected from the groups to work on machines as required. In practice, such teams were formed for work on the ASST and Linac, whereas only liaisons were ever required for the other accelerators. The controls effort for the individual machines is discussed in the sections of this report dealing with each accelerator. This section deals only with the global system.

The Specification Tree as it related to global control systems underwent several changes over the course of the project. The version of the specification tree for Global Controls finally agreed to but never formally approved included the items discussed in this report. Documentation was proceeding according to this tree.

Global Controls

Under Global Controls, the Work Breakdown Structure Dictionary specifically called out three activities: (1) Global Software (all software commonly applied), (2) Data Communications, and (3) Central Systems (e.g., Control Room consoles and servers). In addition, three other activities were identified as being global in nature: (1) Definition of hardware standards, (2) Definition of subsystem interface standards, and (3) Process Controls.

These global activities are discussed in the sections which follow. The global architecture is driven by both hardware and software requirements. The design evolves by the interplay and iteration of both hardware and software considerations. For clarity, the discussion which follows artificially separates software from hardware issues. Software is discussed first, as it must be considered more equal than other factors. The global architecture is discussed under Communications.

Software

Software common to all machines was considered Global Software. This included system and kernel software, communications software, common drivers, common services and applications (e.g., alarm handling, logging, operator displays, network monitoring, etc.), human interface software, and toolkits for software development.

In order to achieve some degree of vendor independence, it was agreed from the outset that control system software would be UNIX based. It was further felt that object oriented analysis and design methodologies should be used, and that C++ would be used wherever possible. Several possible methodologies were evaluated, and those of Rumbaugh[4] as extended for real-time by Firesmith[5] were selected. It is difficult to find a CASE tool which maps completely to any OO methodology; however, Paradigm Plus was selected as the most useful.

Software development was to be based upon a "software toolkit" or "software bus" approach. The "Integrated Scientific Toolkit" (ISTK) developed collaboratively at CERN, Fermilab, LBL, Cornell and the SSCL was initially selected.[6] This toolkit was designed specifically with accelerator controls in mind, and contains powerful tools for GUI building and for sequencing, among others. Using these tools, work began on a Global Software design.

Meanwhile, a control and data acquisition system was being developed in an ad hoc manner in support of the ER string test at Fermilab. When the string test was moved to the N15 site (ASST) new software was developed, this time combining some ISTK tools, some software ported from ER, and much newly developed data acquisition software. Deadlines were tight, corners were cut, and the software effort was considered to be completely non-prototypical. This software is discussed in Ref. [7]. At the same time as the ASST effort was getting under way, work was proceeding on the Ion Source control system, followed very quickly by other Linac segments. Because little progress had been made on a global design, another control system, TACL, developed at the Continuos Electron Beam Accelerator Facility (CEBAF) and used in several laboratories on many small projects, was used for Linac controls in the laboratory.

Disaster loomed. ISTK was advertised but not in use. Moreover, those individuals most capable of supporting ISTK had left the Department. Ad hockery ran rampant at the ASST. TACL was being used on the Linac. And there seemed no way to get out of "fire-fighting mode" to design the imagined "ideal" global software system. The advice of colleagues at an April 1992 Controls Workshop to examine the possibility of using existing software, either commercial or from another laboratory, was taken. A number of criteria were set: the software should be UNIX-based; and the software should be capable of running the earlier machines—at least the Linac—without modification. This was to help the team out of the "fire-fighting mode"; source code must be available; software developed for accelerator applications would be preferred; and DOE developed software would be preferred, in the spirit of DOE order 1330.1 enjoining DOE laboratories to share software where possible.

These criteria quickly reduced the field to two possibilities: the CEBAF-developed TACL system, and the LANL/ANL developed Experimental Physics and Industrial Control System (EPICS). TACL was already in use on the Linac, and the Controls Department had considerable TACL experience and expertise acquired from CEBAF. EPICS was also in use at the SSC, having been acquired as part of the RFQ control system, purchased from LANL. TACL was deemed to be much farther evolved at the top end, providing sophisticated graphical programming tools which EPICS lacked. EPICS was felt to be stronger and more flexible at the front end, based as it was upon a popular real-time kernel, VxWorks.[9] The underlying idea behind EPICS, called "Channel Access," and the design of the distributed database in many ways resembled the Department's ideas. The fact that EPICS was already being developed as a collaboration among DOE laboratories also seemed important, as did the expressed interest of some commercial firms in the software. It was decided to base the global system software on EPICS. EPICS is extensively described in the literature, in laboratory design notes, and in its own manuals.[10]

EPICS is a client-server system normally distributed on a LAN such as Ethernet. Clients typically run applications on UNIX workstations, and data comes from front end servers known as "Input-Output Controllers" (IOCs), running VxWorks on embedded processors. The database and front end processing is distributed among the IOCs, which may act as clients as well. Although it was felt that EPICS "out of the box" could run the Linac, (a selection criterion), the staff recognized that many changes and improvements would be required to meet the requirements of the SSC. More powerful (TACL-like) graphical tools would have to be provided to facilitate database entry and low level programming. It was decided to incorporate a nameserver and caching software into channel access to help deal with the large number (approximately 2000) of IOCs in the SSC system. The global communications architecture which had evolved in parallel with the software discussions was not directly compatible with EPICS Channel Access, although every effort was made to adapt the communications hardware so as to be transparent to EPICS.

A weakness with EPICS, as with other candidate systems considered, is the absence of higher level machine applications (Beam Control) such as are found in the mature systems at

Fermilab, SLAC and CERN. Discussions had begun towards establishing a standard high level interface to EPICS such that applications could be interfaced in a standard way. An initial successful attempt was the implementation of an LEB simulator using EPICS IOCs.[12]

The decision to base control system software development on the EPICS toolkit had a major impact on software development approaches. EPICS is not explicitly object-oriented (although many OO concepts are evident) and it is written in C, not C++. Methodologies that had been worked out earlier were required to be modified. A compromise was necessary between the rigid review and documentation procedures being required by the DOE, and the needs as perceived by the implementers. Such a compromise was devised, and a new Software Development Plan was prepared.[13] This plan insured that OO approaches would continue to be applied where possible. A number of technical peer reviews were defined, and documentation was to be kept in a series of software project notebooks. Software Requirement Specifications (SRSs) and Test Plans were written for many Linac software development projects.[14] As the collaboration grew, the need for stricter configuration management, bug tracking, and source and release control was apparent, and the SSC group took the lead in this. CVS was the mutually agreed mechanism. Following discussions and design reviews with our EPICS collaborators, the SSC Controls Department began the design and implementation of graphical database and programming tools. This work could not be completed, and has been passed on to Argonne Laboratory's Advanced Photon Source (APS) Controls Group. Preliminary documentation can be found in Ref. [16].

Communications

The Controls Department Communications Group was responsible for all aspects of data communications related to accelerator controls. Because of the long distances and high bandwidths required, and for improved noise immunity and reduced cost, it was decided that all data communication would use optical fiber. Radiation hardness was a concern from the outset, and studies were done to mitigate that concern.[17] Various approaches were considered and analyzed, and the final design for the Collider tunnel called for fiber to be laid in conduit in the concrete floor. Pull boxes would be placed in the tunnel, in line, outside of each niche (i.e., every 450 m). Pulls of this length are routine. Because of its higher bandwidth, lower losses and higher resistance to radiation, single-mode fiber would be used throughout. A description of this infrastructure can be found in Ref. [19].

The Group was also responsible for specifying fiber for other ASD communication systems, such as voice and video, personnel safety, and timing. The department would offer bandwidth and provide an interface to the controls network to other groups wishing to use the same technology, such as physics and conventional systems. Not all of these issues had been resolved at project termination.

Earlier accelerator control systems have used Local Area Networks (LANs) such as Ethernet for data communications. Recently, higher bandwidth has been achieved by using FDDI, a token passing LAN. Both the performance and the determinism of these technologies deteriorates rapidly with increasing distance and, more importantly, increasing number of nodes. For this reason it was decided instead to use a time-division-multiplexed, point-to-point technology commonly used in the telephone industry. This system would have a high-speed backbone known as SONET carrying standard T1, which would be the lowest speed interface to equipment. Data is gathered at 64 kbyte/sec rates (DS0) or less ("channelized" DS0) and then time-division-multiplexed onto standard T1 lines, and subsequently onto higher and higher bandwidth lines as required. Appropriate data streams are demultiplexed at their destinations. Multiplexing and demultiplexing is done using commercial "add drop multiplexors" (ADMs).

The advantages of this approach are evident. Because there is no contention, the system is completely deterministic and the full bandwidth can always be achieved. Equipment is commercially available, and downwards compatible upgrades can be expected from the telephone industry. Equipment is industry standard, and therefore there are multiple, competitive suppliers. Because the equipment is used in the telephone industry, it is extremely reliable. The equipment appears expensive; however, equal performance systems using LAN technology would be more so. The major disadvantage, and the one that most affects control system design, is that this system provides only point-to-point communications. Without special arrangements such as routing, which would adversely affect some of the advantages listed above, each processor cannot communicate with every other processor as is the case with conventional LANs. The system architecture was designed accordingly. A more detailed discussion of the technology, its application to SSC requirements and test results may be found in Ref. [20].

Selection of the technology influences but does not fully determine the architecture. The first architecture considered reversed recent trends by proposing a highly centralized system in which data gathered in unintelligent front end modules would be transported over SONET to a central "reflective memory," which could then be accessed directly (like local, virtual memory) by central processors running applications. Data would be constantly updated in this memory, whether it was required or not, and would always be current. A description of this proposal can be found in Ref. [21]. Such a system is said to be "data driven," and there have been successful applications of this idea in both the accelerator and industrial worlds. Commercial reflective memory systems are available, although not using SONET as a transport mechanism.

The very large amount of data generated by SSC front end equipment, especially beam instrumentation modules, would have required a memory far larger than is presently commercially available. In addition, problems related to the synchronization of rotating buffers so that analysis of beam data related to the same turn or bunch appeared very difficult to resolve. The advice of colleagues from other accelerators, given at the April 1992 Controls Workshop,[22] was to drop the reflective memory idea, and hope for only "one miracle," —the success of the choice of SONET!

This advice, coupled with the decision to use EPICS software, resulted in the adoption of a far more conservative and conventionally distributed design, with intelligence throughout the system. This architecture is described in Ref. [23]. Front End equipment (interfaces to all accelerator devices) is distributed in approximately 2000 VME or VXI crates, each of which contains a processor (the IOC) providing local intelligence. In addition to the IOC, each crate must contain an interface to the communications network. Software was written and tested for a commercial T1 communications interface;[24] however, a newer, lower cost interface, packaged on an Industry Pack (IP), had also been built and tested. This would be mounted on each IOC board. The IOC would then be used for communications as well as for its other tasks, reducing by half the number of processor boards necessary. The communications module software, the IP design, and test results are documented in Ref. [25]. To provide full TCP support (and hence transparency to EPICS), a dedicated broadcast channel was provided in addition to the standard PPP (point-to-point) links. A "directed broadcast" capability was included to accommodate the large number of IOCs in the SSC system. Availability requirements coupled with the criticality of network integrity necessitated detailed network monitoring. SNMP was to be used for this task. An SSC Management Information Base (MIB) including remote reboot capabilities had been designed and tested. Results of this work are documented in Ref. [26].

Responsibility for the SSC timing system was shared between the Controls Department Communications Group and the ASD Beam Instrumentation Department. Neither the timing system design, nor even its requirements had been fully worked out and agreed upon. A preliminary specification was being prepared. One possible implementation included a "dumb" precision timing system and an intelligent "Message Broadcast System." A prototype Message Broadcast receiver had been designed and implemented in IP format.[28]

Central Systems

Very little work had been done on Central Systems. It was agreed that all accelerators would be controlled from a single main control room. This control room would be located on the SSCL campus, close to other facilities, and it would incorporate physics data acquisition facilities. A preliminary specification (DRD) for the main control building was prepared.[29] First estimates were that the main control room would contain 12 consoles, each 5 bays wide and containing multiple screens. None of this had been reviewed or confirmed. No analogue signals were to be brought into the main control room; because of the distances involved, it was technically impossible to do so. Satellite control rooms located at principal surface buildings would provide limited local control capabilities for commissioning and maintenance.

Construction of the campus was delayed, and with it the main control room. A temporary control room located close to the Linac was proposed,[30] for control of the warm machines, but not constructed for financial reasons. A trailer was being equipped for control of the Linac, and it is likely that this trailer would have been used and possibly expanded for warm machine control.

The choice of EPICS somewhat dictated the nature of the computer equipment that would have been in the main control building—UNIX-based workstations and servers capable of running EPICS applications. Multi-headed HP workstations had been purchased for the Linac control room. A test bed including console was set up in the Controls Department Integration Laboratory.

Hardware Standards

The Controls Department Front End Group was responsible for all crate-based systems installed close to the accelerator equipment, for instance in the Linac gallery or Collider niches. This work and equipment fell under individual machine activities, and therefore is not discussed in this report. The same group, however, was responsible for establishing standards for all front end hardware (crates and cables, and, with the software group, modules). Standards were written for VME and VXI crates and buses, signals, and some modules.[32] A cross-connect block was specified, designed and a prototype delivered.[33]

Interface Standards

A critical first task in control system development was to define interfaces and interface standards at all levels as early as possible—before work on the various subsystems had begun. The SSC Controls Department failed to do this in a timely manner. The result was that mini controls groups developed in many of the technical departments, and interfaces were defined in an ad hoc manner by each of them.

The adoption of EPICS resolved much of this difficulty for software interfaces, defining with channel access the Application Program Interface (API) and the front end interface to specific modules, the "EPICS drivers." [34] Nonetheless, the actual point of interface and demarcation of responsibility had already evolved such that it differed between subsystems.[35] Although this situation was not ideal, careful interface definition documents and cooperation made it workable.

Process Controls

The process control systems for which ASD was responsible were, in decreasing order of size and complexity: cryogenic systems, including both refrigerator plants and underground distribution systems; vacuum systems, including both beam and insulating vacuums; and low conductivity water (LCW) sytems. These systems are distinguished from other accelerator control systems in three major ways: (1) they are slow relative to other systems (typically a 10 Hz scan rate is sufficient) and they need not be synchronized with beam-related systems; (2) they must be extremely reliable as they must operate at all times, whether or not the accelerators are running; and (3) they may be amenable to the use of commercial control systems. The SSC WBS in no way distinguished between process control systems and other systems, except that responsibility was ambiguous, and seemed to be distributed among various Departments, including Controls.

At an early Design Review for Global Control Systems the review committee suggested that an integration and standardization effort was required for process control systems. A task force was established which included all interested parties. The result was the establishment of a Process Controls Group within the Controls Department. Together, the task force and the Process Controls Group prepared specification documents[36] and considered many possible solutions, ranging from commercial Distributed Control Systems (DCSs) to the application of EPICS. A budget estimate and implementation plan were drawn up. A summary of this effort may be found in [38]. This effort was treated globally, and the budget estimate included in the global part of the revised project cost estimate of 1993. This change in approach had not been approved however, and it is quite possible and likely that the activities, once agreed, would have reverted to the individual machines.

Conclusions

The effort on the Global Accelerator Control Systems (GACS) had a good start. The most significant decision, one that affected both the SSC and the broader accelerator controls community, was to join the EPICS collaboration, and to attempt to realize the long-held but never-fulfilled dream of sharing control system software. Indications were positive, but it cannot be said that the concept had yet been proven. Significant progress had been made on the application of telephone technology to the SSC data communication problem. The requirements were particularly demanding, and the proposed solution was innovative and new to the accelerator world. It would have been satisfying to have proven the concept, and learned the pitfalls from experience.

Much of the work mentioned above can be found in the references cited. However, consistent with the approach of the accelerator controls community, most of these references and much more are available in the SSC Controls section of the World Wide Web. It assumed that a means will be found to maintain this data when the light is turned off.

Chapter 13. Commissioning and Operations

(T. Elioff)

Over the last four years efforts were undertaken to develop the plans for pre-operations, commissioning, and operations of SSCL accelerators and associated facilities. Specific definitions were important to properly estimate the required funding for each area. In particular the funding for pre-operations was earmarked to be included within the Total Project Costs (TPC), while operations costs were outside of the TPC.

In order to facilitate this effort, an accelerator facility was defined as a major system of the overall Laboratory complex that could achieve independently an operational status with regard to its mission. For a given facility, the sequence of events leading to "operations" are "construction completion" followed by a "commissioning" phase. This final phase is used to test all systems and components together to insure that the facility functions as planned. The time sequence of events is outlined in Figure 13-1. The definition of each phase is provided below.

Construction Completion - This is the point at which all major systems of a facility are in place and ready to operate together to provide the basic objective of that facility. In the case of an injector accelerator it is expected that each technical subsystem (e.g., magnets, power supplies, RF, controls, etc.) will have been individually tested during the construction phase.

Pre-Operations - This phase provides for training of the operations staff who will help to commission and subsequently operate the facility. The operations crews are expected to assist in the tests of individual components in the final construction phases noted above. The pre-operations phase is initiated before construction completion and includes the commissioning period.

Commissioning - During commissioning all systems are tested and operated together to insure that the basic technical objective is achieved. In the case of an accelerator, this primary objectives are accelerated beam. This period allows for tuning, timing, debugging, and perhaps modifications of individual components to optimize performance as well as reliability. Commissioning is complete when the facility can supply adequate beam for "start-up" and commissioning of the next higher-energy accelerator. In addition, the commissioning tests should provide evidence that the machine has the capability to reach design performance and that the methods of achieving full design performance are understood.

Operations - The start of operations is signaled by utilization of the facility following commissioning. In the case of injector accelerators, this includes operations for continued improvements, service to other accelerators (apart from commissioning), and operations for test beams and physics experiments.

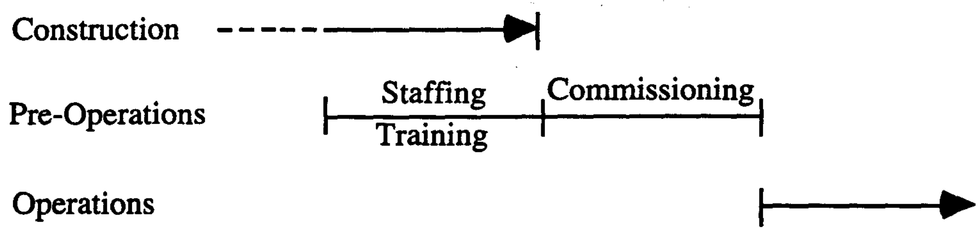

Figure 13-1. Example Accelerator Schedule.

Estimates Prior to June 1990

The first estimate[1] for pre-operations costs (99M$) was made by The Central Design Group. This was revised to 113M$ (FY86$) by a detailed operations cost analysis in September 1986.[2] These reports served as the basis for the DOE request of January 1987. A number of estimates for *pre-operations* were presented in the DOE Construction Project Data Sheets prepared for the annual Congressional Budget Request starting in January 1987. These are summarized in Table 13-1 below:

Table 13-1. Pre-operations Cost Estimates.

Budget Request Date	Pre-Operations Costs (AY - M$)
January 1987	202
January 1989	400
January 1990	360
January 1991	193

The next estimate that provided a breakdown of the pre-operational funds by injector accelerators and Collider was presented in the June 1990 DOE Review of the overall SSCL costs. The total pre-operations costs were estimated at 130.7 M$ (FY90 dollars) as shown in Table 13-2. This estimate *did not* consider that pre-operational funds would be required for an operational lower energy injector when it was being utilized to commission a subsequent higher energy machine. It was assumed that this task required only a minor fraction of the operating time for the lower energy injector. Low level cost details as well as specific time periods for the commissioning of each accelerator were not developed for the June 1990 estimate.

Table 13-2. Pre-Operations Cost Estimate.

WBS	Description	FY90 M$
4.1	Accelerator Pre-Operation	130.8
4.1.1	Linac Systems	4.0
4.1.2	Linac T/L	0.5
4.1.3	LEB Systems	4.6
4.1.4	LEB T/L	0.7
4.1.5	MEB Systems	11.6
4.1.6	MEB T/L	2.8
4.1.7	HEB Systems	15.6
4.1.8	HEB T/L	4.2
4.1.9	Collider Systems	76.1
4.1.10	Collider Abort	2.4
4.1.11	Test Beam	1.4
4.1.12	Accelerator Global Systems	7.0

The first cost estimate for operations of each accelerator after construction completion was made by the CDG in September 1986.[2] For the operations cost of each accelerator following its commissioning completion, but within the construction period, the first integrated estimate was presented by SSCL at the June 1990 DOE Review. At that time the operations functions were defined by WBS 6. The major categories included Physics Research and laboratory overhead as well as the operations of accelerators and experimental facilities. The results are summarized in Table 13-3. Lower level WBS details were provided in the back-up material for the review. The total annual costs indicated in Table 13-3 (404.6 FY90 M$) have been expressed in a range of values in actual year dollars (460.0 to 507.6 M$) depending on changing escalation rates and schedules.

Table 13-3. Annual Operations Cost Estimate.

WBS	Description	Costs (FY90 M$)
6.1	Physics Research	102.4
6.2	General Laboratory Overhead	137.3
6.3	Accelerator Operations	164.9
	Total	404.6

The June 1990 review report[3] by the Office of Energy Research Review Committee (ERC) did not address the issue of how to fund operating costs for facilities after commissioning. The ERC expressed its judgment that the SSC Laboratory estimate for these costs was reasonable. The ERC noted that, in the past, laboratory operating costs have been met from program operating budgets rather than from within the total project cost.

Developments in FY91–92

The DOE site office personnel did not accept the early methods for determining the pre-operations and operations costs. Their initial position was that operations of a given injector accelerator could not commence until that accelerator had achieved full design performance in terms of beam characteristics and intensity. Discussions were held with DOE leading to a formal presentation and discussion of operational issues on June 22–24, 1991. The general results of this review were as follows: (1) No precise definition for commissioning completion could be agreed upon. There was general agreement that the commissioning period should provide evidence that there are no major obstacles that would limit the ultimate achievement of full design performance; (2) The estimate of costs for overhead functions (WBS 6.2) was rejected. It was recommended that the SSCL develop an overhead policy that could be consistently applied to all operations areas in the future; (3) The request for operations funds for completed facilities such as the ASST and other laboratory buildings was rejected. DOE allowed that buildings and facilities attendant to a specific accelerator could only become operational when that accelerator achieved operational status; (4) The commissioning completion of individual Collider sectors was rejected. The DOE position required the operation of all Collider sectors with stored beam before any part of the Collider could become operational; and (5) The Physics Research Division request for operations funds appeared high but not unreasonable. It was suggested that they submit a proposal to HEP suitable for peer review.

Following the above review (July 26, 1991) DOE requested: a detailed commissioning plan for each accelerator, a detailed report on operations costs, a Physics Research Proposal for Operations, and a plan for spares. In response to the request the following information was developed and provided: a detailed commissioning report[4] was provided on April 1, 1992, a draft report on Operations in FY2000 and beyond was provided in September 1992. This was extensively reviewed by a DOE Task Force in October 1992. A final report[5] was submitted in November 1992, a Physics Research Proposal[6] was submitted on April 1, 1992, and an analysis of accelerator spares requirements (with details developed by SSCL consultants) was submitted on April 1, 1992.

The Operations and Commissioning Report

The goal was to present a plan for the sequential commissioning and operation of individual accelerators and other technical facilities of the SSC. Some general features of the model used for this report are presented below. Detailed specifics of manpower, schedules, operational shifts, laboratory overhead, etc., are found in the report.[4]

Major SSCL Facilities Definitions

Injector Accelerators - There are four injector accelerator systems, the Linac, LEB, MEB, and HEB, and associated beam transfer systems that deliver beam from one accelerator to the next. It was expected that the injectors would be constructed, tested, and commissioned in sequence such that the Collider could be commissioned with beam delivered from the HEB in

FY99. The conventional facility structures associated with each accelerator were to be completed before the installation start of the technical components. Other conventional systems including power and utilities were to be available for component tests before the start of commissioning.

Test Beams - The test beam facilities are comprised of the beam transport lines and the associated experimental facilities. The commissioning of these facilities requires the operation of the Linac, LEB, and MEB accelerators. After commissioning it was expected that there would be a continuous utilization of these facilities by experimental physics groups for test and calibration of various detector systems and components.

The Collider - Each of the ten sectors of the Collider is comprised of two superconducting magnet systems, each of which is near the size of the HEB. There are almost one thousand superconducting magnets in each sector. While each magnet would undergo testing procedures at room temperature, a large fraction would not have been tested at liquid helium temperatures. The commissioning process represents the first time that the complete ensemble of all magnets in a sector could have been cooled to 4 K and tested. The commissioning program was intended to filter out any remaining magnets that have marginal characteristics and to ensure that the complete ensemble would function according to design specifications. The sequence of sector commissionings was scheduled to extend over a 3-year period. All ten sectors of the Collider were projected to be in operational readiness for the first circulating beam tests in the Collider by March 1999. The period of beam commissioning for the Collider extended to September 1999.

Magnet Test and Development Facilities - It was intended that after the construction project mission of providing magnets for the initial installation in the HEB and the Collider, the magnet Research and Development group would enter an operational phase to conduct research projects on superconducting magnets and materials as well to provide continuing support for accelerator operations. The operations support included magnet repair, magnet replacement, and R&D as required to resolve operational problems.

Experimental Facilities - When an experimental hall and its surface structures was ready for beneficial occupancy, the task of assembling the complex detectors were to begin. The detector design and fabrication is managed by each detector collaboration. The assembly of the detector and its integration with the experimental facilities required SSCL management and technical support staff. The SSCL staff was to manage the facility, oversee the detector assembly program, and provide technical support. In general it was to the responsibility of the SSC staff to provide for all utility connections from the detector to established distribution points. The SSC group would provide experienced crane operators, riggers, and technicians to support the detector assembly program. The SSC staff would also act as a liaison group to assist the detector collaboration in obtaining other laboratory services. A primary responsibility was to be in the area of environment, health, and safety.

Physics Research - A strong in-house physics group was planned in order to facilitate the liaison between the experimental collaborations and the conventional construction as well as other SSCL Divisions. Such liaison is required in the design of the experimental facilities and the Collider design (beam pipes, IR magnets, etc.) in the vicinity of the detectors. Another responsibility is the design and operations of test beam facilities. Finally, the in-house group would have responsibility was the design, fabrication, integration, installation, and commissioning of detector subsystems and components including controls, on-line and off-line computing, and overall networking.

Summary of Results

The cost estimate for pre-operations of each major accelerator system is summarized in the second column of Table 13-4. While the final estimate is not significantly different from the baseline, the global area (WBS 4112) has increased significantly due to the inclusion of costs for the operation of lower energy accelerators when they are utilized to commission high energy machines. This report provided the first estimate for the operations costs of injection accelerators beyond the commissioning period that was based on a detailed manpower analysis together with other appropriate accelerator operating costs. The results of this report, together with other data, were utilized to provide the basis of the January 1993 Revised Baseline, which is indicated in the third column of Table 13-4. The DOE Review of August 1993 accepted the results of the Operations and Commissioning Report except for the Collider area. A 10M$ increase was recommended based largely on preliminary results of the incomplete June 1993 rebaselining effort. This is indicated in column 4 of Table 13-4.

Operations Following Total Project Completion

The "model" plan was based on a number of assumptions. It was expected that the plan would be updated as the laboratory developed a better understanding of the performance capabilities of the machines and the detectors. Future experience would also provide additional information with regard to staffing needs for operations and support. The assumptions for the plan are summarized as follows. At the beginning of FY2000, the injector accelerators, collider, detectors, and experimental facilities would have successfully completed their commissioning phase in accordance with the current project schedule, and plan outlined in Ref. [4]. The Linac, LEB, and MEB would be operating reliably at the full intensity specified for the Collider and for test beam operations, although the emittance goal in the collider-filling mode may not have been achieved. This was reasonable considering the extensive operational experience with these machines that would have been gained by the beginning of FY2000. At the beginning of FY2000, the HEB would not yet have achieved its design performance or reliability, but this would not be a significant limitation in the Collider performance for the three-year period during which the complex would be brought to full design luminosity. The Collider would begin operation with reduced bunch intensity and/or larger emittance, and perhaps with a smaller total number of bunches than ultimately provided. The relatively conservative assumption was made that the resulting instantaneous luminosity would reach 1% of the design luminosity by the end of the first year. It was intended that the beam energy would be 20 TeV at the outset.

The report summarized the physics goals for detector operations during the first five years. The Physics Division operations were described in terms of in-house physics research, the support functions for users, and operations functions for the experimental halls and associated facilities. All of the tasks associated with the Accelerator Division operations of the injectors and the Collider were discussed, and a detailed manpower analysis for each task was provided. Finally, the laboratory support areas were described and manpower estimates provided. The support areas include the Directorate, the Administrative Services and Support Division, and the Laboratory Technical Services Division. The support for general plant projects was included in the Technical Services Division responsibilities.

The draft report of this plan (August 28, 1992) indicated a total SSCL operations cost of 336 M$ (FY91 $) for the year FY2000. An extensive review was conducted by the DOE and its consultants on September 14-16, 1992. The consensus of the review was that "the total estimate (336 M$) was in the right range, but may be possibly on the high side." As a result of the review discussions, several revisions were made. The revisions included a reduction in the manpower support levels required for operations of the experimental areas and a revised estimate of the power costs. These modifications were incorporated in the final report,[5] resulting in a total operations cost of 317.2 M$ (FY91 $) for the year FY2000. This total included costs for all laboratory manpower (2,428 FTEs), materials and supplies, power and utilities, cryogens, equipment, accelerator improvements (AIP), and general plant projects (GPP).

In March of 1993, a DOE technical review group again reviewed the electric power estimates for SSCL operations. Their report[7] concluded that the SSC estimate could be slightly high (~10%) but was well within the uncertainties of the various models for operations and maintenance modes of the different accelerators and laboratory systems. The SSCL estimate was judged appropriate for the purpose and need to complete the Request for Proposals for permanent electric power for the laboratory.

FY93 Revisions

Pre-Operations

In May 1993, an SSCL rebaselining effort was initiated. The preliminary information from this exercise indicated higher costs for commissioning (particularly for the Collider) than that of Ref. [4]. Some of this increase was traced to higher than normal labor rates; however, the exercise was terminated with no final determination of costs. As previously noted, the DOE August 1993 review projected a 10 M$ increase for the Collider relative to the previous estimate. This was based largely on the preliminary information from the incomplete rebaselining exercise.

In October 1993, the laboratory initiated a value engineering exercise to examine the increased costs implied by the above rebaselining effort and the subsequent DOE review. While the value engineering exercise was not completed for all accelerators, a review was completed for the Collider. The detailed analysis provided the results indicated in column 5 of Table 13-4, which are consistent with the projections of Ref. [4].

The value engineering exercise also focused on the special requirements of the Linac in the pre-operations period. The Linac group planned for a separate commissioning phase for the RFQ, each of the four sections of the drift-tube linac, and for two sections of the coupled-cavity linac. This scenario required more manpower and time than that of previous estimates. The results of this consideration are responsible for the increased Linac costs in column 5 of Table 13-4. The revised results shown in Table 13-4 (column 5) for other accelerators are based on the information from Ref. [5]. These results projected a larger staff for the HEB and a significantly reduced staff for test beam operations.

Table 13-4. Pre-Operations Cost Projection Record
FY93 K$.

WBS New	WBS Old	System	1990 Baseline	April 92 Ops/Commis. Report	Jan. 93 Revised Baseline	Aug. 93 DOE Review	Oct. 93 Revised Estimate
211-9200	411	Linac }	4,897	4,622	3,493	4,622	8,575
212-9200	412	Linac TL }					
221-9200	413	LEB }	5,685	5,089	5,033	5,089	6,280
222-9200	414	LEB TL }					
231-9200	415	MEB }	15,735	7,723	8,075	7,723	8,375
232-9200	416	MEB TL }					
311-9200	417	HEB }	21,513	12,697	10,861	12,697	15,744
312-9200	418	HEB TL }					
321-9200	419	Collider }	85,616	74,730	76,445	84,730	75,600
322-9200	4110	Collider Abort}					
561-9200	4111	Test Beams }	1,486	5,591	5,719	5,591	2,250
562-9200	4113	Target Hall }					
411-9200	4112	Global	7,600#	19,577	30,970	19,577	21,500
411-9200	–	Test Training	–	–	654	–	654
–	–	IR Halls	–	6,777	–	6,777	–
116-0930	–	Ops Mgmt	–	–	1,282	–	1,282
			142,532	136,812	142,533	146,806	140,260

#Not for commissioning subsequent machines

Operations

The various estimates for operation costs for the injection accelerators following their commissioning completion for experimental facilities and for physics research are summarized in Table 13-5. While the overall total has not changed significantly, the details have varied considerably.

The first estimate (June 1990) greatly underestimated the physics research needs. The plan also assumed that operations for accelerators could begin as early as FY91 prior to the commissioning of any accelerator. This was not in accord with the definitions later developed with DOE and resulted in a considerable overestimate. Plans for operation of the Magnet Department and for the Experimental Facilities were not well understood. This early estimate did not include any significant costs for accelerator equipment nor any costs for accelerator improvement projects (AIP) that are normally utilized for accelerator operations at other laboratories. The overhead estimate (WBS 6.2) was later rejected by DOE as inconsistent with standard policy.

The Operations/Commissioning Report[4] of April 1992 provided a detailed estimate of manpower and associated costs of operations for all of the WBS 6 categories. The results are given in column 2 of Table 13-5. This report provided an update of SSCL physics research plans and the first estimates of costs for operations of the Experimental Facilities and the Magnet Department. This report was provided to DOE in April 1992, and was again reviewed by the DOE Baseline Review group in August 1993. No significant changes were recommended by these reviews.

The final values noted in the last column of Table 13-5 resulted from changes in projections by the SSCL that became apparent during FY93. The need for test beam operations and hence full-time operation of the Linac, LEB, and MEB was reduced as a result of projected schedule delays. The reduction in costs for Experimental Facilities operation was a result of the DOE Review of FY2000 operations (in October 1992). They recommended less manpower for the facilities operation. Table 13-5 shows the effect of the reduction (WBS 6.3.3) when it is applied to the period prior to FY2000. While the total costs for physics research remain at 260 M$, it is noted that the *actual costs* for FY92 and FY93 have been far less than requested. This could be recovered in later years or the total estimate should be lowered slightly. The current analysis for operations from FY91 through FY99 projects an integrated cost of approximately 517 M$ (AY$).

Table 13-5. SSCL Operations Cost Projections (AY M$).

WBS		June 90[2]	Ops/Com Report April 92	DOE Review Aug 93	Revisions Oct. 93
6.1	Physics Research	127	260	260	260
6.2	SSCL Overhead	169	—[3]	—[3]	—[3]
6.3	Facility Operations				
6.3.1	Accelerators	168	135	135	120
6.3.2	Magnet Dept.	9	28	28	28
6.3.3	Exp. Facilities	34	137	137	109
	Total	507	560	560	517

[1]For the period FY91 through FY99.
[2]This column is escalated from the data of Table 13-3.
[3]Overhead factors were applied to the 6.1 and 6.3 direct costs.

PART II. EXPERIMENTAL AREAS AND TEST BEAMS

PART II. EXPERIMENTAL AREAS AND TEST BEAMS

Chapter 14. Experimental Areas

(H. L. Lynch)

It was planned that initially the SSC would have four interaction regions (IRs) for experiments; they were designated IR1, IR4, IR5, and IR8. It was intended that there be two large experiments (of the scale of $500M each) and two smaller experiments that would occupy the IRs. The halls for the large experiments would have floors of the order of 30 m × 100 m; the other detector halls would be smaller.

Because the bulk of the Laboratory facilities, i.e., all the low energy machines and the office areas, were to be sited at the West Complex, it was intended that the large experiments be placed at IR1 and IR4, which are on the West Complex. As a consequence, the smaller experiments would be placed on the East area at IR5 and IR8. Early geologic tests, however, indicated that this choice would be problematic. In particular, the large experiments at the West Complex would be resting on Eagle Ford shale instead of Austin Chalk. The reports by the PB/MK and Underground Technology Advisory Panel made the following observations concerning the Eagle Ford shale: its recompression strength and overall deflection limitations may not be adequately predicted, even after data are analyzed from the large diameter drill hole; it heaves dramatically when the overburden is removed; its expansion characteristics when exposed to moisture, including moisture in the air, are unpredictable; and its deflection limits under load are unknown and unpredictable. In contrast, Austin Chalk was greatly superior to the Eagle Ford Shale in its characteristics for supporting the detectors, whose weights are of the order of 30 to 40 kTons. The chalk was both elastic and predictable. In November 1991 it was decided[1, 2] to place the large detectors on the East side and the smaller detectors on the West.

By the end of 1991 it was assumed that the large detectors would probably be SDC and GEM, and specific designs for the underground halls were developed. There was no comparable assumption for the smaller experiments, because these were much less developed. The baseline budget for all the experimental facilities was $149M.[3] It was clear that this amount of money would not satisfy the initial needs of the two large experiments alone. There was considerable iteration in developing plans to fit the financial constraints, involving discussions within each collaboration on what compromises could be made. It was determined by a coin toss that GEM would occupy IR5 and SDC would occupy IR8. With this choice made, design work on the underground halls began.

Much effort was given to making the buildings serve multiple purposes. Also, where possible, designs for different structures, especially the underground halls, were made as similar as possible for the two experiments to reduce design and construction costs. One option explored was to lease buildings off site instead of constructing assembly buildings, but it was determined that this was not cost effective.[4] Although the rental alone was advantageous, the transport of large detector pieces to the IR would have been very expensive. As part of a package to keep the entire Experimental IR Facilities costs within the baseline budget, the scope of the smaller experiment facilities was reduced[3] compared to that in the SCDR.[5]

Interaction Region 5 GEM

In late 1991 the user requirements for the GEM experiment were developed, and a document called the GEFUR[6] (GEM Experimental Facilities User Requirements) was prepared in April 1992. The document had been revised since inception, and the most recent released version was Rev. D. The GEFUR provided the primary reference for a description of the facilities. Section 1 gave an overview; section 3 gave an overall functional description of each of the buildings and the underground hall. More detailed descriptions were given in a separate section devoted to each part. The facilities consisted of an underground hall, two large assembly buildings, a utility building, and some miscellaneous small buildings. A view of the plan for the IR5 surface facilities is shown in Figure 14-1.

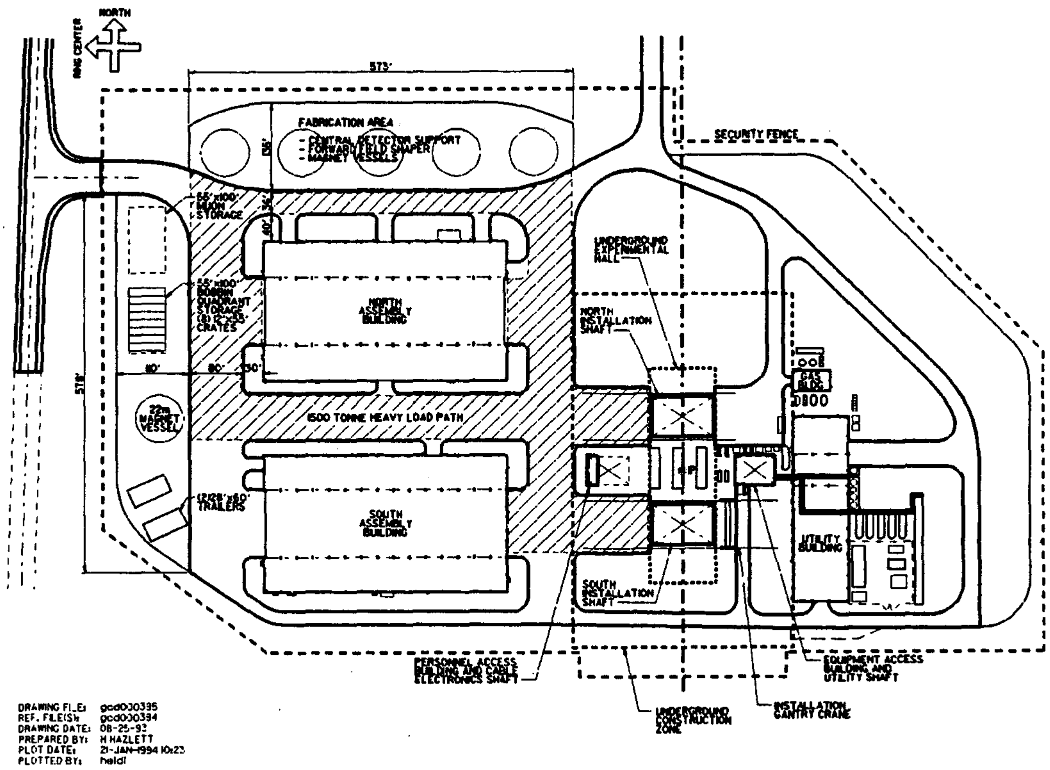

Figure 14-1. Plan View of Surface Facilities at IR5.

The bulk of the experimental equipment[7] was to be housed in the underground hall, where the beams from the Collider could pass through the detector. The assembly buildings on the surface were to be multi-purpose and used first for the assembly of parts of the large GEM magnet then later for other parts of the detector. The Utility building housed such things as HVAC equipment and transformers. The miscellaneous buildings consisted of the Gas Mixing Building, the Gantry Crane area, the Equipment Head House, and the Personnel Access Head House.

A major part of the GEM assembly work consisted of winding and assembling the coil for the large superconducting magnet. The winding of coil segments was to be done in the South Assembly Building (SAB). The segments would be transferred to the North Assembly Building (NAB) for assembly of complete coil halves. To do this the SAB had to be finished about six months earlier than the NAB. Once the magnet work had been done, the SAB and NAB were to be used for other detector assembly work. The gas mixing building was where the various gases would be mixed for the detector below ground. The two head houses were entry ways to shafts leading down to the level of the floor of the underground hall. They offered shelter from the elements as well as radiation safety isolation. No construction at IR5 had begun as the project shut down.

An unusual characteristic of the GEM detector was the very extensive stray magnetic field from the detector. Magnetic fields of 1000 Gauss or more in the experimental hall required special selection of electrical equipment such as power supplies. The cranes required a mechanical securing to resist magnetic forces. Equipment at the surface had to be able to function in a field of 45 Gauss, while equipment in the shafts had to tolerate fields as high as 170 Gauss. A personnel safety region at the surface of the earth was required because of fields as high as 40 Gauss. For more information see the GEFUR[6] section 1.5.2.

Underground Hall

An elevation view of the underground hall is shown in Figure 14-2, and a plan view is shown in Figure 14-3. The Collider beam is shown about 50 m below the surface of the earth at IR5. The detector itself is large, requiring excavation placing the floor 13m below the beam height. The hall itself is about 30 m × 100 m and 45 m high. The floor dimensions are set by the size of the detector and space needed to assemble the detector in the hall. The height of the hall is determined by the minimum roof thickness to control radiation produced by *p-p* collisions in the hall. This is 14,400 kg/m^2 or the equivalent of 6m of concrete.

The GEM detector was to be built in place in the experimental hall. This would require lowering pieces down through the access shafts to the hall where final assembly would take place. The assembly sequence is described in the GEFUR section 2.2 and the GEM TDR[7] section 9.4. Accomplishing it would require extensive crane services. A gantry crane running on the surface would be used to lower the pieces to the hall. For very large pieces, an additional heavy lift jacking frame would be rented. Once in the hall, two 100/20 ton bridge cranes would handle the parts that could not roll on the floor. The floor of the hall had to support the weight of the detector, about 11,000 tons, and to contain rails for moving large parts. The rails would be essential for the construction of the detector and for opening and closing the detector for access to its interior.

On the west side of the hall was the electronics shaft (cf. GEFUR section 4.2.3), which offered access from the surface to the underground hall by elevator. In addition, the fast electronics were located on several floors in this shaft to minimize the cable lengths between the detector elements and the data acquisition electronics. A part of the design was that the shielding against radiation be good enough that unrestricted access by personnel would be possible even while the machine was running. This was done instead of restricting access to radiation workers so that access by outside people, such as equipment service technicians, would be easy administratively. Such shielding would require at least 15,600 kg/m^2 or 6.5m concrete equivalent between the inside of the shaft and the hall. Because of the magnetic field of the detector, the electronics shaft would incorporate magnetic shielding to reduce the field inside to less than 50 Gauss. The utility shaft (cf. GEFUR section 4.2.4) would provide access to the experimental hall by two elevators and a stairway. It would provide the primary ingress and egress for personnel as well as passageway for the utilities, such as AC power, DC power for the magnet, HVAC, water, gas, and cryogens.

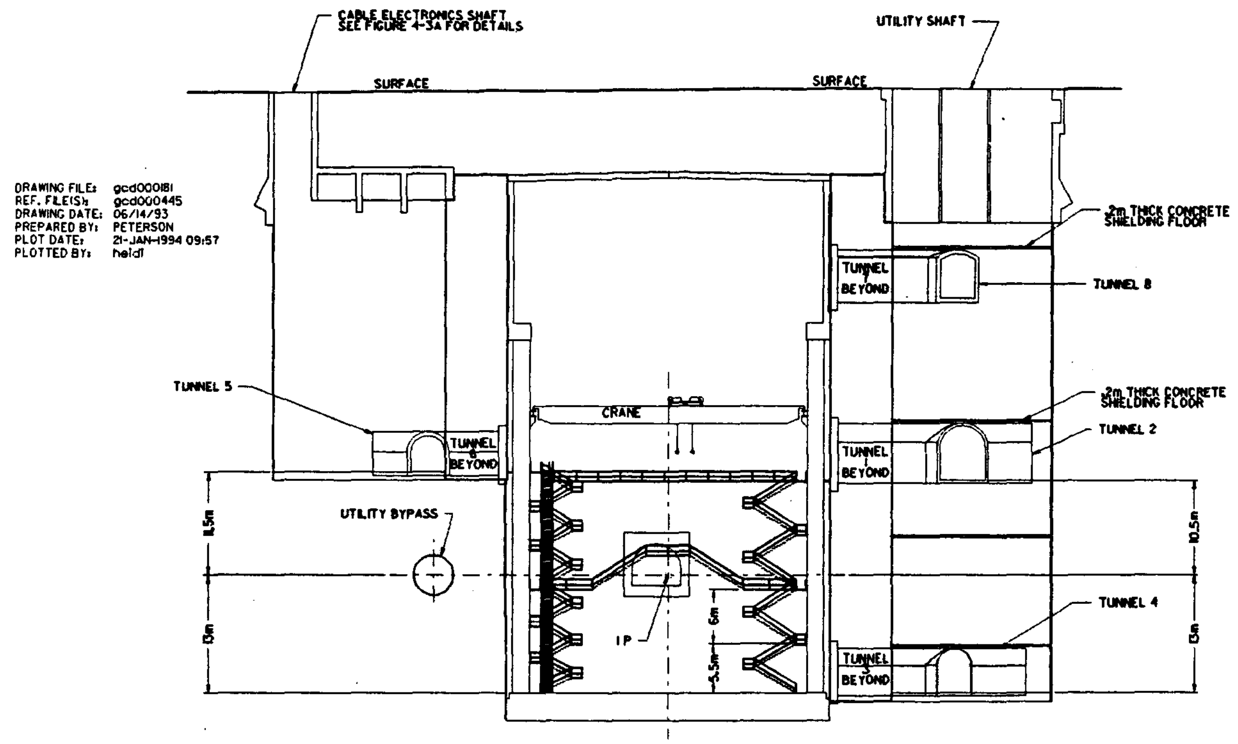

Figure 14-2. Elevation view of the GEM Underground Hall.

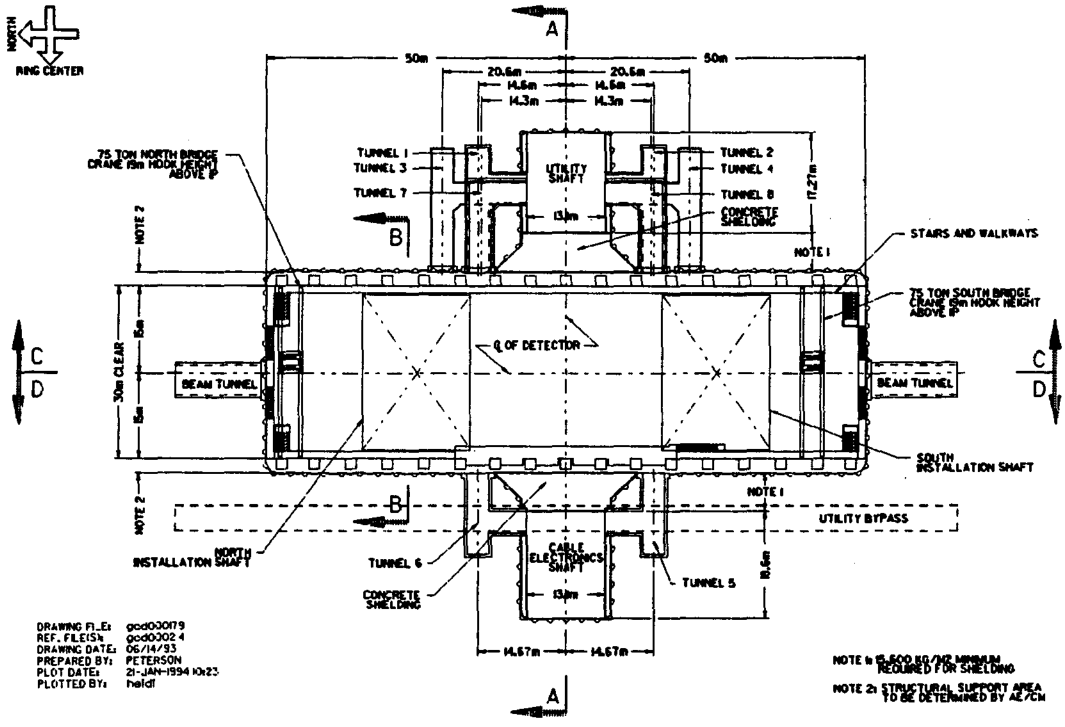

Figure 14-3. Plan view of the GEM Underground Hall.

South Assembly Building

The South Assembly Building (SAB) (cf. GEFUR section 6) was 60 m × 110 m, of which the central 30 m × 100 m was a high bay area. The building served first as a multipurpose assembly area and later a portion would serve as the detector operations and computer center. It had two 35/10 ton cranes. The winding of the coil segments in the SAB would occupy the western 3/4 of the center high bay area, and the remainder would be used for muon prototype production. After the coil winding had been completed, the high bay space would be used for the storage and regular assembly of the muon system. The north side low bay area would have space for a shop area, small muon parts storage, coil winding supply storage and shops, and miscellaneous storage. The south side low bay area would consist of two floor levels. Offices, detector operations areas, and on-line computing space would be located on these floors near the west end of the building to be as far as possible from the GEM magnet and its magnetic field. The east end of the south low bay would be used for muon chamber test and storage on the first floor and as an electronics shop and an additional general storage on the second floor.

North Assembly Building

The North Assembly Building (NAB) (cf. GEFUR section 7) was 64 m × 110 m, of which the central 30 m × 110 m was a high bay area. The building would serve as an assembly area with two 45/10 ton cranes. Coil segments wound in the SAB would be transported to the NAB and assembled into a stack in the high bay area. Once the stacks had been transported to the underground hall, the NAB high bay area would be used for the assembly of the muon monoliths and for calorimeter assembly. The north side low bay of the building would be used for assembly and testing of the tracker and calorimeter. The south side of the low bay would be used for storage of the barrel and endcap muon modules prior to assembly into the monolith.

Utility Building

The Utility Building (cf. GEFUR section 8) would be 24 m × 80 m to house mechanical and electrical equipment for HVAC, chilled water, LCW, AC power distribution, DC power supply, emergency power, cryogenic refrigerator, and safety systems.

Interaction Region 8 SDC

In 1991 the user requirements for the SDC experiment were developed, and a document called the SEFUR[8] (SDC Experimental Facilities User Requirements) was prepared. This was revised several times, and the version current at closure was Rev. G. The SEFUR provided the primary reference for a description of the facilities. Section 1 gives an overview; section 3 gives an overall functional description of each of the buildings and the underground hall. More detailed descriptions are given in a separate section devoted to each part. The facilities would consist of an underground hall, one assembly building, a utility building, and some miscellaneous small buildings. A plan view of the IR8 surface facilities is shown in Figure 14-4.

The bulk of the equipment[9] would be housed in the underground hall where the beams from the Collider could pass through the detector. The assembly building on the surface would be multipurpose and used for assembly of first the muon components and the calorimeter components. Later it would be used for assembly of the tracker and forward muon chambers. The Operations Building was the control center for the experiment. The Utility building would house such things as HVAC equipment and transformers. The miscellaneous buildings would consist of the Gas Mixing Building, the Gantry Crane Area, the Installation Head House, and the Personnel Access Head House. The gas mixing building was where the various gases would be mixed for the detector below ground. The two head houses would be entry ways to shafts leading down to the level of the floor of the underground hall to offer shelter from the elements as well as radiation safety isolation.

The only construction work done at IR8 as the project ended was the beginning of the Assembly Building and site preparation for the underground hall. The heavy slab for the Assembly Building had been poured and some steel girders erected.

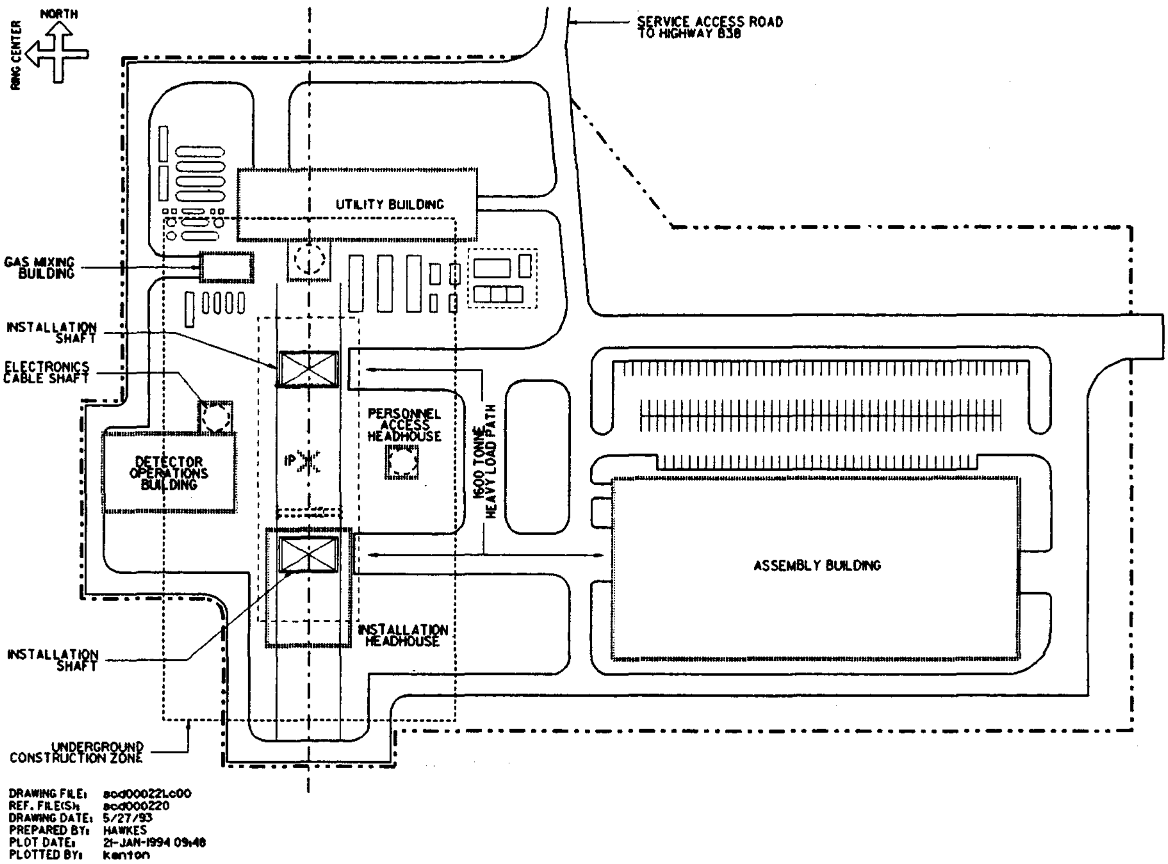

Figure 14-4. Plan view of IR8 Surface Facilities.

Underground Hall

The underground hall is described in the SEFUR section 4. An elevation view is shown in Figure 14-5, and a plan view is shown in Figure 14-6. The Collider beam would be about 50 m below the surface of the earth at IR8. The detector itself would be large, requiring excavation placing the floor 14 m below the beam height. The hall itself would be about 30 m × 100 m and 45 m high. The floor dimensions were set by the size of the detector and the space needed to assemble the detector in the hall. The height of the hall was determined by the minimum roof thickness required to control radiation produced by *p-p* collisions in the hall. This was 14,400 kg/m^2 or the equivalent of 6 m of concrete.

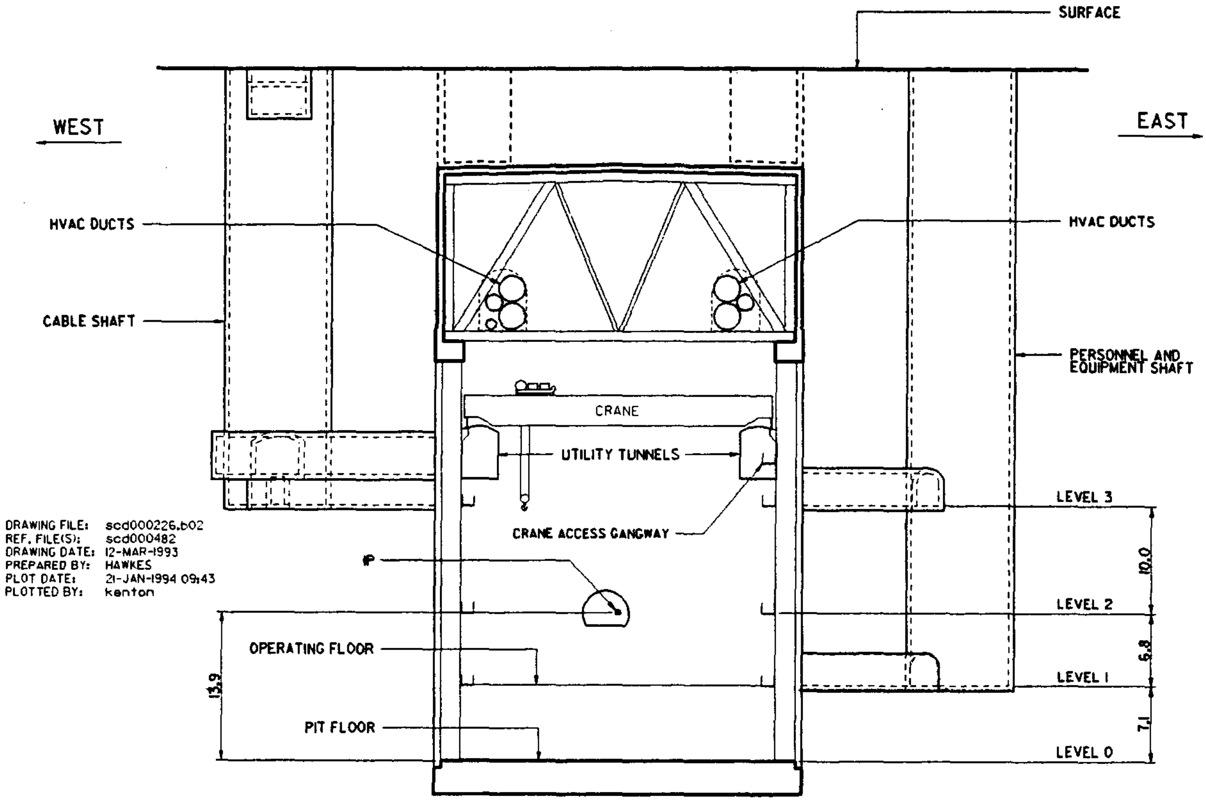

Figure 14-5. Elevation view of the SDC Underground Hall.

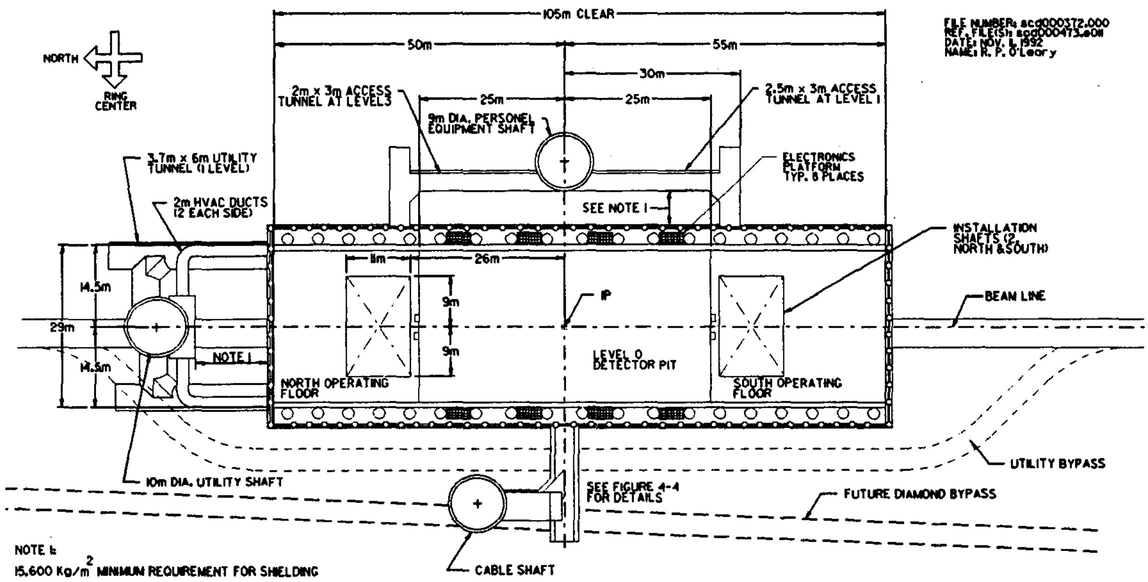

Figure 14-6. Plan view of the SDC Underground Hall.

The SDC detector would be built in place in the experimental hall. This would require lowering pieces down through the access shafts to the hall where final assembly could take place. The assembly sequence, which is described in the SDC Technical Design Report (TDR)[9] section 13, would require extensive crane services. A 100/20 ton gantry crane running on the surface would be used to lower pieces to the hall. Once in the hall, the two 100/20 ton bridge cranes would handle the parts. The floor had to support the weight of the detector, about 40,000 tons, and to provide rails for moving large parts.

There were three access shafts from the surface to the hall, the cable shaft, the personnel/equipment shaft, and the utility shaft (cf. Figure 14-6). The cable shaft provided the shortest path for signal cables from the detector to the Operations Building. It also contained an elevator and a stairway for access by personnel. The personnel/equipment shaft had an elevator for personnel and equipment as well as a stairway. The utility shaft provided the optimum routing for utility service to the detector, such as AC power, DC power, HVAC, water, gas, and cryogens.

Assembly Building

The Assembly Building (cf. SEFUR section 6) would be 60 m × 134 m, of which the central 30 m × 134 m would be a high bay area. It would provide space for assembly of the calorimeter, the muon system, and the tracker as well as an industrial shop. It would also provide office space and a conference area. It had one 50/10 ton bridge crane and two 20/5 ton bridge cranes. Assembly of the calorimeter would place stringent floor loading requirements on the west end high bay. This area would have to handle 4700 tons of equipment supported on three points with a maximum of 800 tons concentrated on a 0.5 m × 1.0 m area. There would be an 18 m wide, 12 m high door at the west end and a 14 m wide, 12 m high door at the east end of the building. Both would have smaller doors for access by trucks without opening the whole door to decrease the HVAC load.

Operations Building

The Operations Building (cf. SEFUR section 12) would be 26 m × 44 m on two levels to provide space for the operations center, Data Acquisition room, electronics room, a mechanical/technical room, and some office space. It would be situated very close to the cable shaft to minimize the cable lengths from the detector to the electronics housed in the Operations building. Special care would be required in designing the cable entry to control radiation originating in the hall.

Utility Building

The Utility Building (cf. SEFUR section 9) would be 24 m × 80 m and would house mechanical and electrical equipment for HVAC, chilled water, LCW, AC power distribution, DC power supply, emergency power, cryogenic refrigerator, and safety systems.

Interaction Regions 1, 4

User requirements for IR1 and IR4 were never developed because the smaller experiments to be placed in the west area were not as far advanced in planning as were the large experiments. See the section on Smaller Experiments below for a discussion of the Expressions of Interest received by the SSC. For planning purposes it was assumed that one area would have a modest hall, perhaps suitable for an experiment like the FAD.[10] The other area would be only the machine tunnel, suitable for a smaller experiment. Only modest surface facilities were anticipated. No construction work had been done as the project closed down.

Chapter 15. Test Beams

(D. Henning, J. McGill, and R. Schailey)

The development and operation of research detectors at the SSCL would have required extensive testing and calibration to be done by exposing the detector components to controlled sources of particles (p, mesons, e, μ, etc.) similar to those that would be encountered when the detectors were operating in the Collider. The SSCL designed a test beam facility to meet the needs of the proposed detector collaborations using protons extracted from the 200 GeV/c MEB (see *Test Beam 3A Specification*[1], E10-000042, for top-level test beam requirements and detailed design parameters).

General Layout

The test beam area comprised: (1) a half-integer resonant extraction system of MEB ring magnets consisting of 4 quadrupoles and 4 octupoles; (2) an extraction channel from the MEB M75 Utility Straight Section consisting of two electrostatic septa and two Lambertson magnets and a C-Magnet separated by 90° phase advance; (3) a primary beamline 500m in length, with switching (upgradable to splitting) capability to three independent targets; (4) three independent target stations with target drives and adequate shielding against ground water activation; (5) three independent secondary hadron or electron beamlines 500m in length; and (6) a Calibration Hall for mounting three independent test stands to support detector elements.

Slow Spill Extraction from the MEB

The MEB would operate in two modes: collider fill and testbeam. While in collider fill mode, the MEB would provide the next machine in the injector chain, the HEB, with a 200 GeV proton beam in single turn extraction (13 μs). In the test beam mode, a slow spill (1 second), half-integer, resonant beam extraction[2] would be used to provide a 200 GeV beam to three target stations. By exciting a mixture of quadrupole (Q242, CQ366, Q642, CQ766) and octupole (O338, O440, O738, O840) fields, the stable phase space area available to circulating beam would be gradually reduced in size until it equaled the beam emittance. At this point any further reduction would cause a fraction of the beam to become unstable. The particles would execute progressively larger amplitude betatron oscillations on each successive turn. At some point in phase space, the large amplitude particles would be intercepted by an electrostatic septum and deflected into two Lambertson septa for extraction. The two "corrector" air core quads (CQ366, CQ766) would be used to "smooth" the extracted beam current. They would use a beam current monitor, downstream of the extraction channel, as feedback for the excitation waveform.

Primary Optics

The primary beamline would use four sets of doublet quadrupole optics to transport beam through a number of limiting apertures until focusing the 200 GeV protons on any one of three independent target stations. The horizontal dipole magnets would be used to separate horizontally the three independent primary beams at both the target stations and the Calibration Hall. The vertical dipole magnets would be used for, first, bending beam up from the MEB to reach reasonably close to the surface and, second, bending the beam down to follow the terrain to the Calibration Hall. This would allow for passively "burying" the muon vector from the targeting stations. The nominal operating beam intensities would have a range of 1×10^{11} through 1×10^{13} protons per pulse. The operating cycle for MEB slow spill test beam would be 1 second pulse length of beam every 8 seconds.

Targeting Systems

General Layout

Secondary hadron (p, π, K, ...) and lepton (e, μ) beams would be produced from 200 GeV protons on three independent targets. The secondary beams would come off these targets at a production angle of 5 milliradians, allowing for the elimination of non-interacting protons. The momentum selection would be done by a four bend achromat in the secondary beamline. The solid angle acceptance would also be determined by magnet apertures in the secondary beamline. Consequently, the hole in the primary beam dump, which defines the secondary beamline, would match the solid angle acceptance of the secondary beamline.

For electrons, a sweeper magnet, just downstream of the production target, would be energized to sweep all charged particles away from the hole in the primary beam dump, which would define the secondary beamline. Photons, which pass through the beam dump hole, would be converted with a thin piece of lead to yield $\gamma \rightarrow e^+e^-$. The electrons would be selected by the polarity of the secondary beamline. The purity of the electron beam, relative to pion contamination, was still being studied as the project ended. The goal was to deliver a 1000:1 purity ratio for the $e{:}\pi$ electron beam to the Calibration Hall. For hadrons (p, π, K, ...), the sweeper magnet, just downstream of production target, would not be energized. Charge selection would be given by the polarity of the secondary beamline. Purity of hadron beam, of 1000:1 ($\pi{:}e$) would be obtained by eliminating electrons at the intermediate focus with a thin lead degrader.

Particle Production

(W. Burgett)

The calibration of the SSC detectors required both a hadron and an electron test beam to be generated by letting an extracted 200 GeV proton beam be incident on an aluminum target (see *Test Beam 3A Specification,*[1] E10-000042, for exact layouts and parameters). Aluminum was selected as the target material based on both safety and production criteria. Although beryllium is superior to aluminum in terms of production and has been used at other facilities, it was deemed unacceptable because of its carcinogenic nature. Beryllium oxide was considered as an alternative to aluminum, but it hadn't been adequately studied at the time of project cancellation.

Because of the requirements to switch efficiently from a hadron beam to an electron beam (within a few hours), plus allowing for the flexibility to change targets and direct beams to different calibration experiments, the targeting system designed for the test beams consisted of three target stations enclosed in a shield of steel and concrete. The target pile was to be located at a point approximately 500 m from the MEB and 500 m from the Calibration Hall where the detector components were to be tested.To calculate the optimum length for the targets, a formula was used that optimized the competing processes of production versus target transmission.This optimization concluded that the target length for the pion test beam should be 39.4 cm, which is easily shown to produce the required 10 MHz pion flux for the expected incident proton flux.

For the electron beam, the incident protons would interact in the aluminum target to create neutral pions, which subsequently decayed into two photons. The photons that made it out of the target, and through the production hole located at 5 milliradians off-axis with respect to the incident beam, would then be incident on a lead converter to produce electrons via pair production. For this case, the requirement was to optimize pion production and photon transmission in the aluminum target. The optimum target length was determined to be 20.1 cm.

Secondary Optics

The secondary beamline optics used two sets of doublet quadrupoles in a two stage, point-to-point scheme. The first doublet was used to collect flux from the production targets and to place a momentum dispersed focus at the middle of the secondary beamline. The second doublet placed the final focus in the Calibration Hall. A four bend achromat for momentum selection of secondary beam of 2 GeV/c through 170 GeV/c was placed between the quadrupole doublets. The acceptance, solid angle, and momentum bite, were driven by magnet apertures and determined by the ray-tracing code TURTLE. The magnet settings were "fitted" with the beam transport code TRANSPORT.

Tagging Instrumentation

(H. Fenker)

Precise calibration of the detectors for SSC experiments, as indicated both explicitly and implicitly in their respective design documents, required beams of particles that are identified and momentum analyzed. In this context, identification meant determination of the particle species (hadron, electron, muon). Generally, the identification efficiency and momentum precision required of the beamline were similar to or somewhat better than those that would be achieved by the detector element under test. See the Test Beam PDRR notes[3] (PDRR held 11/20/92) for details of the requirements.

Design Plans

Momentum tagging, which was always constrained by the final bend angle as defined by the optics of the entire beamline, would be accomplished with three 50 micron pitch silicon strip detectors. These would be arranged with one detector plane upstream of the final bend and two downstream of it. Species tagging, specifically electron/pion separation, would be provided by a combination of Transition Radiation Detector (TRD) and Synchrotron Radiation Detector (SRD) to cover the entire momentum spectrum up to 200 GeV/c. Muons could be identified by a scintillation counter placed downstream of a beam stop or shielding wall. The TRD was capable of cleanly identifying electrons in a background of muons and pions up to an energy of about 70 GeV. Above this energy there was sufficient synchrotron light radiated by electrons deflected by the 8 milliradian analysis magnet for the SRD to tag them efficiently. Cerenkov counters were considered but passed over as not covering a useful momentum range when constrained to fit within the planned beam optics.

Design Status

The system described above was designed by considering "average" properties of devices and beam particles. The design was tailored to provide the tagging precision and efficiency required of the SSC experiments. A plan for thorough simulation and certification of these tagging systems was developed, but it was curtailed by project termination. The plan involved modeling the operation of the beamline elements and detector systems. Effects such as multiple Coulomb scattering, photon absorption, backgrounds, detector inefficiencies, and magnetic field variations were to be included. An early stage of simulation revealed that the system proposed would provide the required momentum tagging precision if statistical requirements could be met. These statistical requirements established a minimum amount of data that would be needed at each of the several beam momenta and therefore determined the operation of the detector calibration program. Thus, full certification of the tagging system plans would have required approval of the resulting operations program by the experiment collaborations. The primary difficulty to be carefully modeled involved precise momentum determination. Here the combination of small magnetic deflections and noticeable thickness of the silicon strip detector planes combined to set a lower limit on the momentum resolution. Particularly at energies below 20 GeV it would be necessary to accumulate a large sample of events so that the inherent response function of the beamline spectrometer could be unfolded from the observed response of the test detector. Implementation of the silicon strip planes was largely a matter of specification and procurement. Vendors (Micron and Hamamatsu) interviewed could see no difficulty with the proposed installation, including insertion of the silicon into the beamline vacuum.

Species identification by the SRD was reasonably straightforward. Sufficient light was generated at beam momenta above 75 GeV/c to provide better than 100:1 electron tagging within a pion background. This ratio was better at higher energies and was worst in the region where both the TRD and SRD are useful. Thus the full energy range was efficiently covered by the combination of both TRD and SRD at the intermediate energies. Simulation was needed to provide statistical information relating to the loss of SRD signal through absorption of photons by the silicon, or to beam halo backgrounds. Engineering design of the SRD itself, however, had been completed. The TRD for the SSC test beams was to be essentially a copy of a device existing at Fermilab[4]. This is a modular design that can be expanded as needed to provide the required level of particle discrimination. No further design or simulation of the TRD was carried out at the SSC.

Calibration Hall

(K. Schlindwein)

Requirements

The design requirements of the Calibration Hall were developed in conjunction with the specifications of the test beam and in cooperation with the SDC and GEM Collaborations. The configuration of the initial construction of the Calibration Hall provided the operational environment, counting rooms, shops, and staging areas to support 200 GeV MEB test beams at the SSCL. Provisions were also made in the facility design to allow for expansion to accommodate possible future 2 TeV beamlines originating from the HEB. The areas immediately to the north and west of the facility were kept clear of structures and utilities to allow for this anticipated expansion. Permanent office and conference facilities were not provided in the initial construction, but the use of temporary modular structures was anticipated. Versatility and expandability were key to the philosophy of the Calibration Hall design development.

Design Criteria

Rationale for the Calibration Hall design criteria was initially defined in the *SCDR*[5] of the SSCL. The Conventional Construction *Design Requirements Document* [6] further refined requirements for preliminary design. As the test beams evolved and the needs of the facility users were better understood, the Experimental Facilities Department prepared the *Calibration Hall Requirements*,[7] which represented the final state of the facility design criteria.

Three beamline bays were designed to accommodate the detector testing and calibration needs of the SDC, GEM, and the small experiment groups of the SSCL. The criteria established were to provide dedicated beamlines with independent control and operational capabilities for each experiment. Independent counting room facilities and separate utility interfaces were provided for each beamline. Each experiment bay was designed to be independent of neighboring beam conditions. Provisions were made to adequately shield for radiation, provide for individual egress, and incorporate the use of Personnel Access Safety Systems (PASS) during operations. Removable shielding was to be used for beamline separations and other areas where shielding reconfiguration was anticipated.

Design Status

At the time of project termination, the conventional construction contract bid documents and the first contract addendum had been issued. Addendum No. 2 for electrical loads and distribution changes to the Calibration Hall was pending. Most technical system designs were ready for review. The following requirements were documented at the time of project termination: *Mixed Chilled Water*[8] and the *Preliminary Safety Analysis.*[9]

Radiation Safety Design

(J. Bull)

The shielding for the test beams, including the Target Hall and the Calibration Hall, was designed in accordance with the design guidelines expressed in the *SSCL Environment, Safety, and Health Manual.* [10] In summary, those guidelines recommended that the annual radiation dose equivalent be less than 20 mrem/yr for open areas, including all outdoor areas, and 200 mrem/yr for controlled areas. In addition, a catastrophic beam accident should result in no more than 10 mrem per incident in open areas, and 100 mrem per event in controlled areas. Per SSCL practice, the design of permanent shielding, such as berms and labyrinths, for the test beam facility up to the calibration hall was based on the high-intensity test beam facility (5×10^{13} protons per pulse) described in the SCDR.[4] A total of 3×10^{20}, 200 GeV protons could be incident on one target each year. Designing to this beam current would allow upgrades over the initial beam intensities without forcing major civil reconstruction. The secondary beam intensities were based on the amount of beam that could be transported down the beam lines. The calibration hall, however, was designed for an average beam current, which is 10% of the maximum, 10^6 protons per pulse every 8 seconds.

In most instances, the shielding requirement was incorporated in the civil construction design. The test beam enclosures and beam lines prior to the target hall were placed deeper than the 27 ft of cover required to meet the controlled area requirements. After the target pile, the shielding requirements were mostly determined by the muon flux from the target, requiring 30 feet of cover down to a point halfway between the Target Hall and the Calibration Hall, where the cover requirements were reduced to 20 ft of compacted fill. However, high beam losses would be possible at the magnet enclosures, requiring additional shielding measures in these areas. A major difficulty in the shielding design of these enclosures was the need to provide adequate radiation protection and still meet the egress requirements for underground enclosures. This was solved by incorporating several multilegged labyrinths to reduce the dose equivalent at the surface, and yet still allow unhindered egress for emergencies.

The shielding for the target pile itself was determined by groundwater activation requirements. The design guidelines for groundwater activation state that federal drinking water standards be met one meter from the outer enclosures. For the targets piles, 150 cm of steel was required to meet this guideline for the high-intensity beam currents. The top of the piles were then to be covered with over 4 m of concrete to reduce the annual dose equivalent to controlled area levels inside the target hall. In the calibration hall, 6ft-wide block walls were to be put in place to allow access into one experimental pit while beam was available to the others. At the surface, most of the area, including the counting rooms, was designed to meet open area criteria through the use of shielding walls and setbacks away from the experimental pits.

PART III. PHYSICS RESEARCH

Introduction

(F. Gilman)

The initial round of SSC experiments was planned to explore the range of physics opened up with the operation of a proton-proton collider with a center-of-mass energy of 40 TeV and a luminosity of $10^{33}cm^{-2}sec^{-1}$. For the major detectors that were proposed with the capability of investigating physics at the highest accessible mass and transverse momentum scales, detector collaborations and construction projects of unprecedented size and complexity were required. Each of the large detectors could be considered as a major laboratory in itself, with over a thousand collaborating scientists, a full scientific program, and a construction cost of hundreds of millions of dollars. At the same time there were the added complications of starting a new laboratory, dealing with collaborations and construction projects of a multinational character (roughly half of the participants were from non-U.S. institutions), and the fact that the detector projects had to be successfully embedded in the overall SSC Laboratory.

It was necessary to establish an appropriate management and organizational structure to deal with the technical, financial, schedule, safety, and other aspects of the construction and commissioning of the initial round of detectors. The structure had to allow for decentralized design and construction of the detector subsystems (and for similarly decentralized physics analysis at a later stage), while providing centralized overall detector project management to integrate the detectors and other aspects of the experimental program into the SSC project and to bring the detectors and related facilities into operation with the Collider itself, on schedule and within budget. Responsibility for implementation of the experimental program and all the closely associated elements was placed within the Physics Research Division (PRD), and formalized in a Project Management Plan for Detectors that described the detailed responsibilities and interrelationships of PRD and the rest of the SSC project.

The following were the major elements of the experimental program.

1) *An extensive program of detector R&D that was initially launched as part of the work of the Central Design Group.* An SSC Detector R&D Committee of international composition provided expert advice on the program to the head of the Physics Research Division. During 1990 much of the generic detector R&D program was being completed and the next step, a program of detector subsystem R&D, was begun. The latter program was continued on an expanded scale in 1991, after which it was, to a large extent, merged into the engineering/R&D efforts of SDC and GEM for those technologies that had been incorporated into the respective technical design reports. R&D support for smaller experiments continued until the termination of the project. Complementary funds were provided to university groups working on the SSC detectors by the TNRLC. The detector R&D program (see the discussion below in this chapter) was successful in moving from the 1980s, when questions were raised about the possibility of operating large detectors at a hadron collider with a luminosity of $10^{33}cm^{-2} sec^{-1}$, to those of the 1990s, when competing technologies were established for many detector subsystems at $10^{33}cm^{-2}sec^{-1}$, and the state-of-the-art was pushing operation at $10^{34} cm^{-2}sec^{-1}$.

2) *The Experimental Facilities Department of PRD that was responsible for providing the technical specifications for experimental facilities, planning and conceptual design for test beams, and specialized and general engineering support for the detector projects.* Most of the specifications and designs were complete when the project was stopped, as described in Part 2, and the resulting facility user requirements documents had been transmitted to the Laboratory's Conventional Construction Division for implementation.

3) *The Computing Department of PRD, with responsibility for the plan, design, implementation, and operation of the off-line computing systems needed for detector design and data analysis and storage.* Upon the advice of the SSC Computer Planning Committee in 1990, the Physics Detector Simulation Facility (PDSF) was developed within PRD. This facility employed fiber-linked processors from RISC/UNIX workstations. With non-proprietary systems that conform to industry standards, PDSF proved to be a cheap and easily upgradable system that provided the primary computing power for a worldwide effort to simulate physics processes in potential SSC detectors and to optimize their design. The first stage of PDSF was implemented in 1991, and it was upgraded twice so that it provided a computing power of 7000 MIPS at the time of project termination (See Chapter 36). The prospective data rates for large SSC detectors (1 to 10 terabytes per day) presented challenging problems in data storage and accessibility and in obtaining the raw computing power needed for data analysis, but those problems seemed tractable given expected advances in computing technology and the likelihood that solutions would be in place in time for detector turn-on.

4) *Two major detectors, SDC and GEM, that were under design and construction of subsystem prototypes.* The detector program was the result of a process that started with Expressions of Interest first submitted in May 1990. Four collaborations proposed large detectors: SDC, L*, EMPACT, and TEXAS. At the next stage of submitting Letters of Intent in November 1990, EMPACT and TEXAS joined forces. Through a careful process of evaluation involving the PAC, SPC, and Laboratory management, SDC was given approval to develop a full Technical Design Report; subsequently, first EMPACT/TEXAS and then L* were not given approval to do so. In 1991 a new collaboration, GEM, was formed. It submitted an Expression of Interest in July 1991 and a Letter of Intent in November 1991, and was authorized to proceed to a Technical Design Report. The SDC Technical Design Report was submitted in April 1992 and received an intensive review, first by the PAC and outside experts, and then by a DOE team. The GEM Technical Design Report was completed approximately a year later and was in the process of a similar review when the SSC project was terminated. These two major detectors were designed to be complementary and competitive: SDC had design goals that emphasized charged particle tracking, hermetic calorimetry, lepton energy measurement and identification, and vertex detection; GEM in contrast had design goals that emphasized identification and precision measurement of gammas, electrons, and muons, with capabilities for higher luminosity. No outstanding technical problems stood in the way of constructing either detector. Further details are given in the discussions of these detectors below.

5) *Smaller experiments that were seen from the beginning as an important part of the initial SSC experimental program, adding diversity and important physics at comparatively low momentum transfer and mass scales.* Funds were set aside for these experiments, and two interaction regions on the west side of the ring were to be used for their deployment. A number of Expressions of Interest were submitted, including several that considered exploring *B*-physics at the SSC in either collider or fixed target mode. These are also discussed in more detail below.

6) *Strong in-house groups of physicists that were seen, from the beginning, as necessary to carry out successfully the design, construction, and operation of the major experiments.* The scale of the major detectors for the SSC meant that not only the final phase of construction of the whole detector, but certain subsystems such as full size muon modules, had to be to be completed at the host laboratory. Laboratory physicists participated in the tasks associated with the design and integration of the experiments, served as liaison between the collaborations and other organizations inside the SSCL, provided for coordination and commonality between detectors, and made their own contributions to high energy physics research both inside and outside the SSCL. As the project ended, there were approximately 60 experimental and theoretical physicists within PRD, either members of the SSCL scientific staff or guest scientists.

In providing overall management of the activities above and carrying out its responsibilities, PRD sometimes used previous organizational models or extended them to meet the new scales. In other cases, different solutions were developed to deal with the scope and unique character and constraints of the SSC project. Scientific advice was received from the PAC and SPC, as well as from a number of other committees that provided input in particular areas (such as R&D or computing) or on specialized issues. Liaison and coordination were established with other parts of the Laboratory on matters such as the accelerator/detector interface, conventional construction, safety, quality assurance, systems engineering, and issues related to financial reporting and monitoring. The project managers for the SDC and GEM detectors, were senior members of the respective collaborations who headed departments within PRD, as did the managers of experimental facilities and computing. A heterogeneous mixture of physicists and other technical and support personnel was to be found in each of the PRD departments so as to integrate physics requirements with state-of-the-art technology. As the project ended, the major detectors, experimental computing, and experimental facilities were proceeding as planned, with no known significant technical obstacles still to be overcome.

Chapter 16. The SDC Detector

(T. Thurston, R. Houde, M. Piazza, T. Prosapio)

Brief History

The Solenoidal Detector Collaboration (SDC) grew out of several initially independent U.S. efforts concentrated at LBL, ANL, and Fermilab, all with strong university participation. It also drew on the simultaneous activities of a number of Japanese high energy physicists who organized and participated in a series of workshops in Japan. All these studies were aimed at the design of a solenoidal detector for doing high-p_t physics at the SSC. At a workshop held in Fermilab in September 1989, the various groups, finding much commonalty in their designs, decided to combine their activities and form a single collaboration to prepare an Expression of Interest (EOI) for submission to the SSC Laboratory. A governance document was drafted, discussed, and modified at the first collaboration meeting in December 1989, and ratified shortly thereafter.

The SDC submitted its EOI in May 1990, presented its design concept to the SSCL PAC in June, and responded to ensuing PAC questions in July. The SSCL responded by requesting that proponents of large high-p_t detectors combine forces where appropriate and submit Letters of Intent (LOIs) by the end of November. The SDC submitted its LOI, and made its verbal presentation to the PAC in December. In January 1991, the SDC detector was approved to proceed to develop a full Technical Design Report.

When the SDC was initially formed in 1989, it sent out a letter to the international HEP community inviting interested collaborators to join. After the birth of the Collaboration, a large number of new institutions from both inside and outside the United States joined the SDC. The collaborators at time of termination, including physicists and engineers, numbered about 525 from within the United States and 330 from outside the United States.

Motivation

The term "solenoidal detector" referred to a substantial cylindrical volume, concentric with the beam, surrounded by a solenoid coil and filled with tracking detectors. The system was capable of measuring precisely the momenta of charged tracks emitted from the interaction, within the detector's very large angular acceptance. On the outside of the solenoid was a hermetic calorimeter with fine-sampling electromagnetic sections and somewhat coarser hadronic compartments, and with a special finely segmented detector near electromagnetic shower maximum. One of the major goals was to have excellent electron identification and precise measurement of the energies of isolated electrons and photons. To avoid degradation of these energy measurements, the solenoid coil was designed to be very "thin," and through special weighting of the signals from the first calorimeter detection layer, it was expected that even further such degradation could be reduced. Outside the calorimeter was an extensive muon system, including magnetized iron toroids, tracking chambers and scintillation counters, to provide muon identification, trigger capability, and in combination with the inner tracker already mentioned, excellent momentum resolution. The precision calorimetry and tracking systems extended to pseudorapidities of 2.5, and more coarse hadronic calorimetry went out to pseudorapidities of 6, to allow detection of non-interacting neutrals through the measurement of overall missing transverse energy.

The detector design built upon the successful Colliding Detector Facility at Fermilab (CDF) experience. Its aim was to enable the measurement of the largest possible number of independent quantities for each trigger event. They included identification, sign of charge and energy measurement, detection and measurement of isolated photons, measurements of jet energies and directions, identification of jets with b-hadrons, determination of charged particle multiplicities, and detection of non-interacting neutrals. It was the ability to combine all these elements of information simultaneously for a given event that gave the SDC detector its unprecedented power, both in the ability to establish (rather than just suggest) new unexpected phenomena and in the redundant identification of interesting processes predicted by current models. If past experience with collider detectors (both hadron and electron positron) had shown anything, it had demonstrated abundantly that with multiple independent capabilities, a detector is far better than the sum of its parts or subsystems. Since the expected ratio of interesting events to backgrounds would be far smaller at the SSC than in current colliders, all the capability that could be provided would be needed.

Clearly the design choices for such a detector always represented a balance between physics needs and available resources. The twenty-fold increase in energy and nearly 1000-fold increase in luminosity relative to the present Tevatron experience introduced unprecedented demands on speed-of-response, pattern recognition capability, excellent momentum resolution, and segmentation adequate to identify fine structures. The intent was to measure quarks and gluons (jets), leptons, photons, and individual hadrons. There had to be superb monitoring and calibration capability to ensure proper performance of all subsystems. The HEP community could not afford many such detectors, hence the detector had to be sufficiently robust and resistant to radiation damage to promise good performance over many years. Finally the potential for luminosity increased beyond the design value of $10^{33}cm^{-2}s^{-1}$ had to be considered. The detector had to be capable, with manageable modifications, to operate at higher luminosities up to $10^{34}cm^{-2}s^{-1}$ with sufficient functionality to attack those physics problems whose study would require the higher luminosity. It was believed that the proposed detector met all those qualifications. Furthermore, in defining the scope of the detector and doing cost/performance optimization, differentiation had to be made between scope reductions which, if the need arose, could later be removed through upgrades, and those other scope reductions whose effects would remain forever. Among the latter were such issues as central tracking volume, iron toroid thickness, and calorimeter depth. Even though savings could be achieved through reductions in those parameters, it was felt that such reductions below the levels proposed in this document could have led to unacceptable technical and performance risks. The detailed subsystem section of this chapter are an attempt to justify these parameter choices.

Technological Choices

When the SDC detector was first presented in the EOI, there were listed, among others, five potential technologies for the central calorimetry and two for the outer central tracking (where yet another choice was a hybrid of the two). The R&D programs sponsored by the SSCL, beginning with the generic R&D and continuing with the large subsystem efforts, eventually leading to the detector specific R&D activities current at project close, provided much of the technical bases for making informed choices. The criteria for choosing particular technologies included feasibility, adequacy of performance, survivability, acceptable technical risk, affordable cost, and, finally, the strong interest of members of the SDC to build with the chosen technology.

The technological choices for the SDC detector were made via an involved process. The decision process in most cases involved the definition of requirements for the systems in question, the preparation of Conceptual Design Reports by the proponents of the various technologies, oral presentations, recommendations by a technically well qualified ad hoc review committee, review and recommendations by the SDC Technical Board to the Collaboration, and final ratification by the SDC Executive Board.

The Collaboration

From its inception, the SDC involved a close partnership between physicists from the United States and physicists from other countries. The original steering committee that wrote the draft bylaws had British, Italian, and Japanese as well as U.S. members. Over the last two years, additional groups from the United States and from Brazil, Canada, China, France, Israel, Italy, U.K., and from countries in the former Soviet Union and from Eastern Europe joined the collaboration. These groups provided essential intellectual capital and important financial resources. Given the limited detector resources available through the SSC Project, the SDC had to add those resources as extensive in-kind contributions from its non-U.S. members if it was to produce a detector with all the needed capabilities.

In the preparation of the EOI, LOI, and the Technical Design Report, the SDC governance was exercised through the Spokesperson, Acting Project Manager/Technical Manager, three Deputy Spokespersons, and three different bodies (Boards) with separate roles. The Institutional Board, with one representative per collaborating institution, dealt with general issues of collaboration membership and the conduct of elections for the Executive Board. The latter, which consisted of 17 elected members of the SDC as the project ended, dealt with all issues of scientific policy, approved all important appointments to positions of responsibility, and also approved major technical decisions. Finally the Technical Board, appointed by the Spokesperson and Project Manager with the approval of the Executive Board, consisted principally of the leaders of the subsystem activities as well as other experts. The Technical Board made recommendations on all major technical and technological decisions. As the project moved to the construction phase, a new management organization was to be put into place to oversee the final design and fabrication of the detector.

Summary

The last three years of the project saw increasingly intense efforts by the SDC to design a detector adequately matched to the immense opportunities opened up by the construction of the SSC. While its design had drawn on recent experience with the Tevatron, the large increases in both energy and luminosity required an instrument vastly more ambitious than any built in the past. By requiring excellent capabilities in tracking, calorimetry, and muon systems, the SDC believed that its proposed detector would embody maximum redundancy, an essential feature for establishing rare new phenomena in an ocean of backgrounds. The process of establishing potential responsibilities for non-U.S. collaborators was well under way at termination, but formal approval from the relevant funding authorities was still to take some time. The specific apportionment of U.S. responsibilities among national laboratories and universities was to be accomplished during 1994. As the project ended, the SDC was prepared to meet the schedule of collider turn-on for physics in late 1999 with a detector properly matched to SSC opportunities and with a team ready to exploit the physics.

Project Status at Termination

The SDC project submitted a Technical design Report (TDR) and received Stage I approval to proceed to final design. At SSCL termination, the project was proceeding towards Stage II approval which would allow the fabrication of detector components. The remainder of this section outlines the status of each of the major SDC subsystems at the point of SSC termination.

Silicon Tracker

At the SSC shut down, the silicon tracker group had attained several major accomplishments necessary for the construction of a device for use at the SSC. In addition, several long lead time items needed for the fabrication were close to completion, needing only about one more year to be ready for use. The primary R&D accomplishments were in the demonstration via a beam test of the first prototypes of the front-end electronics system and silicon sensor. In addition the devices were evaluated in radiation, which assured their functionality in the harsh SSC environment. At termination, the second prototype versions were in the middle of preparations aimed at needed improvement upon features of the first prototype. Improvements involved using a faster front-end system to reduce time walk and a somewhat improved detector implantation structure to reduce voltage breakdown. The goal was that the second prototypes should be very close to the final devices required to begin construction. In the area of construction, setting up test facilities for module tests at several sites was far along. The machine needed for producing assemblies was also close to completion at Los Alamos, where, in addition, the laser holography system required for micron scale measurements over a wide field of view had been successfully tested.

Finally the work on heat removal had been partially completed. The evaporative cooling concept had been demonstrated to work using carbon wicks. Work on liquid cooling had begun with the goal of allowing a comparison between the two techniques. A decision between the two, one of the remaining critical decisions needed to complete the conceptual design, had been planned for what turned out to be the Laboratory's final year. The remainder of the conceptual design had been largely completed, including, the dimensions of all assemblies and the sizes of the units they would be made out of.

Straw Tracker

At termination, the straw outer tracker system had been chosen as the baseline system for the SDC detector, and design of the straw modules themselves was nearing completion. The carbon fiber epoxy foam laminate shell design was nearly complete, and inspection procedures were being developed with the company. The overall layout of the outer tracking system was being redesigned with the inner superlayers moved to larger radii. The support cylinders and support structure were being modeled, and prototype work was being done by two companies under the engineering direction of the Westinghouse Science and Technology Center (WSTC). The shim rings that attach straw modules to the support cylinder were under development, and a prototype module attachment had been developed by WSTC and Oak Ridge National Laboratory.

Prototype modules had been assembled at Duke University, Indiana University, and University of Colorado/Colorado State University. Four of these modules were tested in a beam at Brookhaven National Laboratory in July 1993, using front end electronics developed at the University of Pennsylvania and drift time measuring electronics (TMCs) developed at KEK in Japan. At the time of termination, beam test data were being analyzed, and tests were being carried out in university laboratories to understand further the module performance. Areas still requiring further understanding were drift gas, wire diameter, endplate connections of the wires to the front end electronics, internal termination of the wires, and operation with baseline-restoring high-rate front end electronics. These areas were being further investigated as part of the close-out work, and final results are to be made available in a publication.

Intermediate Tracker

The baseline technology for the Intermediate Tracker Detector (ITD) was Gas Microstrip Detectors, a new technology as yet unproved in large-scale experiments operating at colliders. For this reason a back-up detector using Silicon microstrip detectors was also under study. A tracking layout using either Gas or Silicon microstrip detectors had been designed. Preliminary, but not full, simulations of the tracker with detectors of both technologies had been made. They indicated that, for similar cost, the Gas Micro strip Detectors would yield a small but significant performance and redundancy advantage over the Silicon micro strip detectors.

The gas microstrip detector R&D was being carried out at collaborating institutes in Canada, the UK, and the United States. Considerable progress had been made. The initial problems of loss of gas gain with time after turn on and rate limitations had been solved, and a remaining problem of aging was well on its way to solution. Prototype detectors of the appropriate size had been built and operated. The detailed performance characterization of the large area detectors, the largest ever built, had started. Smaller detectors had been operated in a test beam at CERN. These demonstrated the rate capability, position and time resolutions, and provided the information necessary for detailed design work on the front end electronics to start. This R&D was still continuing with a view to using gas microstrip detectors in the two experiments (ATLAS and CMS) being planned at the Large Hadron Collider (LHC).

Engineering conceptual design work for the ITD was nearing completion, and detailed design was about to start. Significant progress had been made in the characterization of materials combining high strength and stability with low mass and long radiation length. The progress made has been valuable in the mechanical design work currently going on for the ATLAS experiment at LHC.

Scintillating Fiber Tracker

The Fiber Tracking Group (FTG) completed and published the results of four major experimental tests of the concepts required to achieve charge particle tracking and triggering in the extreme environment expected at the SSC. Two of the experiments were conducted using cosmic rays, and two were conducted in test beams at Fermilab and Brookhaven.

Each major experiment that was completed verified that although fiber tracking is a new technology its application and performance is superior to older approaches to tracking. Experiments proved that high resolution was achievable by correlating to high precision the fibers in the tracking system. Fourteen-meter-long fibers less than 1 mm in diameter were capable of producing enough light for high resolution tracking. The results showed that the light yields were a factor of ~3 larger than required, providing a comfortable safety factor in the construction of a large system. Furthermore, a low density stable base support system was suitable for SSC tracking, and a VLPC cassette could have been designed to meet the high density required of the SSC. The fourth generation visible light photon counters (VLPC) exceeded the performance requirements of the fiber tracker system. A sub-cooled liquid Helium cryostat could be designed and was expected to operate in the confined space of a solenoid detector. Multiclad fiber and high transmission optical splicing could be produced, and a fiber tracker in the SSC environment gave excellent performance based on simulation results of test experiment data.

Calorimeter

At the termination of the project, most of the central calorimeter subsystem was in final design and preparations were being made for production. The barrel calorimeter was most advanced. A pre-production prototype barrel wedge module was being assembled. The lead absorber for the EM section of the prototype designed by ANL and Westinghouse was nearly ready for casting. A prototype steel hadron absorber module had been manufactured in China under the supervision of IHEP Beijing and had been shipped to Fermilab. A second module was in fabrication at Fermilab. Tooling parts for the mating of the lead EM and steel hadronic sections had been received and were ready for setup. The tiles and fibers for the EM section had been designed by ANL and Tsukuba and were ready for fabrication by Japanese industry. Tiles and fibers for the Chinese wedge had been shipped from Japan to Fermilab for assembly of the prototype.

The endcap EM section was in advanced design at LBL. Beam tests at CERN were under way to verify performance of the EM, its calibration, and its readout system. The tests also included models of the shower max detectors to be made by Saclay for both the barrel and endcap EM calorimeters. The design of the endcap hadronic section was under design by engineers at Fermilab and Dubna, and the scintillator tile arrays for the endcap hadron calorimeter were under design at Pisa.

Photomultipliers for the EM and hadron calorimeters had been selected and the base and readout systems had been designed at Fermilab. The multichannel photodetectors for the shower max being developed by Minnesota, UCLA, and Northeastern were under test. Preparation for cosmic ray and beam tests of the prototype were under way at SSCL, UTA, Purdue, VPI, and Argonne. The components included the source driver calibration systems, light flashers, a cosmic ray test stand, and a data acquisition system. A large-scale effort to develop radiation hard scintillators for the end cap calorimeters was under way at FSU, Michigan, Fermilab, IHEP, and ANL.

Forward Calorimeter

At the time of termination, the high pressure gas calorimeter system was undergoing conceptual design and prototype testing. A prototype tube hadronic calorimeter was tested successfully at CERN in July 1993. It was filled with 95% Ar + 5% CH_4 gas mixture at 100 atm. Signals were read out by fast and low electronic noise preamplifiers designed and constructed by the high pressure gas group. The calorimeter proved very safe and performed reliably throughout the beam test. Preliminary results for the test beam data analysis show that, though adequate for the SDC forward calorimeter, design modifications could significantly improve the performance of the calorimeter. A preliminary design for an improved prototype EM calorimeter was produced, and techniques for manufacturing were developed. Testing of the new design was not conducted.

Extensive radiation damage tests on high pressure gases and on components of the proposed calorimeter were also performed successfully. Radiation damage and beam tests showed that high pressure gas calorimeters, based on the proposed design, were safe, fast, radiation hard, and cost effective, and that they could successfully operate at the very forward region of the high energy, high luminosity colliders.

Muon System

The final design of the muon barrel toroid Magnet was nearly complete. The magnet design featured a large block, bolted design with a minimum solid angle support system, quick and easily certified assembly, and a very reliable design. The coil design was innovative and again had quick certifiable assembly. Substantial progress was made in chemistry and material specifications for Russian steel for use in magnets. The Russian suppliers were able meet the specifications, and working relations were developed with personnel in both Atommash fabrication facility and the Novolipetsk steel production facility. Two prototype blocks had been completed and tested. Production was expected to begin in the summer of 1994.

The muon modules consisted of large assemblies of drift tubes and support structures. The drift tube design was complete, and production facilities were being set up in the Washington and Boston areas. Material was on hand to begin initial production and certification of the production process. Design of the barrel and intermediate prototype modules was also in process.

A good mathematical model of the alignment system was created to better understand error budgets and the interaction of components. Several devices were prototyped and were being prepared for testing. The alignment system included a liquid level system, concatenated Straight Line Monitors (SLM), and Range Emitter-Receiver (RER) heads that were configured to provide placement information of the entire muon and tracker system. A systematical effort to understand the source and magnitude of the background radiation problem was under way. This included the first comparison of U.S. and Russian transport codes as well as a careful look at detector response to these backgrounds.

Superconducting Solenoid

Most of the prototype magnet was funded and produced by Japanese collaborators, led by Akira Yamamoto. The prototype magnet was completed at Toshiba Company in late November and tested briefly before being shipped to KEK National Laboratory for High Energy Physics in Tsukuba, Japan.

At KEK, the magnet was connected to power and cryogenics facilities and cooled. Once the mechanical and thermal integrity of the magnet was checked, it was ramped to 10,000 A and the liquid helium coolant flow was stopped. As the magnet warmed up, a quench occurred at 6.35 K, exactly as predicted. Then after several training quenches, the maximum current before quench was 11,250 A, compared to the nominal design current of 8,000 A. It was found that the source of the quench was not the main coil, but rather at the interface to the chimney portion of the cryostat, where there was less mechanical support and cooling. All quenches occurred within acceptable parameters and resulted in no damage. The preliminary performance figures indicated that the full-size solenoid would perform at SDC parameters with a large safety margin and showed that the solenoid subsystem was one of the great successes of the SSC project.

Electronics

The Electronics Subsystem of the SDC Experiment encompassed three major subsystems: (1) Front-End Electronics, which interfaces directly with the detector elements (e.g., drift chamber wires and PMTs) and processes and buffers the detector signals for subsequent readout; (2) Real-Time Systems, which consist of the hardware and software that reads out detector data from the front-end electronics, stores data onto permanent media, and controls the operation of the detector; and (3) Trigger Systems, which provide the timing control of the front-end electronics and the selection of events that will be read out and stored.

The primary challenges to the Front-End Electronics of SDC were the requirements of speed (to match the 16-nsec bunch crossing interval), deep fast event buffers (to store approximately 256 16-nsec crossings), large channel counts (hundreds of thousands of channels per detector subsystem), and in some cases radiation hardness or radiation tolerance. The challenges were being addressed by an aggressive R&D program in custom integrated circuit development. A set of custom analog and digital ICs, as well as a system design, was under development for each detector subsystem (silicon microstrips, gas microstrips, straw drift tubes, scintillating fibers, scintillation calorimetry, and muon drift tubes). No fundamental limitations had been encountered, and, in all cases, advanced (but not yet final) prototype ICs existed.

To address the new challenges of SSC data acquisition and on-line computing, Real-Time Systems were actively studying applications of emerging commercial technologies from the communications and computer industries, such as high-speed data switches and fiber optic systems. A small number of candidate technologies had been identified and were under study. In addition, behavioral modeling of data acquisition architectures was under way using advanced modeling techniques. Completed software components were in the process of being integrated to provide the first complete model of the entire SDC data acquisition architecture when the SSC was terminated. Another major effort within Real-Time Systems was the development of a flexible data acquisition system suitable for many different laboratory and test beam installations and based upon UNIX workstations. This "portable" DAQ system, including all software, was operational at least twelve installations within SDC (including some at CERN and KEK).

To address the formidable challenge of triggering an SSC detector, SDC adopted a multilevel architecture incorporating technologies that spanned a range from custom digital integrated circuits for addressing decision making at the 60-MHz SSC crossing rate, through embedded processors for decisions to be made on the time scales of hundreds of microseconds, all the way to powerful farms of commercial microprocessors for performing the final sophisticated event selection on processing time scales of seconds. This architectural solution required an active program of studying the physics requirements of the trigger (i.e., the trigger goals of the experiment and the necessary event selection algorithms) and of exploring techniques for implementing the algorithms within the constraints of the Electronics Subsystem as a whole. Requirements and algorithm studies were in an advanced state when the SSC was terminated, and a number of important technology studies, including custom chip developments and data transmission techniques, were under way.

Computing

At the time of SSC termination, the SDC Computing Subsystem had made significant progress on two fronts: planning and system design for the future SDC hardware and software computing architecture; and preparation and use of the SDCSIM system for detector simulation and analysis using existing programs and software tools.

The future SDC system was planned around up-to-date software tools and methodologies. The conceptual architecture had been described in the document "SDC Offline Software Concepts," and plans were under way for execution of several projects (on data modeling, software design procedures, and overall software frameworks) in collaboration with GEM and the Physics

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Research Division Computing Department. Hardware designs were presented in the SDC Technical Design Report, and studies of an architecture based on worldwide regional computing centers had been performed.

SDCSIM had been up and running for more than two years, providing an important tool for detector design studies, as well as an example of how to manage a large and geographically diverse group of physicists working together on a large software project. Several versions of the software had been released, and the software was maintained on the Physics Detector Simulation Facility (PDSF) facility.

Conventional Systems & Facilities

The conventional systems for the SDC detector had been in a conceptual and preliminary design phase. The detail design was to be staged around the facilities construction milestones and the needs of the detector. The preliminary design of water, air, gas, and cryogens was brought to a point where facilities layout and design could be accomplished. The support facilities for the SDC detector were very well advanced when the program was terminated. The underground experiment hall was designed and bid, and the contractor selection was about to be made. The main surface assembly hall was under construction with the floor slabs and foundations completed and steel erection work under way. The preliminary design of the head houses, cranes, utility buildings, and operations building were in various stages of final design. In all cases preliminary design of the detector and support systems existed for the specification of the facilities. The requirements for the facilities and support systems can be found in the SDC experimental Facilities User Requirements (SEFUR. SCT-000001) document.

Physics Performance

The range of physics that would have been accessible to the SSC, with its 20-fold increase in collision energy and 1000-fold increase in luminosity over the current generation of hadron colliders, was immense. Figure 16-1 provides a visual survey of the physics processes. The total inelastic cross section would give an interaction rate of 10^{15} events per SSC year (defined to be 10^7 seconds of operation at the design luminosity of 10^{33} cm^{-2} s^{-1}). Most of these events would involve small momentum transfer and would not probe the mass scales of interest. Nevertheless, processes involving production of heavy objects, which are rare at today's hadron colliders (the CDF detector at Fermilab recorded about 40 $W \rightarrow e\nu$ events per day towards the end of its last run) would become commonplace at the SSC (the SDC detector would be capable of recording $W \rightarrow e\nu$ events at a rate of 10 Hz at design luminosity). A second example was the production of the t quark. For M_{top} = 150 GeV/c^2, Fermilab would produce about 100 events during the next several years, whereas the SSC would have produced 10^8 events per SSC year.

The largest interesting cross section at the SSC was that for the production of two jets. One event out of 10^4 (i.e., a rate of 10^4 Hz) had two jets with a dijet mass of greater than 400 GeV/c^2. This cross section was 10^7 times larger than that for photon pair production, which served as a reminder that robust photon and lepton identification would be essential for SSC physics. Heavy quarks and other colored objects such as gluinos would be produced with large cross sections. Even for a mass of 1 TeV/c^2, there would be at least 10^4 events produced per year. Heavy new Z bosons would also be prolifically produced, with the observable cross section extending out to a mass of 4 TeV/c^2. Finally, the Higgs production cross section was very small. At most one event out of 10^9 would contain a Higgs boson, and the branching ratios useful for its detection would also be small. For the decays of the Higgs to two photons or to four leptons, the branching ratios were typically 10^{-3}.

The sections below briefly describe the physics capabilities of the proposed SDC detector, and its performance is summarized in Table 16-1. The results displayed here assume data samples corresponding to an integrated luminosity of 10 fb^{-1}, or one year at the SSC design luminosity of 10^{33} cm^{-2} s^{-1}. Any exceptions are explicitly noted.

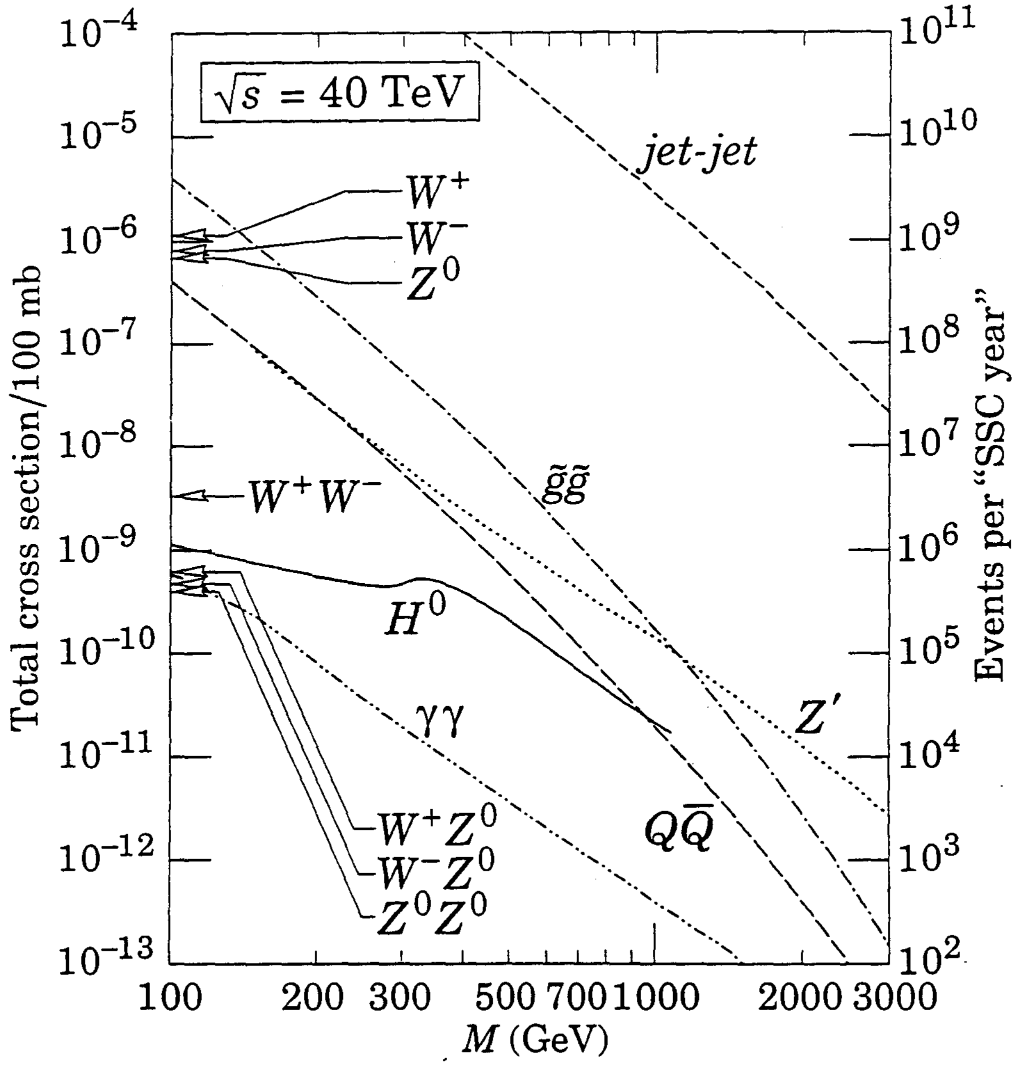


Figure 16-1. Cross Sections as a Function of Mass.

Table 16-1. Physics Capabilities of SDC.

Physics Process	Mass Region	Physics Signature
Associated Higgs Production	80 – 150 GeV/c^2	
	80 – 150 GeV/c^2	$W + H,\ t\bar{t}\ + H \rightarrow\ \ell\ \gamma\gamma$
Direct Higgs Production		
	130 – 180 GeV/c^2	$H \rightarrow ZZ^* \rightarrow 4\ell$
	180 – 800 GeV/c^2	$H \rightarrow ZZ \rightarrow 4\ell$
	500 – 800 GeV/c^2	$H \rightarrow ZZ^* \rightarrow 2\ell\ 2\ \upsilon$
High Mass Boson Pairs		
Requires integrated luminosity of at lease 50 fb^{-1} for complete studies	1 – 2 TeV/c^2	$Z\gamma \rightarrow\ \ell + \ell - \gamma$ $W^+Z \rightarrow \ell\ + \ell\ + \ell\ - \upsilon$ $W^+W+ \rightarrow \ell\ ^+\ell\ +$
Discovery of t Quark	$\lesssim$ 1 TeV/c^2	$t\bar{t}\ \ \rightarrow\ W+\ \ W- + X \rightarrow$ $\ell\ ^+\mu^- + X$
Mass Measurement of t Quark	$\lesssim$ 500	$t\bar{t}$, one $t \rightarrow W\,b;$
Sequential Dilepton Mode		$W \rightarrow e\upsilon;\ b \rightarrow \mu + X$ the other $t\ \rightarrow$ 3 Jets
Lepton + Jets + b-tag Mode	$\lesssim$ 500	$t\bar{t}$, one $t \rightarrow W\ + X;$ $W \rightarrow \ell\ \upsilon;$ the other $t\ \rightarrow Wb\ \ \rightarrow + b +$ 2 Jets
Non-standard t Decays		
Violation of t Universality	$M_H \lesssim\ M_{top\text{-}15}$	$t \rightarrow H \pm b;\ H\pm \rightarrow \tau \pm \upsilon;$ $\ell\ \pm \rightarrow \pi \pm + X$
Peak in 2-Jet Mass Distribution	$M_H \lesssim\ M_{top\text{-}25}$	$t\ \rightarrow$ H $\pm b;\ H\pm\ c\bar{s}$
Gluino and Squark Searches		
Missing - E_t + Jets	300 – 1000	$q\bar{q}\ \ \rightarrow\ \ E_t^{miss}$ + 3–6 Jets
Like Sign Dileptons	200 – 2000	$q\bar{q}\ \ \rightarrow \ell^{\pm}\ell\ ^{\pm}$ + 4 Jets
New Z Searches		
Discovery	$\lesssim$ 4 TeV/c^2	$Z'\ \rightarrow \ell\ ^{\pm}\ell^-$
Width and Asymmetry	$\lesssim$ 2 Tev	$Z'\ \rightarrow \ell\ ^{\pm}\ell\ ^-$
Compositeness	$\gtrsim$ 25 TeV	Inclusive Single Jet Spectrum

Electroweak Symmetry Breaking

The single most important physics issue for the SSC was the study of electroweak symmetry breaking. In the context of the Minimal Standard Model, the existence of a fundamental scalar field provides the symmetry breaking mechanism. In this case, a single Higgs boson is the only observable particle associated with the symmetry breaking sector and its mass is the only unknown parameter. It was imperative that a general-purpose SSC detector be capable of observing such a Higgs boson at any allowable mass to either verify its existence or rule it out and force consideration of alternative mechanisms.

The search for the Standard Model Higgs divides naturally into three mass regions, each with its associated strategy. For the low mass region ($80 < M_{Higgs} < 130$ GeV/c^2), the dominant Higgs decay modes are $H \rightarrow b\text{-}b$ and $H \rightarrow T^+T^-$, which are both overwhelmed by backgrounds from the decays of t quarks. The most useful mode in this kinematic region is the rare decay $H \rightarrow \gamma\gamma$, which occurs at next-to-leading order through loop diagrams. The Higgs itself is very narrow in this region (the width is less than 100 MeV for Higgs masses below 160 GeV/c^2) so that this decay mode provides a very distinctive signature. However, the direct production of the Higgs through gluon fusion suffers from a large background of QCD continuum production of photon pairs. The production rate for a Higgs in association with a W or $t\bar{t}$ pair is suppressed by a factor of 10 to 20 compared to the gluon-fusion rate, but the presence of an additional high-p_t lepton from the W or t decay provides significant background suppression. A complete analysis of the associated production processes shows that the SDC detector, studying the egg final state, should have been capable of discovering a Higgs in the low mass region within a single SSC year.

For the intermediate mass region ($130 < M_{Higgs} < 180$ GeV/c^2), the branching ratio for $H \rightarrow ZZ^*$ becomes significant (the * denotes a virtual particle). This decay mode provides a very distinctive signature of four isolated high-p_t leptons, with little background. The SDC detector, studying this final state, should have been able to observe a Higgs anywhere in the indicated mass region after one SSC year.

For the heavy mass region ($180 < M_{Higgs} < 800$ GeV/c^2), the WW and ZZ decay modes dominate. In the lower part of this mass range, discovery via the $H \rightarrow ZZ \rightarrow 4\ell$ mode appears straightforward. As the Higgs mass increases, the cross section for its production decreases, and its width increases dramatically (an 800 GeV/c^2 Higgs has a width of 270 GeV/c^2), making discovery more difficult. The $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow ZZ \rightarrow 2\ \ 2\nu$ decay modes were studied in detail. The latter has six times the event rate of the former, but requires particular scrutiny because of the requirement of observing the missing transverse energy from the neutrinos. The conclusion was that, through a combination of the two final states, a Higgs with a mass of < 800 GeV/c^2 should have been observable within one SSC year. Above this mass region, the signal becomes marginal at SSC design luminosity. For this reason, the $H \rightarrow ZZ \rightarrow 2\,\ell + 2\,jets$ and $H \rightarrow WW \rightarrow \ell\ \nu + 2\,jets$ decay modes were also studied (their branching ratios are 20 and 150 times larger than that of the $H \rightarrow 4\ell$ mode). The signal to background ratio is much less favorable, due to the large contributions from the $W/Z + jets$ and $t\bar{t}$ processes. Nevertheless, these modes could provide an additional method for studying the very heavy Higgs region, allowing searches to be extended into the TeV region.

Following these studies in the context of the Minimal Standard Model, it is natural to explore what happens in more general models of the symmetry breaking sector. A more complex, but theoretically attractive, model is the minimal supersymmetric version of the Standard Model (MSSM). In this model, there are five Higgs bosons: three neutral (h^o, H^o, A^o), and two charged ($H^{\pm}$). The theory has two fundamental parameters and the analysis is more complex. It appears that over much of the parameter space, at least one of the neutral Higgs bosons should be visible, either in the SDC detector, or at LEP-II. However, some regions of the parameter space remain inaccessible.

The previous discussion focused on the W^+W^- and ZZ final states, where the Higgs appears directly as a resonance. It is also important to study other boson pair channels to probe the electroweak theory more thoroughly. In particular, if no Standard Model Higgs is found below 1 TeV/c^2 in mass, it is almost certain that the symmetry breaking sector is strongly coupled. In this case, in analogy with QCD, one might expect resonant analogous of the ρ and ω to appear in the WW, WZ, and $Z\gamma$ channels. The discovery of such resonances would have been well within the capabilities of the SDC detector. The strong breaking could also manifest itself in non-resonant channels such as W^+W^+ , where the strong coupling would produce an excess of events over the Standard Model predictions. Further work remains to demonstrate convincingly that one can reduce the large like-sign $t\bar{t}$ background to the W^+W^- final state to a manageable level. Preliminary studies, using lepton isolation and topological cuts, appear promising. The excellent lepton-charge measurement ability of the SDC detector would have played a crucial role in removing the large opposite-sign backgrounds to the like-sign WW signal.

Physics of the t Quark

The t quark is one of the few remaining ingredients of the Standard Model that has not been directly observed. Its existence is crucial to the Standard Model, and precision electroweak measurements restrict its mass, in the context of the Minimal Standard Model, to lie in the range $90 < M_{top} < 200$ GeV/c^2. The discovery and study of this quark would thus allow stringent tests of the model.

The CDF and D0 experiments at Fermilab may very well discover the t quark in the next several years. If its mass is 150 GeV/c^2, these experiments may hope to reconstruct a handful of events. However, the SDC detector would be capable of reconstructing approximately 10^7 $t\bar{t}$ pairs in a year of SSC running. Such data samples will allow an accurate determination of the t quark mass by one of several methods. The mass measurement was studied using the sequential decay of the t quark to an isolated electron (from the W decay) and a non-isolated muon (from the b-decay product of the same t quark.) The dilepton mass spectrum provided a useful estimate of the t quark mass, with an estimated uncertainty that is predominantly systematic, of 3 GeV/c^2 after one SSC year. A second study was also performed, using a lepton tag for one t quark decay and then reconstructing the mass of the three-jet system arising from the decay of the recoiling t quark via $t \rightarrow Wb \rightarrow b + 2\,jets$, where the b-jet was tagged in the SDC tracking system. This method would have had a statistical error of 100 MeV/c^2 after one year of running, but it suffered from systematic uncertainties on the jet energy scale. The mass of the two non-b jets provided a clean W peak which could be used for a calibration, and the remaining systematic error on the mass measurement was estimated to be 3 GeV/c^2.

In addition to the mass measurement, it is important to study as many other properties of the t quark as possible. For example, in supersymmetric and other non-minimal models of the Higgs sector, the t quark can decay to a charged Higgs instead of a W. The charged Higgs will then decay to a tau lepton ($H^+ \rightarrow \tau\nu$) or to two jets ($H^+ \rightarrow c\bar{s}$) . The branching fractions depend on the values of the parameters in the model. The former process manifests itself as a violation of lepton universality in t decays. The latter appears as a second peak in the mass distribution for the two non-b jets. In the context of the Minimal Supersymmetric Standard Model, if the charged Higgs is at least 20 GeV/c^2 lighter than the t quark, it would be possible for the SDC detector to observe its effects in t decays for any value of the remaining free parameter in the model.

SUSY Searches

Supersymmetry has many theoretical attractions. For this discussion, it is assumed that SUSY particles must be produced in pairs, and that the lightest supersymmetric particle (LSP) is stable and neutral and therefore behaves like a heavy neutrino. These assumptions are natural in many theoretical models. Two basic discovery signatures were considered that could be used to search for squarks and gluinos (the supersymmetric partners of ordinary quarks and gluons).

The first signature involved jets and missing transverse energy. The expected final state involved 3 to 6 jets plus missing transverse energy arising from the missing LSP. The cross section for gluino pair production is large, allowing the exploration of masses up to 1 TeV/c^2. The most difficult case, due to the small expected missing transverse energy, is for a relatively light gluino with mass < 300 GeV/c^2. The SDC detector should have been capable of finding a gluino in the mass range of 300 GeV/c^2 to 1 TeV/c^2.

The second signature involved like-sign dileptons and jets. The like-sign dilepton signature is sensitive to a wider range of gluino masses than is the missing transverse energy signature. Final states were considered with two like-sign leptons and four additional jets, and it was estimated that a gluino in the mass range of 180 GeV/c^2 to 2 TeV/c^2 could be found in this manner. Furthermore, this signature provided a useful method to estimate the gluino mass with a precision of 10%.

Heavy Boson Searches

Models that enlarge the gauge group of the Standard Model predict the existence of additional gauge bosons. At the SSC new Z bosons were considered that arise in E_6 models (theoretically popular models that arise in many grand unification schemes, e.g., "superstrings"). The properties of the new Z bosons that arise in such models were studied, concentrating on their decays to lepton pairs, where the mass, width, cross section, and forward/backward asymmetry could be measured. Two extreme models within the E_6 family were chosen, and new Z bosons with masses of 800 GeV/c^2 and 4 TeV/c^2 were studied. The former would provide a striking signal of more than 10^4 events per SSC year in the final state $Z \rightarrow \ell^+ \ell^-$, while the latter would be at the limit of observability, giving some tens of events per SSC year. The detector resolution for the two-electron final state would be adequate to extract the width of a new Z, and hence deduce some information about its couplings. Studies of the forward/backward asymmetry are possible in both the electron and muon pair final states, again providing strong separation between different models.

Compositeness

If quarks are made of more fundamental objects with a binding scale of order Λ, then one expects an enhancement of the inclusive jet cross section, relative to QCD predictions, at large values of the transverse momentum. To observe this effect, one fits to the shape of the inclusive jet spectrum for small transverse momentum and then extrapolates to large values to look for an excess. The technique places stringent requirements on the linearity of the jet energy measurement. With the jet linearity expected in the SDC calorimeter, and with proper single-particle calibrations, the systematic errors could be controlled, and the measurement would be limited by statistics, leading to a bound on Λ of about 25 TeV/c^2 after one SSC year.

QCD Tests

It was expected that initial SSC physics priorities would include Standard Model processes with large cross sections. The expected rates for single and multiple jet production, heavy quark cross sections, and distributions, were surveyed along with single and multiple gauge boson production. The study of these theoretical predictions played a particularly important role in understanding the expected backgrounds in the more exotic processes that the SDC detector was to study.

Summary of Detector Parameters

A detailed list of parameters for the preliminary baseline detector and its options can be found in Ref. [1]. An isometric view of the baseline detector configuration is shown in Figure 16-2. Surrounding the interaction point is a sophisticated tracking system consisting of an inner silicon tracker and an outer tracker. The outer tracker option is a straw-drift-tube barrel tracker covering $|\eta| < 1.8$ together with an array of gas microstrip detectors covering the region $1.8 < |\eta| < 2.8$.

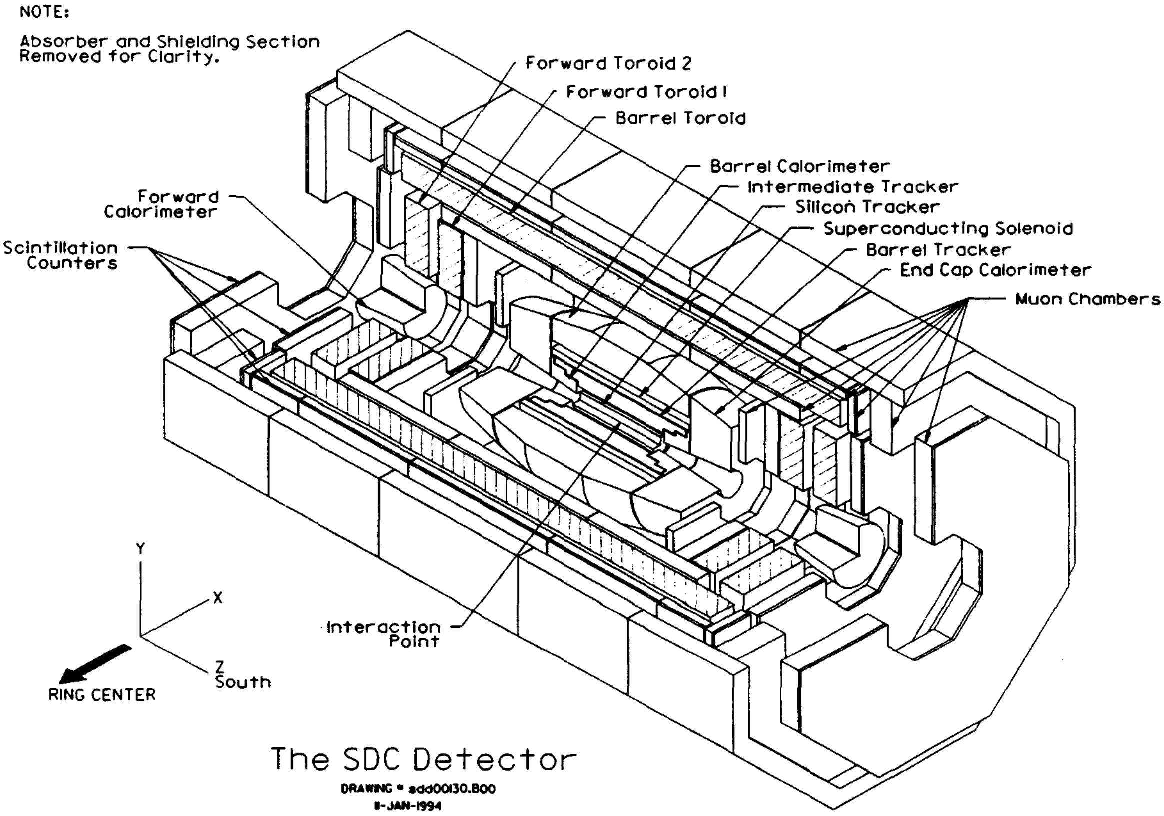


Figure 16-2. Isometric View of the Baseline Detector Configuration.

The tracking system is contained within a superconducting solenoid that provides peak field at the interaction point of 2.0 T. The solenoid and tracing system are surrounded by hermetic calorimetry. In the central region, $|\eta| < 3$, this calorimetry consists of scintillating tile and wavelength-shifting fiber readout with lead (electromagnetic section) or iron (hadronic sections) absorbers. A fined-grained shower-maximum detector is contained in the electromagnetic section of the central calorimeter to aid in electron and photon identification. The central calorimeter is divided into a barrel section ($|\eta| < 1.4$) and two endcaps ($1.4 < |\eta| < 3$). Hermeticity is completed by forward calorimeters covering $3 < |\eta| < 6$ at both ends of the detector. High-pressure gas ionization readout or liquid scintillator in tubes were the options under consideration for this region. A large system of magnetized-iron toroids, wire chambers, and scintillation counters for muon identification and momentum measurement surrounds the calorimetry. Muon triggering and identification for $|\eta| < 2.5$ are provided by this system and muon momenta are precisely determined by a combination of measurement in the central tracking system and by deflection measurements in the iron toroids. The high data rates at the SSC would require a very sophisticated electronics plant. In general, front-end circuitry is located either on or very close to the active detection elements for all systems to preserve high-rate capability. Data are stored locally on the detector and then shipped via high-speed optical fiber links to the data collection point located on the surface above the interaction hall. Data are stored, discarded or transmitted in response to trigger signals from a three-level trigger system. The Level 1 system provides triggers within 4 μs of an event, and the Level 2 system within about 50 μs. The Level 3 trigger is formed by an extensive array of parallel processors controlled by high level software to select events for permanent storage. An on-line computing and control system monitors and controls the detector.

An elevation view of the detector is shown in Figure 16-3. The detector sits in a pit in the interaction hall supported by a jacking system to accommodate floor movements during installation and operation. The central calorimeter is also supported by an hydraulic jacking system to allow small movements and adjustment independent of the barrel toroid. The superconducting coil and the tracking system are attached independently to the barrel calorimeter. Electronics for the tracking system and central calorimeter are located in crates on the exterior of the calorimeter. Access to these electronics is obtained via pathways on either side of the forward muon system. The endcap calorimeters may be retracted approximately 1.2 m for access to the tracking system. The bulk of the forward muon system remains stationary and only the chambers FW1 (Figure 16-3) move to allow the endcap to retract. Hence routine maintenance of the detector may be performed without moving the heavy components of the forward muon system and the delicate alignment of this system can be preserved. For major repairs or upgrades to the tracking system, the forward muon system components can be moved on rails and temporary bridges onto the operating floor of the underground hall. (See Table 16-2.)

Table 16-2. Summary of Preliminary Baseline Detector Parameters.

Tracking system	
Silicon tracker	
Number of channels	6.5×10^6
Total active area (m^2)	17
Rapidity coverage	$\|\eta\| < 2.5$
Barrel straw-tube tracker	
Number of channels	141,404
Number of superlayers	5
Rapidity coverage	$\|\eta\| < 1.8$
Gas microstrip intermediate tracker	
Number of channels	1.5×10^6
Number of superlayers (each end)	3
Rapidity coverage	$1.8 < \|\eta\| < 2.5$
System performance $\Delta p_t/p_t$ @ 1 TeV/c p_t	0.16 ($\|\eta\| = 0$), 0.60 ($\|\eta\| = 2.5$)
Calorimetry	
Barrel scintillating-tile/fiber	
Number of channels (pre-shower, em and hadronic)	17,794
Number of shower-maximum detector channels	28,672
Total depth including coil (= 0)	10 λ
Total weight (metric tons)	~ 2,400
Endcap scintillating-tile/fiber (both ends)	
Number of tower channels (pre-shower, em, hadronic)	14,720
Number of shower-maximum detector channels	20,480
Total weight (metric tons) (both ends)	~ 1,280
Total depth ($\|\eta\| = 3$)	12.1 λ
Forward high pressure gas or liquid scintillator	
Number of tower channels (both ends)	1,056
Total weight (metric tons) (both ends)	~ 300
Total depth	12 λ
System performance	
Central calorimeter ($\|\eta\| < 3$)	
$\Delta E/E\|EM$	$(0.10\text{-}0.17) / \sqrt{E} \oplus 0.01$
$\Delta E/E\|HAC$ (single η)	$\sim 0.6 / \sqrt{E} \oplus 0.04$
Forward calorimeter ($3 < \|\eta\| < 5.5$)	
$\Delta E/E\|HAC$	$\sim 1.0 / \sqrt{E} \oplus 0.08$
Muon system	
Barrel toroid weight (metric tons)	16,406
Forward toroids weight (metric tons) (both ends)	4,688
Number of muon chamber channels	85,200
Number of scintillator counters	6,480
System performance $\Delta p_t/p_t$ @ 1 TeV/c p_t	0.11 ($\eta = 0$), 0.18 ($\eta = 2.5$)
Superconducting magnet	
Field (T)	2.0
Stored energy (MJ)	146

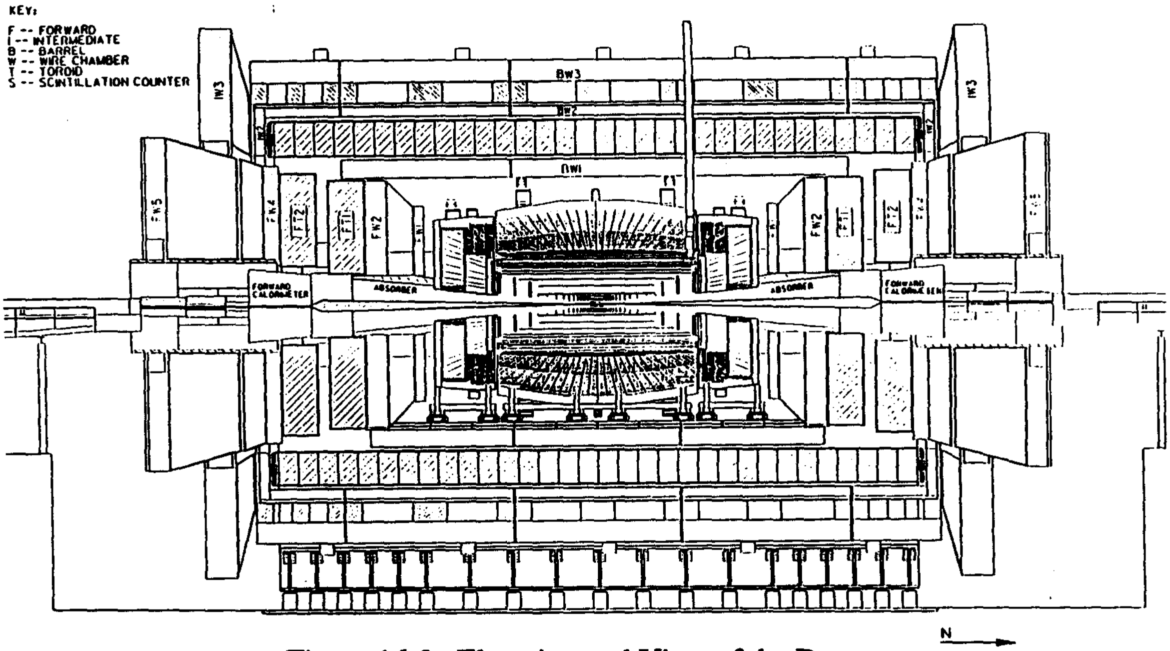


Figure 16-3. Elevation and View of the Detector.

Tracking System

The baseline tracking system is composed of an inner silicon tracker, a barrel straw-tube tracker, and a gas microstrip intermediate tracker. An all scintillating-fiber layout for the outer tracker was an option until a down-select decision in February 1993. After that time, the scintillating-fiber layout was studied only as a technology back-up.

Silicon Tracker

The silicon tracker consists of approximately 17 m^2 of instrumented silicon strip detectors. The silicon tracker is composed of a barrel region consisting of eight cylindrical layers of double-sided silicon strip detectors, which provide axial and small-angle stereo measurements. The baseline silicon tracker has thirteen double-sided disk detector arrays on each side of the barrel to complete the system. Each double-sided detector is about 300 μm thick and has a strip pitch of about 50 μm. The detectors and the on-board electronics are mounted within a low mass, highly precise space frame. This structure is in turn enclosed by a thin double-walled vessel, since cooling of the electronics heat load is provided by evaporating butane. At SSCL termination, the baseline design was being changed to lower the silicon disk count to ten on each side of the barrel to allow for likely intermediate tracker size changes. Testing of the butane cooling system indicated that, while functional, it was not as efficient as desired. Therefore, an investigation had begun to look at water cooling instead of butane. This investigation, of course, was not completed.

The silicon tracker covers the rapidity range $|\eta| < 2.5$, and is the key element for pattern recognition within the tracking system. In combination with the outer tracker, the track finding efficiency for isolated tracks (e.g., leptons from standard Higgs particle decay) is near 100% over the entire rapidity range at design luminosity. The silicon tracker also provides the ability to reconstruct, with good efficiency, tracks of p_t above a few GeV/c even within jets of transverse energies up to a few hundred GeV. The presence of b-hadrons may be tagged with reasonable efficiency from the displaced vertices produced by their weak decays. The silicon tracker does not contribute to the Level 1 trigger, but is used in the Level 2 trigger to provide precise information in ϕ and in p_t for combination with calorimetric information or data from the muon system. At the design luminosity, the expected lifetime of the silicon tracker, including the on-board electronics, ranges from about 10 years at the innermost radius to about 100 years at the outermost radius.

Straw-tube Barrel Tracker—Baseline

The straw-tube barrel tracker was chosen for the preliminary baseline configuration because its performance is relatively well understood. It was felt that the combination of the established drift tube technology together with the new gas microstrip technology would have lower risk than an all scintillating fiber option for the outer tracker. The status of all three technologies was reviewed in depth in early 1993, and a final baseline design was selected. This choice should be re-examined in any future detector design.

The 4 mm diameter straw tubes are contained in carbon-fiber-foam modules that provide a precise and rigid structure to both locate the straws and maintain the wire tension. The modules are located precisely on machined composite rings supported by carbon-fiber-foam composite cylinders. The cylinders are supported by a spaceframe composed of carbon-fiber-epoxy elements. All structural elements have been designed to be as low-mass as possible while still providing structural rigidity to maintain alignment tolerances. Both axial and stereo measurements are provided by this system. A Level 1 trigger is provided by identifying high-p_t local track vectors in any two out of the three axial superlayers. Each axial (stereo) superlayer contains eight layers of straws. The modules are 4m long or less with a termination, but no active electronics, at the middle at $\eta = 0$.

A gas mixture of tetrafluoro-methane (80%) and isobutane (20%) is used in the straws. The mixture provides a maximum drift time of about 30 ns, which is reasonably matched to the SSC interaction rate. The straw-tube cathodes are very thin copper-coated Kapton, which have been demonstrated to have better radiation resistance than aluminum cathodes. The expected lifetime of the straw-tube system, including the front-end electronics on the ends of the straws, exceeds ten years at the minimum superlayer radius at the design luminosity.

At the design luminosity, the expected occupancy of the innermost (outermost) straw superlayer is 0.10 (0.02). Preliminary pattern recognition studies indicated that isolated tracks, for example, leptons from standard Higgs decay, could be found with efficiency > 97% by the combined silicon-straw system even at six times design luminosity.

Gas Microstrip Intermediate Tracker—Baseline

In the rapidity interval $1.8 < |\eta| < 2.8$, a new technology using gas microstrip detectors was proposed. A gas microstrip detector (GMD) consists of fine metallic anode and cathode traces placed on a thin substrate (e.g., glass) separated by a gap of a few millimeters from an electrode to provide a drift region. High voltage connections are made to the cathodes, drift electrode, and substrate. Signals are read out on the anodes. The anode pitch is typically a few hundred microns and in the SSC design varies with rapidity. The GMD technique has spatial resolution, two-track resolution, and speed of response that are well matched to the requirements of the intermediate tracker.

The gas microstrip intermediate tracking detector (ITD) consists of three sets of planes (superlayers) on either side of the silicon and barrel trackers. A layer in the ITD consists of an array of gas microstrip tiles approximately 15cm on a side finely segmented in. Each superlayer consists of two layers with radial anodes (ϕ measurements) and two layers with stereo anodes of opposite inclination to provide a local space point. A Level 1 p_t-sensitive trigger is formed from the radial layers by measuring the change in from one superlayer to the next, in coarse η bins defined by the tile dimensions.

Gas microstrip detectors are a new technology that has not been used extensively in previous experiments. An aggressive international research and development program is under way to demonstrate that these detectors can be used on the scale envisioned for the ITD and that they have adequate lifetime for use in an environment like that at the SSC. The ITD resides in a region where the annual radiation dose is up to 10 krad at design luminosity. Research and development is still required to demonstrate survivability of the GMD in such an environment.

Barrel Tracker—Scintillating Fiber Option

The design of the scintillating fiber tracker has doublets of scintillating fibers precisely arrayed on the inside and outside of carbon-fiber foam composite cylinders. The cylinders are held by a precise composite framework located at the ends of the cylinders. Both axial and small-angle-stereo measurements are provided by the fibers. The scintillating fibers are coupled to clear fibers that transmit the light to solid state photosensors, Visible Light Photon Counters (VLPCs) that are located on the outside of the central calorimeter. The VLPCs have high quantum efficiency (up to 80%) and are located in helium cryostats to maintain the 7 K temperature required for their operation. Electronics for the fiber tracker are also located on the back of the central calorimeter.

The scintillating fiber option has an occupancy that is significantly less than the straw-tube option and thereby might be expected to provide better performance at luminosities greater than the design value. The trigger is implemented by correlating signals in the inner three superlayers, providing uniform trigger coverage up to $|\eta| < 2.3$. However, there is somewhat greater material, on average, in the fiber option, although concentrations of material due to electronics and supports in the straw-tube/GMD option are eliminated by the design. There is also a reduction in rapidity coverage in the current fiber design, which covers only $|\eta| < 2.3$.

Superconducting Solenoid

The tracking system is enclosed within a thin superconducting solenoid that provides a peak field of 2.0 Tesla. The principal parameters of the solenoid are given in Table 16-3. At the time, a research and development program was under way in Japan to verify the design of the solenoid and to make the thinnest feasible structure. This program culminated in late 1993 with the construction of a quarter-length full-radius prototype. At SSCL termination, the next planned step was to test the prototype to simulate the compressive forces anticipated in the final coil.

Table 16-3. Parameters of the Superconducting Coil.

Inner radius of cryostat (mm)	1700
Outer radius of cryostat (mm)	2050
Total length of cryostat (mm)	8726
Mean conductor radius (mm)	1810
Central magnetic field (Tesla)	2.0
Nominal operating current (amps)	8000
Maximum temp. after quench (°K)	< 100
Maximum voltage after quench (V)	< 500
Stored energy (MJ)	146
Thickness at $\theta = 90°$	$1.2\ X_0,\ 0.25\ \lambda$
Total weight (tonnes)	25
Cold mass (tonnes)	20
$\int B \times dl$ (tesla-meters at 90°)	3.4

Calorimetry

The goals of the calorimeter systems are to provide electron and photon identification and energy measurement (in conjunction with the tracking system), to measure the energies and directions of jets and to provide hermetic coverage for missing transverse energy measurements. In the central region, the choice of technologies was scintillation calorimetry with lead absorber and iron absorber for the electromagnetic and hadronic sections, respectively. The scintillating detection elements are divided into tiles, each tile being read out by a waveshifting fiber. The fibers are brought to the rear of the calorimeter, bundled, masked and read out by photo multiplier tubes. In the forward region ($3 < |\eta| < 6$), two options were being considered: high pressure gas ionization readout and liquid scintillator in small tubes.

Central Calorimetry

The central calorimeter is composed of a barrel section, which in turn is built in two halves, and two endcap sections. In the original baseline design, each endcap section had a removable "hadronic plug"covering the high rapidity region (about $2 < |\eta| < 3$) that is most susceptible to radiation damage. During an early 1993 review, the endcap was redesigned and the hadronic plug was deleted. In the barrel region there is a single electromagnetic depth segment, which can be upgraded to two depth segments by rerouting fibers and adding photo tubes. In the endcap section, there are two electromagnetic depth segments to allow for better correction of radiation-damage effects, which are more important in this region. In both the barrel and endcap, the iron hadronic absorber is segmented into two depth compartments (HAC1 and HAC2). The transverse segmentation is $\delta\eta \times \delta\phi = 0.05 \times 0.05$ in the electromagnetic sections and 0.1×0.1 in the hadronic sections, except near $|\eta| = 3$ where the granularity is coarser.

A shower maximum detector (SMD) composed of crossed strips of scintillator about 1.2cm wide is located near the shower maximum point in both the barrel and endcap regions. The SMD aids substantially in the identification of electrons and photons by measuring the shape and location of the electromagnetic shower. The SMD is also used in the trigger to provide correlations with the central tracker. Both the tiles in the tower segments and the strips in the SMD are read out by waveshifting fibers embedded in grooves located in each tile or strip. The fibers are routed to the back of the calorimeter. For the tower segments they are bundled and masked on a fiber-by-fiber basis using filters placed between the fiber bundle and the photomultiplier tube. This masking technique can smooth out variations from tile to tile to provide a more uniform response in depth. The required degree of masking as well as the responses of the tiles are determined by an extensive system of remotely movable radioactive sources that can illuminate and calibrate all tiles. The fibers from the SMD are read out by multianode phototubes. Avalanche photodiode arrays were being studied as a technology back-up to the phototubes. Local electronics for the calorimeter (and the central tracker) are mounted in crates on the back of the calorimeter to minimize the high-bandwidth cable paths.

Scintillation calorimetry has the advantage of an intrinsic speed of response that comes close to matching the 16 ns time between crossings at the SSC. However, degradation of light output from radiation damage is an obvious concern. At design luminosity the maximum dose at electromagnetic shower maximum is about 6 krad/yr in the barrel region. Irradiation of electromagnetic modules in intense electron beams in China, Japan, and France have demonstrated that readily available scintillators will allow electromagnetic energy measurements in the barrel region for about 100 years at design luminosity with little degradation in resolution. The radiation dose varies strongly with polar angle, approximately as $(1/\theta)^3$, and thus the annual dose in the forward part of each endcap will be large. New scintillators with increased resistance to radiation were being developed. At the design luminosity, replacement would be necessary every few years if new scintillators could not be developed. Preliminary results on radiation resistance of small samples of newly developed scintillators indicate potential lifetime improvement factors of two or more, but large scale tests are required to validate these results.

Forward Calorimetry

The forward calorimeter covers the rapidity range from $|\eta| = 3$ to about $|\eta| = 6$. Measurement of jet energies and angles in this region is critical to the measurement of missing transverse energy. In addition, tagging the presence of jets in this rapidity region may reduce backgrounds in the observation of signals in the central detector. The energy resolution and segmentation requirements for the forward calorimeter are not as stringent as in the central region. The forward calorimeter is located about 12.5 m from the interaction point. With the segmentation chosen, the angular resolution provides adequate measurement of missing transverse energy and identification of forward jets.

Radiation doses are much higher in the forward direction, and the feasibility of operation under such extreme conditions to a large extent determines the technologies that can be employed. Two options were under consideration for the sampling medium in the forward calorimetry: high pressure gas (about 100 atm of argon) and liquid scintillator in glass tubes. In both cases the sampling medium would require periodic replacement after accumulation of large doses of radiation.

Muon System

The muon system provides the capability to identify muons, trigger on them, and make independent measurements of muon momenta. Large magnetized-iron toroids cover the rapidity range $|\eta| < 2.5$. Drift tube chambers measure the deflections of muons in the iron toroids, and scintillation counters provide a precise timing signal to tag the bunch crossing of interest. At design luminosity, the primary muon momentum measurement in the central rapidity region is performed by the central tracker. In the forward region, the muon system itself has better momentum measurement capability at high p_t because the central tracker resolution is poorer at those angles.

The barrel iron toroid is composed of large iron segments bolted and welded together. The barrel toroid sits on a support structure that is designed to accommodate to both long-term floor motion and short-term motion from the movement of the remaining detector components into the toroid. The thickness of the toroid was designed as the minimum depth needed to provide a reasonable Level 1 trigger rate and good muon detection efficiency. The forward toroids are octagons with inserts to make the field as uniform as possible. Muons in the forward direction typically have higher momenta than those in the central region and greater stand-alone momentum measuring precision is also required. Three meters of magnetized iron is just sufficient to provide adequate measuring power for TeV muons.

In the baseline concept, all muon chambers consist of round drift tubes with field-shaping electrodes, which provide a near-linear time-to-distance relationship with the appropriate gas mixture (for example Argon-C02) and thus better spatial resolution (about 250 μm) than simple drift tubes without field shaping. In addition, the field shaping allows for two-track resolution of about 5 mm, which is needed to find muon tracks in the presence of electromagnetic debris created by the passage of multi-hundred GeV muons through the iron toroids and the chamber walls. The diameter of the drift tubes is larger in the barrel and intermediate regions, where the muon rates are lower than in the forward region. In the barrel and intermediate regions, the chamber elements are packaged as supermodules on the surface, lowered into the underground hall and mounted on the barrel toroid. A similar procedure is used for the forward system. Alignment systems are used throughout to calibrate the plane-to-plane alignment to an accuracy of about 150 μm in the barrel/intermediate region and the forward region.

Measurements in the muon chamber system are primarily for determining the muon deflection in the toroids (measurements), but stereo measurements are also made in the barrel/intermediate region and stereo measurements in the forward region. Stereo measurements are needed to associate tracks in the non-bend direction. The measurements are used for pattern recognition and, in association with the central tracker, to improve the momentum measurement precision at high transverse momentum.

A p_t- sensitive Level 1 trigger is formed by measuring the track deflection due to the toroids in the outer chamber layers (BW2/BW3, IW2/IW3 and FW4/FW5). The drift tubes are arranged to be projective to the interaction point. The measurement of drift-time differences between selected planes provides information related to the transverse momentum of the muon. Trigger p_t thresholds can be varied by selecting different windows in the time differences. Since the drift time in the tubes can be as much as 1 microsecond, the scintillators are used to identify the correct beam crossing. There is a single layer of scintillation counters, each with two phototubes, in the barrel/intermediate region and two layers of counters, each with one phototube, in the forward region, where rates are higher. Cerenkov counters in the forward direction have been carried as a possible upgrade option to reduce the sensitivity to neutron backgrounds, but further study is required.

Electronics Systems and On-line Computing

Front-end electronics were being designed to match the requirements for each distinct detector subsystem. All detector subsystems required the design and fabrication of application-specific-integrated-circuits (ASICs) to meet performance requirements for the front-end systems. Specific front-end circuits are required for the silicon tracker, the straw-tube tracker or the fiber tracker, the gas microstrip tracker, the calorimetry and the muon chambers. The circuitry for the gas microstrip tracker shares many features with the silicon design, and the muon front-end circuitry is similar to but less complex than the straw-tube circuitry.

A subset of information from the detector subsystems is used by the Trigger system. Correlations among the detector trigger elements at Level 1 are used to form a complex array of triggers. At Level 2, additional information and correlations are added to reduce the rate flowing into the Level 3 processor farm. Selection at Level 3 is controlled entirely by software, which may include near-complete event reconstruction. The data acquisition and on-line computing systems control the flow of data from the detector to the Level 3 farm and its subsequent permanent storage, and provide the interface to control all detector subsystems.

Off-line Computing

The principal challenges for off-line computing were the storage of and access to the vast amount of data that would have been accumulated during the operation of the experiment, and the management of the software development for event reconstruction and analysis by the diverse international community of the SDC. The actual processing hardware requirements of about 105 mips are probably not as challenging, but they would have represented a significant investment.

The development of code for the detector was envisioned to be divided into two broad categories. First, there would be a "kernel" of software that provides the structure to which other code may be attached. The second category comprises the detector-specific codes that were to be developed throughout the collaboration by physicists and a few software professionals within the collaboration.

Data storage and access to data perhaps represented the most challenging problems. Automated data storage systems containing upwards of 10^4 volumes would be required. More challenging was the development of suitable databases to allow fast access to data in response to very diverse sets of interests and criteria from the hundreds of physicists who would eventually be analyzing the experiment.

Detector Support Systems

Surface facilities were designed to support assembly, installation, and operation of the detector. The site configuration evolved from the study of subsystems assembly, detector installation, and detector operations. Included in the surface facilities were an Assembly Building, an Operations Building, a Utility Building, a Gas-Mixing Building, and the headhouses over the installation shafts that led down to the underground Interaction Hall.

Many of the components making up the detector were to would have been developed and produced in various parts of the U.S. and abroad. Some components, particularly the Muon barrel chambers, were to be manufactured in the Assembly Building. Many of the subsystem elements were large and heavy. The sizes and weights of elements to be transported to the site would have been as great as $10 \times 10 \times 3$ m^3 and 100 tons. Even larger and heavier components could have been moved between the surface facilities at IR8. The calorimeter subassembly was roughly 4 m long and 10 m in diameter and weighed 1500 tons. Subsystems were to be assembled in the surface facilities and then installed in the underground hall.

Gas, water, and power utilities associated with the site infrastructure were required for both construction and operation of the detector. A central site emergency power source was planned to provide standby power for all life safety and emergency loads at the IR8 site. Site utilities also included signal, control, and communication conduits, both between and within buildings.

Most of the waste heat rejected to the cooling water systems would have been transferred to the atmosphere by means of evaporative cooling systems consisting of cooling ponds, cooling towers, or a combination of both. The hall ventilation system provided a source of air to assure sufficient oxygen for occupancy and sufficient outside air to dilute any gases escaping from the detector. The detector ventilation system provided a source of 100% conditioned air for the interior of the detector. During run periods, this air served as a means for removing any gases escaping in the detector and as a heat sink for the small amount of heat not removed by the water cooling systems. The common vent system was designed to collect nonflammable gases discharged from the detector, vacuum pump exhaust, cryogenic relief valve discharge, mechanical room exhaust, and other nonflammable gases.

The gas-mixing building was to house the gas systems equipment. The mixed gases would have been argon and carbon dioxide for the muon chambers, and CF_4 and isobutane for the straw tube option. The silicon tracker included a butane cooling system to reject its heat through a condenser into the mixed chilled-water return line. The silicon tracker, and possibly the entire tracking system, would have been inerted by gaseous nitrogen.

The helium refrigerator/liquefier cryogenic system was to be used to support the superconducting magnet and, possibly, visible light photon counters. The specified refrigeration/liquefaction capacity was approximately 1200W.

At shutdown, the Assembly Building was under construction and the Interaction Hall contract had been let. Preliminary Design Requirements Reviews had been held for the Cryogenics Project Segment (for the superconducting magnet) and for the low Conductivity Water Systems. The Muon Gas System PDRR report was in the draft review stage.

Cost and Schedule

Schedule Summary

As of the date the U.S. Congress voted to terminate the project, preliminary schedules for detector subsystems design, fabrication, and installation had been developed and documented. (See references 1 and 2.) Major milestones are presented in Table 16-4. The SDC project schedule is summarized in Figure 16-4.

Note that at the time of termination, efforts had been made in completing a "stretch-out" schedule with a planned completion date for the commissioning of the SDC detector in 2002. The plan was developed following President Clinton's request for spreading out the funding profile by extending the completion date by three years. Because this plan was in the consideration stage and had not yet received approval, no part of that schedule is contained in this section.

Table 16-4. Major SDC Milestones.

Milestone	Date
Submit technical design report	April 92
Stage I approval complete	August 92
Stage II approval complete	December 92
Detector construction begins	December 92
Earliest surface building beneficial occupancy	March 94
Beneficial occupancy of underground hall	March 96
Commissioning begins	March 99
Ready for operation	October 99

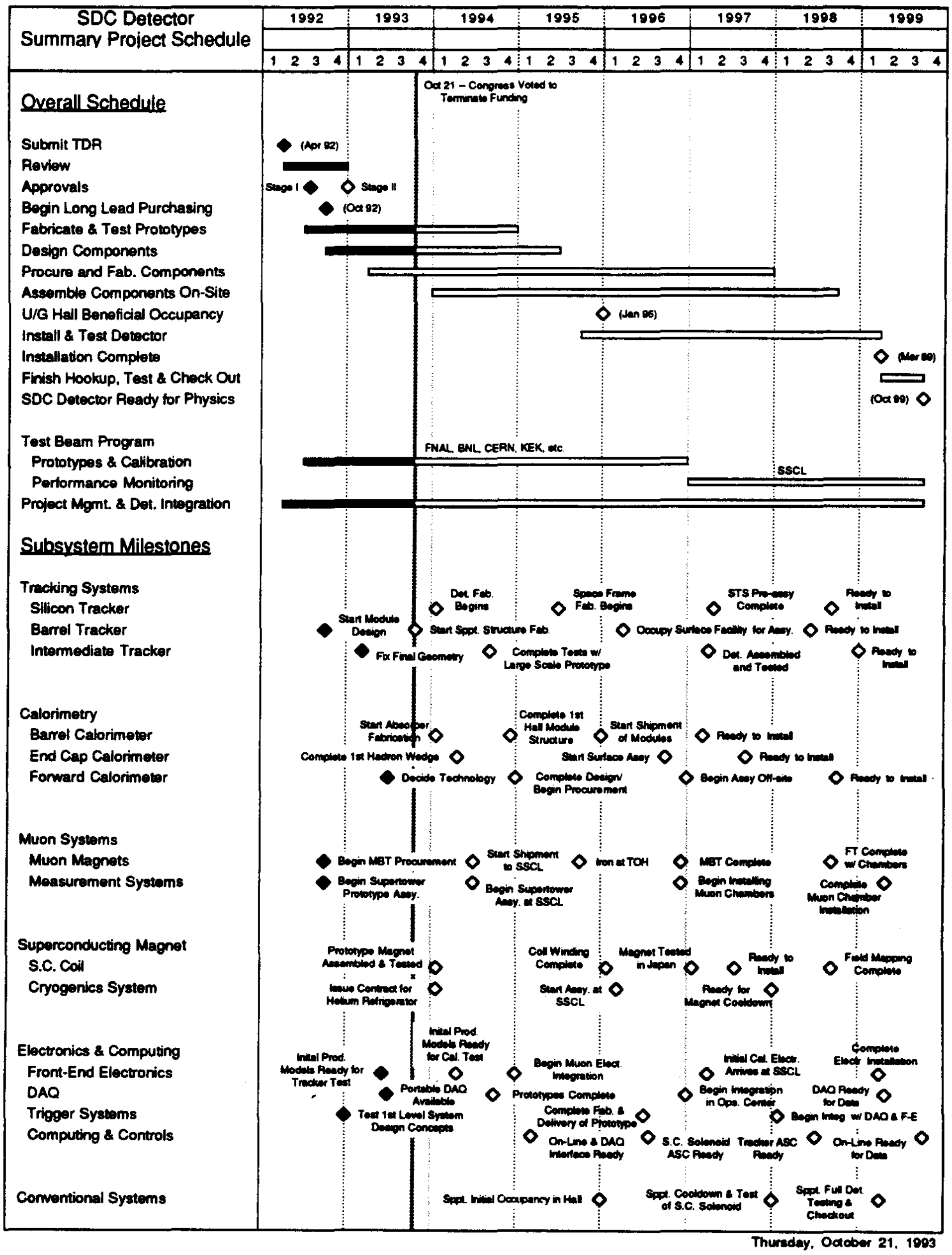


Figure 16-4. SDC Project Schedule.

Summary of Cost

The cost of the SDC Detector was estimated from a "bottoms up" approach for all subsystems of the detector. A detailed Work Breakdown Structure (WBS) was created, reporting the cost estimate to the lowest reasonable level for all subsystems. WBS elements of the cost estimate were translated into fiscal year budgets in the SSCL Project Management Control System (PMCS) and actual expenditures were tracked against these budgets. A summary of the cost-to-date by subsystem is given in Table 16-5. FY92 and prior years costs were not broken down to the subsystem level when the PCMS system was initiated in FY93, therefore these costs are presented as a lump sum for the total detector.

Table 16-5. Cost of the SDC Detector in Equivalent U.S. FY93 K$.

	Project Expenditures FY93 To Date (K$)	**Cost Estimate 25 Oct 92 ($K)**
1 TRACKING SYSTEMS	**6,811**	**94,800**
1.1 SILICON TRACKING SYSTEM	3,752	42,100
1.2 BARREL TRACKER	3,059	31,600
1.3 INTERMEDIATE TRACKER		21,000
2 CALORIMETRY	**4,414**	**159,800**
2.1 BARREL CALORIMETER	3,730	88,100
2.2 ENDCAP CALORIMETER	654	61,700
2.3 FORWARD CALORIMETER	30	10,000
3 MUON SYSTEM	**4,457**	**121,700**
3.1 MAGNET SYSTEMS	1,416	58,700
3.2 MUON MEASUREMENT SYSTEM	3,041	63,000
4 SUPERCONDUCTING MAGNET	**0**	**41,900**
4.1 SUPERCONDUCTING SOLENOID	0	35,000
4.2 CRYOGENIC SYSTEM	0	6,900
5 ELECTRONICS SYSTEMS	**1,711**	**94,700**
5.1 FRONT-END ELECTRONICS	1,108	42,600
5.2 DATA ACQUISITION SYSTEM	187	20,400
5.3 TRIGGER SYSTEMS	416	27,800
5.4 ANCILLARY CONTROLS	0	3,900
6 ON-LINE COMPUTING	**0**	**9,300**
7 CONVENTIONAL SYSTEMS	**66**	**12,700**
8 INSTALLATION AND TEST	**134**	**35,000**
8.1 TEST BEAM PROGRAM	134	6,500
8.2 SUBSYSTEM INSTALL. AND TEST	0	28,500
9 PROJECT MANAGEMENT	**1,989**	**19,100**
10 GENERAL DETECTOR DEVELOPMENT	**6,585**	**0**
(FY93 & After) TOTAL	**26,167**	**589,000**
Pre-Proposal, FY92, and Prior	**14,890**	**20,000**
TOTALS	**41,057**	**609,000**

Management and Organization

The SDC was a large international collaboration whose goal was the construction of a detector to exploit the physics opportunities to be opened up by the SSC. It was expected that almost 40% of the detector components would have been provided by collaborating groups from outside the United States. The principal management officers of the SDC were the Spokesperson and the Project Manager (PM). The PM also played the role of co-spokesperson. The responsibilities of these officers are described below. Together with the Spokesperson and PM, three bodies (boards) provided management oversight for the SDC: the Institutional Board (IB), the Executive Board (EB), and the Technical Board (TB). The functions and modes of selection of these boards are also described below.

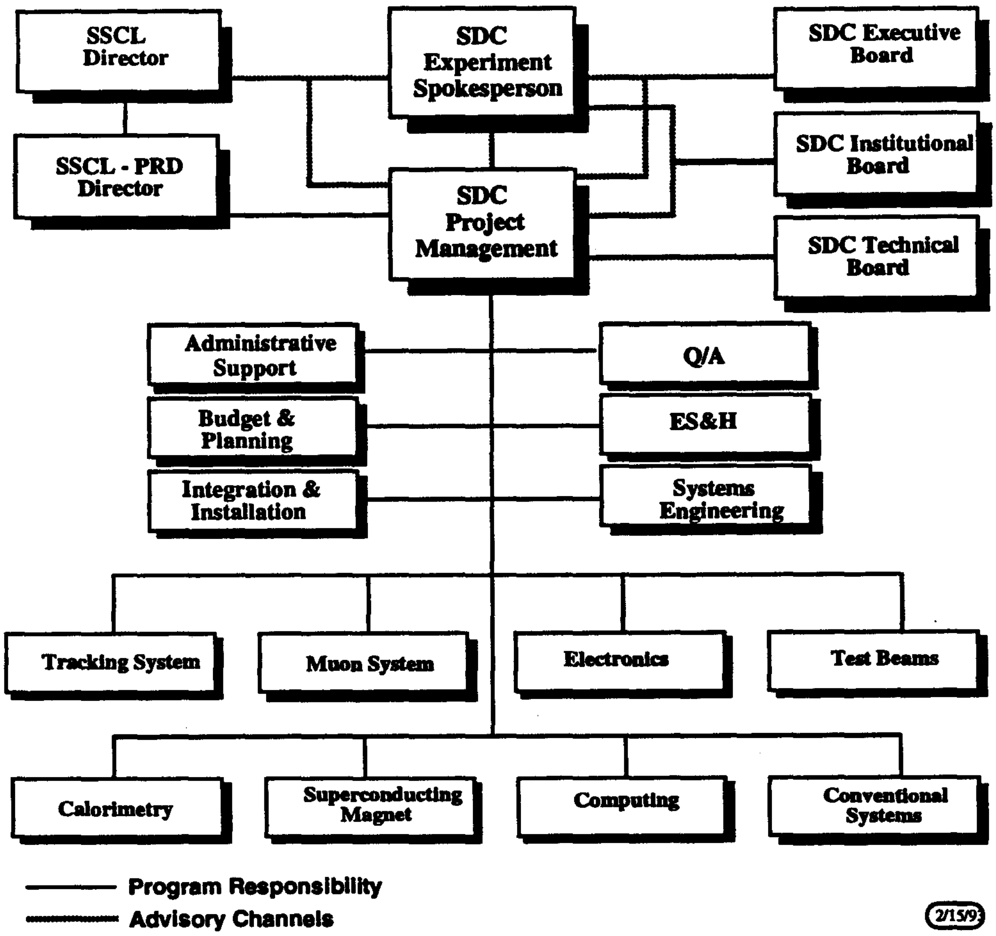
The Institutional Board (IB), whose membership consisted of one representative selected by each collaborating institution, dealt with general issues that concerned the Collaboration as a whole. They included the governance of the Collaboration, the policy on admission of new members and institutions, and publication policy. The IB carried out the process for admission of new institutional members of the SDC, and also conducted the yearly election of the Executive Board. The Executive Board (EB), in concert with the Spokesperson and Project Manager, provided the scientific direction for the SDC project and physics efforts. In consultation with the Director of the SSC Laboratory, the EB appointed the Spokesperson and the Project Manager. It reviewed and approved recommendations of the Spokesperson, PM, and Technical Board on major technological issues. It also approved appointments to the Technical Board and met from time to time with SSCL management to discuss issues of mutual concern.

The members of the EB normally served three-year terms, with one third of the members up for election each year. There was no more than one member per institution. Elections to the EB were conducted by the IB, starting with a slate of nominees prepared by an ad hoc nominating committee, plus additional candidates proposed by any petition of 30 voting members of the Collaboration. Some non-U.S. groups represented on the EB chose their representatives through their own systems, although it was expected that eventually, as all the collaborators became well-known to each other, the whole EB membership would be chosen by Collaboration-wide ballot. Up to late 1992, the composition of the EB as set by the SDC bylaws was as follows: four from U.S. national laboratories, eight from U.S./Canadian institutions, five from Japanese institutions, two from European institutions not including the Former Soviet Union (FSU), and two from the FSU. The Spokesperson, Deputy Spokespersons, and PM attended and participated in EB meetings, and the Spokesperson chaired the EB.

The Technical Board (TB) consisted of scientists and engineers involved in leadership roles in the various technical areas of the SDC project. The members of the TB were subsystem leaders and others appointed by the Spokesperson and PM with the approval of the EB, and they included both U.S. and non-U.S. members. The TB was chaired by the PM. The TB reviewed and recommended to the Spokesperson and PM on all major technological and technical decisions relevant to the SDC detector. The TB also had a central role in the change control process.

The SDC Spokesperson was appointed by the EB in consultation with the SSCL Director, and his or her selection had to be ratified by the Collaboration. The Spokesperson was the representative of the Collaboration in scientific, technical, and managerial concerns, and was authorized by the SDC to speak and negotiate on its behalf. The Spokesperson chaired the EB and articulated its decisions and their rationales to the Collaboration, as well as to outside persons and bodies. The Spokesperson was responsible for establishing the scientific goals in concert with the baseline proposal and the means for the Collaboration to pursue these goals successfully. He or she was also expected to pursue the identification of resources needed by the SDC, and to seek the commitment of such resources toward the development of the SDC detector and program. The resources consisted generally of scientific groups who proposed to collaborate in the SDC program, as well as their various sources of funding for that purpose. The Spokesperson did not have to be an SSCL employee. There were also three Deputy Spokespersons, one from Japan, one from Europe, and one from the U.S./Canada. The Deputy Spokespersons provided support and assistance to the Spokesperson in the leadership of the SDC experiment. They were appointed by the EB in consultation with their constituencies and with the Spokesperson.

The Project Manager carried the responsibility for the design and fabrication of the detector. The PM established technical work plans within the context of the Technical Design Report, and was responsible for meeting cost, performance, and schedule goals for the SDC detector and for the preparation of required reports and documentation. The PM was responsible for managing the SDC technical efforts required to meet the goals set forth in the approved Proposal and for implementing Memoranda of Understanding (MOUs) with SDC institutions both in the United States and abroad. He or she was also the leader of the SDC Department at the SSCL. The PM was an SSCL employee, reporting to the Associate Director of the PRD. The Collaboration chose to give the PM the title of Co-Spokesperson. The non-U.S. groups also set up their own reporting mechanisms as required by the funding agencies of their countries.



The SDC Organization.

At the point of termination, the project the following were the principals of the SDC Management Organization. The organizations and participants of the subsystems and executive and technical boards were defined as part of the Project Management Plan, which can be seen in the SDC Summary Documentation Package, SDT-000263.

SPOKESPERSON:

George Trilling	Lawrence Berkeley Laboratory

PROJECT MANAGER AND CO-SPOKESPERSON:

Tom Kirk	Superconducting Super Collider Laboratory

DEPUTY SPOKESPERSONS:

Giorgio Bellettini	INFN and University of Pisa
Daniel Green	Fermilab
Takahiko Kondo	National Laboratory for High Energy Physics (KEK)

DEPUTY PROJECT MANAGERS:

M.G.D. Gilchriese	Lawrence Berkeley Laboratory
Takahiko Kondo	National Laboratory for High Energy Physics (KEK)

ASSOCIATE PROJECT MANAGER AND CHIEF ENGINEERING:

Tim Thurston	Superconducting Super Collider Laboratory

Chapter 17. The GEM Detector

(N. Baggett, M. Diwan, K. McFarlane, and G. P. Yost)

The GEM collaboration was formed in June 1991 to develop a major detector for the SSC. The primary physics objectives of GEM were those central to the motivation for the SSC: to study high p_T physics—exemplified by the search for Higgs bosons—and to search for new physics beyond the Standard Model. The GEM Collaboration had, at the time of SSC termination, organized itself into a mature collaboration of more than 100 institutions from 17 countries. A Technical Design Report (TDR)[1] was submitted on April 30th, 1993 and reviewed by the SSCL PAC. A series of questions was returned to GEM and responded to; the overall tone of the PAC report[2] was extremely favorable.

The GEM TDR[1] presented a detector with broad capabilities for the discovery and subsequent study of electroweak symmetry breaking, the origin of mass and flavor, and other physics requiring precise measurements of gammas, electrons, and muons—hence the name, GEM. (See Figure 17-1.) In addition, as a design goal, care was taken to provide the robustness needed to do the physics that requires high luminosity. Finally, good coverage and hermeticity allowed for the detection of missing transverse energy, $\not{E}_T$. A GEM overview document[3] describes the status of the Collaboration and detector and presents a comprehensive bibliography of relevant GEM documents. The Work Breakdown Structure is described in the GEM WBS Dictionary.[4]

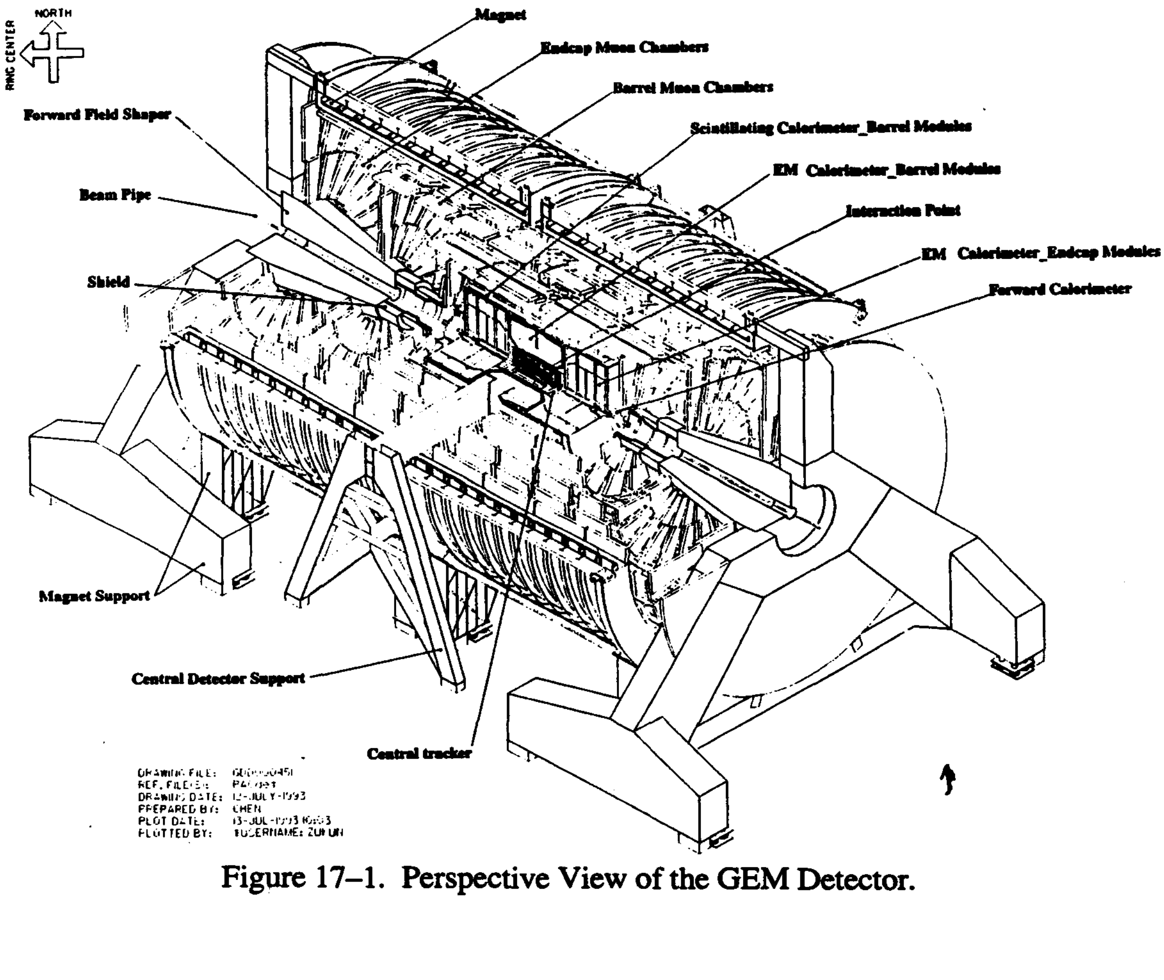


Figure 17–1. Perspective View of the GEM Detector.

Table 17-1. Physics Signatures at the SSC.

Physics	Signatures
Standard H^0	$\gamma\gamma$, $(\bar{t}t\ /\ W)\ H^0 \rightarrow \gamma\gamma\ \ell^{\pm}\ X$
	$ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$
	$ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-\ jj$,
	$\ell^+\ell^-\ \nu\bar{\nu}$
Extended $H^0, h^0, H^{\pm}$	Same as above
	$t \rightarrow H^+ b$
	$h^0, H^0 \rightarrow \tau^+\tau^-$
Heavy $Q\bar{Q}$	$W^{\pm}q \rightarrow$ jets + isolated $l^{\pm}$
Z', W'	$\ell^+\ell^-$, $\ell^+ + E_T$
Technicolor	$\rho_T \rightarrow jj, WZ\ (\rightarrow \ell^{\pm}$ jets)
	$\rightarrow \pi_T\pi_T$
	$\pi_T \rightarrow$ heavy $\bar{f}f$, dijets
Supersymmetry	$\not{E}_T$, jets, $\ell^{\pm}\ell^{\pm}$, mullti-leptons
q substructure	high-mass dijets
q/ℓ substructure	high-mass dileptons, $\not{E}_T$
None of the above	All of the above

The GEM design emphasized clean identification and high resolution measurement of the primary physics signatures for the high p_T physics summarized in Table 17-1. The approach was to make precise energy measurements that would maximize the sensitivity to rare narrow resonances, to detect the elementary interaction products (quarks, leptons, and photons), and to build in the features required to reduce backgrounds. The design of the GEM detector was based on the following principles:

(1) Very precise electromagnetic calorimetry without a magnet coil in front of it. This would have provided the best measurements of gamma and electron energies, to allow the reconstruction of the mass of narrow states with good resolution.

(2) A precise 4π muon spectrometer in a large superconducting solenoidal magnet, allowing measurement of the momenta of high energy muons with a minimum of multiple scattering. The muon system was to have operated in a quiet environment, shielded by the thick calorimeter.

(3) Hermetic hadronic calorimetry for the measurement of jets and the reconstruction of missing energy.

(4) Central tracking in a magnetic field with sufficiently low occupancy to operate reliably at the highest luminosities that could be anticipated at the SSC ($10^{34}cm^{-2}s^{-1}$). The central tracker was to be compact, allowing for a compact calorimeter and a large muon tracking volume.

At project close, all technology decisions for the GEM detector had been made, with the relatively small exception of the forward calorimeter hadronic section. The technologies chosen provided good performance even at the highest luminosities at the SSC. Reliance on the calorimetry and the muon system to provide the precise gamma, electron, and muon momentum measurements, and thus to allow precise mass reconstruction, further ensured undiminished performance at the highest luminosities available.

The GEM detector was designed to the cost goal of $500M (in FY90 dollars). A careful cost estimate was carried out for the GEM baseline design described in the TDR, and presented in detail in the "GEM Summary Cost and Schedule Book."[5] The projected completion date at the time of the TDR was in 1999; subsequently, the completion date was extended three years in concert with that of the Lab. It was possible to meet the cost goal without any permanent sacrifice in the required performance of the detector. However, a number of items were removed from the baseline design that could have been added as upgrades. Significant further cost reductions would have seriously compromised the physics performance of the detector. Careful physics simulation studies demonstrated that the baseline design current at shutdown was cost-optimized to do the physics for which the SSC was being built. The physics reach of the GEM design for topics of major interest to the SSC is summarized in Figure 17-2.

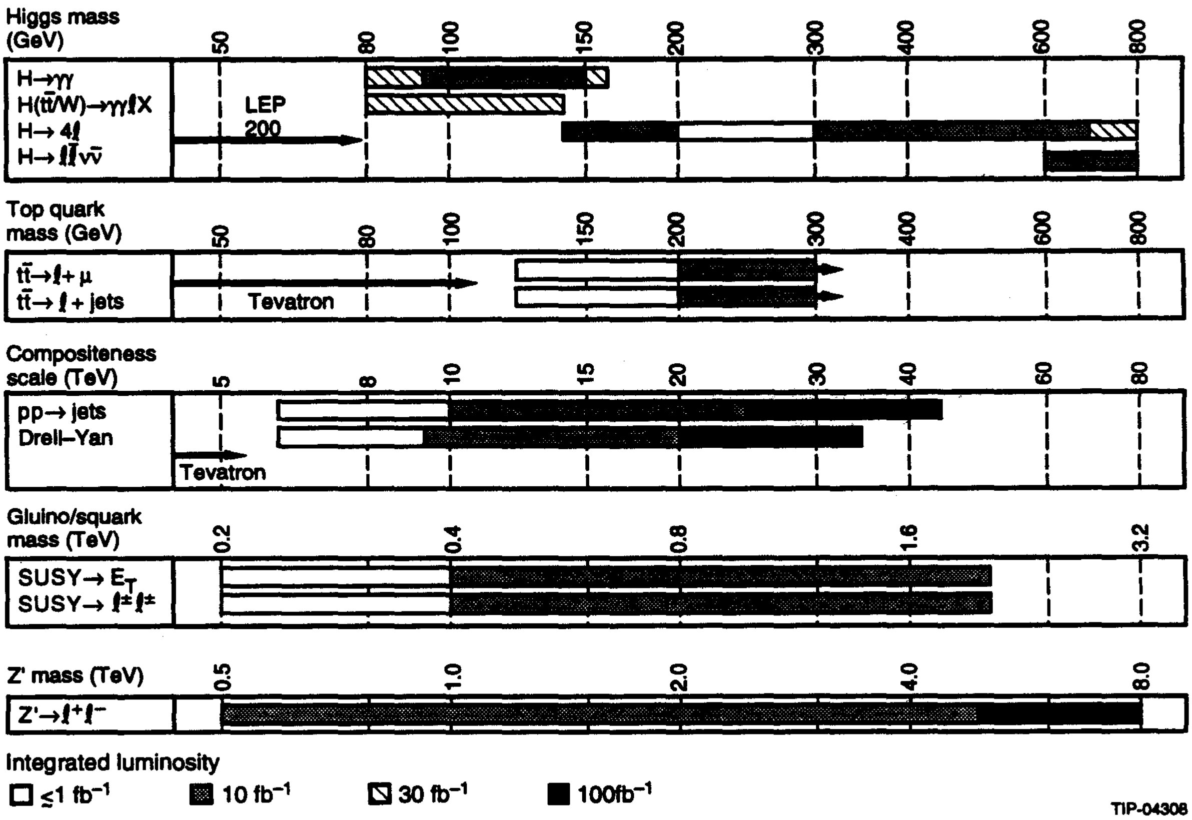


Figure 17–2. The Physics Reach of the GEM Detector.

Physics and the GEM Design

One of the primary goals of GEM was to provide complete coverage for Higgs physics from 80–800 GeV/c^2. The lower mass represented the limit of the LEP II reach, while the upper mass represented the highest value for which the basic idea of the Higgs mechanism made sense theoretically. As a high-precision lepton and photon detector, GEM had a discovery potential illustrated by its ability to detect Higgs particles in the challenging "intermediate mass" range between 80 and 180 GeV/c^2. In particular, the distinctive $\gamma\gamma$ decay mode would allow GEM to explore the gap between 80 GeV/c^2 and 140 GeV/c^2. The production of the Higgs boson in association with a $t\bar{t}$ pair would provide important confirmation of the $\gamma\gamma$ signal.

$H^0 \rightarrow \gamma\gamma$ detection placed stringent requirements on the overall detector design, especially the design of the electromagnetic calorimeter. In the 80–140 GeV/c^2 mass range, the $\gamma\gamma$ invariant mass must be measured with high precision and good background rejection to detect the signal above the background. In the context of the minimal Standard Model, the production cross-section is 160 to 260 fb, as compared to an irreducible direct $\gamma\gamma$ background that is more than 1000 times larger, in addition to QCD jet background. A Higgs boson signal can still be detected, due to its narrow decay width (5 to 10 MeV/c^2), but only if the resolution is sufficiently high and background rejection is good enough. For GEM, this stringent set of requirements motivated the use of a liquid krypton fine-sampling electromagnetic calorimeter. In this crucial energy region, both precise resolution for the stochastic term ($\leq 6\%/\sqrt{E}$ in the barrel; $\leq 8\%/\sqrt{E}$ in the endcap) and good control of the systematic term ($\leq 0.4\%$) are required. Much care was given to the development of a calorimeter design that would meet these requirements for GEM. To reduce backgrounds, the GEM design includes longitudinal sampling and good pointing ability (40-50 mrad/$\sqrt{E} \oplus 0.5$ mrad, where the $\oplus$ symbol denotes addition in quadrature) in the calorimeter. The combination yielded a signal/ background ratio sufficient for the discovery of the Higgs boson at design luminosity, and for the exploration of the Higgs sector at luminosities up to 10 times higher.

Of similar difficulty is the detection of a Higgs boson in the next higher mass region, approximately 140-180 GeV/c^2, where the best modes are $H^0 \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$. Because this region is below threshold for producing two real Zs, the rate is low, again making the detection difficult. In GEM, the plan was to measure all modes — $e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$ — with good acceptance and resolution.

For a standard model Higgs boson mass between 200–800 GeV/c^2, the signature of four isolated leptons from two Z decays is very clean and straightforward to detect. However, as the mass increases, the rates fall and the Higgs broadens. At the highest mass (~ 800 GeV/c^2), where the rates are lowest, it is necessary either to run at higher luminosities or to add the complementary modes $\ell^+\ell^-$ jet and $\ell^+\ell^-\ \nu\bar{\nu}$, to be able to discover the Higgs boson in one year at the standard luminosity ($L = 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$).

The considerations necessary to make a detector robust at high luminosity—choice of technologies, segmentation, ability to withstand radiation, and integrated shielding from backgrounds—are all important. Particular attention was paid to these points, and it was expected that GEM, without major upgrades, would have important capabilities up to the highest luminosities ($L = 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) expected at the SSC. This ability is demonstrated in Figure 17-3, which shows the signal expected in one year at this luminosity for $Z' \rightarrow e^+e^-$ at a mass of 4 TeV/c^2. Note the rapidly falling Drell-Yan background, the signal with good resolution, and the small residual background under the signal peak. The observed width is model-dependent, and the mass resolution of 0.3% would make it possible to distinguish among models. It should also be noted that in GEM, the couplings of the Z' to fermions could be probed by high luminosity studies of angular distributions of the muons from $Z' \rightarrow \mu^+\mu^-$. The muon system's unique ability to measure multi-TeV muons with negligible charge confusion would have enabled the study of couplings of the heaviest Z' that could be produced at the SSC.

If supersymmetry exists—for example, as in the minimal supersymmetric extension to the Standard Model—the detection and study of supersymmetric Higgs bosons is likely to be more difficult than in the simple examples given above. The highest possible lepton and photon resolution would have been needed to maximize the detector's ability to discover the supersymmetric Higgs boson within the first few years of running at the SSC. These examples are characteristic of areas where the physics motivation of GEM determined the design. More generally, GEM was designed to aim for all the physics goals listed in Table 17–1. The philosophy was to cover this wide range of physics with the idea that whether or not any of these specific ideas proved true, GEM's capabilities would have provided the tools needed to discover and explore whatever unknown physics might have existed at the SSC.

A complementary strength of the GEM design, with a compact inner tracker, modular calorimeter, and large volume muon system, was its adaptability to major advances in physics (or particle detection technology) that might have occurred in the course of the SSC experimental program. Although the GEM design was optimized to cover the broad range of new physics scenarios and signatures that were envisioned at the time, progress in understanding might have led to new requirements for higher performance in the long term. Replacement of an inner detector subsystem or extension of the muon system's lever arm outside the magnet coil could then be implemented at moderate cost to extend the physics reach in specific directions. This adaptability ensured that GEM would have been able to continue to do front-line physics for many years, well beyond the first phase of the SSC program.

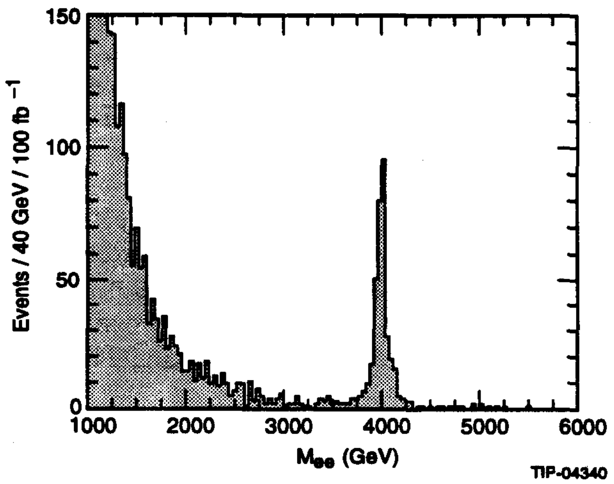


Figure 17-3. The High Luminosity ($L = 10^{34}$ cm^{-2} s^{-1}) Performance of GEM for Detecting a 4 TeV/c^2 $Z' \rightarrow e^+e^-$ in One Year of Running.

Detector Design

In the design of GEM, extensive use was made of simulation techniques to set requirements and to evaluate performance of the proposed detector. Full GEANT simulations were used in detailed studies and design of the subsystems. In physics simulation studies, for efficient use of the available computer resources, either parametrized studies were used or, where necessary, hybrids of full and parametrized simulations. The physics performance for a wide variety of processes using these tools was evaluated, with an emphasis on the parametrized program *gemfast*, which simulates detector performance well. The approach was founded in a broad range of specific full-simulation studies.

A vertical cross-section view of the large, 0.8-T magnet, with the detector elements placed inside, is shown in Figure 17-4. The main elements were a compact central tracker and hermetic calorimetry for precision electromagnetic measurements of electrons and photons, plus the detection of jet energy and $\not{E}_T$ with good resolution. The region outside the calorimeters provided a large volume, well shielded from the interaction point, where accurate muon momentum measurements were to be made. The top-level specifications for the GEM detector are given in Table 17-2. The detector approach described here is complementary to the SDC detector, going beyond its physics reach in specific areas, while maintaining an important degree of overlap in the two detectors' capabilities. The SDC detector featured a large tracker, while GEM emphasized precise measurement of gammas, electrons, and muons, plus unique capabilities at high luminosity. Detailed descriptions of the GEM detector subsystems, including technical features, implementation and integration issues, and studies of expected performance are given in the TDR.[1]

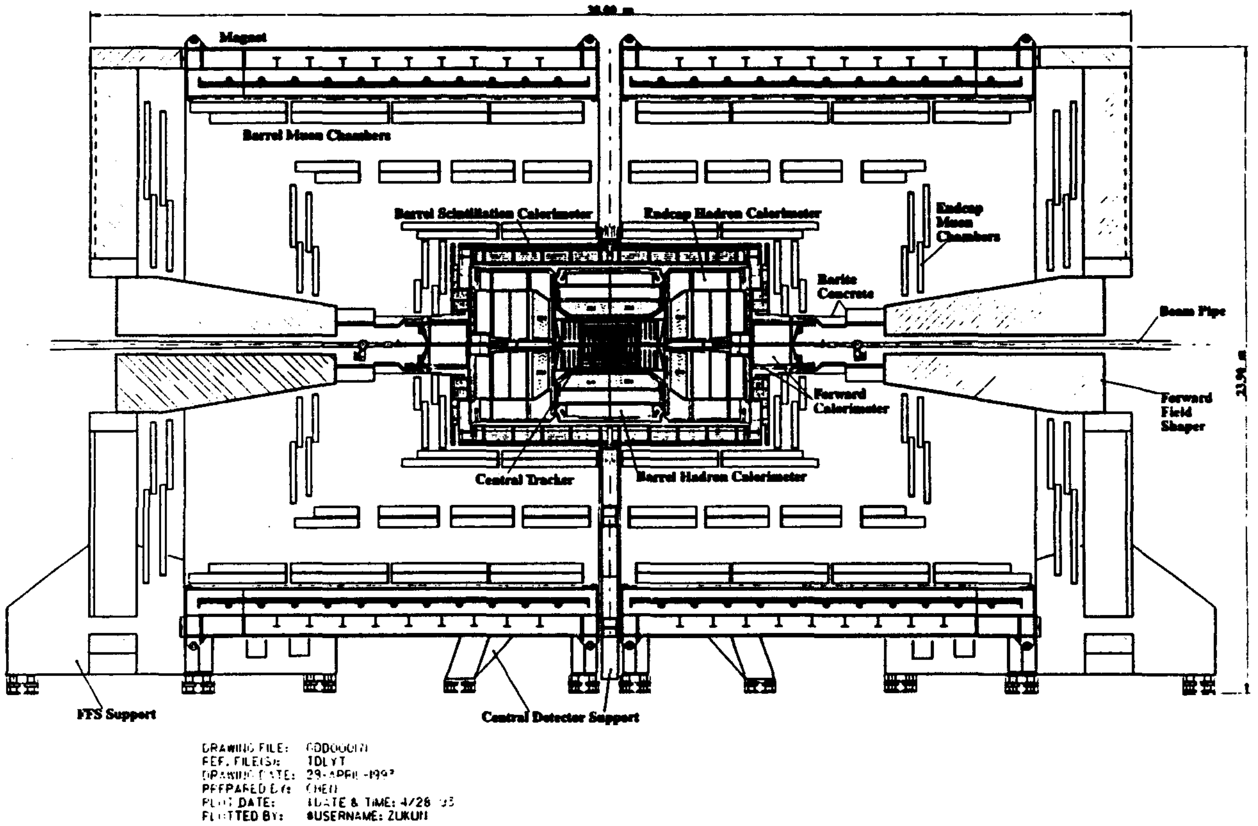


Figure 17-4. Vertical Section of the GEM Detector.

The detailed optimization of the GEM design was determined by the physics requirements, the practical ability to meet the necessary performance specifications, and cost/schedule constraints. Particular attention was paid to detector integration issues, such as radiation shielding and the interface between the beamline and the inner radius of the detector. The detector design resulted from a detailed research and development and engineering design phase that led to the choices of detector technologies and to their application in an integrated system optimized for physics discovery. The technical choices were based on overall detector performance, a philosophy of simplicity and uniformity of design, reliability and ease of calibration, flexibility in the means of access and installation, and the issues of cost and schedule. In making the major technology choices, a process of comparative review was used (often including outside experts), along with open discussions at GEM Collaboration Council meetings, technical documentation through GEM internal notes, discussion and recommendations by the GEM Executive Committee, and, finally, decisions by the spokesmen.

Table 17-2. Top-level Specifications for the GEM Detector.

Magnet	
Central field	0.8 T
Inner diameter	18 m
Length	31 m
Muon system	
Coverage	$0.1 < \|\eta\| < 2.5$
$\Delta p_T/p_T$ at $\|\eta\| = 0$, $p_T = 500$ GeV/c	5%
$\Delta p_T/p_T$ at $\|\eta\| = 2.5$, $p_T = 500$ GeV/c	12%
Charge separation ($\eta = 0$)	$p \leq 6.5$ TeV/c at 95% C.L.
Electromagnetic calorimeter	
Coverage	$\|\eta\| < 3$
Energy resolution	$6–8\%/\sqrt{E} \oplus 0.4\%$
Position resolution	$4.4\ \text{mm}/\sqrt{E}$
Pointing resolution	$40–50\ \text{mrad}/\sqrt{E} \oplus 0.5$ mrad
Hadronic calorimeter	
Coverage	$\|\eta\| < 5.5$
Jet resolution	$60\%/\sqrt{E} \oplus 4\%$
Tracker	
Coverage	$\|\eta\| < 2.5$
Charge separation at 95% C.L. ($\eta = 0$)	$p \leq 600$ GeV/c
Momentum resolution	
at high momenta (measurement limited)	$\Delta p/p^2 = 1.2 \times 10^{-3}$ (GeV/c)$^{-1}$
at low momenta (multiple scattering limited)	$\Delta p/p = 3.5\%$

Magnet

GEM employed a very large superconducting solenoid that surrounded the detector elements. In the forward region, field shaping iron poles were employed. The magnet design was optimized for field, radius, and length, with a nominal field of 0.8 T, an inner diameter of 18 m, and a length of 30.8 m, as described in Chapter 3 of the TDR.[1] (See Table 17-3.)

Table 17-3. Major Design Parameters of the GEM Magnet.

Magnet:	
Central field	0.80 T
Inductance	1.98 H
Operating current	50.2 kA
Stored energy	2.5 GJ
Axial force on conductor (each half)	52 MN
Mean radius of windings	9.5 m
Length of cold mass (each half)	14.25 m
Total mass of magnet (each half)	1300 Mg
Forward Field Shaper (FFS):	
FFS cone minimum z	10 m
FFS cone maximum z	18 m
FFS cone inner radius (minimum)	0.350 m
FFS cone outer radius (maximum)	2.5 m
Total mass of FFS (each)	899 Mg

The very large size of the GEM magnet dictated the choice of a superconducting solenoidal coil design. In addition, cost and risk considerations led to a conservative design with a single-layer winding, using a niobium-titanium superconductor with a large stability margin. Savings in cost and installation time were achieved by selecting a design with no return yoke.

The magnet provided a nearly uniform axial field in the region of the central tracker, allowing measurement of the momentum of emerging charged particles from the interactions. This allowed sensitivity to same-sign electron and same-sign muon final states, including gluinos over a wide range of parameter space. In the volume of detector outside the calorimeters, the magnet provided a 0.8-T field for muon momentum measurements.

Another feature of the magnet system was the pair of conical forward field shapers, one at each end of the solenoid. The field shapers introduced a radial component to the forward field through concentration of the field lines, enabling the muon system to meet the momentum resolution requirement in the forward direction. The final element in the magnet system was the stainless steel central detector support (CDS) that supported the calorimeters and the central tracker.

The coil was to be manufactured in two halves on the surface, lowered into the underground hall, and mounted on each side of the CDS. The coil halves were designed to be movable along the beamline, which was important for installation and detector access. The field shapers were separate assemblies, also movable along the beam axis.

The principal challenge of the magnet was associated with its size; the superconducting coil design was conservative and carried little technical risk. Because of its size, the magnet had to be constructed at the site. A "request for proposals" for construction of the magnet was issued, proposals had been received, and the proposal evaluations were under way. The scheduled completion of the magnet during 1996 required early availability of surface facilities, where the coils were to be wound, and of the underground experimental hall, where the magnet was to be assembled.

Muon System

Precise muon measurements, robust to high luminosity, were a primary goal of GEM. Muons provide signatures for a wide range of possible important new physics. The GEM design provided excellent muon information up to the kinematic limit of the SSC. At the top end of this range, the ability to operate at high luminosity and to determine the charge of multi-TeV muons is essential for heavy $Z' \rightarrow \mu^+\mu^-$ studies. High-resolution measurements of muon momentum are required to search for $H^0 \rightarrow ZZ^* \rightarrow \mu^+\mu^-\mu^+\mu^-$ in the difficult region from 140–180 GeV/c^2. Good coverage of muons for $|\eta| < 2.5$ is especially important for low rate processes such as $H^0 \rightarrow ZZ^* \rightarrow \mu^+\mu^-\mu^+\mu^-$. Robustness comes into play again for $H^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$ at high mass (e.g., 800 GeV/c^2) and for the search for quark-lepton substructure.

To perform well for this range of physics, the GEM muon system was designed to be precise: $\Delta p_T/p_T = 5\%$ (12%) at $\eta = 0$ (2.5) for $p_T = 500$ GeV/c. In addition, it was shielded very well from background sources, both by the thick hermetic calorimeter and by other shielding, which would enable it to be sufficiently robust to operate at the highest luminosities ($L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$) attainable at the SSC. The major design parameters of the muon system are given in Table 17-4.

Table 17-4. Major Design Parameters of the GEM Muon Subsystem.

Coverage:	
Barrel region:	$0.1 < \lvert\eta\rvert < 1.3$
($29.23° < \theta < 84.3°$)	
Endcap region:	$1.4 < \lvert\eta\rvert < 2.46$
($9.75° < \theta < 27.71°$)	
Number of sectors in ϕ	48
Lever arm:	
Barrel	>4.2 m
Endcap	>8.6 m
Chamber parameters:	
Single-layer resolution	75 μm (RMS)
Timing resolution	3.5 ns
Beam-crossing tag efficiency	>99%
Internal chamber alignment	50 μm
Superlayer-to-superlayer alignment	25 μm
Radiation length/chamber layer	1.1%
No. of chamber planes per superlayer (SL1:SL2:SL3)	6:6:6 barrel 8:6:6 endcap

Muons were identified by their penetration through the calorimeter system (Figure 17-5). Muon momentum was to be measured using the sagitta method in three superlayers between the calorimeter and the magnet. The resolution in the sagitta measurement varies as BL^2, where B is the magnetic field strength and L is the lever arm of the measurement.

The muon momentum resolution was determined at high momenta by the spatial measurement errors (both inherent and from misalignment), and at low momenta by the multiple scattering in the middle layer of chambers and energy-loss fluctuations in the calorimeter. It was therefore crucial to have high accuracy in position measurements, minimum scattering material, and the best possible measurement of muon energy loss in the calorimeter. Our studies of the effects of the muon resolution on the ability to detect Higgs boson decays through the signature $H^0 \rightarrow ZZ^* \rightarrow 4\ell$, indicated that the middle layer must be less than 10% of a radiation length to avoid degrading the measurement. For very high momentum (e.g., from Z' decay at the highest mass, ~ 8 TeV/c^2, that is accessible at the SSC) the most demanding problem was sign selection for each muon. This requirement demanded single layer resolutions of 75 μm and alignment between superlayers of 25 μm.

Another consideration that affected the design of the muon system was chamber occupancy. To keep the rates in the muon region at tolerable levels for luminosities above 10^{34} cm^{-2} s^{-1}, a thick ($\geq 11\lambda$ at $\eta = 0$, increasing in the forward direction), nearly hermetic calorimeter system was employed with a design for the forward direction that kept the background contained within the calorimeter volume. The thickness was chosen such that the rate from punch-through hadrons was significantly below that from in-flight decay muons.

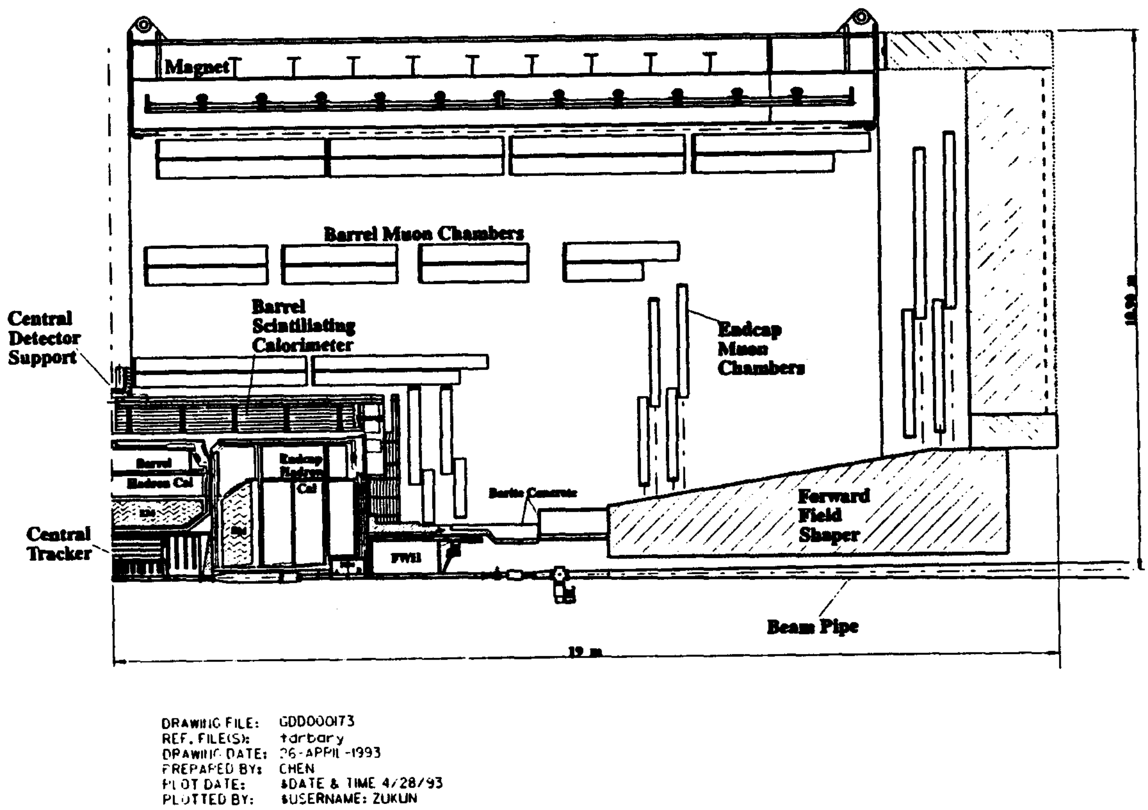


Figure.17-5. Quarter View of the Detector Showing the Muon System, including Shielding.

A notable design feature of the muon system was the use of a 0.2-m open space outside the calorimeter, before the first muon superlayer, to bend away charged particles arising from electromagnetic showers initiated by high-momentum muons. The clear space led to higher reconstruction efficiency for TeV muons than in systems using chambers interleaved with iron.

A very important element was to provide a carefully designed shield to reduce the large neutron and photon backgrounds that would result when particles emerging at large η from the interaction region struck the low-β quadrupoles, the forward field shapers, the forward calorimeters, and the beam pipe, and create electromagnetic and hadronic showers. It is noteworthy that the compact, close-in design of GEM's forward calorimeter system made an exceptionally effective shielding configuration possible at moderate cost. A full discussion of these points is given in Chapter 12 of the TDR.[1]

The choice of technology for the GEM muon spectrometer was based on an intensive research and development program. A variety of systems was considered using pressurized and unpressurized drift tubes, resistive plate chambers, and cathode strip chambers (CSCs). The first consideration was to obtain the required spatial resolution, which was achieved with all technologies. Other important criteria included the determination of the z coordinate, triggering, and occupancy. The CSCs were selected because they met all the requirements in a single technology and could be applied in both the endcaps and barrel. The technology choice was made late in the course of the project, and, although a complete and consistent muon system design was presented that met the design specifications, it was expected that the system would be further optimized for minimum material and maximum coverage. This would have improved the performance and discovery ability for $H^0 \rightarrow ZZ^* \rightarrow \mu^+\mu^-\mu^+\mu^-$ and $\mu^+\mu^-e^+e^-$.

Figure 17-6 shows the muon momentum resolution versus pseudorapidity for the baseline design as a function of transverse momentum, resulting from the baseline GEM muon system and magnet. As shown in the figure, the design provided 5% resolution at $\eta = 0$ for muons with $p_t = 500$ GeV/c and 12% resolution at $\eta = 2.5$.

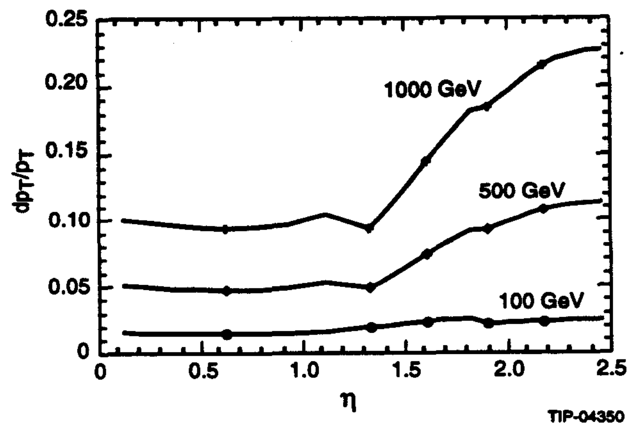


Figure 17-6. Muon Resolution vs. η.

Calorimeter

The major design parameters of the GEM calorimetry subsystem are given in Table 17-5. One of the principal goals of GEM was to achieve the best possible electromagnetic resolution and background rejection. These ambitious goals were motivated by the search for new physics, such as narrow resonances leading to multi-photon and/or multi-electron final states, as well as the search for Higgs particles. Good resolution for hadron jets and $\not{E}_T$ was also required. The general layout for the GEM calorimeter is shown in Figure 17-7.

Table 17-5. Major Design Parameters of the GEM Calorimeter.

Noble liquid section:	
EM energy resolution	
Barrel	$6\%/\sqrt{E} \oplus 0.4\%$
Endcap	$8\%/\sqrt{E} \oplus 0.4\%$
EM position resolution	4.4 mm/$\sqrt{E}$
EM pointing resolution	
Barrel	40 mrad/$\sqrt{E} \oplus 0.5$ mrad
Endcap	50 mrad/$\sqrt{E} \oplus 0.5$ mrad
EM coverage	$\|\eta\| < 3$
Hadron coverage	$\|\eta\| \leq 5.5$
Jet resolution	$60\%/\sqrt{E} \oplus 4\%$
Number of absorption lengths	
at $\eta = 0$	$\approx 11\lambda$
at $\eta = 3.0$	12λ instrumented, $> 16\lambda$ total
Lateral segmentation (η, ϕ)	
EM	0.026×0.026
HAD	0.08×0.08
Longitudinal segmentation	
Liquid barrel	3 EM + 3 HAD
Endcap	3 EM + 4 HAD
Scintillating barrel section:	
Lateral readout segmentation (η, ϕ)	0.16×0.16
Longitudinal segmentation	1 layer
Forward section:	
Lateral segmentation (η, ϕ)	0.2×0.2
p_T resolution for jets	$\Delta p_T / p_T \leq 10\%$
Instrumented absorption lengths	$11.4\,\lambda$
Total weight	2814 Mg

The resolution of an electromagnetic calorimeter can be parametrized as $\sigma/E = a\%/\sqrt{E} \oplus b\%$, where a is the stochastic term and b the systematic term, and the terms are added in quadrature. For both the $H \rightarrow \gamma\gamma$ reaction and the $H \rightarrow ZZ^* \rightarrow 4\ell$ reaction, the typical particle energy is less than 100 GeV; at such energies, minimizing both terms is important to obtaining the required resolution.

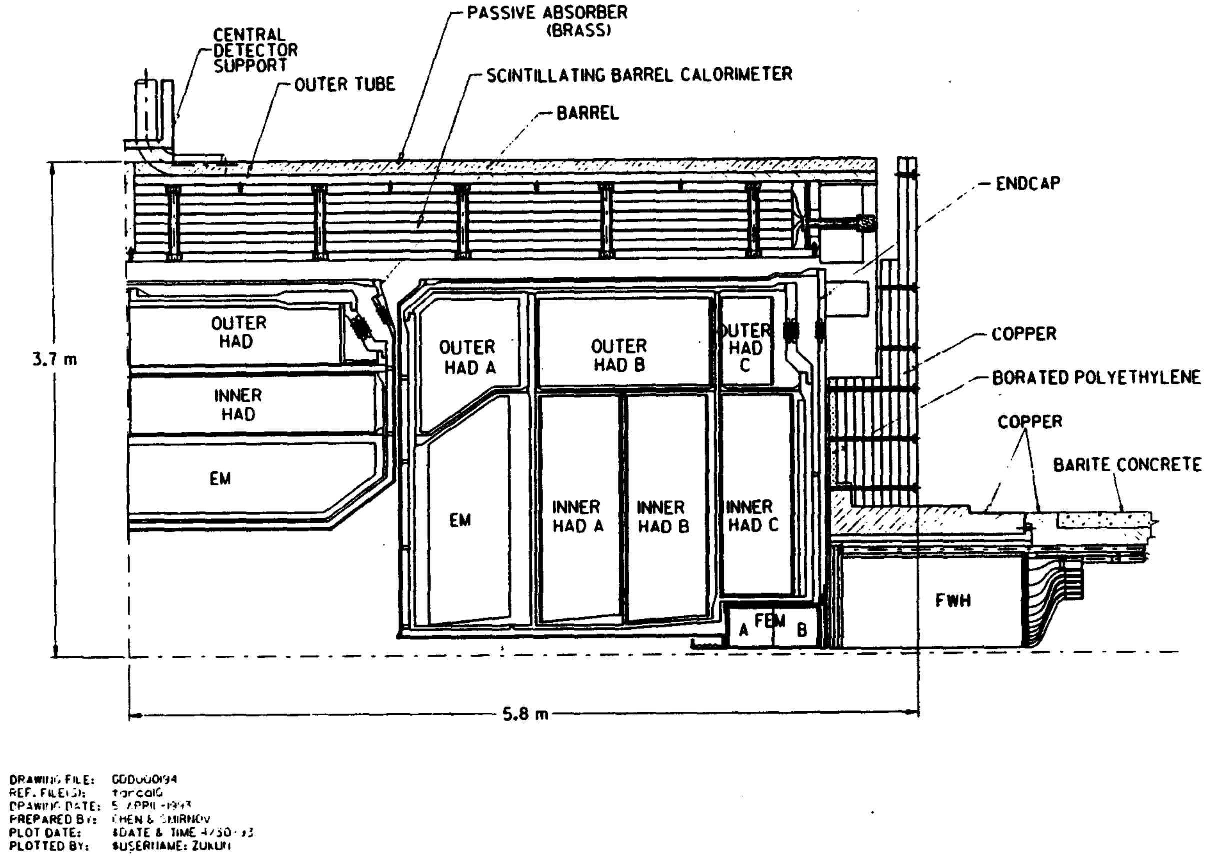


Figure 17-7. Quarter View of the Detector Showing the Calorimeters.

For physics at higher energies (e.g., $Z' \to e^+e^-$) the control of the systematic term is the most important factor. In addition, for small cross-section signals, good background rejection abilities and robustness at high luminosity are essential. For the difficult intermediate mass Higgs boson, 80 < M < 140 GeV/c^2, the primary signature is the decay $H^0 \to \gamma\gamma$. Another important function of the GEM electromagnetic calorimeter was to provide sufficient resolution and background rejection to allow detection of $H^0 \to ZZ^* \to e^+e^-e^+e^-$ and $H^0 \to ZZ^* \to e^+e^-\mu^+\mu^-$. The low rate for these reactions made it important to be able to detect all of the 4ℓ decay channels.

After rigorous R&D studies in which a BaF_2 crystal calorimeter was compared with a noble liquid sampling calorimeter, a liquid accordion electromagnetic calorimeter was selected. The noble liquid option with krypton in the barrel and argon in the endcap was chosen because of its ability to achieve the required resolution, longitudinal segmentation and pointing ability, its intrinsic radiation resistance, its ease of calibration, and the extensive experience that has been acquired with large liquid-argon systems. The accordion geometry provides good hermeticity and allows for faster readout than parallel-plate calorimetry because of lower inductance and capacitance. Results from a prototype accordion calorimeter tested at BNL, with somewhat thicker plates than in the final GEM design, yield an electron energy resolution of $6.7\%/\sqrt{E}$ and a very small systematic term. All aspects of its performance were well reproduced by the simulations. It was thus expected that this technology choice would have provided a system with good intrinsic resolution and a well-controlled systematic term in the electromagnetic resolution. The design goal for the GEM system was $\sigma/E = 6\%/\sqrt{E} \oplus 0.4\%$ for the barrel and $\sigma/E = 8\%/\sqrt{E} \oplus 0.4\%$ for the endcap, where the electron and photon energies are higher.

The performance of the electromagnetic calorimeter in GEM is the most demanding, but the hadron calorimeter also plays an important role. It determines jet energies with a resolution of $\sigma/E = 60\%/\sqrt{E} \oplus 4\%$. The hadron calorimeter is very nearly hermetic because it is used (in conjunction with the forward calorimeter) to measure $\not{E}_T$. Three alternatives for hadron calorimetry in the barrel were studied: an integrated noble liquid hadronic section, a sampling scintillator-based calorimeter, and a hybrid system. The integrated calorimeter was the most costly and required a cryostat too large to manufacture off-site and transport over the road. The scintillator calorimeter involved a difficult problem of bringing the services out of the electromagnetic krypton calorimeter; it had a transition region near shower maximum with thick cryostat walls, and also had radiation damage concerns. The hybrid system that was chosen performed the hadron calorimetry primarily in the noble liquid (in the first ~ 6λ), then was followed by a relatively inexpensive copper/scintillator calorimeter that provided the necessary shielding for the muon system and calorimetry information for late-developing showers.

The primary function of GEM's forward calorimeters was to measure high-momentum particles near the beam pipe. Together with the barrel and endcap calorimeters, they determined $\not{E}_T$ down to the level of irreducible background from standard sources of neutrinos. The design goal was to provide $\not{E}_T$ signatures for massive gluinos and squarks, or other new particles, whose signatures might include jets with measured $E_T \geq 75$ GeV and electrons with measured $E_T \geq 20$ GeV. To achieve these goals, the forward calorimeter must cover the region $|\eta| \leq 5.5$, be sufficiently dense to fully contain hadronic showers, be sufficiently fast to cope with the high-density particle flux in this region, and be radiation-hard. The baseline design adopted had a first section consisting of a specially designed liquid-argon calorimeter, followed by a second hadronic section consisting of a liquid-scintillator-capillary and tungsten calorimeter. The calorimeter was optimized to include good spatial information in the first section and sufficient transverse hadron shower containment in the second section. It also served the prosaic but important function of helping to shield the muon system.

Central Tracker

The purpose of the central tracker in GEM was two-fold: to support the primary GEM goals of measuring gammas, electrons, and muons at high p_T, and secondarily to provide pattern recognition capabilities and vertex resolution for studies involving *b, t,* and τ physics. The primary goals had to be met at high luminosity, $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$, while the secondary tasks needed be accomplished only at the standard luminosity of $10^{33}\text{cm}^{-}\text{s}^{-1}$.

The support of GEM's primary physics goals imposed a series of requirements on the central tracker system, including good separation of gammas and electrons by finding a charged track and measuring the electron sign up to 600 GeV. The former requirement was essential to the search for $H^0 \rightarrow \gamma\gamma$ and to background rejection in $Z' \rightarrow e^+e^-$; the latter, for the gluino search using the signature of same-sign leptons. Another important role for the tracker was to measure the position of the primary vertex, which was crucial for pileup background separation, especially at high luminosities, and for measuring the Higgs boson mass. The tracker had to serve as an aid in particle identification (electron-hadron separation and muon identification) by providing consistency checks with the other subsystems. It was also important for background rejection by enabling track isolation cuts to be made. Physics involving *b, t,* and τ decays requires full pattern recognition capability, including secondary vertex finding and tracking at low momenta. As much of this capability was incorporated as was practical within the scope of the GEM central tracker.

A variety of technologies were considered for the central tracker. The chosen design incorporated two technologies. For the inner section of the tracker, silicon pixels and long-drift silicon were considered, as well as silicon microstrips. The silicon microstrip technology was chosen because it is more mature and gives the required fine segmentation and radiation resistance. For the outer section, straw tubes and scintillating fibers were considered, as well as interpolating pad chambers (IPCs). IPCs were chosen for their low occupancy, their correlation of coordinates on a track to provide "near"-three-dimensional space points, their high-luminosity capability, and their demonstrated operational resolution of 50 μm (see Table 17-6).

Table 17-6. Major Design Parameters of the GEM Central Tracker.

Rapidity coverage	$\lvert\eta\rvert \le 2.5$
Occupancy	
at $L = 10^{33}$ cm^{-2} s^{-1}	$\le 1\%$
at $L = 10^{34}$ cm^{-2} s^{-1}	$\le 10\%$
Charge separation at 95% C.L. ($\eta = 0$)	$p \le 600$ GeV/c
Momentum resolution	
at high momenta (measurement limited)	$\Delta p/p^2 = 1.2 \times 10^{-3}$ (GeV/c)$^{-1}$
at low momenta (multiple scattering limited)	$\Delta p/p = 3.5\%$
Vertex resolution	
along beam direction	$\Delta z \cong 1$ mm
impact parameter	$\Delta b \cong 25$ μm above 10 GeV/c

The central tracker was 1.8 m in diameter by 3.5 m long, surrounding the interaction point. The tracker size was determined by a combination of factors: placing the calorimeter at a distance suf-ficient to allow π^0 rejection by shower shape analysis, minimizing the calorimeter cost, maximizing the tracker resolution, and preserving sign-selection ability to high momenta (see Figure 17-8).

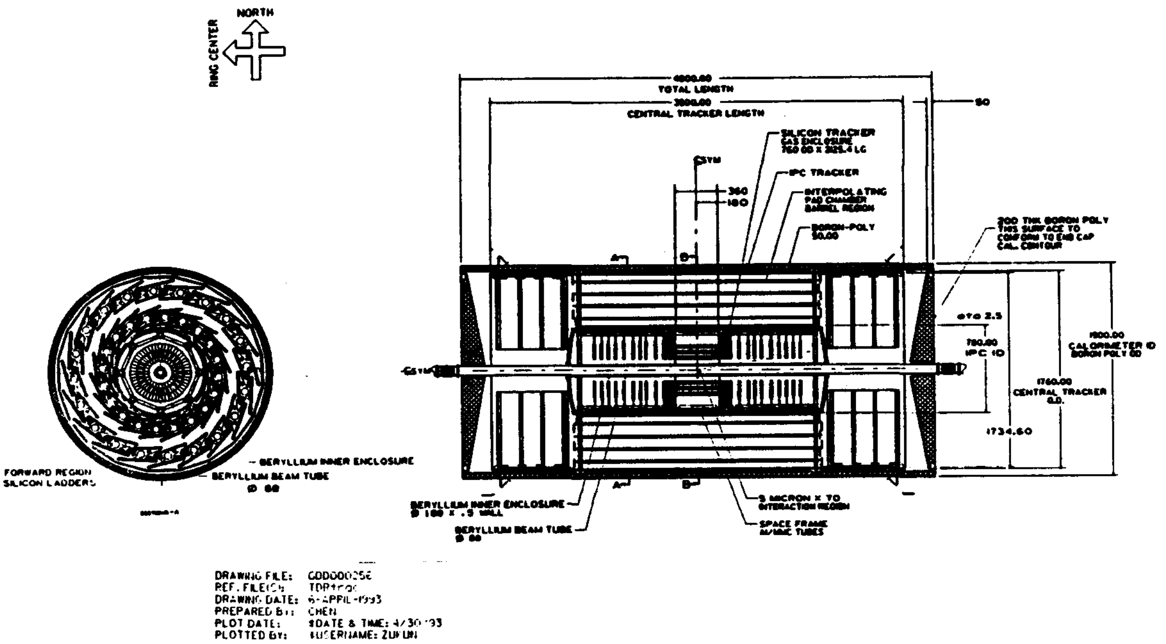


Figure 17-8. The GEM Central Tracker.

Electronics/Data Acquisition

Triggering and data acquisition in GEM was to follow a three-level strategy to provide a system without deadtime that would yield as much information as possible at each trigger level. It was designed for luminosities up to 10^{33} cm^{-2} s^{-1}, with provision for improving its efficiency at higher luminosities with modest upgrades. (See Table 17-7.)

Table 17-7. Trigger System Design Goals.

Level 1	
Rate in	60 MHz
Rate out	10 kHz
Latency	2 μs
Level 2	
Rate in	100 kHz
Rate out	300 Hz
Latency	$\leq$ 500 ms
Level 3	
Rate in	3 kHz
Rate out	100 Hz

The GEM trigger and data acquisition architecture consisted of a synchronous and pipelined Level 1, an asynchronous Level 2 (possibly with special purpose hardware), and a Level 3 processor ranch. In the data acquisition system, full granularity data was available at Levels 2 and 3. Level 1 was designed to handle up to 60 MHz input rate, with an output rate of 10 kHz. Level 2 was designed to handle an average input rate up to 100 kHz, with an output rate of 300 Hz. Finally, Level 3 accepted up to 3 kHz, with an output rate of 100 Hz. It should be noted that the Level 2 trigger was implemented as a "virtual Level 2," using the processor ranch with access to the full event data.

The individual subsystems imposed special conditions on the electronics. The inner silicon tracker was a digital system that needed radiation-hard electronics, and much of the electronics was integrated on the detectors. The IPC system also had to be radiation-hard. It used an analog readout, requiring 1% precision on 400,000 channels. The Level 1 trigger resulted in the digitization of the data stored on the tracker, which were then zero-suppressed and collected through a fiber-optic link. The calorimeter electronics of 128,000 channels required wide dynamic range and excellent timing to identify the beam crossing. Finally, the muon cathode strip chambers used chamber-mounted front-end electronics and low-cost, custom integrated circuits due to the large number of channels ($\approx 10^6$).

Detector Construction

Assembly, Access, and Maintenance

The GEM detector would have been located at interaction region 5 (IR5), which included a large underground detector hall and associated surface facilities for manufacturing, assembly, operations, offices, and utilities. The underground hall was to be 30 m wide, 100 m long, and 41~m high, with two large installation shafts, an electronics shaft, and a utility shaft. It was equipped with two 75/20-Mg bridge cranes for general use and for handling some detector components. To handle the massive assembled subsystems, the floor would have been equipped with heavy duty rails and other equipment. The transport system was to be used for detector assembly, which was to be done mostly in pre-assembled large units, and for detector access and maintenance. The size and general configuration of the hall was determined by the parameters of the detector, its installation and maintenance requirements, provision for adequate shielding, and the requirements for the local accelerator systems.

The two installation shafts were to be used to lower the magnet halves and assembled detector subsystems from the surface into the experimental hall. The principal consideration that established the requirements for the surface facilities was the need to manufacture the large GEM superconducting magnet on-site. Figure 17-9 shows the GEM surface facilities at IR5. The main features were two large assembly buildings, each connected through heavy load paths to the two installation shafts. Detector subsystems would be assembled in these buildings and lowered into the hall for final detector assembly.

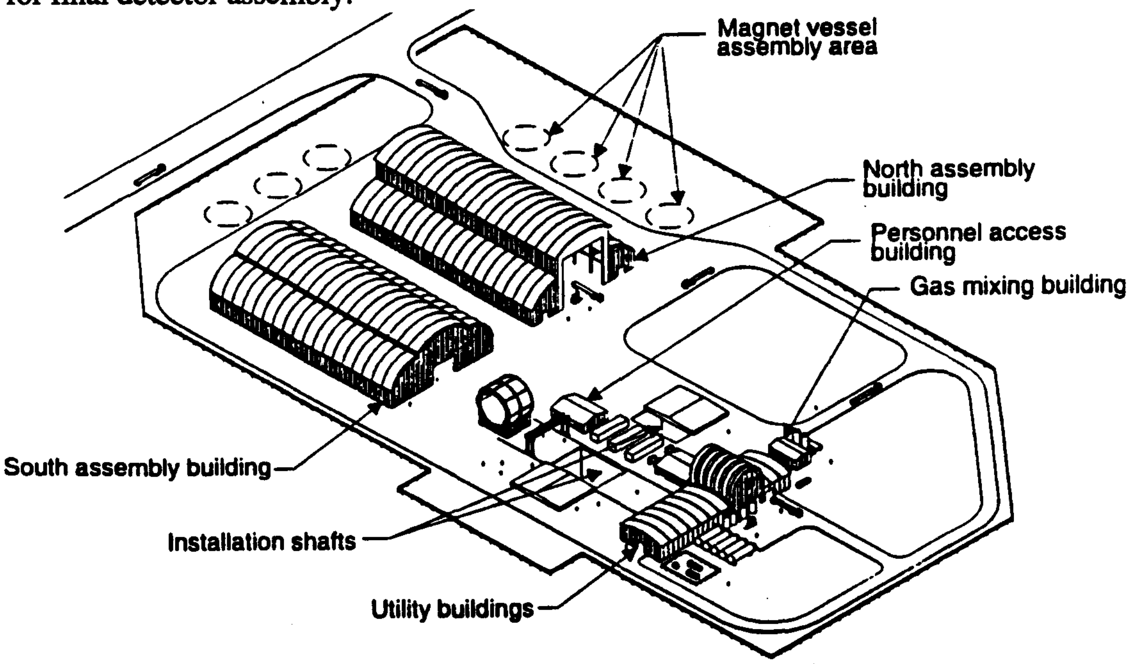


Figure 17-9. The GEM Surface Facilities at IR5.

A detailed schedule for assembly is given in Chapter 9 of the TDR,[1] based on the availability of components and efficient use of the surface assembly space. The symmetrical nature of the detector and its assembly around a fixed central detector support, the two installation shafts, and the large multi-purpose assembly space offered considerable flexibility in installation scenarios.

A view of the assembled detector in the hall is shown in Figure 17-10. All detector components were designed to be accessed and maintained. For access, the capability was incorporated to open up the detector along the beam line, pulling back the magnet halves against the far walls of the underground hall for major access. For detector maintenance, a seven-level scheme (TDR,[1] Chapter 10) of access was developed, determined by access restrictions (beam on/off), location in the detector hall, and extent of disassembly required. Critical components were placed in locations where short-term access was possible ensuring that all components could be maintained within an annual 3-month shutdown period. In addition, attention was given to the feasibility of either upgrading or replacing subsystems as needed for the long-range evolution of GEM.

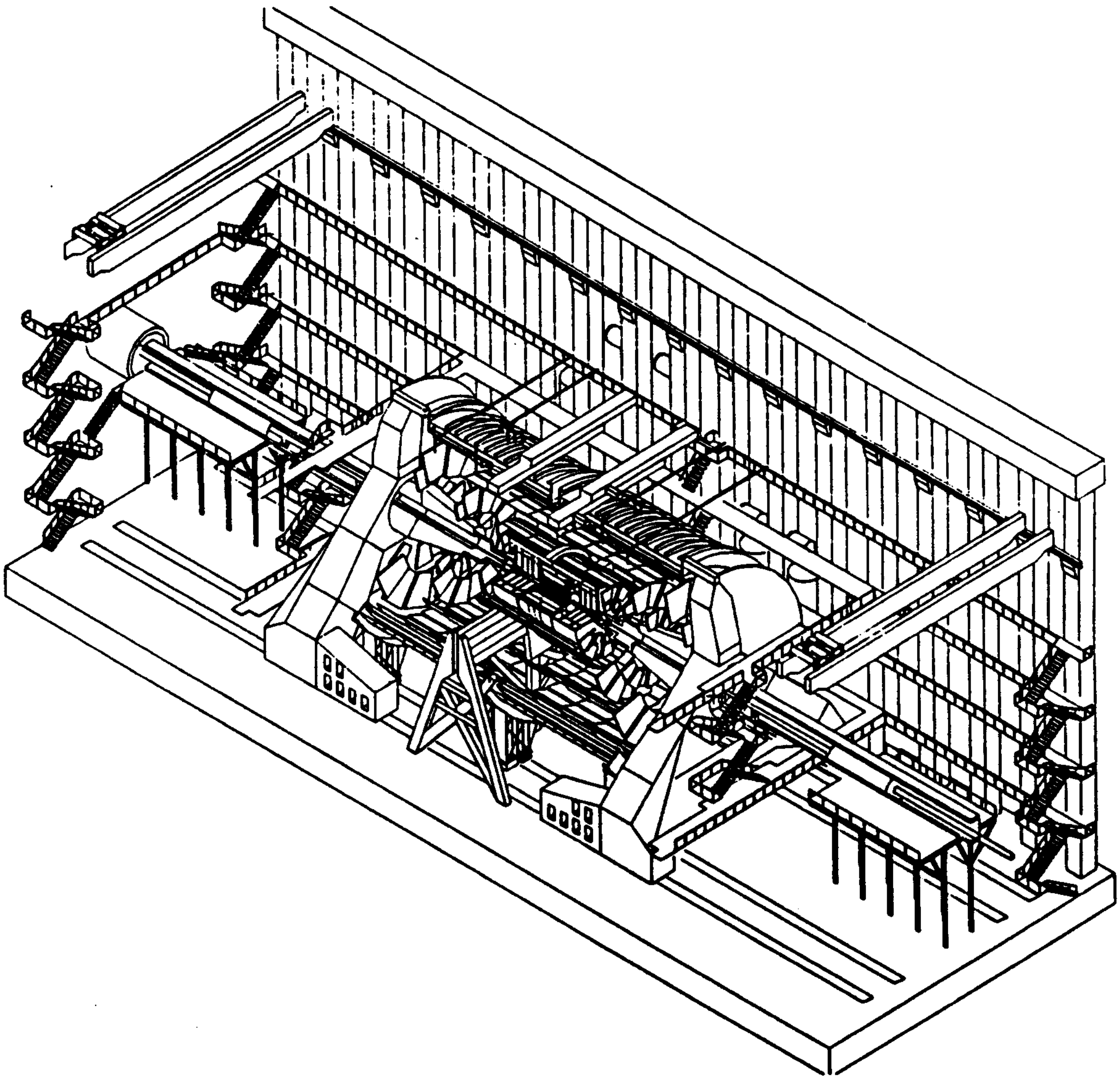


Figure 17-10. Assembled Detector in the Hall.

Detector Integration

Detector integration also received much attention in GEM. The primary integration issue was to select the parameters of the detector to make a coherent, optimized design. The parameters of the detector presented here went through careful trade-off studies for cost, performance, and consistency with the main priorities of GEM. High-level integration issues, such as decisions on the transition between two detector systems, support, services, and access, were decided after meetings between the detector groups, engineering meetings, and final discussions in the Executive Committee (see Chapter 14 of the TDR[1]).

Most integration issues are addressed in appropriate subsystem chapters of the TDR; some were addressed separately. The detector/beamline interface (Chapter 11[1]) involved several issues: attaining the desired vacuum; minimizing secondary interactions in the beam pipe, associated pumps, and related equipment; and facilitating assembly and access. Forward calorimetry places severe requirements on the beam pipe design. It was determined that the best location for the forward calorimeter was contiguous to the endcap calorimeter. This location was much better than further downstream from the IP (interaction point), because it was far easier to shield as a neutron source for the muon detectors and because the calorimeter was then considerably smaller and less expensive. The main problem was to make the beam pipe small enough to permit the required η -coverage for E_T studies. A beam pipe was designed that began with an 8-cm diameter in the region of the forward calorimeter, and then was flared so that it lay in the shadow of the calorimeter.

A second important integration issue involved radiation shielding (Chapter 12[1]). Sources of background in the detector were carefully considered . A well-shielded entrance to the interaction hall prevented radiation from beam-gas interactions from entering the hall. The primary source was from products of *pp* collisions at the interaction point. At SSC luminosities the neutron and photon fluences could be very large. Great care was taken to reduce them to a tolerable level.

The GEM detector was hermetic for $|\eta| < 5.5$ and thick enough to reduce the flux in the muon system. Beyond $|\eta| = 6$, care was taken to minimize material, with the beam pipe shielded by the calorimeter, allowing the scattered particles to strike the collimator at the face of the final low β quads. The quads were placed far downstream and were well shielded from the detector. The practical realization of the shielding presented reduced the n, γ, and charged particle fluxes to a manageable level (see Chapter 12 of the TDR[1]) in all regions of the detector up to the highest luminosity expected at the SSC.

Upgrades

An example of a deferred item that could have been implemented as an upgrade was an extension of the field shaper. It had been shortened by 1.5 m in the baseline design, saving several million dollars. Restoring the extra iron would improve muon resolution by about 10% at $\eta = 2.5$. Another example was to add more powerful Level 1 and Level 2 trigger processors, for which provision had been made in the chosen design.

In addition to these deferred items, there were several other improvements that could have been implemented as future upgrades to enhance the performance of the detector. The muon resolution could have been significantly improved by the addition of a set of muon chambers outside the magnet, where there was enough room for this purpose. The calorimeter resolution could be improved by using krypton in the endcaps, or possibly by using a xenon-krypton mixture throughout. The performance of the central tracker could have been improved at high luminosity ($L = 10^{34}$ cm^{-2} sec^{-1}) by replacing the silicon microstrip inner detector (which probably could not tolerate the radiation levels at this high luminosity) with a more radiation-resistant detector based on silicon pixels or gallium arsenide.

Commissioning and Initial Operation

The physics simulations presented in the TDR were based on the baseline detector at $L = 10^{33}$cm^{-2}s^{-1}, except for Section 2.6, where the strong physics capabilities at $L = 10^{34}$cm^{-2}s^{-1} were addressed. Initial turn-on scenarios at SSCL would probably have involved a period of running at lower than the design luminosity. It is worth noting the physics potential for such early running, beyond its value for detector commissioning.

In particular, integrated luminosities up to 10^{37}cm^{-2} (perhaps early shakedown running) could have been used for elastic and total cross sections, structure function and jet fragmentation studies, *B*-physics, including a precise *W* boson mass determination, and *t*-quark physics. The GEM detector could address these items and do very useful commissioning work with *W* and *Z* events. For integrated luminosities reaching 10^{38}cm^{-2}, detailed studies of *t*-quark decay rates and properties and early searches for light gluinos, techni-rhos, and other new strongly produced particles could begin in a significant way.

At the next step in integrated luminosity, to the level of 10^{39} cm^{-2}, exploration for a Higgs boson could have begun over much of the mass range, as well as significant particle searches. Perhaps as important, running with full capability would have been crucial to having a detector well understood and capable of the full set of physics goals when integrated luminosities of 10^{40} and eventually 10^{41}cm^{-2} were reached.

Test Beams

The GEM Collaboration planned a full range of test beams activities, including exposures at Fermilab, SLAC, BNL, CERN, and the SSCL itself. Of these, the Fermilab running was to have the greatest scope. This is described in detail in a GEM Technical Note.[6] SSCL test beams were planned for a later turn-on, with the exact schedule yet to be specified. An Invitation for Bid had been prepared and was awaiting Lab approval before being sent out. The GEM test beams plans are described in broad terms in the TDR.[1]

Collaboration and Organization

The GEM collaboration consisted of 1026 collaborators (who signed the TDR[1]) from 118 institutions in 17 countries. The membership is listed in the Collaboration Directory.[7] A broad and deeply talented group was formed committed to developing a powerful detector for the SSC. This international collaboration was working closely together on the extensive R&D and engineering program that was needed to design the detector described in the TDR. The Collaboration operated at its inception with a temporary organization, but this was evolving into a more permanent one following the submittal of the TDR.

The Collaboration worked systematically to develop a plan that was well-suited for implementing GEM as it moved past the TDR into the project phase. The general organization plan presented in Chapter 14 of the TDR had been approved by the collaboration before the TDR submittal.[1] The plan represented an evolution of the successful interim structure. It was founded on democratic principles and was built around an active group of institutional representatives (the Collaboration Council) who discussed and approved all major decisions and appointments. The International Committee ensured that all participating countries functioned effectively within the Collaboration, and an Executive Committee advised the spokesmen and project manager on scientific, technical, and managerial decisions as the detector was to have been constructed and operated. Subsystem groups were organized, each with its own organization, and the entire Collaboration was directed by the spokesmen.

The scientific collaboration was integrated into a project organization, responsible for coordinating the overall engineering, budgets, cost, and schedule for GEM. A draft project management plan for GEM was submitted,[8] and the management team was being put in place.

Responsibilities for individual groups were being developed and matched to project needs for implementation of GEM. We would have been developing memoranda of understanding (MOUs) with each institution during 1994. We were paying special attention to defining appropriate roles in GEM for all international collaborators, U.S. universities, and laboratories.

History and Status of GEM at Termination

The GEM Collaboration was formed in June of 1991, following the collapse of the L^* Collaboration. An Expression of Interest (EOI)[9] was presented to the SSC Laboratory on July 8, 1991. Following acceptance of this EOI, a GEM Letter of Intent (LOI)[10] was submitted to the Laboratory on November 30, 1991. The Collaboration was given encouragement to proceed towards a TDR, following a successful PAC review of the LOI. The full TDR[1] was submitted to the Laboratory April 30, 1993. The PAC conducted a full review of the TDR in May of 1993, which was followed by a very positive report[2] containing some questions and advice. The GEM Collaboration responded to these questions in a report dated October 27, 1993, shortly before the cancellation of the SSCL.[11] A more detailed history of the Collaboration may be found in Ref. [12].

Chapter 18. Smaller Experiments

(V. Luth)

Given the uniqueness of the SSC energy and luminosity, it was initially recognized that it would be highly desirable to match this enormous accelerator facility with experiments capable of exploring a diverse set of fundamental questions that could not be addressed at other facilities. In addition to the large general purpose detectors addressing physics at the highest masses, several smaller, more specialized experiments were to be considered. The smaller collider experiments would be placed on the West Complex in Interaction Regions 1 or 4. In the longer term, additional research activities were expected to develop; some might exploit secondary beams or parasitically extracted low intensity beams from the Collider, others might use extracted beams from the medium energy booster ring.

The Experimental Physics Research Program at the SSC Laboratory was proposal driven. In February of 1990, the Laboratory called for Expressions of Interests (EOIs) for "any type or class experiment that might be part of the initial experimental program" at the SSCL. During the following four years, 22 Expressions of Interest had been submitted to the SSC Laboratory. These documents were meant to gauge the community interest and assess the scope of the initial experimental program at the SSC. They also helped the Laboratory assess requirements for interactions, regions, and facilities. Following the selection of the two large experiments (SDC in December 1990 and GEM in July 1991) 11 EOIs signed by 364 scientists from 116 institutions remained under consideration as candidates for smaller experiments.

Table 18-1 lists the Expressions of Interest for experiments addressing physics below the TeV scale. Some of these documents comprise several hundred pages, others are one-page letters. Similarly, the number of authors varies from one to several hundred. The schedule foresaw a call for proposals for smaller experiments in the spring of 1994, although reduced funding and management directed stretch-out of the schedule were expected to have an impact on the planning of all components of the experimental program. At the time of shutdown, no guidelines or global specification had been developed of the smaller experiments.

The smaller experiments were expected to need less time for construction and installation, but they involved much smaller groups, which in general would have to rely more strongly on support specific to the EOIs from SSC Laboratory and Texas National Research Laboratory Commission (TNRLC) funds. Once the situation concerning the major detectors had been clarified, the Laboratory expected to call for more detailed Letters of Intent which were to form the basis for definition and selection for the Small Detector Program. The scope of the program would have depended critically on facilities and funds available.

Table 18-1. Smaller Experiments at SSCL.

LOW P_t EXPERIMENTS		
EOI 02	Orear	Elastic Scattering
EOI 01	Krisch	Polarized Beam Experiments
EOI 19	Bjorken	A Full Acceptance Experiment (FAD)
B EXPERIMENTS		
EOI 08	Lockyer	A Solenoidal Collider Experiment
EOI 13	Rosen	A Gas Jet Experiment
EOI 14	Cox	An External Beam Experiment
EOI 21	Schlein	A forward Collider Experiment
OTHER EXPERIMENTS		
EOI 04	Sobel	A Long Baseline Neutrino Experiment
EOI 15	Giacomelli	Search for Magnetic Monopoles
EOI 17	Bryant	Relativistic Atomic Physics
EOI 22	Okorokov	Σ^+ Hyperon Production by Channeling

Low p_t Experiments

Three experiments fall into the category of low p_t physics:

EOI 02 - Low p_t Physics at the SSC

(J. Orear et al.)

This is a proposal for the measurement of small angle elastic scattering into Coulomb region, large angle elastic scattering, single diffraction disassociation, and other small angle processes that are inaccessible to the larger detectors. The measurement of the small angle elastic scattering is a well known technique that has been exploited at the CERN and Fermilab colliders. To separate the pure Coulomb and nuclear scattering amplitude and obtain a normalization at t=0, it is necessary to extend the measurement to scattering angles of less than 1 μrad. Since this angle is smaller than the typical angular divergence of the colliding beams, the IR optical system has to be set to very large β values, of the order of 2000 m, resulting in a larger beam size and reduced luminosity. The detectors are placed symmetrically below and above the beam at distances of 580m from the IP. They consist of bundles of densely packed scintillating fibers of 200 μm diameter, which are read by a CCD via a two-stage multi-channel image intensifier. The total cost for the detectors was estimated to amount to roughly 2M$.

EOI 01 - Inclusive Spin Effects and Cross Sections Near 20 TeV

(A. Krisch et al.)

This proposal also represents a continuation of work at lower energies, dating back to measurements at the Brookhaven ZGS more than 25 years ago. It addresses a wide range of spin-related effects that have remained poorly understood for many years. The experiment requires a source of polarized protons, so-called Siberian Snakes to maintain the polarization in the circular accelerators, polarimeters, and a magnetic spectrometer of about 90 m length. The spectrometer is placed at 45° to the beam and designed to measure secondary particles up to transverse momenta of 20 GeV/c. The proponents foresaw operation both in fixed target mode with a polarized gaseous target and with colliding beams. The main concern about this experiment was the provision of sufficient space for the location of more than 500 magnets making up the Siberian Snakes in the MEB, HEB, and SSC rings. The preliminary cost was estimated at $35M for the magnets and associated polarimeters, with an additional $20M for the spectrometer.

EOI 19 - A Full Acceptance Detector for Physics at Low and Intermediate Mass Scales

(J. Bjorken et al.)

An experiment that covers a very large fraction of the available phase space and could measure diffractive processes that exhibit jets, rapidity gaps, and any other structure in multi-particle and multi-jet events was proposed by J. Bjorken. The goal was to provide a detector "sensitive to all physics at the expense of not being optimized for anything." The detector was to measure with good efficiency all charged particles and photons. At a later stage it could also have the ability to identify stable hadrons by Cerenkov or TRD and secondary decay vertices from charm and beauty particles. To cover the full rapidity range at the SSC, the detector extends over 500 m on both sides of the IR, with a solenoidal magnet in the center, followed by a spectrometer consisting of a series of quadrupole and sextupole magnets for charged particle momentum analysis. These spectrometers are roughly 100 m long and are backed with a set of tracking chambers for charged particles and calorimeters for the detection of neutrals. Details of the detector design had not been worked out. The detector was to be operated in a medium luminosity IR, allowing for 100 m free space on both sides of the IR. No reliable cost estimate for this detector existed at the time of termination.

B Physics Experiments

At 40 TeV c.m. energy, the cross section for the production of beauty hadrons may be as high as several mb or 1% of the total cross section. These rates should allow for a study of rare decays of *B* mesons and baryons, as well as the measurement of CP violation. In a 20 TeV the fixed target experiment with a c.m. energy of 193 GeV, beauty production is lower by a factor 500 or more. It is recognized that the large general purpose detectors may only be able to trigger on low p_t processes as long as they operate at low luminosity, and thus the measurement of CP violation and rare decay modes of *B* hadrons may require a dedicated experiment. Four different concepts on how to build a dedicated *B* experiment were proposed, two operating at colliding beams with central or forward rapidity coverage, and two others using fixed targets placed either in the stored 20 TeV proton beam or in a parasitically extracted proton beam.

EOI 08 - A Beauty Collider Detector at the SSC

(N. Lockyer et al.)

This is a proposal is for a Beauty experiment covering 11 units in rapidity. It consists of a central detector with a 1 T dipole or solenoidal magnetic field, and two forward spectrometers that are equipped with RICH and TRD for kaon identification, electromagnetic calorimeters and muon detector for triggering and measuring charged leptons. Charged particle tracks are recorded in layers of thin-walled drift tubes. A rather elaborate vertex detector, composed of cylindrical and planar disc arrays composed of silicon strip detectors is designed to detect secondary vertices with a precision of 50 μm. The trigger is provided by either single or multiple leptons or the evidence for displaced vertices. With this rather loose hardware trigger condition, the data acquisition system has to handle rates of 500 Gbytes/s. The data selection is performed in large arrays of processors operating in parallel. The experiment can be operated at a luminosity of 10^{32} cm^{-2} s^{-1}. The proponents placed the cost at $208M, but it was judged that this estimate might have been low by more than 50%.

EOI 13 - Internal Target Beauty Physics

(J. Rosen et al.)

This proposal is for a Beauty experiment using an internal target placed in the stored collider beam. The Cs jet target is to provide a 50 μm point-like interaction region in three dimensions. The spectrometer consists of a dipole magnet, an imaging Cerenkov counter, and lepton detectors (not yet specified). The vertex detector is to be placed at a distance of a few mm from the stored beam, and it must be retractable during injection. It is composed of orthogonal silicon strip detectors placed transverse to the beam inside so-called *Roman Pots*. The trigger is to be provided by leptons or transverse energy measurements. It is conceived that this experiment will be mounted near one of the interaction regions with the proton beams separated by more than 10 m. No design or cost estimate existed at time of closing.

EOI 14 - A Super Fixed Target Target Facility

(B. Cox et al.)

This proposed experiment relies on parasitic extraction of protons via channeling in a bent mono-crystal that is placed in the halo of the stored collider beam. The experiment will be located more than 1,000 m from the extraction point in a dedicated underground hall. The active target made of silicon strip detectors is followed by a 70 m long spectrometer consisting of a vertex detector, a pair of dipole magnets and several stacks of drift chambers. This is followed by a RICH counter for kaon identification and charged lepton detectors. The trigger will be derived from leptons produced at intermediate transverse momentum. As a possible location for this experiment, the utility straight section on the east side of the Collider ring has been studied. In fact, it would be advantageous to combine the extraction with the beam momentum scraping system. The cost for the extraction system and potential modifications to the tunnel have not been ascertained. The detector costs are estimated to be of the order of $30M.

EOI 21- A Collider B Experiment

(P. Schlein et al.)

This proposed experiment is an extrapolation from a proposal submitted by the same group for an experiment at the CERN SPS collider. The experiment consists of a two-arm spectrometer covering polar angles from 10 mrad to 600 mrad relative to the beams. The vertex detector consists of planar arrays of silicon strip detectors mounted on a retractable support inside the vacuum pipe. Each of the spectrometers consists of two sections covering different angular ranges. Each section is equipped with an e.m. calorimeter and a RICH in front of a large aperture magnet, which is followed by tracking chambers. The first magnet in each arm is a larger aperture quadrupole, the second is a large dipole. The trigger employs a fast hardware processor and relies on the detection of secondary vertices. It is based on fast track information extracted from the vertex detector. This detector could be placed in one of the interaction regions with a wide spacing of the IR quadruples, resulting in peak luminosities of the order of $10^{32}cm^{-2}s^{-1}$. The cost was estimated to be of the order of $25M for each spectrometer arm.

Other Experiments

A number of experiments were proposed for a variety of external beams provided by the SSC accelerators systems.

EOI 04 - A Very Long Baseline Neutrino Oscillation Experiment

(H. Sobel et al.)

The goal of this proposed experiment is to extend the limit on the neutrino mass difference and mixing amplitude. The experiment employs two water filled Cerenkov detectors placed in a ν_μ beam that is produced by 200 GeV protons from the MEB. The first detector of 20t is set at a distance of 1 km, the second detector of 1000t is located in Arkansas, some 400 km apart (a project that was proposed independently and unfortunately did not receive funding). The two detector set-up permits a relative measurement of the charged to neutral current interactions, thus reducing systematic uncertainties. The cost for this experiment is dominated by the cost for the construction and instrumentation of the ν beam line, the stated cost of $2M was derived from actual costs for a similar beam at CERN, but may be as much as a factor of three too low. The cost of the excavation and construction of the detector facility was estimated to be of the order of $1.2M, probably also too low.

EOI 15 - A Search for Magnetic Monopoles

(G. Giacomelli et al.)

This proposal relies on the detection of highly ionizing tracks produced by magnetic monopoles and resembles similar experiments that have been performed at other accelerators. The detector consists of stacks of CR-39 and lexan sheets that are centered on the interaction region on the outside of the beam pipe. The dimensions and the cost of this experiment are very small, allowing for quick installation at any of the available interaction regions.

EOI 17 - Relativistic Atomic Physics at SSC

(H. Bryant et al.)

This is a proposal for an experiment to be performed at the H^- Linac with the principal goal of studying the dynamics of the two-electron system using laser excitation, relativistic Doppler shifts and multi-photon techniques. The experiment can also benefit the development of monitoring techniques for the Linac beam. The experiment would have been located in the Linac housing where provisions for special access would have had to be made.

EOI 22 - Σ^+ Hyperon Production by Channeling

(V.V. Okorokov et al.)

The purpose of this proposed experiment is the observation of resonant (coherent) production of Σ^+ hyperons via the interaction of relativistic protons with the Coulomb field in a crystal structure. To obtain coherent production, the energy of the proton beam has to be tuned to match the spacing of the atoms in the mono-crystalline structure. A major difficulty is also the accurate placement of the crystal relative to the stored beam and the separation of the Σ^+ decay products from the stored beam. As of shutdown, the proponents had not given any details about the layout and composition of the detector. It was not obvious whether one could have combined this experiment with the crystal extraction system proposed in EOI-14.

Chapter 19. Detector R&D

(H. L. Lynch)

At the inception of the project, a vigorous detector R&D program was undertaken directed towards the development of specific proposals for detectors. There were many ideas that had to be explored to make coherent proposals. The areas of investigation included precision vertex detectors, tracking detectors, particle identification, electromagnetic calorimetry, hadron calorimetry, muon detection, electronic design, data acquisition, data processing, trigger logic, and magnet design.

Proposals and Funding

Calls for proposals were sent out in the summer of each year of the project by SSCL, and responses were received and evaluated in the fall by an R&D Advisory Group reporting to the Associate Director (AD) of the Physics Research Division (PRD). The group consisted of people with expertise in the appropriate fields from laboratories and universities both inside and outside the United States. The recommendations of the Advisory Group were received by the PRD and acted upon. A summary of all proposals funded can be found in an internal PRD document,[1] which lists the proposal, the MOU number, the title, the institutions involved, and the amount of money granted. The actions are briefly summarized in Table 19-1, which shows the number of proposals funded and the amount of money granted by PRD by fiscal year. Note that the actual amount of money received in FY93 was smaller than that granted because of budget cuts in July 1993, which necessitated reductions in outstanding commitments.

Table 19-1. Number of Detector R&D Proposals Funded and Amount of Money Granted by Fiscal Year.

Fiscal Year	Number Funded	Amount ($K)
90	24	10860
91	30	15053
92	11	1553
93	15	1208*

*Actual funding reduced to $848K because of budget cuts.

Relatively large amounts of money were allocated in FY90 and FY91 before specific Letters of Intent (LOI) for SDC and GEM were generated. This work played a major role in the preparation of the LOIs. In particular it was necessary to examine the feasibility of various options for detector technologies to determine the amount of work needed to bring the subsystem to a working condition and to determine the approximate cost of building the subsystem.

In subsequent years, the guidelines were changed so that R&D specific to the proposals SDC and GEM were charged directly to the detector budgets rather than to the generic detector R&D. The generic (i.e., not associated with either GEM or SDC) R&D was funded in the amounts shown in Table 19-1. This work was intended to be directed towards smaller detector development, for IR1 or IR4 or a possible fixed target program. In some cases the work could have had applicability outside the SSC.

The funding for FY93 was complicated by the budget shortfall caused by the lack of money expected from the State of Texas. This problem in turn was due to the clouded picture of the U.S. funding of the SSC for FY94. As a response to the need for large reductions in expenditures late in the fiscal year, nearly all outstanding Memorandum Purchase Orders (MPOs) to the national labs were reduced in value, which caused them considerable difficulty. The money that had been transferred to the universities was not touched by these reductions in commitments.

No call for proposals was issued for FY94 because of uncertainties in the funding for the SSC in that year. PRD has proposed that some of the closeout money be used to fund a very small amount of ongoing R&D to preserve a large investment already made, and DOE had approved $200K for completing pixel detector work as this report was prepared.

R&D Activities

R&D money was allocated to 11 areas of work. The largest amounts were devoted to calorimetry, precision vertex detectors, and electronics, in that order. These areas represented the greatest needs for developing sound proposals for detectors. (See Table 19-2.)

Table 19-2. Money Allocated to R&D Activities.

Topic	Total Allocated ($K)
Precision Vertex Detector	4724
Tracking Devices	2515
Particle Identification	904
EM Calorimetry	7052
Hadron Calorimetry	3968
Muon Detection	1202
Electronics	3183
Data Acquisition	405
Trigger Logic	425
Magnet Design	1795
Other	935

Because of the universal need for good electromagnetic calorimetry, a great deal of effort was put into such work. This included noble liquid calorimeters, based on argon, krypton, or xenon, warm liquids, and scintillating crystals, such as barium fluoride. Hadron calorimetry received somewhat less attention because the demands were less severe. All experiments recognized the need for multiple vertex identification and measurement to deal with heavy meson decays. As a result much work was done on precision vertex detectors based on silicon strips or pixel devices. Because of the state of the technology, the proposals concentrated on silicon strips, but it is recognized that a pixel based device is ultimately desired to deal with high particle fluences.

Because of the very high data rates expected for SSC detectors, much work was needed to define architectures for front end electronics and signal processing to cope with the very severe demands. The electronic design had to be part of the thinking associated with the rest of the detector technology, such as the calorimeter or tracking device. Similarly, trigger logic and data acquisition are very challenging problems for a hadron collider such as the SSC. The relatively small amount of money actually spent on the latter topics under this program is the result of priority decisions made at the time of proposal submission. Considerable work was done within the context of GEM and SDC R&D money.

Magnet design studies were made for a large solenoid, originally for the L* experiment, but it was also applicable for the GEM proposal. Other studies were made for muon superconducting toroid magnets. Particle identification studies looked at various kinds of Cerenkov light detectors and transition radiation detectors. The SDC and GEM proposals placed primary emphasis on particle identification technologies for electron/muon/pion separation. Other work consisted of studies of signal transmission, radiation hard scintillating plastic, radiation hard diamond detectors to replace silicon, and optical fiber crazing. Another area of research was a study of a bent crystal 20 TeV beam extraction system for fixed target work.

Grant Process

The grant process started with recommendations by the R&D Committee. The AD of PRD then decided how much to offer, based on the Committee recommendations and the amount of money available for that fiscal year. The successful proponents were then notified, and the lead person for the proposal prepared a Memorandum of Understanding (MOU) for the entire collaboration (if more than one institution was involved). The MOU defined the institutions involved and the contact people at each, the work to be done, the amount of money needed to perform the various tasks, and the amount of money to go to the various institutions. Once the MOU was approved by the Director of SSC, it was forwarded to DOE for concurrence. Copies of the MOUs for different proposals are stored in the PRD central files. Funding of work done at one of the U.S. national laboratories was done through a MPOs. Funding of work performed at a university was done through DOE, usually as a supplement to an existing grant.

Progress Reports

Progress reports were usually submitted each year along with requests for new money in the following year. In a few cases a progress report was submitted but no new money was requested. At the termination of the SSC project, all funded proposals that had not submitted progress reports for FY92 or FY93 were asked to submit reports. Progress reports are filed in the PRD central files.

PART IV. THE SSC SITE

Introduction

(J. Sanford and O. Orban)

This section summarizes information about the Ellis County, Texas, site that was selected by the Department of Energy in 1989. After assembling the initial staff in temporary facilities, the SSC Laboratory began site-specific design work. The resulting design for the SSC accelerators, experimental areas, and Laboratory facilities was described in the *Site-Specific Conceptual Design Report*[1] of July 1990. Subsequently, design specifications for the technical components and conventional facilities were formulated. A significant amount of surface and underground construction was initiated, many buildings were completed, and testing of prototypes for most technical components was well advanced at project termination. The construction phase of the SSC project was approximately 20% complete as of October 1993.

Upon termination, it became appropriate to capture the design work that had taken place since 1990. The *Technical Site Information*[2] (TSI) document records regional and physical information used in site studies, summarizes the site studies for conventional facilities, and presents site layouts for buildings and utilities as they would have been at the end of the construction project. The TSI summarizes and complements the work of many groups in the SSC Laboratory, the Texas National Research Laboratory Commission (TNRLC), and several subcontractors to the SSC project. The document contains extensive references to their work contained in draft and final reports. In particular, it borrows heavily from the *Site Development Plan*[3] (released in draft form in January 1992) which guided aspects of site development.

Chapter 20 contains information on the SSC site region extracted from the TSI. Chapter 21 briefly discusses the requirements for the construction phase of the SSC project. It then summarizes the studies and decisions that led to the facilities and utilities layouts described in Chapter 22.

Chapter 20. Regional Conditions

In July 1983, the High Energy Physics Advisory Panel recommended to the U.S. Department of Energy (DOE) consideration of a multi-TeV high-luminosity proton-proton collider. After initial feasibility studies, DOE decided to proceed with a conceptual design of the SSC.

The Site Selection Process

After reviewing the *SSC Conceptual Design Report*[4] (March 1986), DOE recommended the project to the Reagan Administration, which approved it for submission to Congress in January 1987. In February 1987, the Secretary of Energy announced a site selection process to assure an open and fair site competition. DOE issued its *Invitation for Site Proposals for the SSC*[5] (ISP) in April 1987, and received 43 site proposals by the cutoff date, September 2, 1987. Of these, seven sites did not meet all the basic qualifications and one site was withdrawn from consideration by its sponsors. For the remaining 35, a joint committee of the National Academies of Science and Engineering provided an independent evaluation of each proposal's information, which resulted in the announcement of an un-ranked Best Qualified List (BQL) of sites in January 1988. DOE's SSC Site Task Force then reviewed all available information on the BQL sites, visited the sites for formal presentations and review, and presented follow-up questions to each site's sponsors. Based on the evaluations and the EIS analysis, DOE selected the Ellis County site proposed by the State of Texas and published its Record of Decision in January 1989. In March of 1989, DOE's Maintenance and Operations contractor (URA) began to develop the SSC Laboratory in temporary facilities near the site. Figure 20-1 shows the Ellis County site and the surrounding region.

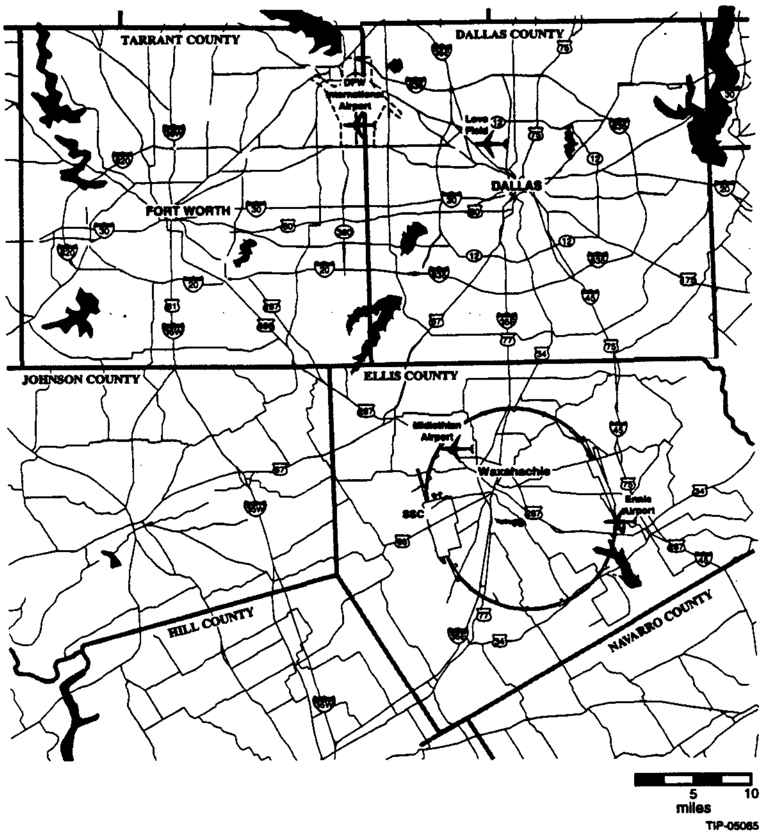


Figure 20-1. SSC Project Site Region.

Footprint Description

The Collider was to be housed in a 54-mile, oval tunnel divided into four sections—the North and South Arcs and the West and East Complexes. Because of the great length of the Collider tunnel, two types of land were purchased—fee simple and stratified fee. Fee simple purchases involved a transfer of land title and rights to the U.S. DOE. Stratified fee purchases provided a "right-of-way" for the tunnel to pass underneath lands that would require no construction on the surface. By requesting stratified fee lands in the arcs, the Laboratory reduced the project's impacts (such as relocations) on the region.

The Collider was to be serviced by surface facilities in the West Complex and the East Complex and at 18 service areas around the Collider arcs. The West Complex, the largest site, was to contain the injectors (used to accelerate the particle beams to 2 TeV), the Collider West Utility Straight (to inject, accelerate, and dump the beams), and two interaction regions (to collide the proton beams at interaction points). The East Complex contained a utility straight and two interaction regions. The service areas around the arcs were to house cryogenic and conventional facilities for cooling the Collider ring and ventilating the tunnel. For safety reasons, the project also required fee simple monitoring areas near the West and East Complexes (see Figure 20-2).

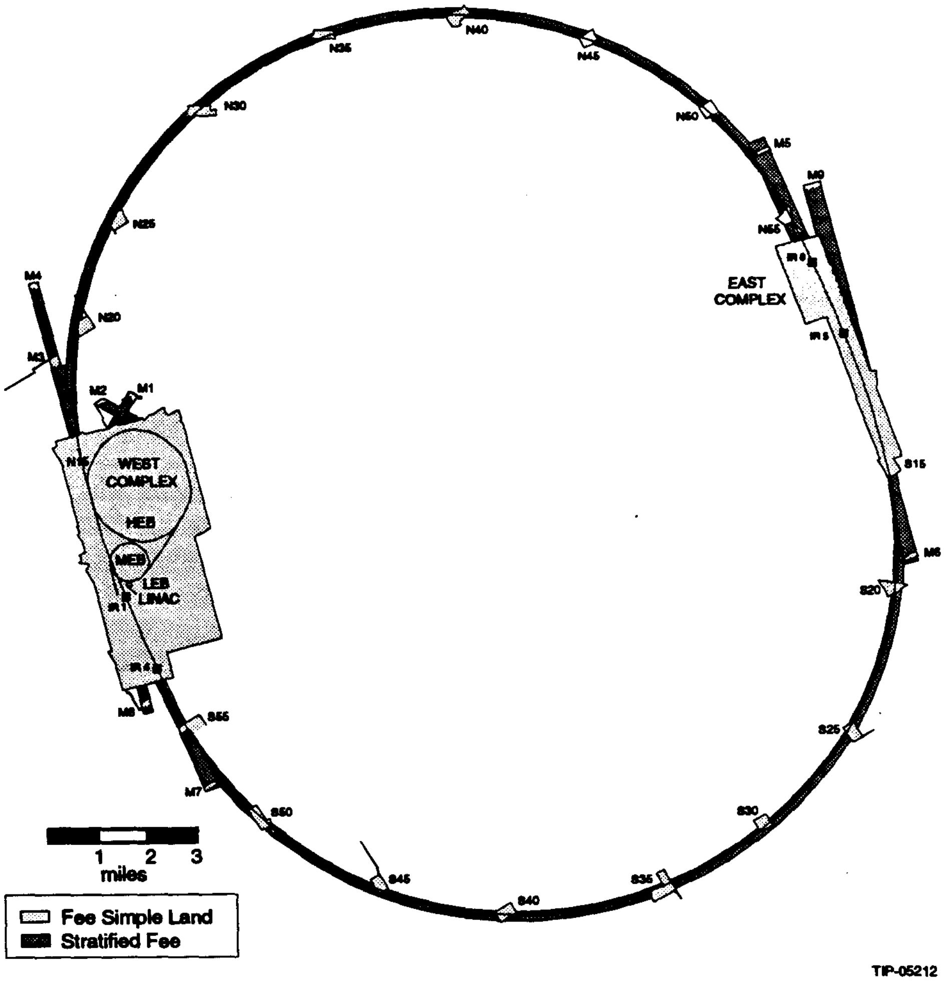


Figure 20-2. The SSC Footprint.

Determination of the SSC Footprint

During the site selection process, it was understood that Texas's proposed position for the Collider ring and the boundaries of the associated surface areas would be subject to adjustment by DOE and the SSC Laboratory. One of the first major tasks of the new Laboratory was to fix the site boundaries so that land acquisition could proceed. The technical arguments behind the siting of the Collider are explained in the *Footprint Characterization Document*[6] (June 1990). Technical changes in the Collider and the injector were incorporated into the footprint. The Laboratory waited for the completion of the geotechnical surveys before it made final the precise tunnel elevation. The Laboratory requested its A-E/CM subcontractor to compare several tunnel elevations that would reduce the length of tunnel running through the Eagle Ford shale (a less desirable rock). The A-E/CM considered geotechnical data, shielding and safety criteria, and costs before making its recommendation in the *Collider Tunnel Elevation Study Report*[7] (October 1991). The elevation change raised the Collider in its western half and lowered it in its eastern half. The raising of the ring maintained the criterion of 30 ft of cover everywhere, but necessitated the purchase of a small amount of additional fee simple land near five creek crossings. The new elevation did not affect other fee simple land boundaries.

Land Acquisition

Following the determination of land requirements, the Laboratory transmitted to TNRLC the coordinates of land plots needed for the construction of the accelerators and research facilities. The land requirements for the West and East Complexes were transmitted in the *Computer Aided Design of the Digital Footprint*[8] (March 1990). After the tunnel elevation was finally determined and the N & S sites were evaluated, the final fee simple boundaries and the final stratified fee boundaries were transmitted in the *SSC Real Properties Requirements Volume I*[9] (December 1991). Based on these coordinates, staff members of the TNRLC determined the location and extent of the specific parcels of land to be acquired (see Table 20-1). The table shows the acreage originally requested and the acreage required after all modifications and studies were complete. The acquisition of land began in 1990 and had been largely completed by 1993.

In its EIS, DOE committed to preparing a *Supplemental Environmental Impact Statement*[10] (SEIS) (December 1990) which assessed the effects of technical and siting changes and updated the information in the initial EIS. Among the major changes addressed were the change of Collider injection energy and an increase in the number and size of the Collider service areas. Other differences from the EIS arose from additional site-specific data gathered on the defined sites and the application of more sophisticated analyses. DOE issued the draft SEIS in August 1990, and held public hearings in mid-September. DOE issued the final SEIS in December 1990, and published its related Record of Decision to proceed with construction in February 1991.

Table 20-1. SSC Land Requirements.

Functional Area	Invitation for Site Proposals (acres)	SSC Revised Requirements (acres)
Fee Simple		
West Complex	5,510	7,520
East Complex	1,980	1,921
Service Areas and Access Points	200	984
Monitoring Sites		163
Creek Crossings		40
Subtotal	7,690	10,628
Stratified Fee		
Tunnel 1000 ft.	3,750	4,235
Muon Absorption	4,390	1,887
Subtotal	8,140	6,122
Total	15,830	16,750

Source: SSCL-SR-1041 (Rev. 1), Footprint Characterization Document, June 1992.
SSCL-SR-1049 (Rev. 2), SSC Real Property Requirements, Vol. I, Dec. 17, 1991.

Chapter 21. Site Requirements

Laboratory Population

By the end of construction, the staff population was to be accommodated on-site and at the Central Facility. When the Campus buildings became available, leased space was to begin to be phased out. However, some leased space had to be retained to get the Laboratory through its peak construction population year. Table. 21-1 presents summary information on space availability throughout the sites. The first column shows the availability during 1993. The second column shows the distribution during the peak construction year. Because of the phase-out of leased off-site offices, the model shows a continued need for trailers to accommodate the population. The third column shows the distribution at the start of operation, when it is shown that trailers can be eliminated. The model assumed that the campus space would be ready for occupancy in 1996 and 1997, and that the peak construction year would be 1997.

Table 21-1. Space Projection by Site.

Facility	Office Space Available		
	Current Year	Peak Pop. Year	Start Operation
WN Site			
Technical Facilities (MDL, MTL, and Gray's House)	159	173	173
Trailers	221	50	
WC Site			
Exp. Facilities (Calibration Hall and IR1)		50	100
Support Facilities			12
Trailers	22	100	
WS Site			
Main Campus		1,044	1,044
Experimental Facilities (IR4)			30
Trailers			
EN Site			
Experimental Facilities (IR8)		290	250
Support Facilities			12
Trailers			
EC Site			
Experimental Facilities (IR5)		110	110
Trailers		100	
Off-Site			
Central Facility	1,062	1,166	1,150
Stoneridge	913		
Redbird, Other	148		
Total Capacity	2,525	3,083	2,881

Technical Systems

To meet the goals of the high energy physics program, the Laboratory staff designed an accelerator complex that consisted of four injectors and the Collider. Briefly, the accelerator chain was composed of a linear accelerator, two resistive magnet accelerators (the LEB and MEB), and two superconducting magnet accelerators (the HEB and Collider). (See Table 21-2.)

Table 21-2. Parameters for the Collider and Injection Accelerators.

	Energy	Circumference or Length (km)
Collider	20 TeV	87.12
HEB	2 TeV	10.89
MEB	200 GeV	3.96
LEB	11.1 GeV	0.57
Linac	0.6 GeV	0.35

For purposes of site development, the accelerators were best described at the system level. Briefly, all five accelerators had radio frequency (RF) systems to accelerate the beams and pulsed magnets to inject or eject beams. The four synchrotrons had magnets in a lattice that would bend and focus the beam around a closed path. The HEB and Collider also required cryogenics systems to cool the superconducting magnets to near 40 K. All these systems required separate power supplies, cooling water connections, controls, and communications links. Each accelerator also had an associated beam dump that would absorb the proton beams when needed. A detailed description of technical equipment and components required for the accelerator systems is available elsewhere in this document.

The initial experimental program assumed four detectors at four interaction points around the ring. As of 1993, two large detector proposals—the Solenoidal Detector Collaboration (SDC) and the Gammas, Electrons, and Muons (GEM) detectors—had been selected for fabrication and installation. Consideration of the facilities for the two other detectors were based on model detectors used in conceptual design. This was acceptable for planning purposes because, while the specific choice of detector would directly influence the underground halls, the required surface facilities would be similar for detectors in the same size category (see Table 21-3).

The detector components and systems driving the utilities needs were the large magnets that bent the paths of charged particles for momentum identification and the electronics that read, selected, and recorded events. In addition, the large detectors would require refrigeration plants to cool cryogenic magnets or liquid-argon calorimetry. Complete descriptions of the SDC and GEM components and systems are given in the Technical Proposals submitted by the collaborations (SDC – April 1992; GEM – April 1993).

Table 21-3. Experimental Facilities for the Initial Research Program.

	Location	Detector Volume (cu.m.)	Detector Weight* (ton)
		W × H × L	
Solenoidal Detector Collaboration (SDC)	IR8	21.8 × 21.8 × 40	35,000
Gammas, Electrons, Muons (GEM)	IR5	21.8 × 21.8 × 36	11,000
Detector 1	IR1	5000	N/A
Detector 2	IR4	< 5000	N/A

* Includes weight of support structure.

Facilities

The Collider facilities consisted of the 54-mile tunnel, the shafts, and the associated services supporting the main accelerator ring. Surface facilities were to be located at the 18 service areas around the ring and at the RF, kicker magnet, and beam dump shafts in the West utility straight. The service buildings were required to house power supplies, electronics, and refrigeration plants. The injector facilities included surface and subsurface enclosures, tunnels, and associated electrical and mechanical systems supporting the injectors. The test beam facilities included a tunnel from the MEB to near the surface, service buildings for the magnets enclosures below ground, a target hall, a utility building, and a calibration hall with three test stands.

The experimental facilities were those surface and underground structures and associated support systems to be situated in the four initial detector areas—two on the east side and two on the west side of the Collider Ring. Industrial buildings would have been required for on-site assembly of detector components fabricated elsewhere and shipped to the site. Some office and laboratory space was required at the Interaction Region (IR) areas to accommodate the collaborators who were to oversee the detector installation. Utility buildings would provide controlled environments for power, cooling water, cryogenics, compressed air, and vacuum equipment. The design requirements for the conventional facilities supporting the large detectors are contained in the *SDC Experimental Facilities User Requirements*[11] (SEFUR, February 1993) and the *GEM Experimental Facilities User Requirements*[12] (GEFUR, February 1993). A discussion of experimental facility requirements for other detectors is given in the SCDR.

The campus was to provide offices, meeting rooms, an auditorium, services for personnel, light laboratory space for component and electronics development, and control rooms. Heavy works buildings were to be dedicated laboratories for the fabrication and testing of technical systems. The "environmental health" facilities would handle and temporarily store hazardous waste and low-level radioactive components. The support facilities were emergency response stations, warehouses, grounds maintenance buildings, and fabrication shops.

Infrastructure

The SSC sites were distributed throughout a semi-rural area. The project required the up-grade or construction of roads to provide access to some N & S sites and to link technical areas on the West and East complexes. Off-site, existing dirt roads were to be widened and paved and existing bridges replaced to allow construction equipment access to the remote N & S sites. Roads to magnet delivery shafts at N40, S25, and S40 were to support 50-ft trailer rigs weighing roughly 15 tons. Roads serving the large detector halls were to support the regular delivery of components weighing from 100 tons up to 450 tons. Construction of by-passes around municipalities could have significantly reduced travel time between the West and East complexes and routed heavy traffic away from city streets. Some existing roads running from Interstate highways to the West and East complexes were to be up-graded. On the complexes, construction of new roads would provide north/south links between the technical areas.

The electrical power required for the technical and conventional facilities was estimated to demand an average load of 177 MW during collider operations. Several special requirements were imposed on the electrical distribution system. Because of harmonics generated by ramping the magnets, the LEB, MEB, and HEB power distribution lines would have required filters to prevent buildup of excessive current peaks. Uninterruptible power supplies were needed for supervisory control and data acquisition systems in the central operations center. Electrical power was to be used for climate control at remote sites, while natural gas would be used for heating and dehumidification at the facilities on the Complexes (see Table 21-4).

Site-wide communications systems were required to monitor and control the technical systems and conventional facilities from a central operations center. Operation of the injectors and collider required precision global timing, beam correction controls, a personnel safety interlock system, and a quench protection system. Conventional facilities and utilities were to require site-wide facilities controls, supervisory controls for the utilities, and fire alarm systems. Other communication needs included a local area network, telephones for voice, and a cable television system for video.

Water was required for cooling electrical equipment and the oil coolers for the helium and nitrogen compressors. Untreated (raw) water was needed for the primary side of heat exchangers, and filtered water was needed for generation of low conductivity water (LCW) and industrial cooling water (ICW). Cooling water and cooling water plants would have been required at various points on the West and East Complexes and on the N & S "5" sites. Potable water would have been required at the West and East Complex sites with permanent populations. Water would also have been required for irrigation of the landscape at the West and East Complexes. Another demand on the water system was set by the required water flow for fire fighting; on the complexes, the system would have had to provide 2,000 gallons per minute for a two-hour period.

Three types of wastewater would have been produced by operations at the SSC facilities. Industrial wastewater would have been generated from the operation of the closed-loop LCW and ICW systems and the chilled water systems. Wastewater from the closed LCW systems would have been treated off-site; wastewater from the ICW and chilled water systems would have been discharged to evaporation ponds. Sanitary sewage was to be generated at the facilities on the West and East Complexes. For planning purposes, it was assumed that sewage flows would equal the demand for potable water. Finally, storm water run-off was to be captured by site drainage systems and routed through detention ponds.

Table 21-4. Operational Utility Requirements for SSCL Systems.

Service Area	Electrical (MW)	Gas (MCF/H)	Cooling Water (MGD)	Potable Water (MGD)
West Complex				
Linac	2.2	1.2	incl. MEB	0.01
LEB	10.4	4.1	incl. MEB	n/a
MEB	23.2	5.5	2.6	n/a
Test Beams	2.8	4.6	incl. MEB	0.01
HEB	15.6	n/a	1.7	n/a
Collider RF	8.0	n/a		n/a
Collider - West Ring	36.0	n/a	below	n/a
N15 Facilities	9.1	8.8		0.08
Campus	7.4	17.9	0.7	0.13
Exp. Facilities (IRs 1&4)	*6.6*	*11.7*	*1.5*	*0.08*
Support Bldgs.	*0.2*	*1.0*		*0.04*
Irrigation				0.21
East Complex				
Collider - East Ring	36.0	n/a	below	0.08
Exp. Facilities (IRs 5&8)	19.8	14.4	1.3	0.06
Support Bldgs.	*0.1*	*1.0*		*0.03*
Irrigation				0.04
Collider	above	n/a	4.3	n/a
Total	177.4	80.2	13.6	0.75

Italics = Allowance for areas in conceptual design.
Electric demands from March 1993 ACPR Load List.
Gas from Infrastructure Working Group & SCDR.
Water from Freese & Nichols "SSC Water Supply Report."

Chapter 22. Site Development

Technical Facilities

Collider

Following the determination of the elevation of the Collider ring (as described in Chapter 20), the SSC Laboratory and its A-E/CM sub-contractor made a site assessment of the proposed service areas around the North and South arcs. The service areas were initially determined by projecting the Collider's half-sector shafts to the surface and requesting 50 developable acres around the point. The TNRLC responded to this request with proposed service area boundaries, which were the initial lands to be assessed. A project team investigated each proposed site with regard to physical slope (topography), soil types, vegetation, watersheds and flood plains, near-by noise receptors, site access, and utility easements. The criteria used in the evaluation, the assumptions, and the details of their investigation were presented in the *Service Site Adequacy Study Phase I Draft*[13] (March 1991). As a result of the study, five service shafts were moved to more desirable locations within the service areas. These areas were N25, N30, S20, S35 and S55. Also, four other sites had their boundaries modified to ensure that the sites contained 50 developable acres.

Injector

The original Texas site proposal placed the injectors on the West Complex, and the Laboratory maintained that configuration. The geometries of the injectors and the beam transfer lines were the primary drivers in the siting of their facilities. As the lattice design developed, significant changes affected the geometries. As mentioned above, the increased energies for the HEB, MEB, and LEB resulted in a near doubling of their circumferences. The final design change affecting the geometry occurred in April 1991, when the number of straight sections in the LEB was reduced from six to three, causing a shift in the configuration of the LEB and Linac.

The bases for setting the injector elevations were primarily site geology, cost, and safety considerations. The beam was to lie in a single plane through the Linac, the LEB, and the MEB and then be either directed down to the HEB plane or to the test beam switchyard. The elevation of the injectors near the surface—the Linac, LEB, and MEB—was set after a cost study was performed. Under direction from the Laboratory, the A-E/CM developed cost estimates for four elevations. The study considered the amount of material excavated from the trench, the height of the embankments needed for shielding, and MEB shaft depths. The study also factored in the environmental issues involved in a potential stream relocation. The A-E/CM presented its study in the *Linac, LEB, and MEB Elevation Study*[14] (May 1991). The final construction design placed the three machines on a plane slightly sloping with respect to the site topography.

Because the design of the HEB to Collider transfer line was complicated, the Laboratory planned to fix the HEB elevation at about 50 ft above the Collider elevation. The final Collider elevation adjustment was also used to set the HEB elevation. The adopted Collider elevation had the added benefit of raising the HEB entirely out of the Eagle Ford Shale and into the Austin Chalk. Later, the service facilities for the HEB were sited by the same method used for siting the Collider service areas. The proposed HEB shaft locations were projected to the surface and the areas surrounding the shafts were analyzed for topography, soil, and streams. This resulted in the relocation of one shaft (H40) away from a creek.

Campus

Laboratory staff worked currently at several sites, but it remained the goal to locate most personnel at a single site in a campus setting. The SSC Laboratory directed the work of a site planner/architect subcontractor, who proposed a site for the campus and prepared an integrated conceptual design of the campus. The results were presented in the *Main Campus Development Plan*[15] (May 1993). Four alternative sites were considered for the campus evaluated on the basis of proximity to technical areas, site access, site adequacy (for baseline and future development), and site climate and environment. The four locations were discussed with Laboratory staff, detector collaboration members, and DOE personnel. The location between the IR1 and IR4 sites, the "Boz" site, was selected for further planning.

The campus on the Boz site was envisioned to lie around the edge of a cooling pond, which would serve the campus, IR1, and IR4. Further planning considered pond configurations, water level, facilities layout, and construction phasing. The integrated design included access and parking, footpaths, landscaping, climate control, and energy efficiency. For project function, the campus plan included an operations center, administrative and laboratory space, a library, and a cafeteria. The design could also have been extended to include an auditorium, conference rooms, an education center, and accommodations for visitors.

N15 Area

Both the MTL and the ASST facilities required cryogenics service. The SSC Laboratory planned a closed-loop cryogenics test, in which several cells of magnets would be tested in a tunnel sector. These factors caused the magnet laboratories and the ASST to be sited near the N15 refrigeration service area. This proximity would have allowed the ASST and MTL to use the cryogenics services of the N15 tunnel sector for several years before needed by the Collider. However, by procuring and running a full-size refrigeration plant early, the staff was to gain experience they could apply to specification and procurement of the remaining refrigeration plants. Consequently, the MDL, the MTL, the ASST enclosure and shops, a compressor building for the refrigeration plant, and required utilities were located at the N15 area. A magnet warehouse for storage of industrially produced magnets was also to be constructed in the N15 area.

Experimental Facilities

Test Beams

The test beam line was sited so that it would be tangent to the MEB and HEB rings. In the future, this was to allow test beams to be extracted from the HEB and routed to the test beam switchyard with minimal manipulations. The slope of the test beam plane was set by safety considerations. The paths of the muon vectors projecting from the targets and the test stands were calculated, and the test beams were angled so that the muon vectors would remain below ground for their entire length.

Interaction Regions

As mentioned above, the Laboratory and its Physics Advisory Committee selected two large detectors for fabrication and installation. To track particles to the detector design precisions, the detector collaborations requested stringent alignment requirements. Because of the enormous weight of the detectors, the alignment requirements dictated special attention to the long-term stability of the hall floors and their underlying rock. Under the direction of the Laboratory, the A-E/CM conducted a series of studies comparing the West and East Interaction Region (IR) locations. See the *Experimental Facilities Interaction Region Study Phases A–D.*[16-19]

The studies evaluated the site geology (rock properties and seepage evaluation), modeled site-specific halls and foundations, and ran simulations of long-term deformations based on the geology and models. They also compared costs for two construction options (cut & cover vs. cavern) at the four IR sites. The studies were done in tandem with the tunnel elevation study and assumed that the recommended tunnel elevation would be adopted. The studies concluded that the foundations at East IRs would provide better long-term stability, but the costs of constructing the halls on the East side would be greater than constructing them on the West side. It was decided to shift the large detectors to the East because of the over-riding importance of stable hall foundations. The SDC detector and support facilities were shifted from IR1 to IR8 and the GEM detector and support facilities were shifted from IR4 to IR5.

Support Facilities

The siting of the emergency facilities was driven by response time to calls. The implication was that the facilities must be located with immediate access to main roads and near to population centers. There also were to be two emergency stations providing fire and paramedic services. The one on the West Complex was sited along Industrial Rd. near its intersection with FM 66. The one on the East Complex was sited northeast of the IR8 area, on the east side of the Connector Road. These locations placed the emergency facilities on the main on-site north/south roads, with quick access to east/west roads running from the sites, and next to necessary utilities. In addition to the two stations, space for an Emergency Operations Center, providing security and dispatch services, and a Medical Office were to be available on the Campus.

West Complex Zones

The West Complex had been zoned to reflect the then current site layouts and to allow for future expansions. Technical zones on the West Complex included the injector area (with the Linac, LEB, MEB, and some HEB facilities), the HEB surface areas, and the Collider Utility Straight area. Other technical zones were the Main Campus and the N15 area. Experimental areas were the IR1 (including the Test Beams) and IR4 areas. The support zone was essentially along the utility corridor on the western edge of the complex. The support zone might also have included the West emergency facility and radioactive waste handling/storage facilities. Open zones included a recreation area at the northeast corner of the Complex and a riparian woodland to the south of the Campus. Two large technical reserve zones existed on the West Complex. In the long run, an electron synchrotron might have been built in the southern technical reserve zone. For the short run, a wetland mitigation pond was planned for a small portion of the land (see Figure 22-1).

As part of the required pre-construction site surveys, the A-E/CM performed hydrologic modeling to determine the 100- and 500-year flood plains of the creeks draining the West Complex area. They modeled the Onion Creek, the South Prong Creek, and the Baker Branch (for the S55 site), the Great House Branch, and the unnamed branch of Chambers Creek. The details were presented in *Hydrology Report of Existing Conditions for the West Campus*[20] (August 1991). Figure 22-2 shows the flood prone areas in the vicinity of the West Complex. Development potential on the West Complex was not significantly affected by the flood prone areas, which breach the site at its northeast, west, and south boundaries.

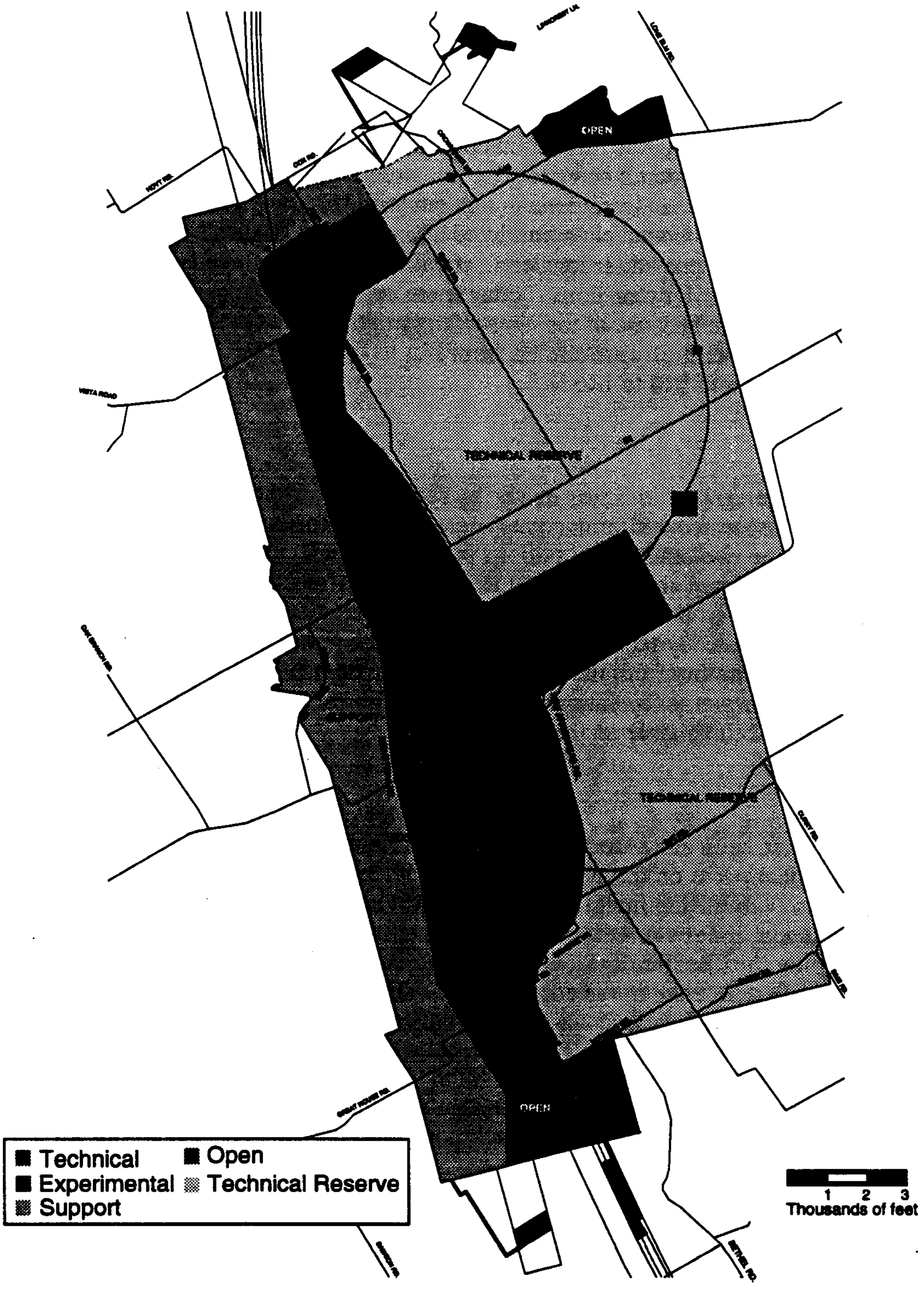


Figure 22-1. Zoning Map for West Complex.

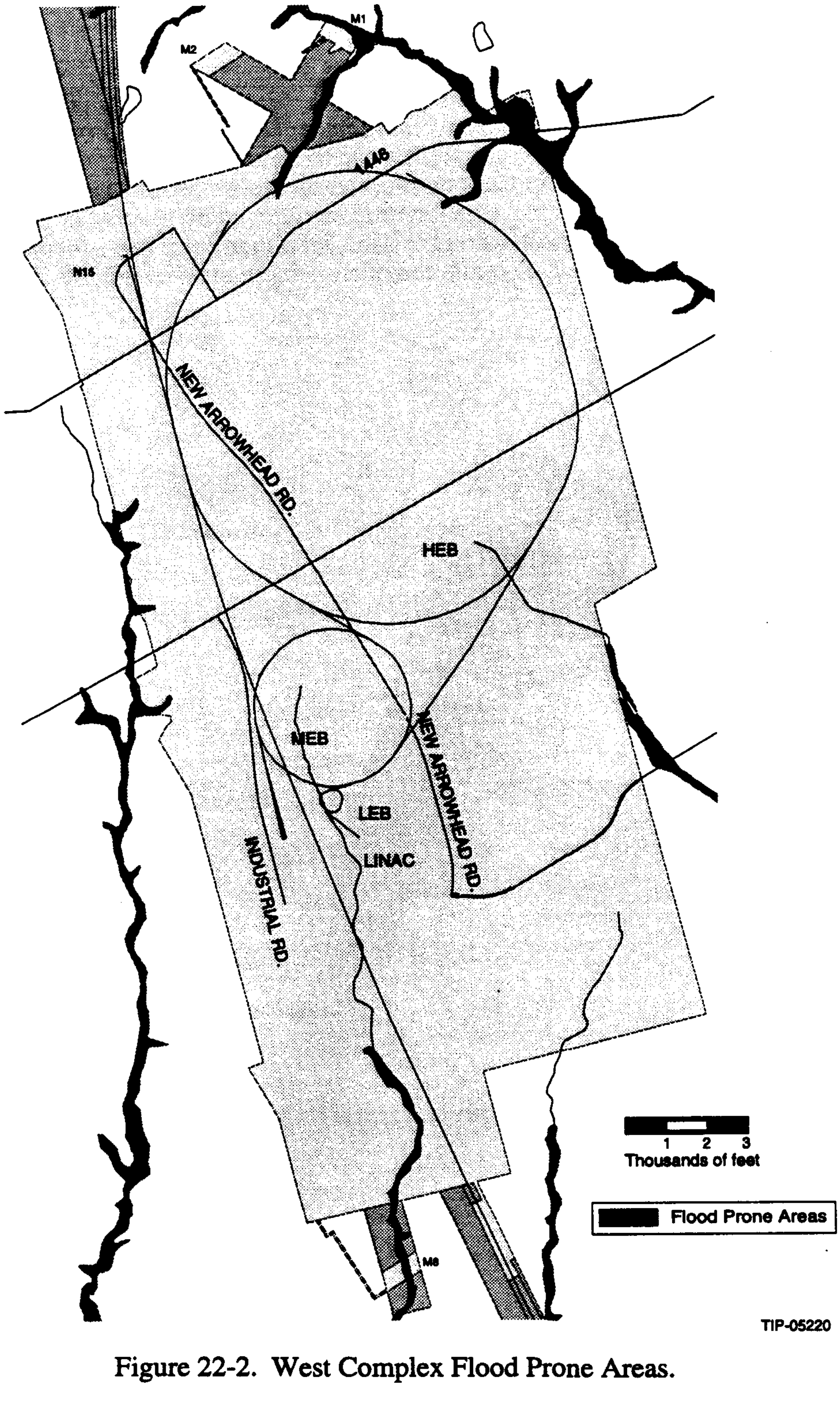


Figure 22-2. West Complex Flood Prone Areas.

East Complex Zones

The East Complex had only one technical zone, the S15 area. The major activities in the East occurred in the experimental zones, the IR5 and IR8 areas. One support area provided a location for the East emergency service facility. Open areas included the flood plains of the Grove Creek and Bone Branch Creek and a wetlands mitigation pond to be built in the flood plain. There were also several technical reserve zones. In the long run, the southernmost technical reserve zone might have been developed for additional experimental facilities using internal or external beams at low intensity. The technical reserve zone along Wilson Rd. might have been developed with an East Campus to accommodate a greater population of experimenters (see Figure 22-3).

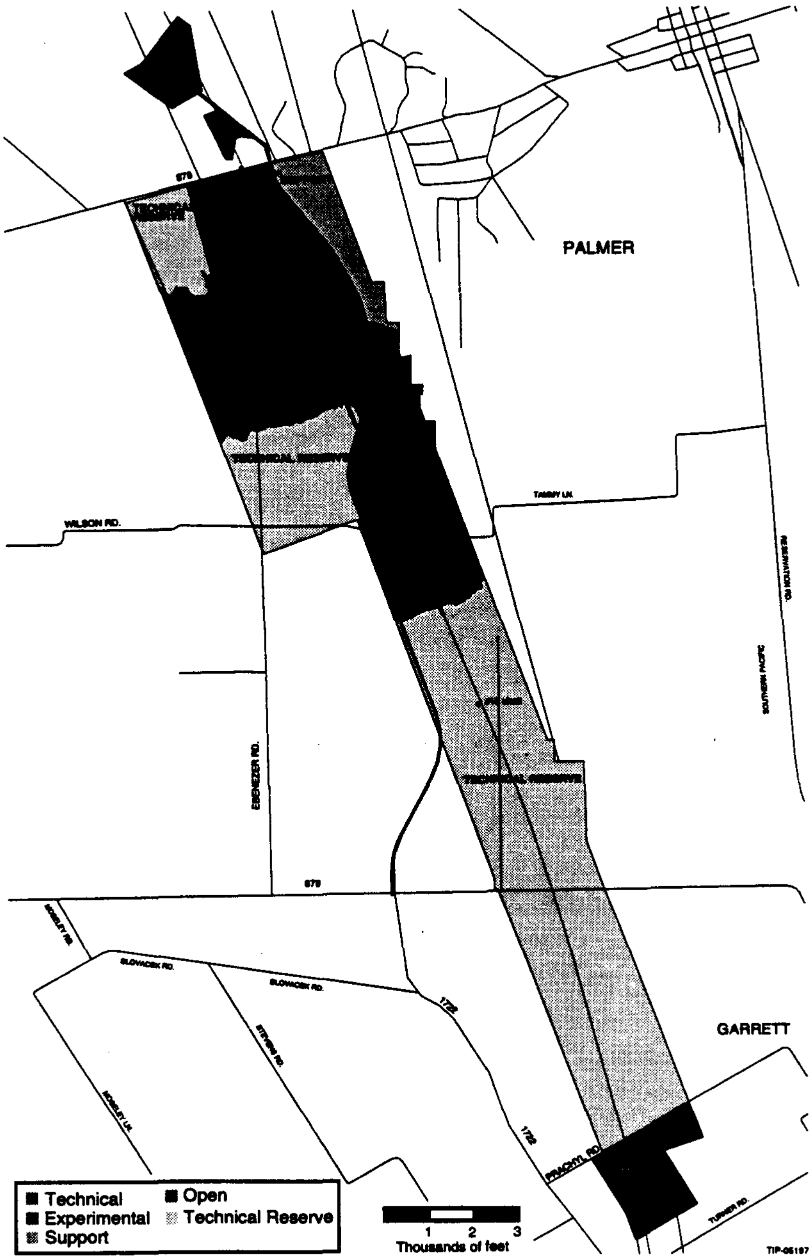


Figure 22-3. Zoning Map for East Complex.

As shown in Figure 22-4, the most pertinent physical features of the East Complex were the watercourses that divided the complex into three parts. The Bone Branch and Grove Creeks run near the northern end of the complex, and Cottonwood Creek cuts through the middle of the complex. As part of the required pre-construction site surveys, the A-E/CM performed hydrologic modeling to determine the 100- and 500-year flood plains of these creeks and Red Oak Creek (for the M5 and M9 sites) and Wolf Branch Creek (for the S15 site). The details were presented in *East Complex Hydrologic Engineering Report*[21] (November 1992). The report's conclusion was that flood plains would not have any impact on the IR5 and IR8 areas, but that they would have an impact on the M9 and S15 sites.

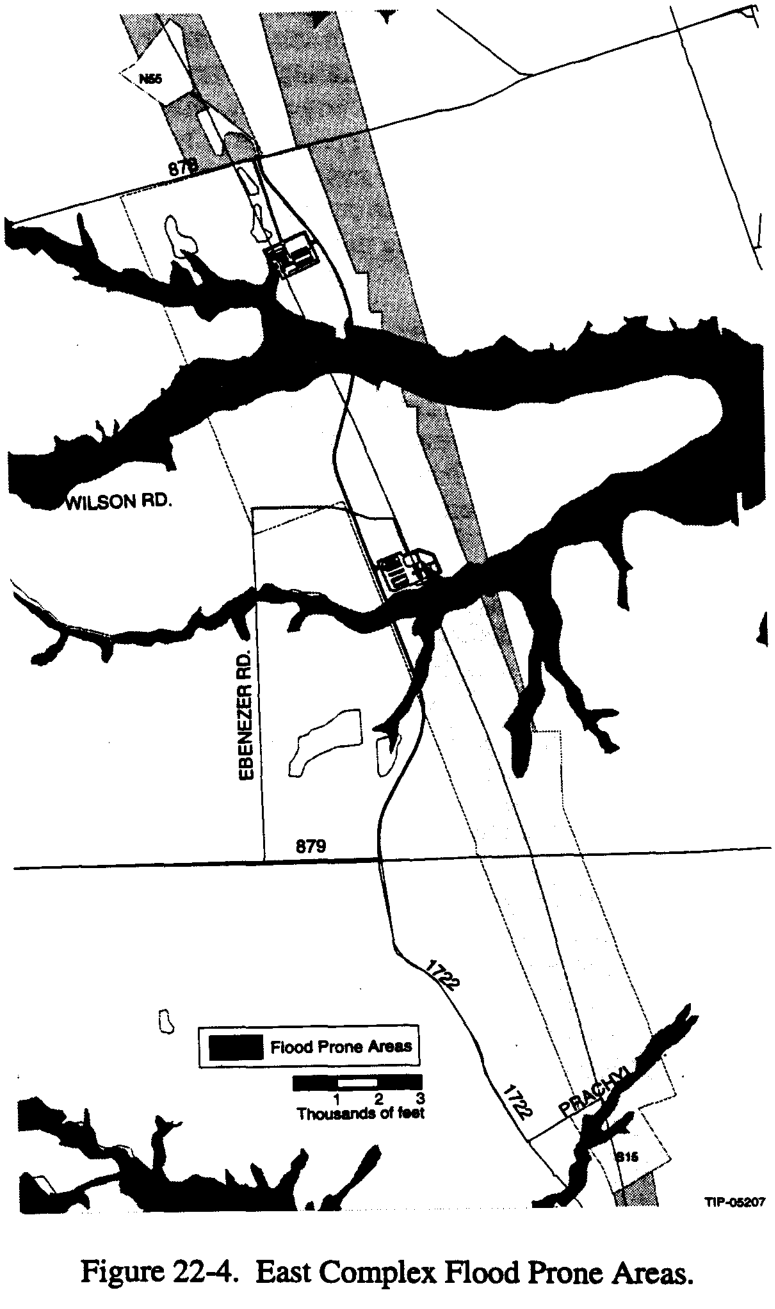


Figure 22-4. East Complex Flood Prone Areas.

Infrastructure

Electrical

Under the direction of the Laboratory, the project A-E/CM assembled an Electrical Task Force to consider options for primary site distribution. The Task Forces suggestions were documented in the *Electrical System Review: Design Concept Re-evaluation*[22] (June 1993). The task force considered the following trade-offs: buried cable vs. overhead power lines and a single substation vs. distributed substations. In the single substation option, major transformers would be located at the main substation, and distribution would occur at two voltages, 69 kV and 12.47 kV. In the distributed substations option, the main substation would transform the power to 69 kV, primary distribution would occur at 69 kV, and each site would have a substation. The task force considered system adequacy, costs, system reliability, and environmental factors such as visual impact. The task force put forward several cost improvements and recommended an option using overhead cable and distributed substations. The project's A-E/CM confirmed the adequacy of the recommended concept by running load flows and short circuit analyses. The Laboratory chose this option with overhead 69 kV primary distribution to the distributed site substations. The visual impact could have been reduced by confining the primary distribution to defined utility corridors.

Permanent electrical service was to be designed that would deliver primary voltage to main substations by the utility and then use 69 kV overhead lines for primary distribution on-site and in the tunnel. The permanent electrical power was to be provided by the utility company through their off-site transmission system. Utility rights-of-way would have conformed to the site constraints. A minimum 450-ft-wide right-of-way would have been required for transmission and primary distribution lines. Costs planned for permanent electrical distribution began at the main switch.

The west main substation was to be located north of Old Maypearl Road on the west side of the Industrial Rd. Transmission lines were to be located in the utility corridor along the western edge of the fee simple boundary. The 345 kV service was to be supplied by two 345kV single circuit transmission lines brought in from two directions. One line would enter from the northwest, running down the utility corridor near the western boundary to the substation. The second line would enter from the west, near the southwest corner of the West Complex, and run north along the utility corridor to the substation.

On-site primary power distribution was to be through 69 kV overhead lines. Lines were to run to three site substations on the West Complex. One near the N15 Technical area was to provide power for the N15 area, the north-west portion of the Collider ring, and the HEB. One substation in the Injector Technical Area was to provide power for the Linac, LEB, MEB, Test Beams, and IR1. A substation located near IR4 was to provide power for the Main Campus, IR4, and the south-west portion of the Collider ring. Collider electrical power distribution was to be through the tunnel at a voltage level of 69 kV. It was to be brought to the surface at the service areas to be transformed down to various operational voltages.

For the East Complex, a regional utility planned to construct a 345kV transmission line running NE/SW through Ellis county. The route of the line was to cross the East Complex and pass near the N55 service. A 345/69 kV substation was to be located north of FM 878 on the tongue of land leading to the N55 site. The primary distribution lines would have run north along the access road to a substation at the N55 shaft and south to substations at IR8, IR5, and the S15 service area (see Figures 22-5 and 22-6).

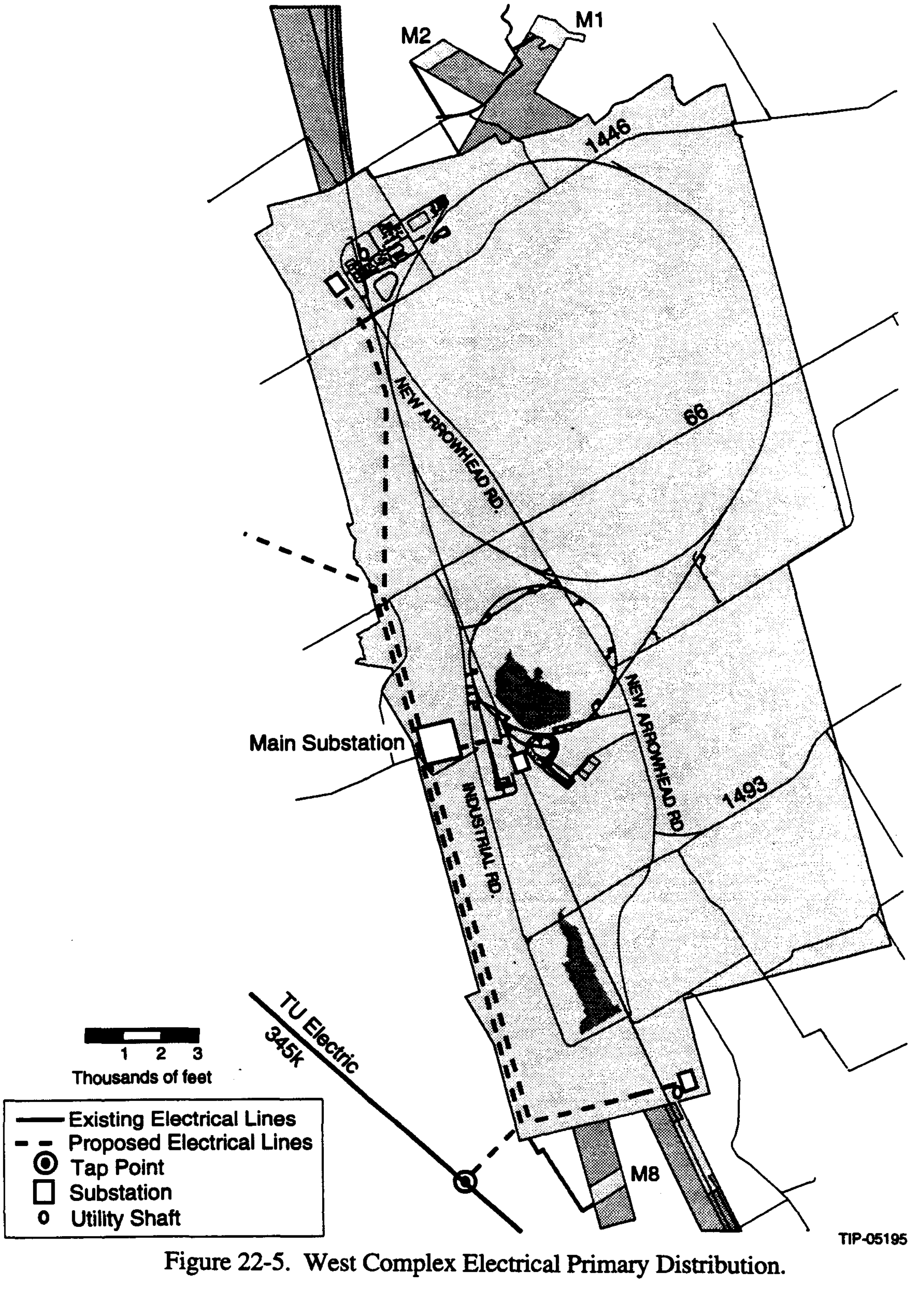


Figure 22-5. West Complex Electrical Primary Distribution.

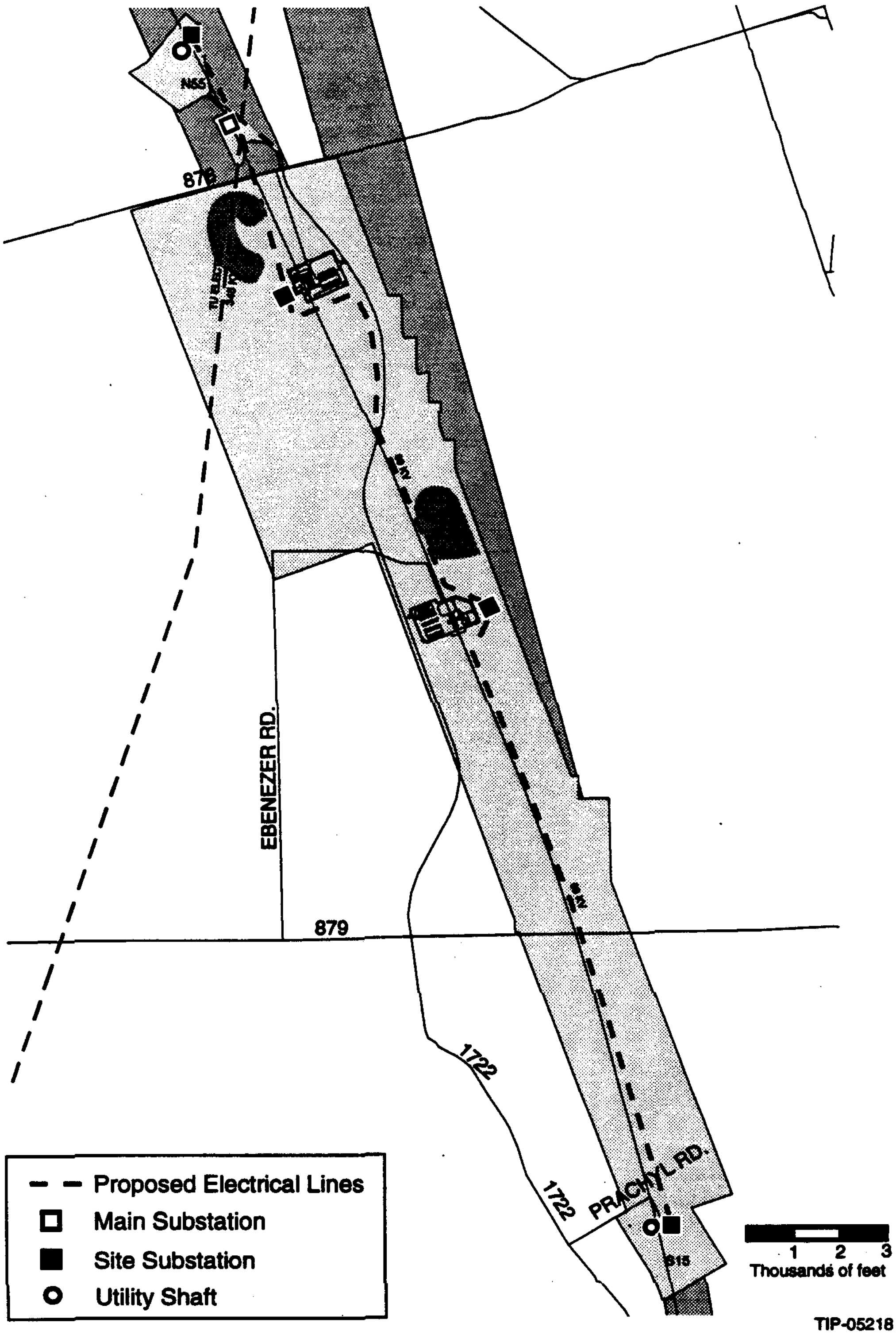


Figure 22-6. East Complex Electrical Primary Distribution.

Natural Gas

Per existing DOE requirements, the Laboratory selected the most efficient fuel for its heating needs. The CCD provided the A-E/CM with heating loads for the West Complex facilities and tasked the A-E/CM to perform a life-cycle cost analysis of feasible heating fuels. The findings were presented in the *West Complex Project Fuel Analysis* [23] (September 1991). Using rates from several vendors, the A-E/CM performed a cost analysis of four fuel types—electricity, natural gas, propane gas, and heating oil. The system cost models included all necessary equipment costs, site distribution costs (for natural gas only), maintenance costs, and utility costs for a 25-year period. The study concluded that a distributed natural gas system would have been the most economical fuel source for the Complex facilities.

Transmission of natural gas to the site from nearby lines was to be through new gas transmission lines. Primary distribution might have been provided by an independent company along the routes shown in Figure 22-7. If it was assumed that the Lone Star Gas Company was the source for the West Complex, a gas line would have followed FM 66 to a single meter point near the intersection of FM 66 and New Arrowhead Rd. The primary on-site gas line would have had to feed six distribution points: the N15 area, the injector area, IR1 and the test beams, the Main Campus, the Emergency Facility, and IR4.

With Lone Star Gas Company as source for the East Complex, the nearest supply line would have been at the northwest corner of the site. Transmission to the site from existing gas transmission lines would have been through new transmission lines with a meter point at the intersection of FM 878 and the Connector Rd. As shown in Figure 22-8, the gas line would have followed the Connector Rd. and fed three distribution points: the Support area, the IR8 area, and the IR5 area.

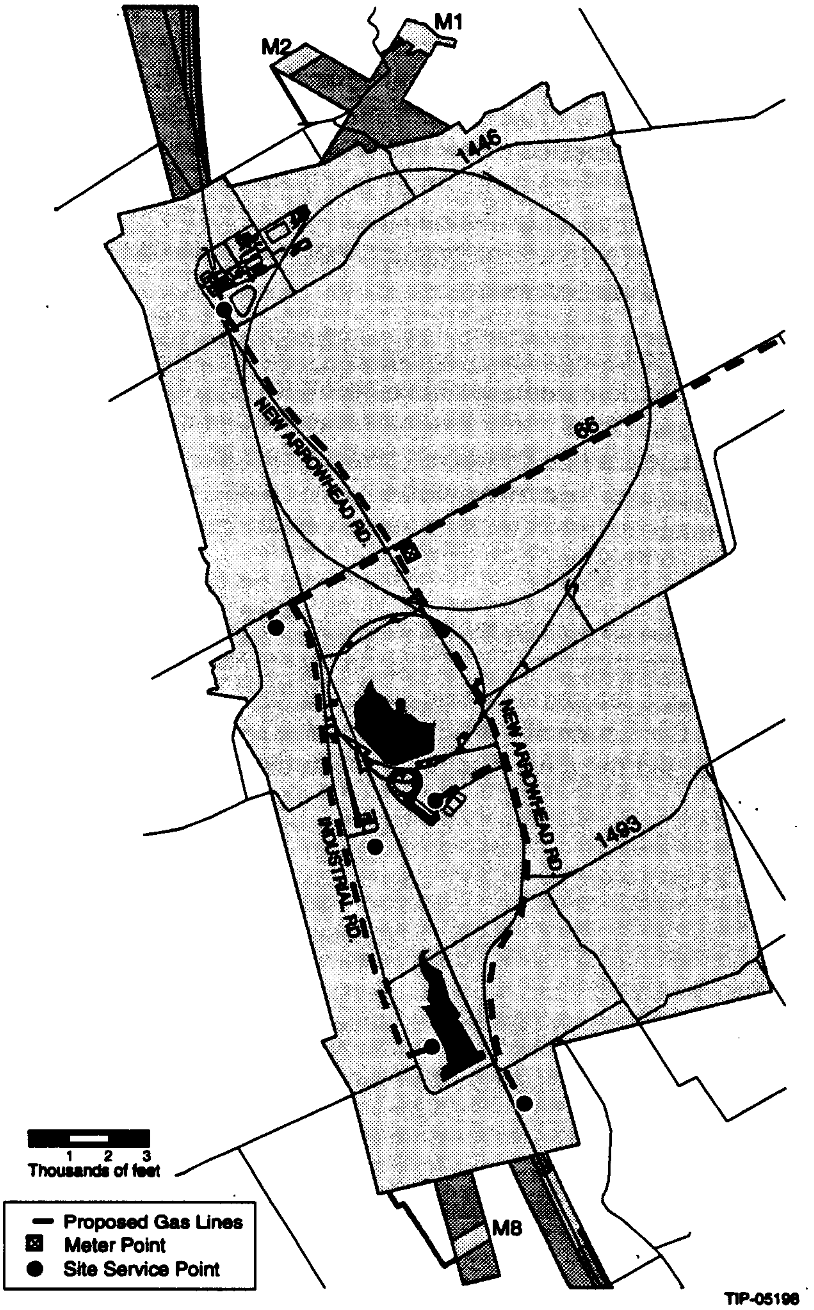


Figure 22-7. West Complex Natural Gas Primary Distribution.

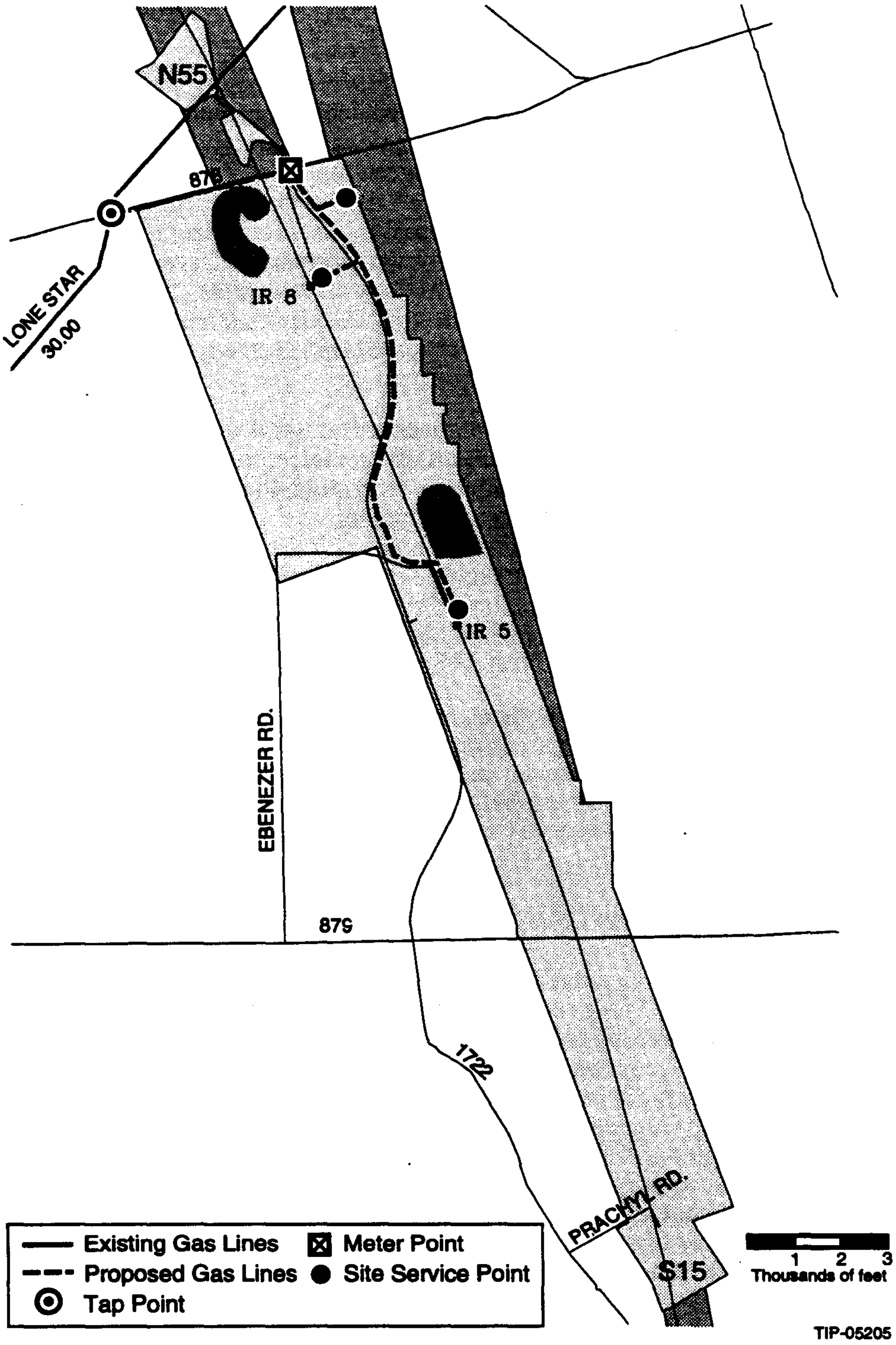


Figure 22-8. East Complex Natural Gas Primary Distribution.

Communications

All accelerators, detectors, facilities, and utilities were to be monitored and controlled from the Operations Center at the Campus. All site controls and communications lines were to link to the Operations Center. The Laboratory Telecommunications Infrastructure Task Force considered two options to provide a communications link between the West and East Complexes. The first option would route all communication through the Collider tunnel. The second option would route communications needed for control of the arcs and the service areas through the tunnel and provide a cross-ring communications link between the Operations Center and the East Complex routed along FM 66 and FM 878. Technical benefits, cost and schedule impacts, and risks to system interruption were considered. The Laboratory decided that the cross-ring routing would not provide the technical benefit necessary to justify the added costs, and all communications among the sites were to be routed through the tunnel.

Southwestern Bell was to have a single connection at the West Complex Operations Center to serve SSC needs and to provide an interface with off-site telecommunication systems. All on-site, fiber optic communications lines were to run in underground 4 inch conduits. From the communications vaults, primary conduits were to run across the campus bridge and then south to IR4 and to a utility shaft, where the cables would enter into the Collider tunnel. Primary conduits were to run north along Industrial Rd. and along New Arrowhead Rd. to the N15 site, where the cable would drop down into the Collider tunnel through the utility shaft. Branches from the north conduits were to serve four collection points: at the MEB (serving the injector technical and experimental areas), at the HEB, at the West Main Substation, and at the Emergency Facility.

The East Complex experimental systems and their utilities were to be connected to the Operations Center by conduits running through the Collider tunnel. The cable was to reach the surface at N55. Primary conduits were to run south along the access road and then south along the Connector Road to the S15 shaft. At the S15 shaft, the cables were to run down into the tunnel. Branches from the conduits were to serve the East Main Substation, the East Emergency Facility, the IR8 area, and the IR5 area.

Transmission of Water (Raw and Potable)

The TNRLC, which was to provide water for the SSC site, commissioned several studies of water systems to serve the SSC project. A comprehensive report prepared by a subcontractor to TNRLC summarized previous reports and analyzed several options for providing the SSC project with its water needs. The subcontractor presented its findings to TNRLC in the *Water and Wastewater Feasibility Study for the SSC*[24] (June 1992). Taking as a starting point the demands determined by the Conventional Construction Division, the subcontractor analyzed several options for the regional transmission and on-site primary distribution of both raw and potable water. The report presented the following regional conclusions: (1) two piping systems, one raw and one potable, should deliver water to the complexes; (2) one treatment plant (the existing City of Waxahachie plant) should provide potable water to both complexes; and (3) raw water from two taps on the pipeline should supply raw water to both complexes and most service areas, with raw water from Lake Bardwell supplying the S25 and S35 sites.

For the East Complex, the subcontractor considered the option of providing fire and irrigation water from the raw water system or providing it from the potable water system. Another report, *Water Transmission Study: SSC West Complex Areas*[25] (May 1992), by another subcontractor analyzed the same option for the West Complex. The recommendations in both reports were that the potable water system should serve the irrigation and fire suppression needs, while the raw water system should provide only make-up water for the cooling ponds.

The analyses in the above reports were based on hydrological, environmental, and cost models. The use of well water at the N & S refrigeration sites was dismissed because of the drain its use would have caused on an already low water table. Most of the recommendations were adopted by TNRLC and the SSC Laboratory except for the source of the potable water. The City of Waxahachie was to provide potable water to the West Complex, while the City of Ennis agreed to provide potable water for the East Complex at a more competitive rate.

The raw (untreated) water system was to deliver make-up water to the cooling ponds. The pipeline serving the West Complex was to run west to the complex along FM 1446. It was to be routed to the N15 area and then follow New Arrowhead Road south. As shown in Figure 22-9, it would feed six distribution points on-site: two HEB cooling ponds, the HEB cooling tower, the N15 site, the MEB cooling pond, and the campus pond. The pipeline serving the East Complex was to run north and south from the TCWCID pipeline on site. It was to serve four distribution points: the S15 pond, the IR5 pond, the N55 pond, and the IR8 pond, as shown in Figure 22-10.

The potable water for the West Complex was to be supplied from the Waxahachie Treatment Plant. An existing pipe running west along FM 66 was to connect to an on-site storage tank at the east boundary of the complex. From there existing and proposed pipelines were to route the water to the facilities, the fire systems, and irrigation systems (see Figures 22-11 and 22-12). For the East Complex, the transmission line was to route water from Ennis north along 1722 and the Connector Road to an on-site pump station and reservoir. From there the on-site primary distribution would have run along the Connector Road to a storage tank near the northern site boundary.

The N25, N35, N45, N55, S25, S35, S45, and S55 Areas were to obtain raw water from a proposed network of distribution lines. The N20, N30, N40, N50, S20, S30, S40, and S50 Areas would not have required cooling or potable water for initial operations. Possible future cryogenic upgrades could have resulted in the need for cooling water at the ventilation sites. During operations, the N and S Sites were only to be occupied for brief maintenance periods without requiring permanent potable water systems.

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The N25, N35, N45, N55, S25, S35, S45, and S55 Areas were to obtain raw water from a proposed network of distribution lines. The N20, N30, N40, N50, S20, S30, S40, and S50 Areas would not have required cooling or potable water for initial operations. Possible future cryogenic upgrades could have resulted in the need for cooling water at the ventilation sites. During operations, the N and S Sites were only to be occupied for brief maintenance periods without requiring permanent potable water systems.

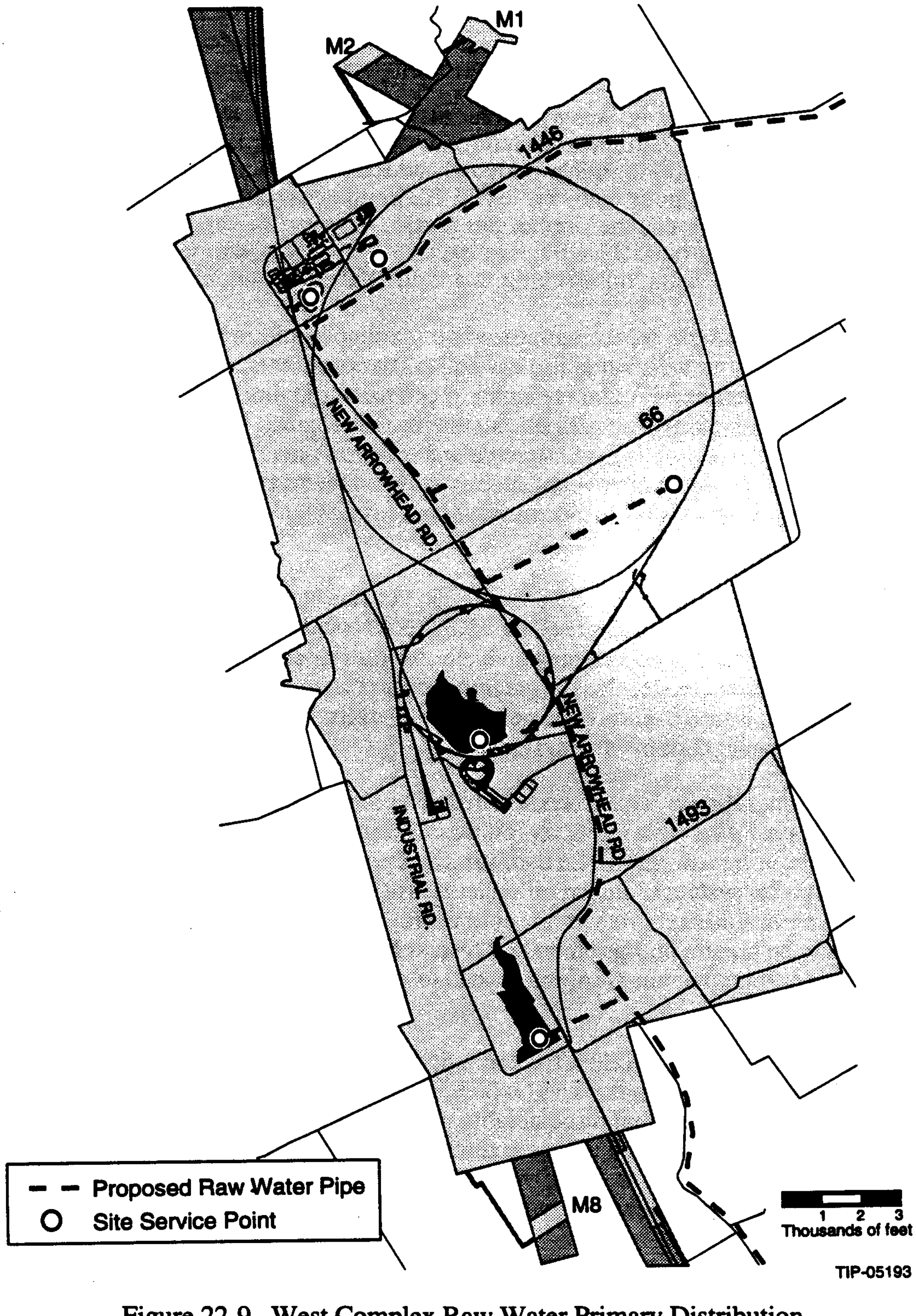

Figure 22-9. West Complex Raw Water Primary Distribution.

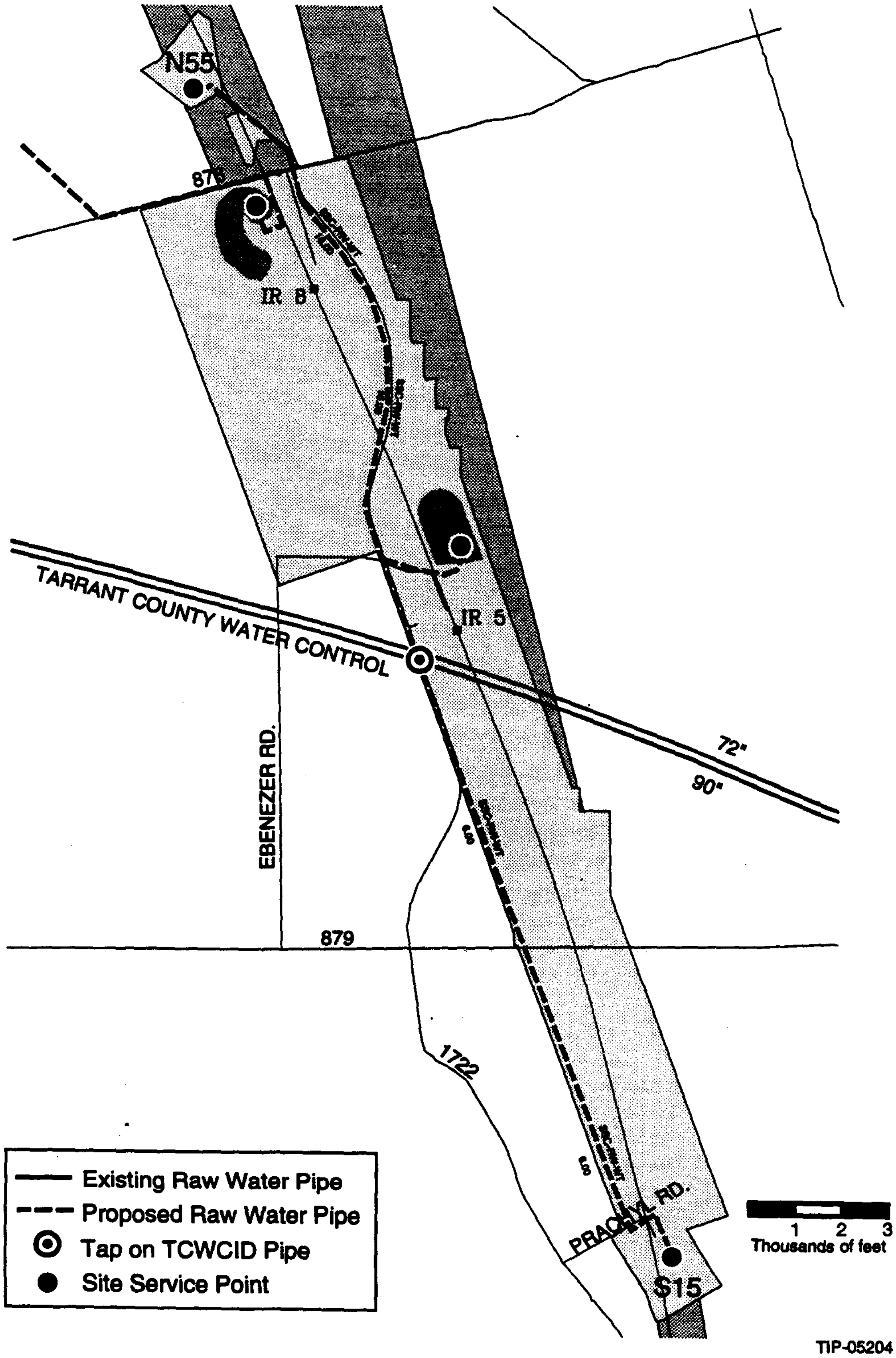

Figure 22-10. East Complex Raw Water Primary Distribution.

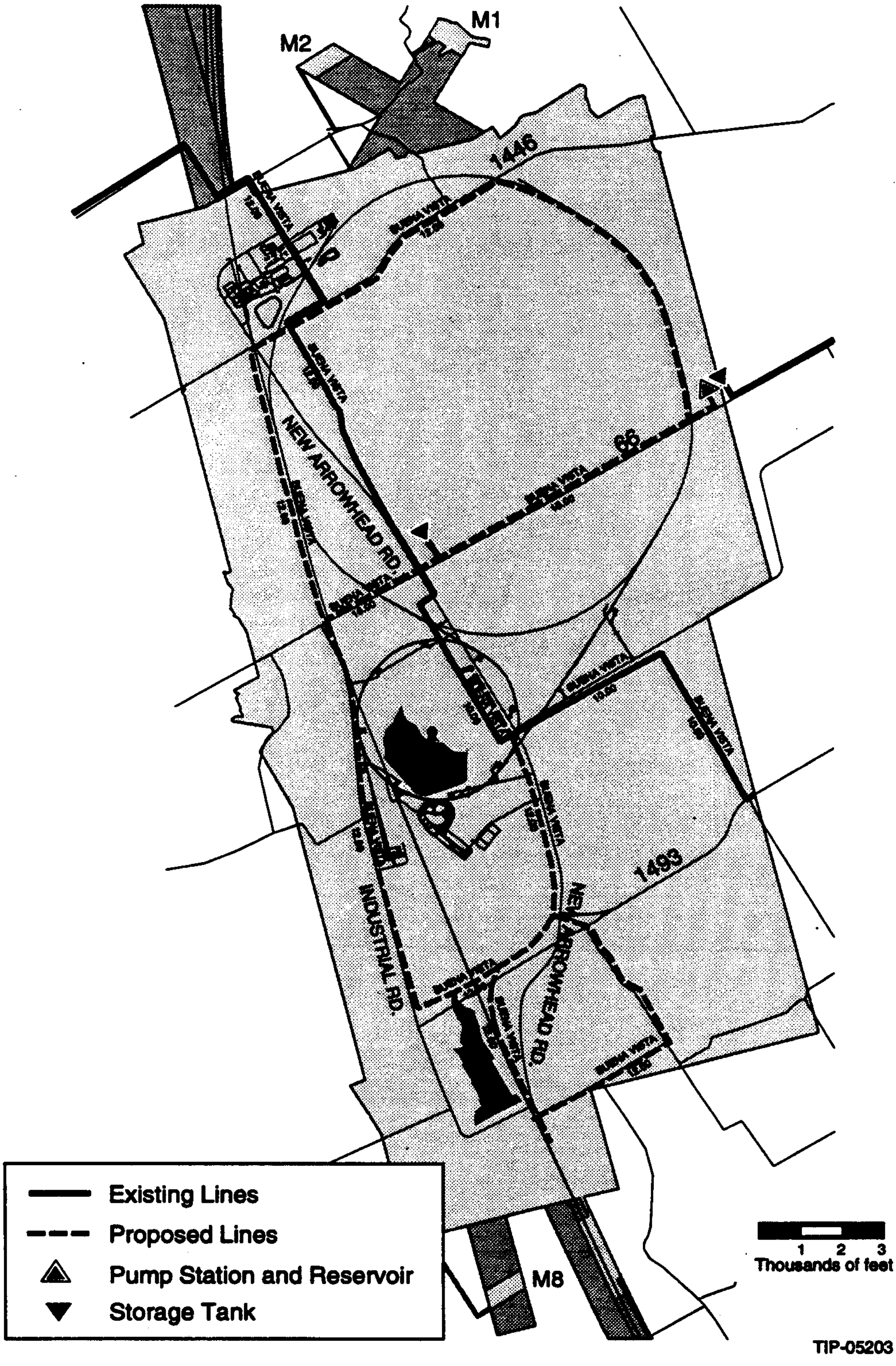

Figure 22-11. West Complex Potable Water Primary Distribution.

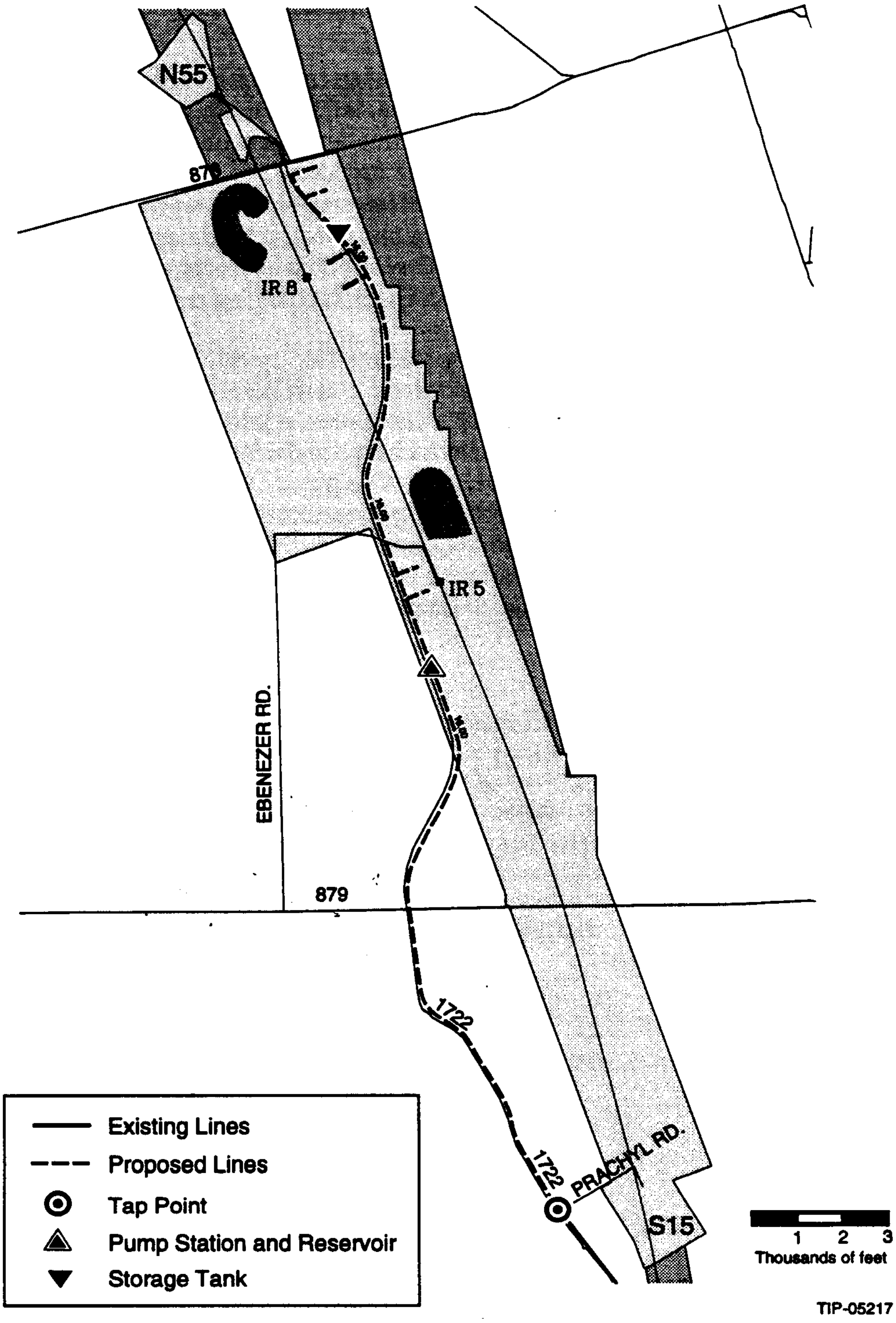

Figure 22-12. East Complex Potable Water Primary Distribution.

Wastewater Systems

The TNRLC agreed to provide funding for the sewer service from project facilities. The above mentioned TNRLC contractors also made recommendations for handling sewage. For the West Complex, they studied the following options: constructing a new on-site treatment plant, constructing a new regional treatment plant, and pumping the sewage to the existing plant owned by the City of Waxahachie. For the East Complex facilities, they considered four options: a new on-site plant, a new regional plant, and the use of one of two existing treatment plants (Ennis's or Palmer's). The report recommended contracting with the City of Waxahachie to accept West Complex wastewater and with the City of Palmer to accept East Complex wastewater.

Pipes to off-site sewage treatment plants were to be provided by the State of Texas. On the West Complex, an on-site pumping station was to serve as a collection point for the West Central and the West South facilities requiring sewer service. The station would have pumped the sewage to the Waxahachie Wastewater Treatment Plant. The N15 area in the West North site had an existing treatment plant that would have continued to serve its needs. On the East Complex, waste from the IR5, IR8, and Support areas was to be collected and pumped to the treatment plant in Palmer. Permanent sanitary sewage disposal was not required at the N and S Areas. Temporary sanitary sewage facilities would have been required at the N and S Areas during construction, and would have been provided by portable units.

Stormwater System

Regulating the rate of stormwater run-off from developed areas was considered as an adjunct to the design of cooling water ponds. Under the instructions of the Conventional Construction Division, the project's A-E/CM prepared a study of options that would provide the facilities cooling water needs. The results of the study were reported in *The Stormwater Detention Cooling Pond Study* [26] (September 1991). The conclusion was that, for developed areas where the site topography is suitable, on-stream ponds would be the best alternative for stormwater detention. The MEB and Campus ponds were to be used to regulate the run-off from the injector, the test beam, IR1, and Campus areas. Stormwater from smaller areas, such as IR4, 5, and 8, was to drain to nearby stream channels.

PART V. CONVENTIONAL CONSTRUCTION

Introduction

(T. Toohig and D. Reich)

The design of the conventional facilities for the SSC evolved with the design of the technical systems, beginning with the 2 TeV pbar-p Fermilab Dedicated Collider[1,2] in 1983. The Cornell Workshop[3] in the Spring of 1983 developed considerations of tunnel design based on magnet size and installation concepts and also developed the basic concepts for radiation shielding requirements for a 20 TeV Collider. The Reference Designs Study (RDS) of 1984 emphasized a plausible cost estimate for the facilities; the main design developments were concepts for accelerator facilities, collision halls, and development of space requirements and architectural concepts for campus and support facilities for the projected population of the facility.[4] The report of the RDS was used to derive siting parameters[5] and an action plan[6] for environmental and geotechnical exploratory activities.

Chapter 23. Design of Conventional Facilities

The conceptual design of the SSC proceeded in two stages: a non-site specific design, prepared by the Central Design Group, which formed the basis of project authorization and site selection; and a site-specific design, prepared by the SSC Laboratory following selection of the Texas site, which established the cost baseline, the basis for land acquisition, and the design of the facility.

Generic Conceptual Design

In the Conceptual Design Report (CDR) of 1986, the primary emphasis in the conventional facilities portion[7,8] was on the design and derived cost for the Collider tunnel, the major cost element for this aspect of the project. For the CDR the major facilities were rearranged, relative to the RDS, to cluster the populated facilities in two areas on opposite sides of the ring connected by two unpopulated, nearly-180° arcs. The rearrangement was initially driven largely by considerations of reducing the extent and costs of conventional facilities while improving the opportunities for communication among the Laboratory community.

To adequately characterize the costs for these facilities, three model sites were developed for the CDR by RTK, the A-E firm supporting the URA/Central Design Group activities. The features of these model sites spanned the range of variation of depth and rock/soils anticipated for sites suitable for the project. The models were used, among other reasons, to develop a tunneling cost model for inter-site cost evaluations.

In the period following publication of the CDR, time-phased computer graphic modeling techniques[9,10] were developed and implemented to explore the range of feasible parameters for the underground spaces. Studies utilizing these techniques led to an increase in the Collider tunnel diameter from 10 ft to 12 ft to accommodate installation requirements as well as transport equipment during operations. The studies also led to a change in shaft concept from single, multifunctional shafts to multiple single-function shafts, and to a design concept for the large experimental halls that accommodated installation, operation, and maintenance of the detectors.

The further development of design concepts by the Central Design Group between the publication of the CDR in May 1986 and the phasing out of the CDG in December 1988 were gathered into five supplementary volumes and formally transmitted to the new project organization. Volume IV and Volume V (1-6) of the supplementary volumes[11] pertain especially to developments in the area of conventional facilities.

Site-Specific Conceptual Design

The major new design considerations for the Site-specific Conceptual Design Report[12,13] (SCDR) in 1990 were an increase in the energy of the HEB from 1 TeV to 2 TeV, an approximately 10-fold increase in the volume of the large detectors, and adaptation of the design to the geography and geology of the Texas site. The change in the HEB approximately doubled the circumference of its tunnel and increased substantially the area of land under impact. The increase in detector sizes correspondingly increased the size of the collision halls needed to house them.

Roles and Responsibilities

Execution of the conventional construction of the SSC Laboratory, including underground facilities, buildings, and infrastructure, was the responsibility of the Conventional Construction Division (CCD). The URA staff of CCD was supplemented by specialized support from the Sverdrup Corporation, a designated subcontractor to URA in the Management and Operations team. The CCD Head exercised his responsibilities through a subcontracted Architect-Engineer/Construction Manager (A-E/CM) firm, the PB/MK Team joint venture, who prepared the designs and managed the construction contracts. Early design work, prior to the accession of The PB/MK Team, was carried out by RTK, the A-E contractor for the CDG and site evaluation phases of the project. To accomplish the construction, the A-E/CM subdivided the project into Construction Contract Units, CCUs, which were logical units of work. The configuration of the CCUs took into account the functional completeness of a unit, pertinent geological boundaries, estimated costs relative to the project's available obligational authority, and the bonding capability of potential contractors. A given CCU could involve several related categories in the project's Work Breakdown Structure (WBS), and, conversely, a given WBS category, like Infrastructure, could be spread over a range of CCUs. The relationships between WBS categories and CCUs are defined in a Project Management Baseline (PMB) crosswalk document.[14]

Documentation

The design requirements for each facility were established by the Conventional Construction Division working with cognizant technical divisions. The requirements were incorporated into a Design Requirements Document (DRD), which was formally approved by the Laboratory and then transmitted by CCD to the A-E/CM for execution of the design. Execution of the design represented in a given DRD might involve one or more CCUs. For each CCU the design process involved formal review documents at the Title I, 60%, and 90% Title II levels. The process led to an Invitation for Bid, which was the basis for award of a contract on a competitive lump sum basis. After award, the contract might be modified by Design Change Notices (DCN). Progress in design was reported in a Weekly Design Project Milestone Report, while progress in construction was reported in Weekly and Monthly Construction Status Reports. Upon completion of the contract, a set of as-built drawings and related documentation (Title III) were provided to the Laboratory by the A-E/CM.

The documents named above constitute the technical documentation of the design and construction process. Documentation is cataloged under the relevant CCU number. The documents are cross-referenced, in a computer database maintained in CCD and in the SSC Laboratory document control system, to WBS categories, to A-E/CM package numbers, and to SSCL Document Control numbers. The status of the documentation is also included in the database for each CCU. It is intended that this database for conventional construction be archived. In addition to the facility-specific CCUs, there were a number of project-wide activities, such as the precision survey grid and the geotechnical characterization of the site, which are documented separately in the database.

Design concepts, specialized studies, Underground Technology Advisory Panel (UTAP) reports,[15] and site characterization activities predating the initiation of construction are documented outside the CCU framework, as are publications in the technical literature and presentations made to professional groups. These reports and publications are referenced in passing in this report and included in the reference listing below.

Chapter 24. Status of Major Project Elements

The major elements of the project, which constituted the first level of subdivision for construction purposes, were the Collider, the Injector, and the East and West Complexes. The Collider was made up of the North and South Arcs and the East and West Clusters; the Injector includes the Linac, LEB, MEB and HEB; the West Complex included the experimental areas, the N15 area, the common infrastructure, and the Campus; while the East Complex included the experimental areas and the common infrastructure. The status of the conventional construction for the project was reviewed periodically in conference reports[16,17] and technical publications.[18] The status of the design and construction and related documentation at time of closing are discussed below.

Site Definition and Acquisition

Environmental Impact

In planning for the site selection process, DOE determined that completion of a full environmental impact statement (EIS) for the chosen site would be a prerequisite to making the decision on the site for the SSC. In practice, this was interpreted by DOE to mean that an EIS must be done for all the finalist sites. DOE contracted with Argonne National Laboratory (ANL) to prepare the EIS, making use of RTK, the A-E subcontractor to the Central Design Group, for technical support. Documentation relative to radiation[19] and operational safety[20,21] considerations was prepared by the URA/CDG to supplement the Conceptual Design Report of March 1986, the definitive basis for evaluation of the environmental impact of the SSC. A Draft EIS[22] (DEIS) was issued in August 1988 encompassing all 8 of the BQL sites. Following a public comment period and public hearings at each of the sites, a Final EIS[23] (FEIS) was issued in December 1988, and a Record of Decision (ROD) selecting the Texas site was issued in January 1989. The ROD included a requirement for a Supplemental EIS (SEIS) to treat the detailed adjustment of the facility to the Texas site. An implementation plan for the SEIS[24] was issued in July 1990. Following an additional comment period and public hearings, the SEIS[25] was issued by DOE in December 1990, and the ROD followed in February 1991.

Site Selection

The major features of the SSC facility, i.e., the clustering of the major machine elements and interaction points on either side of the ring and the determination of the radius of the arcs connecting the clusters, were fixed in the Conceptual Design Report (CDR). A Siting Parameters Document[26] derived from the CDR provided the technical basis for an Invitation for Site Proposals[27] (ISP) issued by DOE in April 1987. Thirty-five responsive site proposals were submitted to DOE in response to the ISP and evaluated by a committee of the National Research Council. From a Best Qualified List[28,29,30] (BQL) of 8 sites provided by the NRC committee, then-Secretary of Energy John Herrington selected the site near Waxahachie, TX, in 1988, for construction of the facility.

Adaptation to the Site

Placement of the SSC facility on the selected site was an iterative process involving the designers, DOE, and the State of Texas. With the exception of an increase in the fee simple land area to contain the enlarged HEB and minor modifications to accommodate revisions to the Collider lattice, the SSC footprint was essentially set in the proposal from the State of Texas for the Ellis County site.[31,32,33] Adaptation of the modified design to the site involved overlaying on U.S.G.S. quad maps a template of the facility requirements, including buffer zones for radiation avoidance, to minimize interference with existing surface and environmental features. The detailed configuration of the land required for the facility was driven largely by radiation considerations[34] and existing property boundary lines.

The elevation and tilt of the Collider ring within the geological setting were selected to minimize the length of tunnel in the soft Eagle Ford Shale and maximize the length in Austin Chalk, while maintaining the specified minimum cover above the tunnel of 50 ft everywhere around the circumference.[35] Setting of the ring involved using bedrock geology[36,37,38] from the site geotechnical characterization program, a precise system of survey monuments,[39] and a program of aerial survey and mapping.

The land requirements defined by these exercises were incorporated into a Footprint Characterization Document,[40] which was prepared by the SSC Laboratory and approved by DOE. The Footprint Characterization Document was supplemented by a digital, 3-dimensional characterization[41] of the required land volumes and areas in hard copy and magnetic formats. These documents specifying the land requirements for construction and operation of the facility were transmitted by DOE to the Texas National Research Laboratory Commission (TNRLC) as the formal specification by DOE for land acquisition by the State.

All the land specified by DOE for the facility, approximately 10,000 acres in fee simple and 6,000 acres in stratified fee, had been taken in possession by the State, either by outright purchase or by right of eminent domain. With the exception of some ongoing litigation by the TNRLC with respect to fair value for lands taken by eminent domain, this phase of land acquisition for the SSC was complete as the project ended. Approximately 2,000 acres in fee simple and 15 acres in stratified fee had been transferred to the federal government. For other areas, both fee simple and stratified fee, the federal government had been give right-of-access for construction.

Geotechnical Exploration

An initial geotechnical exploration program involving 38 borings was carried out by the State of Texas to characterize the geology of the site for the Texas site proposal. Following selection of the Texas site by DOE, an extensive program of approximately 120 borings was carried out for the Laboratory by RTK to characterize further the geology of the site and to optimize the placement of the Collider tunnel, shafts, and experimental halls. The data from this RTK program are recorded in an extensive series of borehole and summary data reports, series SSC-GR-xxx, and contained in a gINT database[42] in the Laboratory archives. In the course of detailed design of facilities, an extensive program of project-specific borings was carried out by PB/MK. These data form the basis of the Geotechnical Design Summary Reports (GDSR), which are incorporated into the design package for each of the CCUs.

Survey and Monumentation

As noted above, the gross siting of the Collider made use of templates overlaid on U.S.G.S. quad maps for the area, initially by the State of Texas for inclusion in the Texas Site Proposal, and later by the SSC Laboratory for the modified lattice. For detailed specification of the land for acquisition by the State, the Global Positioning Satellite (GPS) system was used to establish a network of master (Order B) and primary (First Order) monuments for horizontal survey control.

A precision (First Order) network of vertical survey monuments was established by redundant precision leveling across the diameter and around the circumference of the Collider ring.[39] This high-precision network of monuments was later augmented with a view to installation of the technical components in the tunnel.[43, 44]

The West Complex

N-15 Area

Two early project technical milestones were assembly and operation of a full cell of industrially-produced Collider magnets, and assembly and operation of a half-sector of Collider magnets in a prototype tunnel. The CERN LEP model of having the magnet production and test facilities adjacent to the tunnel insertion point and considerations of maximizing the commonality of equipment and personnel led to the siting of these activities adjacent to the N15 magnet shaft and Collider refrigerator station.

Consequently, the earliest site-specific design activity for the project involved use of the N15 area at the northwest corner of the West Complex for initial magnet testing activity,[45] with a view to early installation and testing of a full refrigeration system including to a testing of a string of magnets in the Collider tunnel.[46] The studies also recognized an opportunity to interconnect the Collider and HEB refrigeration systems through the String Test facility by orienting the facility along the line between the N15 refrigeration station and the adjacent HEB refrigeration station at H20.

The goal of meeting the milestones as expeditiously as possible was the motivation for early construction of the N15 Magnet Delivery Shaft (CCU #A602) and the magnet-related structures in the N15 area. The Magnet Development Laboratory (MDL) (CCUs #D102, D103, D107), was a two-storey structure providing 103,440 sq ft of manufacturing space in three bays, with provision for a staff of 180 persons. The Magnet Test Laboratory (MTL), (CCUs #C201, C202, C203), consisted of three buildings: the MTL, providing 55,296 sq ft in two bays with some office and shop space; the Refrigerator Building, providing 4,095 sq ft of specialized space for the large helium refrigerators; and the Compressor Building, providing 8,740 sq ft of space to house the helium compressors required for the helium refrigerators. The Accelerator Systems String Test Facility (ASST), (CCU #A625), consisted of Refrigerator and Compressor buildings mirroring the MTL and the 600 ft × 14 ft, elongated String Test Building providing laboratory space for connecting long strings of magnets. Additionally, there was a package sewage plant (CCU #D108), along with area infrastructure. These facilities were complete and had been turned over to the Laboratory for operation as the project ended.

Injector Design Activities

A number of technical decisions resulted in changes to the design concepts and load parameters for the conventional facilities of the Injector. They included provision for a future medical facility and an isotopec production facility for the Linac, a change in the LEB to a triangular configuration with longer straight sections and underground RF gallery, provision in the MEB for a higher-power, slow-cycling operating mode, and a shift in the HEB/Collider optics to preserve a polarization option by placing the extraction straight section for the HEB tunnel directly above the injection straight section for the Collider tunnel. The design intensity and allocation of straight sections in the HEB were also modified, requiring acquisition of land beyond the West Complex boundaries to accommodate the beam absorber zones.

Preliminary design activities for the Injector complex, besides incorporating the technical modifications, included a cost optimization study of the elevation of the Linac, LEB and MEB,[47] a program of geotechnical exploration to characterize the subsurface, an optimization study for use of a cooling pond for rejecting waste heat from the Injector,[48] and a survey program to locate the facilities. The elevation study resulted[49] in the Linac, LEB and approximately 600 ft of the MEB tunnel being constructed by cut-and-cover techniques with shielding berms, while the MEB was to be tunnelled. The elevation of the HEB was constrained to be at or near the Collider elevation by the decision to inject both clockwise and counterclockwise proton beams into the Collider in a single long straight section. The cooling pond studies, with cooperation from MIT, resulted in an efficient design for the Injector pond and design concepts applicable to the cooling ponds to be used at the Collider service areas. Except for the HEB portion, the preliminary design activities for the Injector were complete. The overall status for the Injector construction is depicted in Figure 24-1.

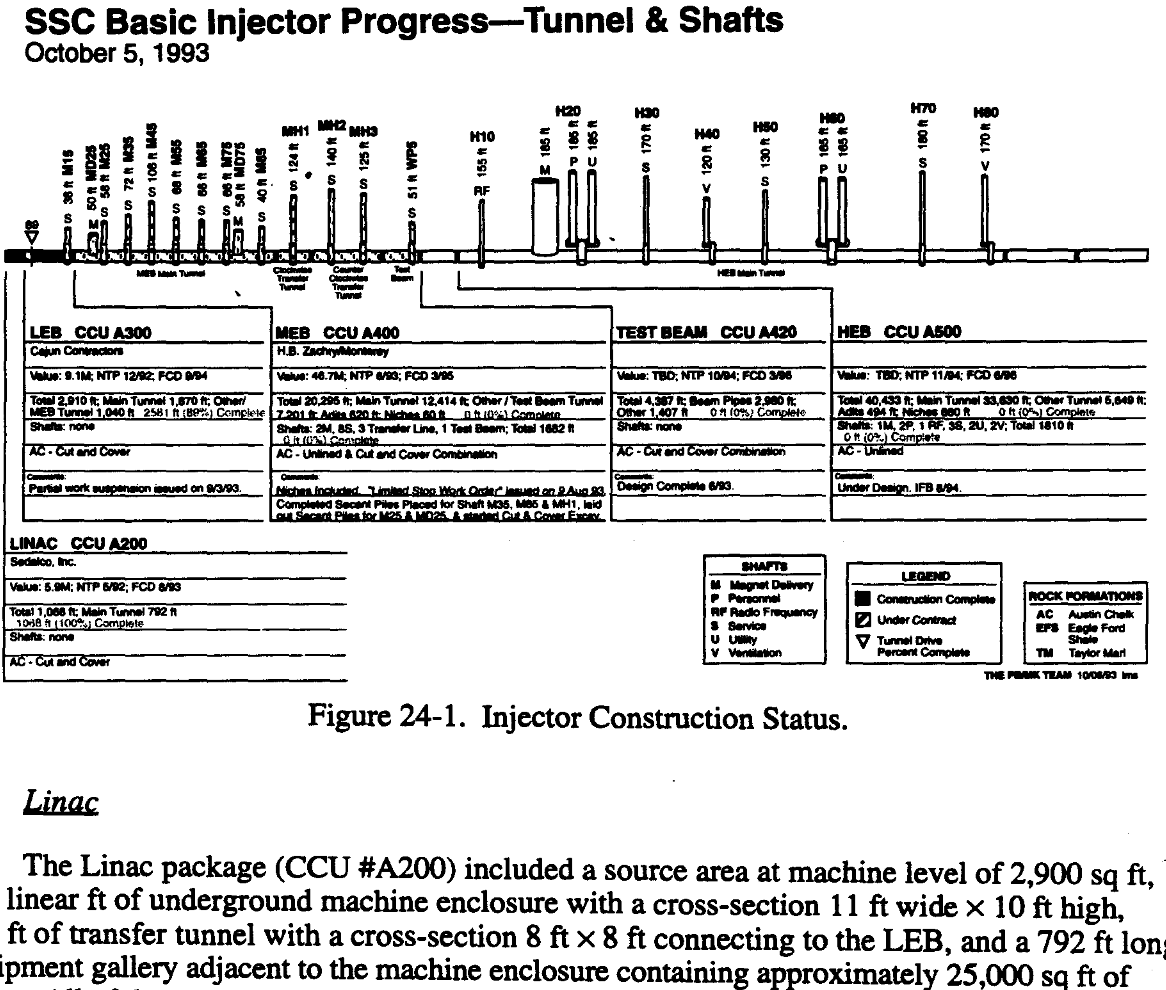

Figure 24-1. Injector Construction Status.

Linac

The Linac package (CCU #A200) included a source area at machine level of 2,900 sq ft, 792 linear ft of underground machine enclosure with a cross-section 11 ft wide × 10 ft high, 276 ft of transfer tunnel with a cross-section 8 ft × 8 ft connecting to the LEB, and a 792 ft long equipment gallery adjacent to the machine enclosure containing approximately 25,000 sq ft of space. All of the conventional construction for the Linac had been completed with the exception of a small LCW Room (CCU #A201) on the south side of the Gallery Building. The opening in the Gallery wall for the LCW room was to be closed with existing siding material. The Linac had been turned over to the SSCL for installation of technical systems.

LEB

The LEB package (CCU #A300) included approximately 1,900 linear ft of underground machine enclosure and associated surface buildings, 300 linear ft of transfer tunnels, and 600 ft of the cut-and-cover portion of the MEB tunnel adjacent to the LEB. The package was under contract and construction was well under way at termination. The LEB tunnel shell was approximately 90% complete, and all but three of the floor slabs were finished. The backfill of the tunnel to grade was 20% completed. The LEB to MEB Transfer Tunnel had been completed and backfilled to grade, and 20% of the shielding berm over the Transfer Tunnel was in place. The 575 ft of MEB tunnel included in the LEB contract had been completed, and 20% of the shielding berm above the tunnel was in place.

MEB and Test Beam

The MEB package (CCU #A400) included approximately 20,000 linear ft of tunnel of which 7,200 linear ft consisted of transfer and test beam tunnels, 14 shafts and associated buildings, the portion of the Test Beams from WP0 to WP8, and the Injector cooling pond. The package was under contract, and construction was under way at termination. Clearing and grubbing for the cooling pond had been completed, and excavation of the cut-and-cover portion of the accelerator tunnel from the LEB tie-in was 90% complete. None of the Test Beam construction had been carried out. The design package for the remainder of the Test Beams facility (CCU #420 WP8-WP12) was complete, and the package was ready for bid at the time of termination.

HEB

The HEB package (CCU #A500) included approximately 40,000 linear ft of tunnel of which 5600 linear ft consisted of transfer tunnels, with 11 shafts and associated surface buildings. The package was in a very early design stage with approximately 21% of it completed.

Campus Design Activities

Several Master Planning activities were carried out to define the location, design, and schedule for the Campus.[50,51,52] Anticipation of commissioning the LEB and MEB forced a tentative decision on the location of the Operations Center, which was to be an element of the Campus. Beyond this, the studies led to no firm conclusion.

The Collider

Design Activities

Changes in Technical Requirements

The Collider lattice had been modified to accommodate insertion of "Siberian snakes" for acceleration of polarized protons, and to provide free space in the arcs for possible insertion of beam scrapers and other devices. The lattice design changes were iterated with terrain and land acquisition constraints with respect to the potential location of shafts around the ring to arrive at a feasible configuration.

Also, as a result of a significant increase in the projection of the heat produced by electronics and power supplies located in niches in the tunnel combined with an in-situ ground temperature above the projected level, extensive studies were carried out on the thermal properties of the geological media, the suitability of various heat rejection systems to meet the temperature constraints of the technical systems along the tunnel, and cost trade-offs for heat rejection options. Factoring in the projected annual operating cycle for the Collider, an insulated chilled water system to remove the heat from the niches while allowing the tunnel to come to equilibrium with the rock was found to be adequate to the technical constraints[53,54] and cost-effective. The tunnel ventilation and cooling systems constituted CCUs #917 and #918, respectively, which were ready for bid at the time of termination.

Access and Safety Concerns

Analysis of the safety codes (OSHA, MSHA, DOE Orders) relevant to work in underground spaces comparable in function to the SSC tunnels[55] led to agreement from DOE/ES&H in Washington on the adequacy of the spacing of the shafts along the Collider tunnel for the operation of the facility.[56] An analysis of conditions during the installation phase of the facility led to the conclusion that applicable OSHA codes were less restrictive than the code for underground construction, OSHA 1926M, so that the more conservative approach of using OSHA 1926M should be adopted during installation.

Concern for the possibility of radiation escaping from the shafts in the event of a catastrophic loss of beam led to intensive studies that factored into the trade-off studies relative to shaft functions discussed below.

Trade-offs in Cost and Functionality

Trade-off studies relative to cost and functionality lead to a number of studies were being out. The cost of bored tunnels as a function of diameter was re-examined in light of recent advances in excavation technology and of the particular geology and placement of the SSC tunnel. The results of these studies were that the flat cost minimum in the classic curve for this dependence, which extends to an excavated diameter of 12 ft, could be extended to 14 ft.[57,58] The inside diameter of the Collider tunnel was accordingly increased to 14 ft.[59] The baseline cost estimate was maintained by keeping the same volume of concrete in the floor of the 14-ft tunnel, the invert, as for the 12-ft tunnel. This resulted in an additional six inches of width on the floor for the magnets and transport equipment. Furthermore, approximately 40 square ft was provided in the tunnel cross section for installation of equipment and utilities without exceeding the baseline cost estimate.

Trade-off studies on the number, size, and configuration of Collider shafts led to improvements in cost, function, and radiation characteristics.[60,61,62] The 10 large, multi-function shafts at the Collider Service Areas in the conceptual design were 35 ft in diameter for the five refrigerator stations and 55 ft in diameter for the areas with magnet handling capability. Observation of tunneling projects in Dallas indicated that excavation of shafts by drilling is very cost effective, because of the drilling experience in the oil industry in Texas. The practical limit on the size of drilled shafts was seen to be about 20 ft in diameter. Providing separate shafts for personnel access and the routing of technical systems would result in shafts approximately 20 ft in diameter, which could be drilled. This change was implemented.[63] The average cost of excavating the 20-ft diameter shafts by conventional methods had been estimated to be $3M; the actual average cost for drilling them was approximately $250K. The magnet delivery shafts, relieved of other functions, were tailored to the magnet profile, long and narrow, reducing the volume and cost of their excavation.

Besides the cost advantages, the reduced cross-section of the shafts improved their radiation characteristics by providing increased attenuation. The radiation characteristics were further enhanced by locating the shafts in a hammerhead arrangement so that radiation from the tunnel had to negotiate a right angle to enter the shaft. The radiation characteristics of the shafts could be tuned by varying the adit length (the "handle" of the hammer) and the offset distance from the adit to the base of the shaft (the "hammerhead"). The availability of the "hammerhead" for placement of the cryogenic and controls equipment required at the base of the shaft also improved the placement of shielding walls to reduce the radiation burden on those items. Ventilation shafts were placed in a "half-hammerhead" configuration for the same reasons of radiation enhancement. With this configuration, these areas could be upgraded at a later date to accommodate a refrigerator station by completing the hammerhead and auguring a utility shaft.

Finally, isolating the magnet delivery function from the access and utility connections allowed the placement of the magnet shafts to be optimized with respect to the available road network and installation procedures.[64] The magnet delivery shaft at N35, with very poor road access, was shifted to N40, adjacent to Interstate 35 and midway in the North Arc. The magnet shaft at N55, with poor road access, was shifted to the north end of the East Complex, adjacent to the major cross-ring road. Placing the magnet shaft on the East Complex also dimished the problem of transporting radioactivated magnets on public roads.

A serious concern with respect to cost and technical constraints was the encroachment of Eagle Ford Shale into the tunnel horizon along the West Utility Straight Section and into the base of the large experimental halls that were planned for IR1 and IR4 on the West Complex. A systematic study[65] was carried out of the degree of impact of the Eagle Ford Shale as the tilt and roll of the plane of the tunnel were varied within the allowable constraints. On the basis of these and related studies, the depth of the Collider ring was reduced at the West Complex[66] to lessen the amount of Collider tunnel in the shale and to place the HEB tunnel, which was at a fixed distance above the Collider, entirely in the Austin Chalk. There was no solution in which the collision halls for the large detectors could be raised sufficiently above the shale to provide the needed long-term stability, so the two detectors were reassigned to IR5 and IR8 on the East Complex.[67,68] At those locations the experimental halls could be founded in Austin Chalk.

Other preliminary design activities included the division of construction contracts between excavation and mechanical/electrical tasks; the excavation contracts were designated as "basic" packages and the mechanical/electrical contracts were designated "finish" contracts in the documentation. Besides the preliminary design activities, field activities in support of design were carried out including: the provision of suitable access roads to all the Service Areas; extension/densification of the survey grid; and supplemental geotechnical exploration. Documentation for these field activities is included under the CCUs for the basic tunnel packages for the areas in which the work was carried out.

North Arc

The North Arc of the Collider extended approximately 22 miles from N15 on the West to N55 on the East. The tunnel from N15 to near N25 was in shale and required installation of a precast liner immediately behind the tunnel boring machine (TBM). The remainder of the North

Arc was in competent Austin Chalk, which did not require a liner. More than 76,000 ft of basic tunnel and 14 of a total of 17 shafts had been excavated on the North Arc at the time of termination. (See Figure 24-2.)

Excavation of the basic tunnel and shafts was covered by CCUs #A602 N15 Magnet Delivery Shaft (MDS) basic, #A610 N15-N20 basic, #A611 N20-N25 basic, #A650 N25-N40 basic, and #A670 N40-N55 basic. All of the North Arc basic tunnel was under contract: the basic tunnel contracts from N15 to N25 had been completed except for the niches, which were to be contracted separately under CCU #A622. The niche design for N15 to N40 was completed, and the contract was under negotiation at the time of termination. Construction of all the shafts for CCU #A650, N25-N40 and the portion of tunnel from N25 to N35 was completed. Except for the 3 shafts at N55, all the shafts for CCU #A670, N40-N55 were completed, as well as the portion of tunnel from N40 to approximately 5000 ft beyond N45. The shafts at N55 were partially excavated.

The finish phase of the North Arc was included in two packages: CCU #A620 N15-N25, and CCU #A690 N25-N55. The design packages for both of these CCUs were completed and on the shelf. An additional CCU, #A711, was prepared to provide stabilization where the chalk tunnel was deteriorating due to the presence of the bentonite marker bed in the tunnel region. DOE decided against implementing this CCU in the interest of minimizing termination costs.

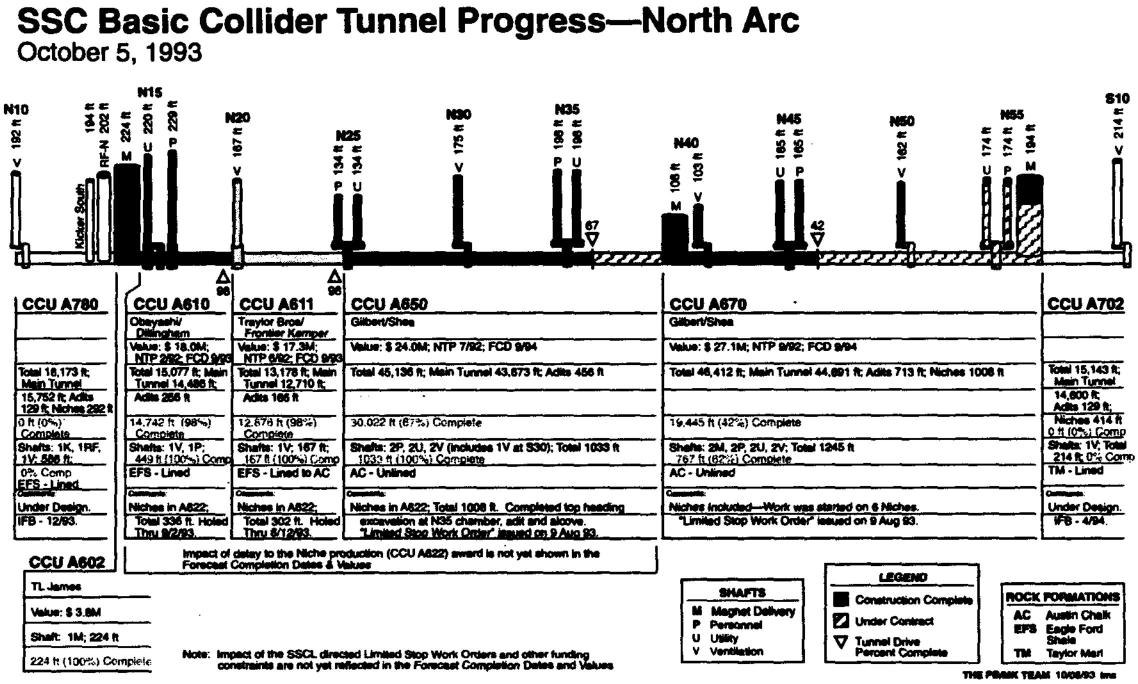

Figure 24-2. North Arc of the Collider.

South Arc

The South Arc extended from S15 on the East to S55 on the West, a mirror image of the North Arc. The eight-mile portion from S40 to S55 was in Austin Chalk and designed as an unlined tunnel, while the remaining 13 miles from S40 to S15 was in Taylor Marl and lined. All the basic tunnels for the South Arc had been designed and were included in

CCUs #A701 S10-S25, #A720 S25-S40, and #A740 S40-S55. The portions from S40-S55 and S25-S40 were under contract. Excavation had been completed on 600 ft of tunnel and 3 shafts with partial excavation of 3 additional shafts. (See Figure 24-3.) The designs for the finish contracts for the South Arc, CCUs #A703, S25-S10 Finish, and #A730, S25-S55 Finish, were incomplete at a level short of Title II.

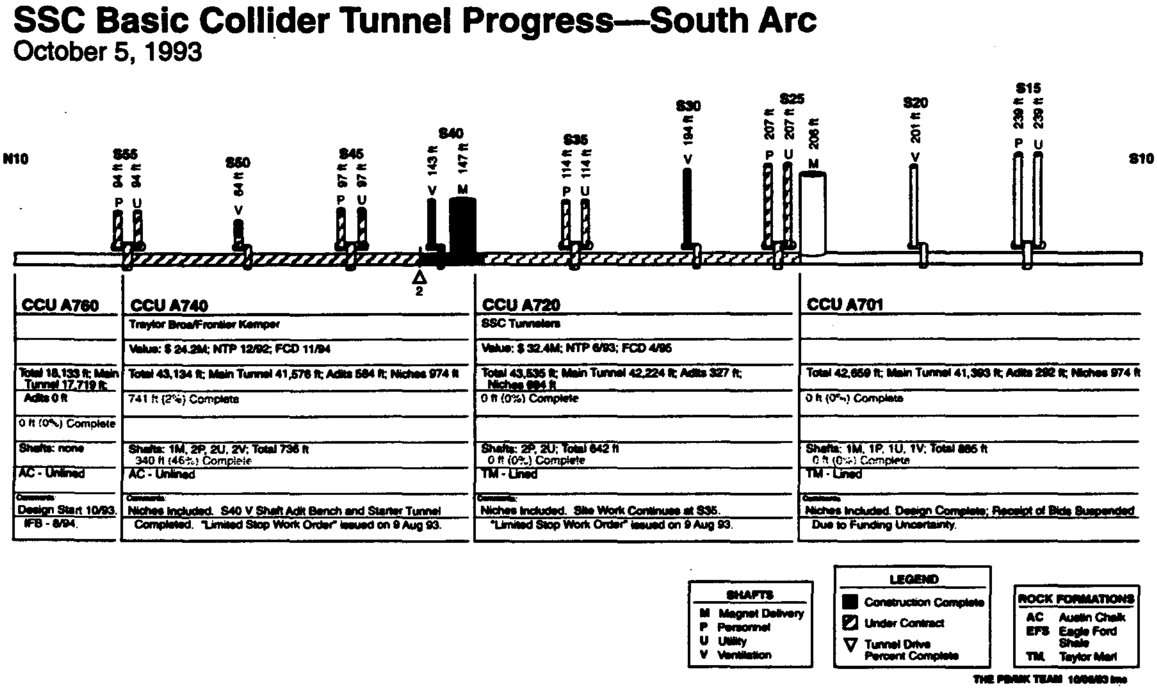

Figure 24-3. South Arc of the Collider.

East Cluster

The East Cluster extended approximately 6.5 miles, from N55 on the North Arc to S15 on the South Arc, and included, on the North, the beam crossing points at IR8 and IR5 and, on the South, the East Utility Straight Section. The basic tunnel excavation for the utility straight section was the same as for an arc tunnel and was included in CCU #701, S25-S10 basic, whose design was complete through issuance of an IFB, which was canceled at termination of the project. The tunnel finish for the utility straight section was included in CCU #A703, S25-S10 finish, whose design was at the Title I level. The basic tunnel through the IR regions was contained in CCU #702, S10-N55 basic. This design was completed through Title II and archived. The tunnel finish for the IR region was contained in CCU #A704, S10-N55 finish, whose design was never initiated.

West Cluster

The West Cluster extended approximately 6.5 miles from S55 on the South Arc to N15 on the North Arc. It included, on the South, the beam crossing points at IR4 and IR1 and, on the North, the West Utility Straight Section. The West Utility Straight Section was the most complicated underground structure in the project, involving crossing injection tunnels from the HEB in the vertical plane, intersecting tunnels for the North and South beam absorber channels in the horizontal plane, enlargements for the radio-frequency (RF) cavities and wave-guides, and various specialized shafts and galleries. Although the South portion of the Cluster was in competent Austin Chalk, the complicated West Utility Region was in weak Eagle Ford Shale requiring careful excavation and substantial support. Excavation for the basic tunnel through the IR region, which had been contained in CCU #A760, was to be combined with CCU #A780, West Utility Straight Section basic, to take advantage of the longer, potentially more cost-effective tunnel drive, if the contractor had the option of driving a uniform cross-section tunnel from N15 through this region. The Design Requirements Document for the West Cluster was completed, but the design did not proceed beyond that stage.

Experimental Areas

Design Activities

<u>Requirements and Limitations</u>

Because the collision halls were a major element in defining the construction program for the facility, it was necessary to scope the configuration and potential size of the halls even in the absence of a defined experimental program. It was also necessary to understand the potential limitations on the size of the halls, and therefore on the size of the detectors, imposed by geotechnical considerations. To explore the potential range of spatial requirements for the collision halls, a generic study[69] was conducted using model detectors from the Berkeley summer study of 1987.[70] In addition, a Workshop on Detector Hall Limitations[71] was held at the CDG, including geotechnical experts, experienced detector builders, heavy rigging experts, radiation physicists, and experienced experimental facilities engineers from U.S. and foreign high energy physics laboratories. The result of these studies was that the largest detectors being contemplated were marginally within the limits of underground space feasibility, which was seen to be 25 to 30 meters. Except for the smallest detectors, the addition of an off-line assembly area for the detector, i.e., a "garage", was ruled out by the inability to span the width that would be required.

<u>Optimization of Underground Space by Modeling</u>

In the absence of an off-line beam level assembly space, the detector hall had to provide space not only for the operating detector, but also for initial construction of the detector and for maintenance activities. Excavation of underground caverns was expensive relative to surface construction, and the span of the detector hall was limited, as noted above. To provide the required space for all these operations it was necessary to study in detail the operations involved. For this purpose a process was developed, making use of advanced, 3-dimensional CAD/E modeling techniques and project scheduling software, to explore dynamically the steps involved in construction, installation, and servicing of the detectors. To minimize the costs and optimize the schedule, it was necessary also to model trade-offs between early assembly of larger modules on the surface and the cost and difficulties involved in inserting the larger modules into the underground space and handling them in the assembly process, e.g., size of shafts, capacity of installed cranes, load-bearing capability of foundations. Following selection of the Texas site, which narrowed the range of potential depths and excavation procedures, a Site-Specific Study[72] was carried out for the facilities for four generic detector designs using these modeling techniques. Subsequently, the techniques were applied to develop the facilities for the two selected detectors, SDC and GEM.

<u>*Development of Construction Techniques*</u>

The first underground construction on the site was an Exploratory Shaft (CCU #E101) near IR1 to examine the in situ properties of the Eagle Ford Shale. The data from these studies contributed to the decision to move the major detectors to the East Complex where they would be founded in Austin Chalk, while the walls of the underground enclosures would be composed largely of Taylor Marl, a soft rock with undesirable expansive properties. From a cost viewpoint, the preferred construction approach for this material was to reinforce the marl by embedding rock anchors in the side walls, a technique used in Europe but for which there is little experience in the U.S. construction industry. A contract was, therefore, initiated at the instigation of UTAP for field tests on the techniques for installing the anchors and on the strength of the bonds achieved between the anchors and the the marl. It was found that, when the boring for placement of the anchors was carried out using tri-cone bits, adequate bond strength could be achieved to support the walls of the enclosure. These results were incorporated into the specifications for the large enclosures on the East Complex.

West IRs

Until the termination of the project, no decisions had been made about experiments for the small West experimental areas, IR4 and IR1, so they remain undefined except for their locations, which were determined by crossing points of the Collider lattice. They were also defined as reference locations for Master Planning purposes, especially for the Safdie Associates campus plan. The cooling ponds to supply heat rejection for these facilities were an integral element of the Campus plan presented by Safdie. There is no documentation for the conventional facilities for these IRs beyond what is found in the SCDR and confirmed in the Site Planning document.

East IRs

<u>*Underground Construction*</u>

Initially, the two large detectors were sited on the West Complex to facilitate communication among experimenters, accelerator staff, and support personnel by focusing the population into the same geographic region. When the geotechnical exploration program indicated that the base of the collision halls would lie in the Eagle Ford Shale, a detailed, time-phased design study[73] was carried out that included considerations of the required stability of the foundations during assembly and operation. In light of these studies and the perceived properties of the Eagle Ford Shale, a decision was made to move the large detectors to IR5 and IR8 on the East Complex. At these locations the detectors would be supported on the Austin Chalk underlying the Taylor Marl, which would form the walls of the enclosures. The GEM detector was sited at IR5, on the South, while the SDC detector was sited at IR8 on the North.

Construction of the underground halls was divided into basic and finish packages, similar to the tunnel construction; the basic packages are CCU #E305, IR8 underground shell, and CCU #E405, IR5 underground shell. The finish packages are CCU #E306, IR8 underground finish, and CCU #E406, IR5 underground finish. The shells were under contract and some site grading had been accomplished at termination. The Title I designs for both finish packages were complete. These experimental areas required extensive infrastructure, as described below, and extensive site preparation and wetlands mitigation. The site preparation for the East IRs (CCU #S445) was completed. However, the wetlands mitigation required by these activities was to be provided in CCU #S499, which was not put under contract before termination of the project.

IR-5

Following the decision to move the major detectors to the East Complex to avoid the Eagle Ford Shale on the West, the GEM detector was assigned to IR5, the southernmost of the collision points on the East Complex. The GEM detector anticipated major assemblies on the surface, including fabrication of a very large air core superconducting magnet, which would be constructed as two half-length solenoids. The design of the collision hall was thereby constrained by a requirement for a very large shaft to accommodate insertion of the half-magnet. The contemplated assembly procedure in the hall precluded both half-magnets being inserted through the same shaft, so that a second very large insertion shaft was required in the design.

The assembly procedure and schedule selected by the GEM group led to an early requirement for two very large assembly buildings on the surface adjacent to the Collision hall with later requirements for a number of ancillary buildings. The design packages for the two assembly buildings, CCU #E408 North and South Assembly Buildings, were complete and had been shelved awaiting funding. A number of the ancillary buildings were combined into the underground finish package, CCU #E406. A preliminary DRD was in hand for the CCU #E419 IR5 Gas Mixing Building.

IR8

Assembly of the SDC detector, as determined by extensive modeling exercises,[57] was to take place mostly underground in the collision hall, and as a result extensive assembly space was not required on the surface. A surface Assembly Building, CCU #308, was under construction at the time of termination with the massive floor slab poured and the supporting steel partially erected. A number of the ancillary buildings were packaged into CCUs #E312, #E313, #E315, and #E319. A final DRD was in hand for #E313, with only preliminary DRDs for the rest.

Infrastructure

The project infrastructure consists of the roads, electrical distribution, natural gas, communications, water, and waste water to within 5 ft of the wall of a building. Responsibility for providing the infrastructure is assigned, in general terms, in the Invitation for Site Proposals; the state is to provide the infrastructure up to a delivery point on the site, and DOE is responsible for distribution within the site. This simple assignment of roles was complicated by the configuration of the SSC into many separate sites, many miles apart, with only a connection through the tunnel under the jurisdiction and control of the project. Roads used by the project in all phases of construction and operation would be primarily public roads, and public access along project roads crossing the East and West Complexes would be required for access to existing housing developments as well as transit along major regional routes. By law, state and county funds cannot be spent on land not owned by the state or county, nor can federal funds be spent on land not owned by the federal government. Thus state and county roads crossing land owned by the Laboratory in fee simple presented a conundrum: mutually acceptable arrangements for upgrade, maintenance, and jurisdiction would be required. Potential water supplies and sewage facilities to support the Laboratory involved regional and municipal jurisdictions. The design for the electrical supply and distribution involved several zones singly-certificated by the Texas Public Utilities Commission (PUC) for individual service providers. To facilitate and coordinate the planning, permitting, design, and construction of these facilities, an Infrastructure Steering Committee was established to represent DOE, SSCL, and TNRLC.

Design Activities

In the absence of an overarching liaison group like the Infrastructure Steering Committee, the SCDR, as an internal Laboratory document, could only specify the infrastructure routing and connections in a general way The generalized requirements became the basis for the Steering Committee's development of a coherent plan for the infrastructure based on the existing regional infrastructure and the Laboratory's design requirements and implementation schedules. The Committee, while developing the plans for the project infrastructure, kept in view the possibility of enhancing the regional infrastructure with mutual benefit to the project and the host region. In this spirit the Committee facilitated a number of regional planning documents that provided the framework for the detailed designs for the infrastructure. The documents included an integrated master transportation plan,[74] a general study of the water supply for the SSC,[75] a water and wastewater feasibility study,[76] and a water transmission study for the West Complex.[77] The TNRLC assumed primary responsibility for these regional studies. The Steering Committee facilitated several studies[78] relative to connection of the SSC to the regional grid, and the impact of the SSC operations on the grid. The Laboratory assumed primary responsibility for these studies, which depended intimately upon the detailed designs and operating characteristics of the facility.

Roads

<u>*Off-site Roads*</u>

Acting under the Integrated Master Transportation Plan, the State of Texas Transportation Commission committed the state, through the Texas Department of Transportation (TxDOT), to make roadway improvements to 30 miles of designated state roadways[79] at a cost of $21.56 million. The improvements, illustrated in the TNRLC Integrated Master Plan drawing,[80] included two categories of access routes for construction and three categories of roads for use during operation of the facility. The categories were matched to the projected operational loads and traffic volumes.

The heaviest duty roads—Primary Industrial Routes—provided North-South access to and within the site along Interstate 35, and East-West access along US287, with a connection to Interstate 45 on the East and access to the West Complex along FM66 on the West. Essentially this involved upgrading the other roads to Interstate highway standards. None of this work had been accomplished at time of termination.

A second category of heavy-duty roads—Heavy Vehicle Routes—was designed to handle the very long dipole magnets. The network of Heavy Vehicle Roads was related the relocation of the Magnet Delivery Shafts to take advantage of existing roads as far as possible. Service to the magnet shaft at N40 on the North Arc was to be along a short length of FM77 from its junction with I35 in Red Oak, while the two permanent shafts at N15 on the West and N55 on the East were to be serviced by FM1446 from I35 and FM878 from US287, respectively. The two magnet shafts on the South Arc, at S40 and S25, were to be serviced from US34 along FM55 and Bozek Lane, respectively. To accommodate this usage, US34 was to be upgraded from I35 on the West to Ennis on the East with a new bypass around Italy. Approximately 5 miles of FM1446, from I35 to the industrial area at N15 on the West Complex, was upgraded in this phase of the program.

TxDOT completed permitting and construction of access roads to all the Service Areas and to the active sites on the West and East Complexes from TxDOT system roads. An additional 22.5 miles of County roadways were to be improved by Ellis County under the Integrated Transportation Plan at a program cost of $7.3 million.[81] A fraction of this County road upgrade had been accomplished either as the project shut down.

On-site Roads

In addition to improvements to off-site roads, the state and county were committed under the Integrated Transportation Plan to upgrade existing state and county roads crossing the site in public rights-of-way. Approximately half of the 5 miles of improvements to FM1446 noted above was actually on-site in the public right of way across the north end of the West Complex.

The Laboratory was responsible for constructing some 35 miles of on-site project roads. These Laboratory roads included access roads at the Collider Service Areas and new heavy vehicle routes on the East and West Complexes to connect to the state road network and to interconnect the major Laboratory facilities. Twenty-eight of the 35 miles of on-site roads were constructed by the Laboratory. Most of them were the access roads for the Service Areas to provide construction access for the basic tunnel contracts. The design and construction of these Service Area roads was included in the CCUs for the related basic tunnel packages, but the final surfacing of roads was to be included in the CCUs for the tunnel finish packages. In addition to the Service Area roads, a Perimeter Road was constructed on the West Complex around the N15 industrial area connecting to New Arrowhead Road at FM1446 on the south and Hoyt Road on the east (CCU S281), while 3/4 mile of Hoyt Road was rebuilt to complete the loop around the N15 site (S270). Approximately 3 miles of heavy industrial road, New Arrowhead Road, was constructed from FM1446 south to FM1493 (CCUs S271, S346). New Bearden Road (Industrial Road) was constructed from FM66 a point north of Greathouse Road, approximately 1.5 miles (CCU S348). On the East Complex the East Connector Road from FM878 south to IR5, approximately 2 miles, was completed (CCU #S445). The design was completed, but never implemented, for an additional 0.5 miles to the south along this alignment (CCU #446) to connect to a future TxDOT alignment from FM879.

More than 11 miles of county roads that would be within the Laboratory area, primarily on the East and West Complexes, were to be abandoned. Many of them were already abandoned as the project ended leaving no completed North-South or East-West connection in the West Complex in the absence of a southerly East-West connector road between New Bearden and New Arrowhead Roads. The design of the South Loop Road was completed, but shelved (CCU #S349). Figure 24-4 illustrates the status of the roadways on the West Complex at termination.

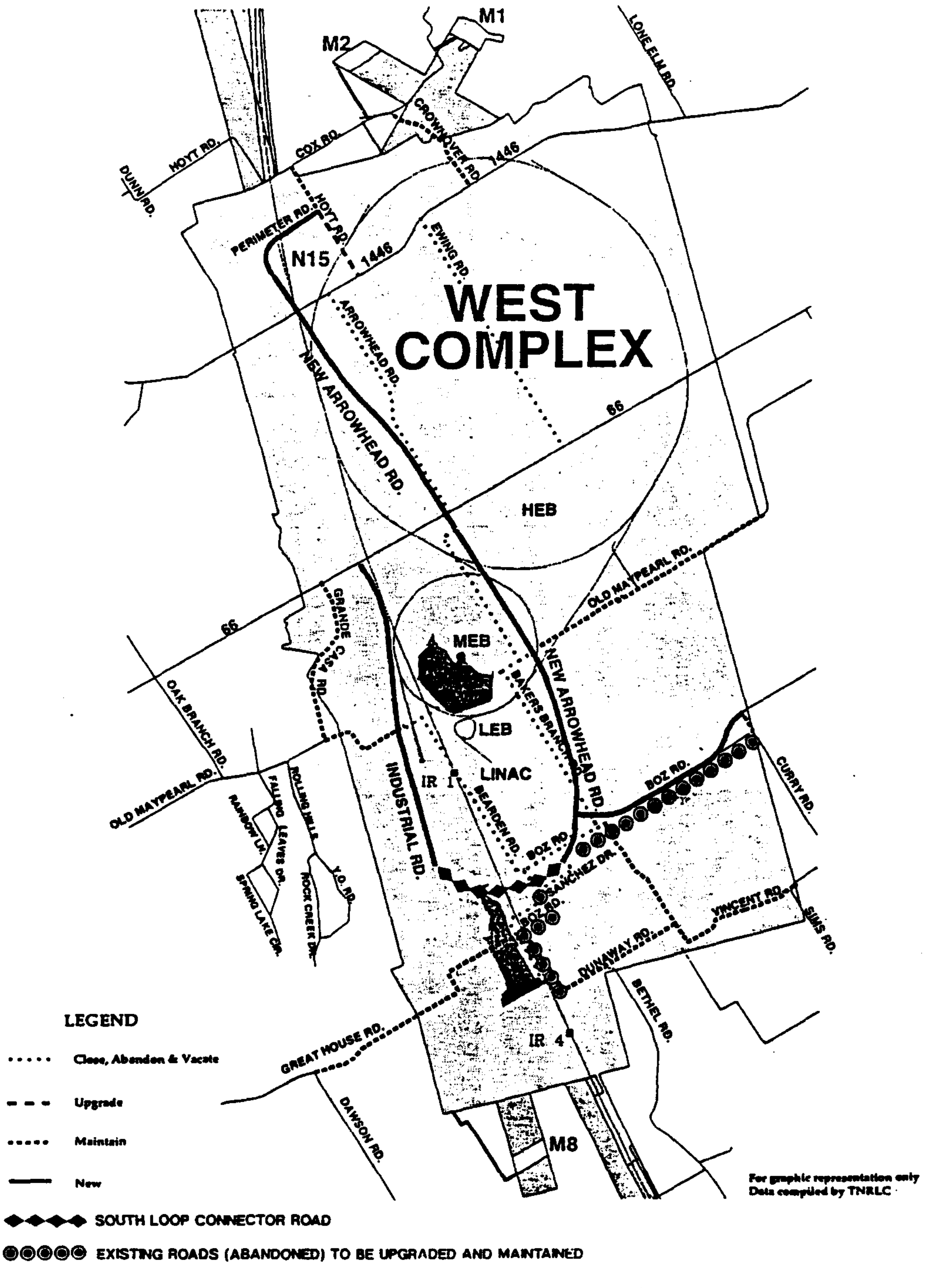

Figure 24-4. Roadways on the West Complex.

Electrical

A major element of the infrastructure for the project was the electrical power, because the SSC is primarily a very large electrical device vitally dependent on the capacity, reliability, and quality of the regional electrical grid. The electrical power supply for the facility involves connection from the primary distribution grid to the site, transformation of the primary voltage to appropriate voltages for distribution within the facility, and transformation of the distribution voltages to end-use levels. Under the terms of the ISP, affirmed in the Texas proposal, the state was to secure necessary rights-of-way and construct the transmission lines from the grid to the site at no cost to the project. Two independent connections were required to ensure power to the base load at all times for reliability and economic reasons. Design and construction of the Master Substations, as well as distribution within the project, was the responsibility of the SSC Laboratory. The procurement of the supply of energy to be delivered to the facility is intimately related to the electrical infrastructure because the grid connections are usually owned by a regional supplier. The Infrastructure Steering Committee facilitated several studies of configurations of grid connections, Main Substations, and distribution voltage levels. Complicating these studies were the pre-existing exclusive service zones on the territory of the site under Texas Public Utilities law. The studies were reviewed in depth by independent review panels[82] and reflected in the design of the system.[83]

As noted above, ownership of the grid connections and procurement of the energy supply are intimately connected. Responsibility for procurement of the electrical energy supply lies with DOE Headquarters. The DOE Project Office chose, with the acquiescence of the Laboratory, to assume from the state responsibility for the grid connections and from the Laboratory responsibility for procurement of the detailed design and construction of the Main Substations and electrical distribution to assemble a single, very large procurement package, including both the energy supply and the design and construction of the distribution systems. This arrangement could potentially avoid complications from the singly-certificated suppliers and transfer distribution costs to the rate structure. After award of the contract by DOE, responsibility for oversight of the design and construction aspects of the procurement was to be assigned back to SSCL.

A Request for Proposals, including specifications for the transmission[84] system, the distribution system,[85] and the 69 kV cable,[86] was completed and awaiting approval from DOE Headquarters at the time of termination of the project. The specification required a 345 kV grid connection at the East and West Master Substations, with 69 kV distribution around the ring within the Collider tunnel. The specification for the SCADA system for the distribution was consistent with the overall site SCADA and EMCS systems.

Natural Gas

Natural gas was specified as the preferred medium for heating the Laboratory facilities because of its economic and environmental advantages. Studies indicated that these benefits could be realized for the concentrated facilities in the East and West Complexes. However, in the case of the Service Area facilities, the low potential usage coupled with the high cost of piping from existing transmission lines in the vicinity of the site made natural gas an uneconomic choice.

Responsibility for procurement of the supply of natural gas lay with DOE Headquarters. Under the terms of the ISP, responsibility lay with the state to provide a delivery point on the West Complex and another on the East Complex. Beyond the delivery points the project was responsible for design and construction of the distribution to the end-use points. From the delivery point in the West Complex, at FM66 and New Arrowhead Road, the gas would be piped to the N15 area, to the Campus area, and to the Experimental Areas at IR1 and IR4. The East Complex delivery point, at FM878 and the East Connector Road, would serve only the Experimental Areas at IR5 and IR8 and any related support buildings.

The DOE Project Office assumed responsibility from the state for procuring the delivery points and from the Laboratory for distribution in order to bundle the cost of the distribution into the rate charges, in a manner similar to the electrical system procurement. Protracted, and ultimately unsuccessful, discussions of this approach within DOE forced substitution of propane for natural gas in the initial buildings on the site. Ultimately the approach was rejected by DOE Headquarters, and no solicitation for the gas supply was issued prior to termination of the project.

Communications

Communications within the scope of Infrastructure includes all the media and routing for transporting signals throughout the SSC facility and between the facility and external nodes. The Infrastructure Steering Committee was concerned with communications only for providing easements along public rights-of-way for connections to the commercial telecommunications network, and for connecting between sites, primarily from the experimental complex on the East across the ring to the Control Center on the West Complex, if required. Possible interferences with other infrastructure systems in the same utility corridors were also a concern of the Committee.

The principal functional elements involved in communications are accelerator control and monitoring, accelerator security and safety, experimental systems monitoring and control, experimental and theoretical data acquisition and transmission, facility monitoring and control, environmental monitoring, emergency services, site safety and security, telecommunications, technical information systems (CAD/E, etc.), and administrative information systems. The magnitude and diversity of this client base and the dramatically changing nature of the communications environment, especially when viewed in light of a 10-year construction schedule for the facility, led to identification of a highly-qualified minority firm to characterize and analyze the requirements for the individual systems with a view to coordinating and synthesizing the requirements into a comprehensive plan that would minimize cost and take advantage of evolving developments as the project unfolded.[87] This initiative lapsed in the absence of an understanding of the breadth of developing concepts of convergence in communications media and a consequent lack of clarity in responsibility for communications.

Planning for communications media was also complicated by the absence of an approved master plan for the project locating the major communications nodes, like the campus and technical support facilities. The major routings for monitoring and control within each accelerator were determined by the distribution of facilities. Thus the main trunks within the Collider tunnel would connect the Service Areas along the arcs to one another and to the East and West Complexes, and similar connections around the circumference would be required for the individual Injectors. Under the pressure of the construction schedule, general guidance for interconnecting the Injectors, the Collider, the Experimental Areas, and the Campus and for locating communications corridors was derived from the existing draft master plans. The sharing of media between systems, the amount and mix of media, the impact of developing digital communications technologies, and the revolution in network technologies were not resolved, with the result that the amount and detailed routing of the ductwork within the corridors was not resolved either.

A communications working group collated requests from potential users for communications ducts along the East and West Complexes; in the absence of realistic budget constraints, it was not possible to obtain an accounting of the number and functions of media to be installed in the ducts, nor could the potential for sharing media be exploited.[88,89] The placement of the major detectors on the East Complex with Detector Operations adjacent to Accelerator Operations at the Operations Center on the West Campus dictated a requirement for major fast communication links from east to west. A right of way for a 15-mile direct cross-ring link along the east-west transportation corridor was requested from the state to accommodate these links[90]. Acquisition was deferred pending better definition of costs, schedule, and operational implications of an alternative 25-mile routing through the Collider tunnel.

In parallel with the activities of the communications working group, and largely motivating the group, ad hoc communications decisions were incorporated into the design and construction of technical facilities. They included a site-wide SCADA system for control and monitoring of the mechanical and electrical systems and, the building environments for conventional facilities, provision for routing of communications in the Collider tunnel, and communications ducts for the Injectors.

Site-Wide Supervisory Control and Data Acquisition (SCADA) System

Incorporation of a site-wide SCADA and Energy Monitoring and Control System (EMCS) requires that the design concepts for the system be decided as part of the design process for the earliest buildings and structures. To this end a study was commissioned to examine feasible options and recommend a preferred one. To ensure compatibility across systems, the study involved all the Laboratory constituencies concerned with monitoring and control. The study recommended a PC-based, Token-Ring system as the most cost-effective solution.[91] The findings of the study were incorporated into a specification for procurement of such systems.[92] The design of the BAS/EMCS/SCADA system[93] (CCU P903) based on this specification was complete at the time of termination.

Communication Links in the Collider Tunnel

Two classes of communication links were required in the Collider. The first class was local communications, gathering and transmitting information to and from the Sector Service Area at the midpoint of the 5.4 mile long sector. The second class was trunk communications between Service Areas and from Service Areas to the Operations Center, or to the Main Substation in the case of electrical distribution relaying. The wide bandwidth, minimal attenuation, and immunity to electomagnetic interference of optical fibers make them the medium of choice for such applications. Local communications would utilize both copper and optical fibers depending on the signals to be transmitted. The available data on radiation damage to optical fiber over the 25-year projected life of the facility using the nominal operating cycle of the Collider indicated that the attenuation of the fiber would be marginally unacceptable at the end of that time. On this basis a tentative decision was made,[94] pending better data, to rout the cables through conduits embedded in the tunnel invert rather than in the less costly overhead cable tray. Besides the cost of installing the conduit, this placement requires frequent pull boxes in the floor of the tunnel, which increases construction and installation costs and complicates operations.

Primary Communication Node: The Operations Center

The design concept for the Laboratory was based on focusing all control, monitoring and data acquisition activities into a central Operations Center, including Accelerator, Detector, and Site Operations. The Campus was to be located near the Injectors, Test Beams, and West Experimental Areas, thereby consolidating the support activities for those facilities for better human interaction and reduced costs. A principal concern of the West Campus studies of Safdie Associates was to locate the Operations Center so that the communications infrastructure to support commissioning of the Linac, LEB, and MEB could be designed and constructed to meet the commissioning schedules for those facilities.[95] A general consensus emerged that the preferred location for the Campus was the Boz site, south of the South Loop Road between the Linac and IR1. The communications node servicing the Operations Center was sited on the west of the proposed cooling ponds anchoring the Campus. No further design was carried out implementing this tentative decision.

Water

The magnitude and distribution of water requirements, potable and non-potable, and of sewage capacity were specified in the SCDR, based on an assumed population of 3000 staff and visitors. Potable water would be required at all locations where personnel would be permanently located; raw water would be required for cooling systems and fire protection where practicable. Raw water would be required for heat rejection from the technical systems and fire protection at the Service Areas, but no potable water or sewerage.

Planning by the state for provision of water and sewerage was based on regional planning for Ellis County with a view to supplying the needs of the SSC while reducing the dependence of the neighboring municipalities on diminishing ground water supplies. Early planning was carried out through the Trinity River Authority whose major water conveyance lines cross the SSC site. Subsequent studies focusing on the general requirements of the SSCL were conducted in 1991 and 1992, as referenced above. The Espey, Huston report, reviewed by DOE and the SSCL, was the basis for planning for water and sanitary systems for all the Laboratory facilities.

Detailed design in anticipation of construction was initiated in 1992 for the State-funded, off-site water supply infrastructure for the West Complex. Design and construction of portions of the West Complex potable water supply were complete at the time of termination of the Project.[96,97,98] Also, detailed design was under way for the City of Ennis for the first phase of the East Complex Potable Water System.[99]

A regional plan for supplying raw water to the Project was developed by TNRLC with the cognizant suppliers[100] and approved by the Infrastructure Steering Committee. The plan included two taps on the TWCID #1 raw water supply main. The East tap, supplying water only to the project would be located at the East Complex near Wilson Road to supply raw water to S15, the East IRs, N55, and N45, approximately 12 miles of piping. The West tap, near N35, would be a regional water raw supply extending for approximately 10 miles to terminate at Lake Waxahachie and the existing Waxahachie Water Treatment Plant. Project supply taps from this line would supply N35, N25, N15, the entire West complex, and S55 and S45 on the South Arc, approximately 20 miles of piping. Raw water for S25 and S35 on the South Arc was to be supplied from Lake Bardwell, approximately 6 miles of piping. In July 1993 detailed design was initiated by the Trinity River Authority for the raw water distribution to the site from its pipelines.[101]

PART VI. ADMINISTRATION AND SUPPORT

Chapter 25. Directorate Activities

From the outset, the Director set two principal goals for the SSC Laboratory: to create a premiere high energy physics laboratory and to serve as a resource for science education. The centerpiece for the Laboratory was to have been the Collider itself, the world's most powerful particle accelerator. Much of the work of the Laboratory was directed toward the design and construction of the Collider and its associated technical systems, and the bulk of this report describes the state of the development of the accelerator. But as the design and construction project progressed, overall responsibility for pursuit of the more general goals stated above was carried out by a Laboratory Directorate.

For organizational purposes, a number of functions were incorporated in the Laboratory Directorate. They included: education programs; technology transfer; international coordination; environment, a users office; external affairs; safety and health oversight; planning, and legal counsel.

Education Programs

(T. Gadsden)

The Superconducting Super Collider had two principal goals—to create the world's premier high energy physics laboratory and to serve as a resource for science and mathematics education. Although the bulk of its effort was devoted to the first of these goals, an active and influential education program was under way at the SSC Laboratory from 1989–1993. The program spanned a broad range involving students and teachers at levels from pre-school through university graduate studies, as well as the general public.

One of the major areas of emphasis was the development and implementation of teacher enhancement activities, particularly those involving precollege teachers. The SSC Laboratory participated with other DOE laboratories in the DOE Teacher Research Associates Program; teachers were assigned to spend summers working with scientists and engineers on research projects and attending seminars that helped in developing instructional ideas that would carry their experience at the Laboratory over to the classroom. The Laboratory supported school district and state staff development activities through in-service and pre-service workshops. Twenty-five workshops were held in eleven states, each tailored to meet teachers' needs to learn effective teaching strategies and to update their knowledge of science and mathematics concepts. Three of the workshops were part of a State Systemic Initiative funded by the National Science Foundation. The Laboratory conducted a Summer Institute for high school physics and physical sciences teachers, funded by the Federal Coordinating Council on Science, Engineering, and Technology. Twenty-eight teachers attended the four-week program conducted by four master teachers and highlighted by lectures with research scientists and hands-on experimental activities.

Much of the Laboratory's education program was devoted to development of a variety of instructional materials and resources to enhance the teaching and learning of science, mathematics, engineering, and technology. The Adopt-A-Magnet Program comprised a series of inquiry-based elementary materials designed to introduce students from pre-kindergarten through ninth grade to the concepts of magnetism, atomic structure, forces, superconductivity, and other areas of science related to the SSC. Interdisciplinary materials were designed for two-to-four-week periods of classroom instruction. The program's name derived from the notion that, after completion of the instruction program, a school could "adopt" one of the SSC's ten thousand superconducting magnets. Two pilot programs that included in-service workshops for teachers and classroom instruction for students were held; in the first, 115 teachers from 13 schools in 2 states attended workshops, and 46 teachers and 12 schools participated in the instruction program; in the second, 181 teachers from 25 schools in 8 states attended workshops, and 20 schools participated in the instructional program. A Background Radiation Monitoring Program was established that allowed students and teachers to gather data and participate in the Laboratory's regular radiation monitoring activity. A Resource Center was set up to allow teachers from kindergarten through high school to access a collection of classroom equipment for demonstrations and teacher training. The SSC Technical Training Project provided technical assistance to Navarro College and Dallas Community College Districts to develop a curriculum for training technicians in SSC-related technologies. An SSC Technology Project provided technical assistance to the University of Houston at Clear Lake to develop a manual for training college teachers and to produce two distance learning broadcasts. In addition, the Laboratory collaborated with outside groups on three activities designed to develop instructional materials. The Laboratory also had a Cooperative Research and Development Agreement with Threshold Communications, Inc., to develop interactive science education materials for elementary, middle, and high school students, and for general audiences using the "compact disc" medium. Laboratory staff served on the board of the National Super Collider Consortium, a private foundation involved in developing hands-on instructional materials for grades K through 5. The Laboratory also worked with the Contemporary Physics Education Project to develop and distribute instructional materials and software on particle physics at the high school level.

The SSC Laboratory programs offered students opportunities in four areas: participation in research, classroom presentations and field trips, tutorial assistance, and special events. The SSC Internship Program offered eight-to-twelve week summer research assignments to high school and college students. The SSC Co-Op Program consisted of alternating school and work schedules for university and college students. In addition, the Laboratory participated in the Graduate Education for Minorities (GEM) Program for minority engineering students enrolled in their junior and senior years. The GEM consortium, using participating employers' fees, provided financial support to the students for graduate studies and for positions at the SSC during summers. The Minority Opportunities in Science and Technology (MOST) Program offered a multi-year commitment of employment at the Laboratory, support seminars, and tutorial assistance to promising, but economically disadvantaged, high school students recommended by school personnel and community groups. The Don A. Edwards Doctoral Program in Accelerator Science was established to permit students to work at the SSC Laboratory on doctoral dissertation research.

Over a four-year period, 585 students from 95 colleges and universities in 22 states participated in the various student research programs at the SSC Laboratory. A group of SSC staff volunteers visited area schools to give classroom presentations on the SSC and its science. A special Minority Schools Program focused on coordinated presentations given to students at various levels from kindergarten to college. In all, more than 40,000 pre-college students and more than 3400 college and university students attended presentations by SSC Laboratory staff members. A number of special events for students were held in association with the SSC. The Laboratory collaborated with the Boy Scouts of America to host a High Technology Seminar Day for Explorer Scouts in March 1990. In 1992 and 1993, the Laboratory provided a day of presentations and tours for participants in the Prairie View Summer Science Academy, a program designed to introduce minority high school and college students to possible careers in physics research. For four years, a Super Saturday Program was held under the sponsorship of the O'Donnell Foundation to provide site tours, technical seminars, and hands-on science activities to interested Ellis County high school students. The SSC Laboratory participated with other DOE laboratories in the DOE Science Bowl, hosting the regional science bowl and sponsoring the winning team in the first two national competitions. The Laboratory was also involved in a distance learning program about the Super Collider that was made available to more than one-million students in March 1993. An Accelerator Technology Course was presented by SSC Laboratory staff members at Southern Methodist University, the University of Texas at Arlington, and the SSC Laboratory.

Technology Transfer

(R. Kasper)

The successful design, development, and construction of the SSC required numerous important advances in technology that could have major impacts outside the SSC. In many cases, the specifications for technical systems and their incorporation in the production of components for the SSC required advances in the industrial state-of-the-art; and those advances have been, or will be, applied to new and future processes or products, or to improvements in current processes or products.

Among the areas in which the Super Collider had significant impact in technology transfer were high precision superconducting magnets, superconducting wire and cable, radiation resistant plastics, parallel computing, image processing, high speed electronics, tunnel boring machines, and pulsed power systems. In addition, before shutdown, the SSC Laboratory had been planning, in conjunction with the University of Texas Southwestern Medical Center, a proton cancer therapy and research center using beams of protons from the SSC's linear accelerator.

Manufacturing technology had been developed at the SSC for producing high precision superconducting magnets with high reliability and performance. Developments in this area would have clear implications for manufacturers of magnetic resonance imaging equipment as well as for potentially new uses of superconducting magnets, such as superconducting magnetic energy storage. Improvements in manufacturing technology and increases in demand, and thus in amounts manufactured, resulted in substantial reductions in the cost of superconducting wire and cable. These efforts will result in reductions in the cost of other equipment that uses such wire and cable, such as magnetic resonance imaging equipment, and will encourage broader applications of the technology. One or both of these state-of-the-art advances has potential application for superconducting electric motors and generators, low-loss electric power transmission systems, magnetically propelled ships, and high speed magnetically levitated trains.

A new treatment was developed that allows the production of radiation resistant plastics that are not susceptible to the yellowing, discoloration, and brittleness that often result when plastics are exposed to bombardment by high energy particles. A potentially significant application of the treatment exists in the area of sterilization of plastic materials used in medicine. Plastics can now be sterilized using radiation in a manner that is more effective, environmentally safer, and less costly than conventional methods.

The need to simulate the results of high energy particle collisions for the purpose of designing particle detectors led to advances in parallel computing. Software and hardware architectures were developed that permit the linking of more than 60 high powered workstations to provide more computing power than is available in supercomputers at a fraction of the cost. High speed image processing systems, developed for the purpose of analyzing the complex particle collisions at the SSC, have potential application in monitoring systems for high speed production lines. The associated high speed electronics will also find uses in numerous other applications.

World tunneling records were set and repeatedly broken during construction of the SSC tunnel. This was due, in part, to the favorable geology of the site, but could also be attributed to the design of new, innovative tunnel boring machines. The machines will have obvious application in other major tunneling projects, such as those for sewer systems or transportation networks.

More than 70 records of invention were filed by the SSC Laboratory and 11 patents were applied for. The first patent was awarded as the project closed down, and licensing opportunities arising from the inventions at the SSC were under study at the time. In addition, numerous other inventions resulted from SSC-funded activities at participating universities and companies in the United States and abroad. The Laboratory had signed one Cooperative Research and Development Agreement (CRADA), and two others were pending at the time of termination. A CRADA permits a government laboratory to work jointly with industry on research and development programs. It also protects intellectual property rights for up to five years.

International Coordination

(E. Duek)

The Office of International Coordination of the SSC Laboratory had as its main objectives the oversight of contacts with other countries who might participate in the construction, operation, and scientific research program of the SSC. The Office was charged with initiating, structuring, supporting, and coordinating technical meetings at the institutional level to discuss areas of participation by foreign scientific entities. The Office also participated in government-to-government negotiations with DOE concerning foreign participation. In addition to these activities, the Office drafted policy statements regarding participation by non-U.S. personnel and industry.

On the personnel front, the Laboratory was structured to accommodate citizens of other countries working under a variety of arrangements. In addition to foreign scientists working as regular employees at the Laboratory, there were visiting scientists participating in the SSC scientific program and guest collaborators and foreign personnel assisting in the construction program, all of them supported either by the Laboratory or by their home institutions. The numbers of such non-U.S. personnel grew steadily, and as of September 1993, they included 256 physicists and engineers from 38 countries.

The need for participation of members of the international industrial community in the construction of the SSC was recognized from the outset with the formation of the International Industrial Symposium on the SSC (IISSC). Although the organization was independent of the Laboratory, the SSC supported its goals and its intention of providing a forum and focus for international industrial involvement in the project. The Laboratory was subject to U.S. government procurement regulations, which provide for competitive bidding by qualified organizations from all countries. A significant number of contracts were awarded to non-U.S. organizations. An example of note is the development contract for the superconducting wire for the magnets for the Collider and the high-energy booster. The value of the wire could have reached several hundred million dollars; in any case, the technology involved in its fabrication will represent a significant advance over fabrication techniques current as the project closed. The new technology was under joint development by the Laboratory and seven selected contractors three of whom were foreign. As of project closing, the Laboratory had awarded contracts to 97 companies in 13 countries outside of the United States.

With respect to international agreements, the Office had major responsibility for the signing of 15 international Interlaboratory Agreements covering partner institutions in Russia, the People's Republic of China, and India. Attachments to these agreements, describing in detail SSC components to be made at foreign institutions, totaled more than $103M in SSC components (which in turn required compensation to the foreign laboratories of about $44M) at the time of SSC closure.

A good portion of several of the SSC injectors were to be produced abroad. Attachments to the agreement with the Institute of High Energy Physics in Beijing laid the foundation for Linac cavities to be produced there. Similarly, attachments signed with institutions in Russia led to the fabrication of the LEB dipoles and quadrupoles for the LEB (with the Budker Institute of Nuclear Physics, Novosibirsk) and for the dipoles and quadrupoles for the MEB (with the Moscow Radiotechnical Institute). All these activities came to a halt with the termination of the SSC.

Primary among the Office's activities were the coordination of SSCL participation in negotiations that DOE conducted with foreign governments. These activities resulted in the signing of two intergovernmental agreements between DOE and the Academy of Sciences of the Peoples Republic of China and with Russia's Ministry of Atomic Energy (MINATOM). Negotiations at the government level also took place with Japan, Korea, Canada, and Mexico.

The government-to-government agreements led to considerable roles for China and Russia in the SSC. The involvement by many institutions and scientists from Russia and China led the Office to organize, in May of 1992, jointly with the Chinese Academy of Sciences, an International Symposium in Beijing on SSC Physics, Technology, and Detectors. A follow up meeting was organized with the Joint Institute of Nuclear Research, and it was held in Dubna, Russia, in May of 1993. These meetings increased the regional visibility of the project and created wide support for it in the participating countries. Highly placed cabinet members of the foreign governments were present at the opening ceremonies of both meetings. As the SSC closed, a meeting was under discussion with colleagues in Italy.

By time of project termination, the government of Japan had halted all substantial negotiations while waiting for a renewal of the invitation to participate from President Clinton. Nevertheless, in the summer of 1992, even as the U.S. House of Representatives voted against continuing the SSC, the government of Japan decided to continue the Working Group meetings; indeed, one such meeting was held, as scheduled, at the end of July 1992. In 1993, when again the U.S. House voted against the project, the Japanese government stopped all working group meetings until the new U.S. Administration clarified its position on the SSC. And yet, at the time of termination, DOE was still involved in the planning of an informal meeting with the government of Japan to discuss ways to internationalize the project.

The Office participated in two Working Group meetings with the Republic of Korea. Several institutions of Korea joined the experimental collaborations, but their government's intentions to participate in the SSC never materialized. Negotiations at the working group level with Mexico never got effectively under way, but an exchange of letters between Secretary O'Leary and the Minister of Energy (SEMIP) in Mexico had cleared the way for the creation of such groups before the project ended. A DOE/SSCL visit to Mexico was hosted by SEMIP, and the Laboratory had every indication that Mexico intended to participate in the construction of the SSC.

Users Office

(P. Hale)

The SSC Users Office was established in August 1989 to provide liaison between the high energy physics community and Laboratory personnel, and to expand this interaction to the industrial community. The Office, staffed by four full-time employees, also provided various services such as typing, word processing, mail, and message handling to visiting physicists. It served as a focal point for physicists arriving at the Laboratory, issuing identification cards, and maintaining extensive records for the high energy physics community at large. The Office was also responsible for administrative and secretarial work for the SSC Users Organization of more than 5000 members, 2300 of whom, both foreign and domestic engineers and physicists, were directly involved with the Laboratory.

Organization and support of physics conferences and workshops comprised a major part of the workload for the Users Office staff. Over the life of the Laboratory, the Office supported 147 meetings with an accumulated attendance of about 12,500 people. Its initial assignment was the organization of the first large physics meeting to be held at the Dallas Hyatt, in October 1989. The meeting, devoted to *Supercollider Physics and Experiments*, served as an introduction for many scientists to the Dallas/Waxahachie areas and provided a forum for presenting plans of the newly-established SSC. Follow-up meetings were held in 1990 at Fort Worth and in 1991 at Corpus Christi. Planning and assistance was also given to the *XXVI International Conference on High Energy Physics* held in Dallas in 1992. There was continuous involvement at various levels with the *International Industrial Symposium on the SSC* (IISSC), including the publication of five volumes of proceedings. Two international meetings, *B Physics at Hadron Accelerators* and the *Lattice Field Theories,* were held in 1993 just before the project was terminated.

External Affairs

(R. Wylie)

An office of external and educational affairs was established at the Laboratory on September 1, 1989, with the appointment of a director. The purposes of the office were to establish relations with the national and international press and the Laboratory's neighboring communities, and to make the Laboratory a resource for science education in the United States. A manager of educational programs was appointed, and two full-time professionals joined the office to assist with the press and undertake programs with the community. A speakers' bureau was formed by the end of 1989. Coordinated by the External Affairs Office, volunteer Laboratory employees appeared before civic, business, and technical audiences. About 1000 engagements a year were scheduled.

A program of tours of the facility for the public was also organized, even though there was little for the public to see in the first two years of the Laboratory's life except for offices, computers, and a few pieces of scientific equipment. By the end of the project's second year, however, construction was well under way on the West Complex. Public tours were restricted in 1990 to Wednesdays to minimize disruptions to Laboratory operations. By the spring of 1993, the Wednesday tours had been reserved through 1995. Tours for visiting officials were scheduled as needed, usually numbering several per week. By the spring of 1993, an estimated 25,000 people had toured the Laboratory facilities.

To involve as many businesses as possible in the project, the External Affairs Office organized seminars on "How to Do Business with the Super Collider," a program carried out in cooperation with the Laboratory procurement staff. Held throughout the Dallas-Ft. Worth Metroplex and in many states, more than 50 seminars had been given by the spring of 1993, a fourth of which were presented to minority business organizations.

In the fall of 1989, the Office began a survey of educational programs provided by various national laboratories. The survey assessed existing programs, analyzed which ones should be duplicated at the Laboratory, and developed proposals for new departures. By the fall of 1990, the following programs were implemented: summer internships at the Laboratory for promising upper division high school and lower division college students; a work-study cooperative program with colleges and universities; and a kindergarten-through-12 grade curriculum enrichment project in particle physics. The magnitude of the educational program lead to a decision to establish a separate Office of Education in the spring of 1991.

Press interest in the Super Collider was extensive and intense. In a typical week, the External Affairs Office distributed at least two news releases and handled an estimated 25 press inquiries, ranging from lengthy interviews with Laboratory executives to brief telephone responses. Over the life of the Laboratory, editorial boards were held with nearly every major metropolitan newspaper in the nation, and two and three persons conferences were held each month. Major press events included a January 1992 press tour of the first shaft completed to tunnel depth. For other major events marking progress on the project, the office made use of video news releases that were distributed by satellite to television stations.

In 1992 and 1993, there was widespread press coverage of the key votes in Congress. At the Laboratory, the events were covered in person by the Texas bureaus of national publications, metroplex newspapers, television, and radio. Following each vote, the office would handle a dozen interviews at the Laboratory, including major Texas television outlets, and often as many as 60 telephone interviews from newspapers and radio stations throughout the United States, and from England, Germany, and Japan. Meanwhile there was a constant stream of communications between the Laboratory and the Washington bureaus of leading newspapers.

Chapter 26. Administration

*(R. Alguire, C. Dan, E. Erdmann,
C. Matteson, J. Richardson, S. Swindall)*

The Administration Division was divided into five departments: Finance, Minority Affairs, Personnel, Procurement, and Records Management. Although very different in function and structure, all were linked by the common thread of Total Quality Management (TQM) which enabled the Administration Division to function as a successful, cohesive, and customer-oriented unit. In September 1991, the Associate Director of Administration spearheaded a movement to introduce the Laboratory to the continuous improvement concept known as TQM . The effort began within the Administrative Services Division with the hope that demonstrated success in this division would lead to the spread of continuous improvement efforts throughout the rest of the Laboratory.

A subcontractor, Organizational Dynamics Incorporated (ODI), was selected to start the TQM process. ODI began by interviewing a selected sample of employees throughout the division and completing a major needs assessment. This was followed by extensive training of senior managers, supervisors, and staff throughout the division. Selected staff were trained in facilitator skills to aid process improvement teams in the use of tools to guide the team members through the process and to keep them focused on the issues at hand. From the beginning, division senior management exhibited a high level of commitment, buy-in, and leadership for the continuous improvement effort. A Quality Executive Council, made up of the Associate Director, Department Heads, and staff from various levels, was formed and met on a regular basis to support and guide the process. A mission statement, a statement of values, and a set of ground rules were developed followed later by a vision statement and a division logo.

As part of the quality process, each department developed a strategic plan that involved all employees within that department. The plans were reviewed on a regular basis to assure that everyone was taking the same general direction. Also, the sessions helped to develop ownership and motivation. All employees were encouraged to have frequent "customer visits" to determine whether needs were being met. The effort to keep the flow of communication open between customers and suppliers proved to be successful when used regularly. Employees were encouraged to serve on Quality Action Teams (QATs), Process Improvement Groups (PIGs), and larger informal and formal groups that crossed departmental and divisional lines. Measurement systems were put in place in several areas to monitor progress.

One critical issue involved finding adequate time to participate in the activities. Because the Laboratory was in a start-up mode, regular work demanded greater than 100% of the employee's time, and TQM was perceived as an additional layer of work and responsibility. Some middle-managers became a factor blocking implementation, but this level is critical because without such participation full implementation cannot take place. There are several reasons why change was resisted: empowering people, a major factor in TQM, implies loss of centralized control; change itself causes many to feel insecure; and implementation means extra work.

A program was developed for recognizing employees periodically for their participation in quality initiatives and continuous improvement. Plans were designed to incorporate into the Laboratory's performance appraisal system an evaluation of supervisors and managers concerning their quality efforts. Division all-hands meetings were held during each year to keep employees informed about progress. The overall results proved that employee involvement did, without exception, improve processes and, generally, lead to greater efficiencies in the work place. Examples included overall output of the Accounting Department in accounts payable, and travel accounting. In Personnel, improvement in the amount of cycle time to get an employee offer in place for a hiring manager, faster processing off-site training requests, and more efficient cycling of tuition aid requests were some of the accomplishments. In Procurement, overall cycle time and response time for various procurements, approvals, and timely hand-offs of work were improved.

There were several cross-divisional successes. In Linac Procurement, members from the Linac staff, Accelerator Systems Division, and Procurement met to identify "disconnects" in the process and "hand-off" problems. These were worked out, shortening the total process and improving considerably communications among the involved groups. Departments and divisions from all sectors of the Laboratory worked intensively together at a high level of quality; and with the commitment of many dedicated individuals, the String Test proved successful before its scheduled date. Through the efforts of a cross-divisional committee and subcommittees, a Project Management Control System (PMCS) was developed to track the cost and schedule variables of the SSCL. The outcome was an accurate and timely CPR monthly report, a single point of contact to track and monitor cost and schedule progress.

In the Summer of 1993, Secretary O'Leary introduced to the Department of Energy her plans for implementing continuous improvement programs within the Department and in all the DOE Laboratories. The Administrative Services Division and those who served on cross-divisional teams achieved milestones that would have contributed immensely to a head-start for a Laboratory-wide program at the SSCL.

Finance

Financial operations at the SSCL can be categorized into four phases, each corresponding to completed fiscal years:

Start-up	Fiscal Year 1990
Rapid Growth with Changing Requirements	Fiscal Year 1991
Improving Service through Quality Improvement	Fiscal Year 1992
Oracle Financials and New Overhead Initiative	Fiscal Year 1993

In each phase, the Finance Department successfully met the challenge of managing required financial operations in an environment where SSCL's growth and changes in management generated a constant need to modify financial procedures and systems.

Start-up—Fiscal Year 1990

In the beginning, the newly formed Finance Department commenced operations relying on a new and unfamiliar set of financial application packages. The SSCL chose DELTEK Integrated Financial Accounting Systems for Government Contractors because of the integration it provided among the critical modules of General Ledger, Project Cost, Procurement/Commitment, Budgeting, and Reporting. The SSCL purchased, configured, and installed DELTEK before October 1, 1989. The Chart of Accounts configuration met Finance's requirements and supported the initial needs of the Project Management Office.

Finance led the SSCL in developing the first year's institutional budget. Finance managed funds and controlled spending at each level of the Organizational Breakdown Structure (OBS). Finance established internal controls through signature authorization by OBS. The Financial

Planning, Control, and Analysis (FPCA) Group fulfilled regulatory requirements for funds control by reviewing all purchase requisitions before Procurement action. FPCA developed off-line spreadsheets to track commitments and costs against Budget and Reporting (B&R) line funding, thus ensuring that costs and commitments did not exceed B&R line amounts.

Finance commenced monthly financial reporting for the first fiscal month of FY90 by distributing a package of key reports to Laboratory and divisional management. The package contained the Job Summary Report (JSR), which related cost and commitments to budgets. It also displayed the amounts for outstanding purchase requisitions. The JSR financial information was organized in combinations of fund type and three levels of the OBS. The package also contained supporting reports itemizing labor hours by employee and other direct costs (ODC) at the transaction detail. Purchase order and purchase requisition detail reports were made available. Standard financial reports for the Department of Energy (DOE), such as the 533M, were also produced monthly. Actual Cost of Work Performed (ACWP) data for project reporting were provided each month according to Project Management Office specifications. The initial Financial Policies and Procedures Manual was also written and distributed during the first year.

Rapid Growth with Changing Requirements—Fiscal Year 1991

Expanded control, data tracking, and reporting requirements in late FY90 caused the SSCL to transfer report generation and selected data files from DELTEK to in-house data management and reporting systems. The new systems were based on Powerhouse which offered a low cost and fast-track method to satisfy some of the expanded requirements. Powerhouse could both read and write to DELTEK's file structure. The expanded requirements that generated the need for Powerhouse applications were: expansion of the charge code structure beyond DELTEK's capability; the new cost code structure that accommodated a four-level OBS, a 12-level Work Breakdown Structure (WBS) and multiple work packages for Fund, OBS, and WBS combinations; first-time requirement for collecting, allocating, and reporting indirect costs; modifications to the ACWP file to support a new Project Management cost processor; budget data and reporting requirements beyond DELTEK's capacity; procurement reporting requirements beyond DELTEK's capacity; and a flexibility to tailor reporting to the diverse needs of SSCL users.

During FY91, Finance played a major role in developing the SSCL Information Systems (IS) Strategic Business Plan. The Plan recommended that (1) all business systems reside on a modern relational data base management system, (2) a Laboratory-wide, experienced IS manager be hired, and (3) functional IS managers be established to develop rapidly or improve each organization's required applications.

Quality Improvement and Oracle Financials—Fiscal Year 1992

The Finance Department joined all Administrative Services Division employees in instituting TQM. All Finance personnel were trained in basic TQM principles; specific employees were selected to become TQM facilitators. Quality Action Teams were established that focused on the financial close cycle, subcontract planning and accounting (in conjunction with PMO), and improved basic order agreement processing and control (in conjunction with Procurement). Many smaller, less formal quality teams were established to improve communications and provide better financial service to the Laboratory.

The Project and the Laboratory, while maturing in some areas, still stressed the financial systems and procedures with the impact of additional changes for FY93. Some of those changes were: the WBS was re-sized into a product-oriented structure with seven levels, and a four-character function code was added as a WBS extension; product (machine) level reporting was now needed; budget/forecasting/reporting by WBS in addition to Fund/OBS was required; the developing cost and scheduling system required changes to the ACWP; and DOE changed the status of the SSCL to a fully integrated M&O Contractor which involved the electronic transfer of URA/SSC site accounting data to DOE's Financial Information System (FIS) in Chicago to allow the use of DOE's general ledger chart of accounts and format.

In addition, the bank through which Finance processed all travel payments closed its travel accounting function necessitating a search for a suitable replacement. Finance selected COVIA software, installed it, and retrained the Travel Accounting Services Section and Laboratory personnel. Finance, along with Procurement and with the guidance of IS, selected, purchased, and installed Oracle Financial Applications. The change was made in accordance with the IS Strategic Business Plan mandate that applications be based on a relational database. The change was also in response to requirements generated by (1) an environment of multiple computing platforms, (2) additional and complex reporting, (3) the size and performance limitations of DELTEK, and (4) the need to integrate the developing Project Management Control System (PMCS).

Oracle Implementation and New Overhead Initiative —Fiscal Year 1993

The SSCL Finance Department joined with DOE and other DOE laboratories during the last six months of FY92 to form the Overhead Initiative Working Group (OIWG). The purpose of the group was to redefine the DOE process for review and oversight of allocable costs, including common definitions and reporting formats. Finance incorporated much of the business practices and terminology from the OIWG in its own overhead accounting during FY93. In addition, Finance developed the system tools required to analyze and report costs for allocable activities. Concurrent with the implementation of Oracle and the new overhead structure, Finance developed and implemented a management control plan, developed and implemented a self-assessment program to assure compliance, and completed a rewrite of the Financial Policies and Procedures Manual covering all current financial operations.

Summary

Throughout the first four years, the SSCL Finance Department accommodated numerous audits performed by external regulators including the Office of Inspector General (OIG), DOE, and the General Accounting Office (GAO). The audits were successfully completed. None of the audit groups reported material weaknesses in the SSCL's financial systems of internal controls or questioned the accuracy of charged costs.

During this period, the SSCL Finance Department developed and maintained application systems such as DELTEK, JSRS, MAP, BFS, and Oracle to provide required budget, cost and commitment information on a monthly basis; first, by Fund/OBS for institutional funds control, and later by WBS/function/charge code as an interim solution to the delayed PMCS implementation. In addition, Finance participated in the Laboratory-wide review and modification of the Information Systems (IS) organization both to support on-going operations and to develop efficient long-term IS solutions.

From the beginning through current operations, Finance successfully controlled the use of DOE funds. It responded in a timely and professional manner to each new change in management requirements. Finance selected and maintained secure financial systems and furnished the SSCL with accurate financial, funding and cost/budget reporting. The Finance team of professionals took great pride in these accomplishments.

Minority Affairs

The Office of Minority Affairs was established in August 1989 to conduct critical monitoring activities and to implement compliance mechanisms in the socio-economic program areas of the SSC. The monitoring activities principally ensured the providing of equal opportunity for all persons employed or seeking employment with Government contractors or with contractors performing under federally funded or federally assisted construction contracts. The Office of Minority Affairs interacted directly with the SSC Personnel and Procurement Departments to ensure that efforts were made to comply with established goals set by SSC internal policies or mandated by federal legislative statutes. This office, since its inception, operated with one overall Director, one Equal Employment Opportunity (EEO) Manager, one Small and Disadvantaged Business Utilization (SADBU) Manager, and two administrative staff members.

To ensure a wide range of diversity in the SSC work force, the Office of Minority Affairs participated in an aggressive minority recruiting activity along with SSC Recruiting Staff. Over the last three years of the Project, the EEO Manager participated in approximately 150 recruiting events with major educational institutions including Historically Black Colleges and Universities (HBCU), minority professional organizations, and other minority associations. One of the elements of the outreach program was the Laboratory's participation in the National Consortium for Graduate Degrees for Minorities in Engineering and Science, Inc., program, which by the end of FY93, had grown to ten students with one third of them from HBCUs. The EEO Manager was also instrumental in developing training programs to ensure awareness of and compliance with all areas of equal employment opportunities.

In the same manner, the SADBU Manager along with the Minority Affairs Director—in coordination with the SSC Procurement Office and the Office of External Affairs—participated in an equally aggressive outreach activity. The department, over a three-year period, participated in more than 110 vendor seminar outreach events to ensure that small disadvantaged and women-owned businesses (WOB) would become aware of the many procurement opportunities available to them. These events were sponsored by congressional offices, chambers of commerce, and trade associations, as well as minority organizations. The achievements were impressive. With the exception of FY90, the Laboratory exceeded its small disadvantaged procurement goals in 1991 by 132%, in 1992 by 181% and in 1993 by 143% (see Table 26-1).

Table 26-1. Small Disadvantaged Businesses (Includes WOBs).

	1990	1991	1992	1993
Actual	$ 6,497,440	$34,321,946	$79,489,238	$ 71,624,279
Goal	18,971,100	25,963,100	44,036,500	50,168,300
Percent of Goal Achieved:				
	34.3 percent	132.2 percent	180.5 percent	142.8 percent

The SSC accomplishments were significant because the Laboratory was the only laboratory mandated by Federal Public Law to award at least 10% of its annual federal appropriations for the design, construction, and operation of the SSC to small disadvantaged and women-owned businesses. By the end of FY93, the SSC Laboratory had surpassed the 10% goal by $53 million, or 38% over the four-year period.

The participation of the Office of Minority Affairs in EEO and SADBU outreach events and significant accomplishments did not go unnoticed. As a result of the SSC's exceeding its 10% goal in FY91, the Secretary of Energy awarded a Special Recognition Award to the SSC Laboratory. Also, in FY93 the National Technical Association awarded the SSC Laboratory its National Affirmative Action Award for the Laboratory's contribution to promoting equal opportunity on a national basis. The two significant awards within a two-year period underscored the SSC management's commitment to equal opportunity without which the recognitions would not have been possible. Further proof of the effort was evident from the reviews conducted by external federal agencies charged with monitoring respective employment and procurement areas. The Office of Federal Contract Compliance Program (OFCCP) of the U.S. Department of Labor conducted two audits over a three-year period and concluded both reviews with no findings of discriminatory practices in the employment area. In addition, the Small Business Administration (SBA) charged with reviewing the SSC subcontracting plans also conducted two reviews over a three-year period. The SBA found the SSC subcontracting plan to be in compliance and issued a "Satisfactory" rating after the first review and an "Outstanding" rating after the second review.

The Office of Minority Affairs will remain proud to have played a significant part in the achievements of the SSC Laboratory in the socio-economic program and will remember with appreciation the support of the Laboratory's senior management and the cooperative efforts of the Personnel and Procurement Departments.

Personnel

The Personnel Department was formed in 1989 to provide the highest level of Human Resources expertise and service to the Laboratory community. The main goals of the Personnel Department from 1989 to 1993 were to: identify, attract, and hire quality scientific, technical, and administrative staff; meet or exceed the Laboratory's Equal Employment Opportunity and Affirmative Action goals and objectives; create, maintain, and administer the Laboratory's Compensation and Benefits systems; establish and monitor Personnel Policies and Procedures with a strong commitment to fair, equitable, and timely solutions to the myriad personnel issues that arose; apply innovative approaches to early identification and resolution of work-related problems; taking prompt and decisive action as appropriate; provide advice and assistance to Laboratory managers, supervisors, and employees; and maintain employee records in a confidential and secure manner. To accomplish these goals, the Personnel Department was organized into five groups: Compensation and Benefits, Data Resources, Employee Relations, Recruiting and Staffing (after July 1993, Employee Personnel Planning), and Training and Development.

Growth and Development

The first years of the project were marked by rapid growth and development. (See Figure 26-1.) In December of 1989, the Laboratory had 400 employees; by the end of 1991, that figure had grown to 1500, the majority of whom were relocated both from within the United States and from other countries. Approximately 800 Laboratory employees were ultimately relocated to work at the SSC. Most applicants learned of openings through the *SSC Laboratory Job Bulletin* and the *Nonexempt/Hourly & Designated Salaried Positions* publications which were issued weekly and biweekly. Over 700 bulletins were mailed each month to locations around the United States and abroad.

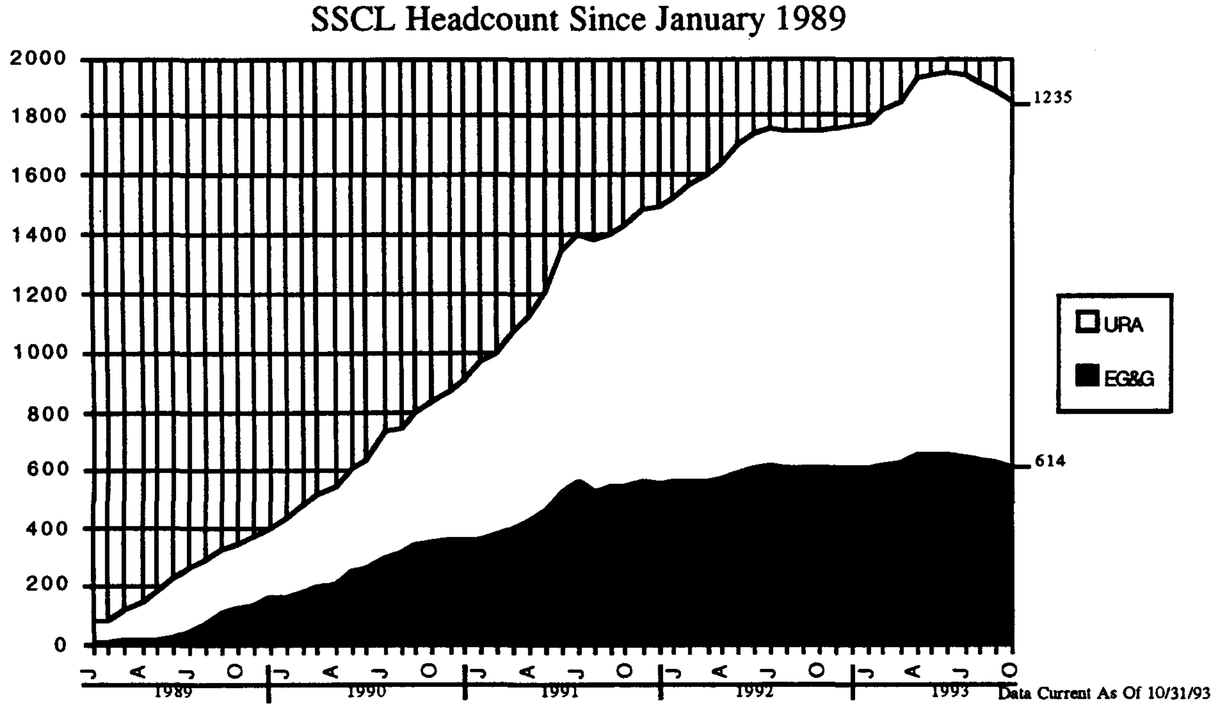

Figure 26-1. Growth during first Five Years of Project.

The Laboratory was fortunate to recruit many talented professionals from around the world to work at the SSCL. The Foreign Visitors Office (FVO) was established in the fall of 1989 to ensure that the SSCL's international employees were in proper work visa status at all times, as well as to provide visa processing and other services for employees, guest scientists, collaborators, and their families. One specialist joined the Laboratory at that time. The impact of the Immigration Act of 1990 coupled with the growing need for additional foreign national scientific expertise contributed greatly to the need for increased FVO staff and extensive training on INS regulations and procedures. Consequently, the FVO staff grew to three professionals to provide visa services; e.g., visa extensions, change of status, waivers, green cards, etc., for approximately 500 foreign nationals at the Laboratory. The FVO was instrumental in developing and implementing procedures for the guest scientist and collaborator programs. The office obtained the systems to facilitate case management and reporting requirements. Verification of employment eligibility (INS I-9 Forms) was also administered by this office. Finally, the FVO held regular customer meetings to educate hiring managers on visa issues and to arrange workshops for the international staff with local immigration attorneys as guest speakers.

The number of international employees coupled with the particular dynamics of the Laboratory necessitated a review of compensation policies and practices. The SSCL had been using the Fermilab classification system for both exempt and nonexempt employees. The explosive population growth soon made it obvious that a new classification system was needed for the unique talent being assembled at the SSC. Development of the Exempt Classification System began in early 1990 and was approved by DOE and implemented in July 1991. Job Analysis Questionnaires (JAQs) were completed by all URA and EG&G exempt personnel; some 800 JAQs were analyzed by Personnel. Supervisors were trained in the use of the system, and the basic elements were presented to all exempt employees.

The basic purpose of the compensation system at the SSCL was to reward performance. As a result, one of the early tasks of Personnel was to develop a Performance Appraisal System. The purpose of the system was to provide guidance to employees regarding their performance relative to their supervisor's expectations and to provide management with information for making personnel decisions. The first performance appraisals were made in mid-1990, and the process continued to be refined each subsequent year.

Another important aspect of the Compensation Program at the SSCL was the development of policies and procedures. As with the classification system and other policies within the Personnel Department, the Laboratory relied on the Fermilab policies and procedures for guidance during the early days of the Laboratory. Unique situations and new federal legislation made it obvious that revised and additional policies were needed. The Compensation policies were constantly under review, and development continued throughout the life of the Laboratory.

All the above elements—a classification system, performance appraisal system, and policies and procedures—combined to form the URA Salary Management System. This allowed supervisors at the SSC to make sound management decisions for the Annual Salary Review and proper position classification. The involvement of a Management Review Committee tied together the system elements to ensure equitable personnel management decisions across the various divisions.

Refinement

After the rapid increase in population had subsided to some degree, the Personnel Department focused on refinement. The Human Resources Information System (HRIS) current as of 1993 had become inadequate for our requirements. Executive management, DOE, and government agencies required regular reporting and information on SSCL labor. The current Human Resource systems lacked flexibility and could not provide required information through common reporting tools. An intensive laboratory-wide HRIS needs assessment was conducted to determine the requirements for a multi-company (URA and EG&G) integrated Human Resource System. The new integrated system was to include vendor software modules for administering compensation, employee benefits, applicant tracking, payroll, personnel policy, programs, and training. At project termination, the Personnel Department was already moving to acquire a new HRIS.

Because the SSCL was staffed through multiple companies (e.g., URA, EG&G, Sverdrup), there did not exist a single repository of information on all labor. HRIS became the definitive database-holding information on personnel working onsite and utilizing resources. Gatekeepers were established and maintenance of the data was distributed through those organizations responsible for the data (e.g., Communications - telephone number, General Services - mail stop and location). The database was recognized as the master listing by management.

Accomplishments

Although this section mentions several "projects-in-process" that were canceled along with the Laboratory, many other projects were completed that can be counted as accomplishments of the Personnel Department. The Americans with Disabilities Act (ADA) went into effect for the Laboratory on July 26, 1992. The act prohibits employment discrimination against a qualified person with a disability. In addition, reasonable accommodations to the known physical or mental limitations of a person with a disability must be made. The Laboratory, under the Personnel Department's direction, was well prepared for its ADA eligibility date and was free from any suits under this legislation for which the Laboratory had made extensive preparations. Among them: all SSCL managers and supervisors were trained as to their responsibilities under the ADA; a professional consulting firm was contracted with to define the Laboratory's responsibilities in terms of compliance with local, state, and federal access laws; job descriptions were analyzed; and benefits policies were reviewed to ensure that there were no provisions that might be interpreted as discriminatory or against the best interests of the disabled.

The Laboratory also prepared for its future scientific and engineering needs through student programs. The Personnel Department was responsible for the SSCL Summer Employment Program, conducted in 1992 and 1993, which was administered by the Recruiting and Staffing Group separate from the SSCL education programs. The program was intended to provide valuable work experience to students aged 16 and older, to recruit young people to assist in short-term projects, to have additional help during the summer months, and to aid regular personnel in lieu of overtime. The program was intended for the economically disadvantaged (50%) and the general public (50%) who were currently enrolled in Metroplex high schools or undergraduate colleges and universities. More than 1400 students applied for 124 positions over the two summers the program was administered. Sixty-two positions were filled by economically disadvantaged students and 47.5% were minorities. Terms ran from June through August for a maximum of ten weeks in duration.

In addition to the SSCL Summer Employment Program, the SSCL brought other gifted students to the Laboratory through the National Consortium for Graduate Degrees for Minorities in Engineering and Science, Inc. (GEM). GEM had been the cornerstone of the SSCL's Affirmative Action and Equal Employment Opportunity Programs at the entry level. The goal of this graduate program was to provide the project with qualified minority engineers who would season and develop their skills through experience while obtaining responsible positions of leadership with the Laboratory. The SSCL became only the second area company to become a member of GEM in 1990 by obtaining two minority engineers. In 1993, the SSCL had a total of eight GEM students working within four major divisions of the Laboratory and had sponsored their first two candidates through their MS degrees. The Laboratory also hired two GEM graduates who had interned at Argonne and Fermilab.

Laboratory Closure

Because of project termination, the Personnel Department underwent significant transformation on October 21, 1993: all staff were mobilized to focus on outplacement activities. Former group lines were abolished from that point on. Personnel staff used their expertise to assist employees in finding new jobs.

Outplacement services were quickly developed to assist all employees in their job searches. By October 26, 1993, a memo had been issued to all employees advertising weekly All Hands Meetings (a question and answer forum for employees), the development of a local/national job opportunities bulletin, on-location personnel liaison people, the establishment of a Personnel hot-line, three job fairs, and outplacement/career management classes. In addition, an Outplacement Center was established where employees could find an extensive resource library, individual workstations with computers and telephones, and interview rooms for use by off-site companies.

In addition, a collection of computer on-line resources called "Infonet" was developed with the assistance of the Library and Information Services to provide electronic resources to all the computer platforms in use at the SSCL. As of this writing, Infonet had included the *sscl employee* *update*, posted job openings, job leads from Laboratory employees, outside resources/job bulletin boards, job hot line information, and general information provided by Texas Employment Commission. It was an on-going project which was expected to replace the weekly hard copy of the job bulletin as time went on.

Conclusion

The Personnel Department achieved its primary goal of providing the highest level of human resources expertise and service to the Laboratory community. Over 1,500 quality employees were hired between 1989 and 1993. With termination of the project, Personnel had to assume the unenviable task of administering the layoffs. Although this was an unpleasant task, the department worked diligently to ensure that terminations were conducted with order, fairness, and dignity.

Procurement

The Early Days (1989)

Following the award of the SSC contract in January 1989 to Universities Research Association (URA), the earliest procurement measures were accomplished by a person on loan from EG&G's Las Vegas procurement department who leased the SSCL's first office space, bought office supplies, and acquired secretarial support through temporary agencies. Very quickly, however, requirements grew to the point where professional procurement assistance was needed on a full-time basis.

In March 1989, EG&G transferred the first full-time procurement professional to the SSC offices in the Stoneridge complex. For the period from April through June of that year, URA assigned a procurement professional from Fermilab to the SSCL on a temporary duty basis. This professional provided URA purchasing authority to the fledgling Laboratory, while the EG&G employee served as the supervisor of the procurement staff. In June 1989, EG&G transferred a manager of administration to the SSC project: at first, on a temporary duty basis, but eventually full time. In late summer 1989, URA hired the first SSCL Procurement Department Director.

Very early, the decision was made not to adopt the procurement policies and procedures of Fermilab for a number of reasons, but the primary one was the very different missions of the two facilities. Whereas Fermilab was an operational laboratory with a stable, homogeneous procurement workload, the SSCL would quickly be involved in a broad and diverse array of procurements, including large-scale construction activities, huge research and development projects, and major production subcontracts. Although attempts were initiated, no comprehensive set of procurement policies and procedures were developed in the early stages.

Transition Period (1990)

A report issued by the Procurement Director suggested reorganizing the Procurement Department around the requirements of its major customers within the Laboratory. The report proposed that three groups be established, with the group leaders reporting directly to the Procurement Director and Deputy Director. The first group would be responsible for the major projects of the SSCL: Magnet Systems, Accelerator Systems, and Conventional Construction. The second group would be responsible for general procurement support for the entire Laboratory. The third group would be responsible for staff support to the Procurement Department: policies/procedures, cost/price analysis, internal review, and data systems maintenance and analysis.

In late summer of 1990, the group leaders were selected for the following groups: Policies and Analysis, Project Procurement Group, and General Procurement. Reporting to the Policies and Analysis Group Leader were the Cost/Price Analysis Section and the Data Systems Section. Within the Project Procurement Group were the Magnet Systems, Construction Management, and Accelerator Systems Subcontracting Sections. The General Procurement Group included the Purchasing, General Subcontracting, and ADP/Telecommunication Sections. With the selection of the group leaders, the reorganization of the Procurement Department was completed early in 1991. In addition to the reorganization, the Project Procurement buying sections were decentralized. The Magnet Systems Subcontracting Section was collocated with the Magnet Systems Division; the Accelerator Systems Subcontracting Section with the Accelerator Systems Division; and so forth. The entire Policies and Analysis Group and the General Procurement Group remained collocated with the Procurement Director's office, except for the ADP/Telecommunications Section, which was collocated with the Information Systems offices.

Growth (1991)

During 1991, the Procurement Department nearly doubled in size, growing from 48 to 92 personnel. This was reflective of the significant increase in procurement activity at the Laboratory. In fiscal 1990, the Procurement Department issued 6,089 procurement actions, totaling $106 million. During fiscal 1991, the Department awarded 8,468 procurement actions, for a total of $278 million.

In December 1990, the SSCL presented its first comprehensive set of procurement policies and procedures—the Procurement Department Standard Practices Manual—to DOE for contracting officer approval. The draft Manual was implemented on an interim basis, pending approval. In May 1991, following the incorporation of DOE comments, the Manual was brought into final form and approved by DOE. In May 1991, DOE performed the first Contract Purchasing System Review of the Procurement Department. Its report, issued in final form in July 1991, recognized SSCL's progress in establishing a procurement system but withheld formal approval. The report included 22 recommendations, which were implemented by the SSCL over the ensuing months.

Maturation (1992)

In early 1992, as a result of efforts begun by the Procurement Director, the Procurement Department led the Administrative Services Division's implementation of TQM techniques. The entire Department was trained in the use of TQM principles, and began developing process improvement teams to responsible for solving problems in specific areas. Among the first problems attacked by these teams was the improvement of the requisition approval process. As a result of this team's efforts, many of the previously required sequential approvals were eliminated or converted to electronic, simultaneous approvals, reducing the requisition approval cycle time significantly.

In mid-1992, the Procurement Department developed and implemented its first Business Strategy Plan establishing clear goals for the Department and assigning individuals with responsibility for associated milestones. One of the most important procurement actions of 1992 was the negotiation of a multi-year extension to the subcontract for architect-engineer/construction management services with Parsons Brinckerhoff/Morrison Knudsen, which took place over the summer. This subcontract extension, valued at approximately one billion dollars, implemented a complex incentive fee arrangement, which replaced an administratively burdensome award fee structure.

Project Termination Decision (1993)

In June 1993, the House of Representatives voted to discontinue funding for the SSC project. This was the second successive year the House had voted against the project, and the prospects of project termination became significant enough to affect Laboratory procurement decisions. Immediately following the House vote against the project, the Texas National Research Laboratory Commission decided to withhold further project contributions by the state. The effect of this decision was to have significant impact on the Laboratory's ability to meet its contractual commitments. The Laboratory took several major steps to reduce its expenditures in an effort to survive the fiscal year without the need to lay off or furlough permanent employees. Among the first actions taken was the dismissal of almost all temporary employees. In late October, a joint House-Senate conference committee voted to terminate the SSC project. On November 17, 1993, the DOE SSC Project Office terminated the prime contract with URA, and immediately thereafter the Procurement Department began terminating its subcontracts.

Records Management

Records Management Plan and Development

Records Management was not formally included in the baseline of the SSCL. It was formed when the position of Archivist was filled in May 1990. The Archivist reported to the Head of Library Services in the Physics Research Division. A records management plan was proposed by the Archivist to management six months later. As a result of the initial proposal, records management was split from the Archivist's responsibilities and organizationally assigned to the Administrative Services Division. A new Records Management Department was formed in February 1991. A Manager of Laboratory Records was appointed to develop a comprehensive records management plan for maintaining and preserving the records of the SSCL project. A committee developed a Records Management Plan[1] for the Laboratory providing for a Vital Records and Disaster Recovery Program, an Inactive Records Center, and preservation of records of long-term, enduring value. Records Management Procedures were in the process of being developed at project termination. A site-specific records inventory and retention scheduling plan was also in the developmental stages.

The Records Management Department operated a Central Files section that collected, indexed, and maintained correspondence with the Department of Energy, subcontractors, and university collaborations. Because it was an option to transfer records to this section, not all divisions participated in the transference of these critical records to the Central Files area. The Uniform Records Indexing System (URIS) was designed after the DOE Order 0000.1A, Standard Classification System, but it was expanded to identify the year of creation, office, and type of record in addition to the unique subject of each record.

The Records Center maintained over 1,500 boxes of semi-active/inactive records through October 1993. The records were stored in two (and sometimes three) different temporary facilities while awaiting space to be constructed for the permanent records center. Facilities were environmentally protected and controlled by the Records Management Department. Reference services and audit support was provided by the Records Center staff. The Records Management Department maintained the Vital Records Vault to secure, in a controlled environment, all magnetic media, rights and interests records of the SSCL and one of its subcontractors, PB/MK.

Technology Utilization and Indexing

The Central Tracking System, a networked database using Powerhouse on the DEC Vax mainframe, was used by staff to create the URIS index for correspondence maintained in the Central Files system. Over the two years that this system was used, more than 26,000 records were indexed into the database. The database could be searched by URIS code, date of origination, originator/author, subject, record receiver, and organization of originator/author. Reports of search "hits" could be printed for the researcher to use in referencing and locating documents. A draft user's manual[2] for this system was being reviewed for approval at the time of project termination.

A Records Storage and Disposition Form was used to accomplish the transfer of records to the Records Center. The form identified the records located in each box as well as the "process owner," file station location code, and the records center storage location code. Space was available on the form to identify the retention schedule/destruction date that was planned for data entry after the site-specific records inventory and retention schedules were completed. Indexed information of all records transferred to the Records Center was maintained on a computer file server utilizing a Filemaker Pro database.

An integrated Document and Records Management System was in process of being procured at the time of project termination. This system was designed by a team of SSCL staff under the leadership of the Information Systems Department. The system was designed for implementation in phases. The first phase was designed to create an index of all recorded information created by the SSCL. Integration of documents released from Configuration Management to Document Control and Records Management allowed for records to be identified in various stages of activity. Records Management was responsible for identifying the appropriate record series of records and assigning the retention schedules for these series. The system could also assign a Vital Record Status code to all records to allow for adequate protection from disasters.

Chapter 27. Technical Services

(S. Phiffer)

Laboratory Technical Services (LTS) provided support services to the SSC Laboratory in the areas of communications systems, facilities services, fabrication shops, heavy equipment, motor vehicles, engineering support, warehouse operations and property control, protective services, technical publications, general staff services, and training. Services were provided in accordance with controlled procedures and in compliance with applicable contractual and SSCL requirements.

Communications

Communications provided multi-level communications services to support up to 3300 Laboratory personnel, including contractors, and all facilities located at the Stoneridge complex, Redbird, Eagle Park, Parkerville, Central Facility, the Gray's House, MDL, ASST, MTL, the Linac, N15, and in trailers. Telecommunications support included acquisition, issuing, and monitoring of all mobile equipment (pagers, cellulars, radios) and acquisition, installation, and maintenance of telephone services, radio systems, and teleconferencing systems internal and external to the Laboratory.

Facilities Engineering

The Facilities Engineering Services Department provided facilities engineering services support for the Dallas/DeSoto facilities including the Stoneridge complex, Redbird, Eagle Park, Parkerville, the Central Facility, 56 temporary facilities including trailers, the Gray's House, and storage containers. Permanent facilities, which were turned over from the Conventional Construction Division, included the MDL, ASST facilities, MTL, and the Linac. Assorted infrastructure included the sewage treatment plant, cooling tower, cooling pond, certain roads, and utilities.

Facilities Engineering and Maintenance

Facilities Engineering provided technical support, construction management, and engineering design analysis for facilities-related systems, structures, and components, engineering management of SSCL construction projects, and planning and development of employee work stations. Operations and Maintenance ensured that structures, systems, and components were maintained and operated in safe and reliable condition.

Central Shops

Central and Divisional Shops

Central Shops consisted of the shops at the Central Facility and area shops in Building 3-Stoneridge, the Magnet Development Lab, and the Magnet Test Lab. All area shops were complete, fully equipped, and functional. The shop at Central Facility was approximately 80% complete and operational. Shops included equipment from small lathes and mills to 48-inch vertical lathes and large machining centers. This equipment covered manual single axis to equipment with CNC 5-axis complexity and capabilities. There were approximately 90 major pieces of equipment operational at the time of project termination.

Vehicles and Heavy Equipment

The purpose of the vehicle and heavy equipment group was to provide for the acquisition, maintenance, and logistics related to government vehicles, cranes, forklifts, trucks and trailers, and other special and common mobile equipment. In providing the service, the group maintained dispatch capabilities, maintenance data bases, and contracts for preventive maintenance and repairs.

Metrology and Calibration Support

The Metrology and Calibration section maintained qualified metrology and calibration/repair laboratories, provided inspection and calibration verification of measurement and test equipment, calibration and electronic equipment repair services, and a secondary standards reference sources. The SSCL Metrology/Calibration & Repair Lab possessed the capability of calibrating and repairing the numerous electrical/electronic devices at the Laboratory. In addition, the section had the capability to calibrate and repair the physical and mechanical attributes of Laboratory equipment.

Engineering Support

Engineering Support was included in the initial baseline of the SSC project. The organization provided critical start-up services, such as standards development support, CAD system evaluation and selection, design/drafting staffing selection for all technical divisions, and the establishment of the Technical Document Control Center. Responsibilities evolved from development to operations and support as the SSC matured into a construction project. Engineering Support Department (ESD) responsibilities included the following areas: CAD Operations and Support, Facilities Design and Drafting, Engineering Standards Support, and Technical Document Control and Reproduction.

CAD Operations and Support

CAD provided planning and operational support for most Computer-Aided Design/Engineering (CAD/CAE) activity at the Laboratory, including development of software standards for each of the application areas. Configuration of CAD systems included in excess of 180 workstations and numerous servers, with a wide range of software and output peripherals. ESD facilitated the general operation, support, and maintenance of these systems which are described below.

The Intergraph system was used generally for architectural and civil applications by the Accelerator Systems Division (ASD), Physics Research Division (PRD), Conventional Construction Division (CCD), Project Management Organization (PMO), and Laboratory Technical Services (LTS) Division to accomplish site layout, facility design and maintenance, cryogenics systems design, and detector interface design. UNIX-based workstations, servers, and software acquired from Intergraph Corporation and third-party suppliers, along with necessary networking and peripheral products, were configured to form a distributed system to accomplish these tasks. ESD support to this environment included hardware and software; programming support; file and data administration, storage and backup; animation and video production; user training; data security; a wide-range of plotting capabilities; and user problem solutions.

Unigraphics II was generally used for mechanical design, modeling, and manufacturing applications. Unigraphics II and extensions were the primary applications used by mechanical engineering organizations for design of magnets, spool pieces, and other mechanical components of the project. Again, a distributed UNIX environment was utilized with in-process data being captured at the work-group level. Support of this application by the ESD organization was in the form of user training, productivity software enhancements, plotting, and on-call problem solutions.

Racal-Redac supplied products for electrical/electronic applications. Its products were used in a distributed UNIX environment by the ASD electrical engineering organization for design and development of electrical/electronic components of the project. LTS/ESD support of this activity provided CAD systems operation and management, applications support, user training, plotting, server facilities, Relational Data Base Management System support, data translation, animation, scanning, and programming.

Design/Drafting

The Design/Drafting Section supported the Facilities Engineering Services organization and other organizations at the Stoneridge and Central Facility locations who did not have drafting personnel. Its responsibilities included documenting existing facilities, improvements, property, safety plans, communications layouts, and other facilities-related data. It provided documentation of all SSCL facilities. The "as-constructed" documentation from the Architectural Engineering/Construction Manager (AE/CM), verified by Conventional Construction Division (CCD) personnel, was released to the Document Control Center for retention and to ESD Design/Drafting for maintenance. Facilities Service Requests (FSRs) for facility modifications or repairs were tracked, and workers were dispatched via information contained in a relational database. Verification of facility additions and modifications was performed by personnel of the Design/Drafting Section and documented as part of the as-built drawing record of the facility.

Engineering Standards

The Engineering Standards Section developed SSCL standards for mechanical, electrical, civil, and structural engineering. It also supported SSCL metrication and drawing quality standards, dimensioning, and tolerancing practices and training. Deliverable products included published engineering standards that became controlled documents of the Laboratory, which set and controlled quality, safety, common practices, and methodologies with regard to engineering functions at the SSCL.

Technical Document Control and Reproduction

The Technical Document Control and Drawing Reproduction Section provided collection, indexing, storage, reproduction, maintenance, and distribution of the released engineering documents of the SSCL (those that described the elements that made up the SSC and its facilities, and their method of construction). Documents consisting of plans, policies, procedures, and practices that describe how the SSCL conducted business were also included.

Document control received, stored, maintained, and distributed all controlled documents. This section assigned document numbers when applicable, maintained hard-copy and/or electronic records, and assisted the user community with the identification of documents to satisfy specific needs. An extensive electronic index of all technical and scientific documents was created in a relational data base. Reproduction of controlled documents for distribution was provided as requested. All drawing reproduction was accomplished on two major pieces of wide-format, plain-paper copying equipment. Page-sized documentation was copied both in-house and in cooperation with the SSCL print services organization.

Materiel and Logistics

General

The Materiel and Logistics Department evolved from a few people located in a 3,000 square foot warehouse to four operating warehouses and three receiving locations with more than 50 personnel to manage property. The Property Management System was certified by the Department of Energy in 1993.

Receiving

Receipt of material was first carried out at Stoneridge Building 2 and then expanded to the Central Facility and the Magnet Development Laboratory (MDL). Average receipts per month were: 969 in 1990, 2005 in 1991, 3093 in 1992, and 2429 in January to June 1993. The highest single month for receipts was August 1992, with 4631.

Shipping

Shipments grew from 52 in October 1991 to a peak of 220 in June 1993, with shipping activities at all three major sites. Personnel attended training for certification in shipment of hazardous and radioactive material during 1992 and 1993. Movement of hazardous wastes from Satellite Storage Areas (SAAs) to Temporary Storage Areas (TSAs) was begun in March 1993. Five personnel attended the 40-hour OSHA hazardous waste course and subsequently assisted ES&H in preparing for hazardous waste shipments to storage sites.

Stores

The Stores operation, which handled recurring and special orders for administrative supplies, was located in Stoneridge, Building 2. There were over 600 regularly stocked items at the peak of business with 50 customers per day, and issues of over $150,000 per month.

Transportation

From a one-person contractor, this function grew to three personnel: a full time import/export coordinator, a negotiator for extraordinary movements and contracts, and a scheduler/auditor of deliveries and freight bills. A Routing Guide was developed for buyers, and classes were given in its use to minimize transportation costs.

Property Control

By project end, the property control system had 23,926 items valued at over $185 million. Considerable progress was made to ensure that subcontractors had adequate property controls, and that property at other laboratories and collaborators was accounted for. An annual wall-to-wall inventory was taken each year, with an accuracy of 99% or better. From 1990 to 1993 over $9.9 million of property was acquired through excess from other government agencies at a cost of $593,400, this was 6% of original acquisition cost.

Warehousing

Various small warehouses were used before the operation moved to the Stoneridge 10,000 square foot facility. Total permanent requirements for warehouse space were 320,000 square feet and an additional 340,000 square feet as a projected need during construction and magnet installation. There were 155,000 square feet of warehouse space in use at time the project terminated. Outside, fenced storage areas were located at the Parkerville and Central Facility, and an open field storage was available at the N-15 site.

General Services

The General Services Department provided laboratory-wide support in areas of Special Services, Office Services, Mail Services, Visual Media Services, Technical Information and Publication Services, and Division Procurement Actions.

Staff Services

Staff Services provided food and catering services, main lobbies reception, and support secretaries. Offices Services handled acquisition, installation and maintenance of freestanding furniture, convenience copiers, facsimile machines and typewriters; employee and equipment moves; and conference and meeting room set-ups. Mail Services included incoming and interoffice mail delivery, outgoing mail, UPS, FedEx, international delivery, courier and shuttle service, and recycling.

Visual Media Group

The activities within the subgroups of the Visual Media Department included Video Services, Photographic Services, Interactive CDs, and Audio Visual. Video Services provided complete support for a variety of services including: shoot, write, edit, and produce original in-house videos for DOE, Training, Safety, Quality Assurance (QA), Video News Releases (VNR), Project Documentation, and Education. Photographic Services included every aspect of photographic processing and printing, transparencies for presentations, group shots, digital imaging, and photographic enhancements. Research and development of interactive CDs to support education and training environments was also provided. As the project terminated, the Visual Media Department was one of only three facilities in Texas that possessed the capability of cutting interactive CDs. The Audio Visual function supported Laboratory personnel and associated departments and/or divisions with presentations, taping, technical documentation, equipment check-out, set ups, audio recording, TV's, VCR's, and Laboratory broadcasting. Major accomplishments included the procurement and implementation of on-line Beta editing system for broadcast quality video tape, the development of livevideo broadcasting from Southern Methodist University to SR and CF, the research and development of digital imaging systems for photography, video/photo project documentation, the development of an in-house photographic darkroom for black-&-white and color capabilities, support for training and education, developing videos and interactive CDs, and specialized training for technical equipment.

Technical Information and Publications

Technical Information and Publications (TIP) assisted the Laboratory in the areas of Graphic Services, Publication Services, Editorial Services, Print Services, Conference Support, Forms Management, and Customer Service. The following services were available from TIP: customer service provided scheduling of all services required from Technical Information and Publications, report number assignment, patent review/copyright protection, distribution of reports, newsletters, etc., and ordering reprints of articles. Graphic Services provided report art, vu-graphs (color and B/W), technical illustrations, presentation materials, graphic design/layout (brochures, newsletters, etc.), and any graphic material (displays, posters, meeting material, etc.). Publication and Editing Services included keyboarding of text, document layout/design, scanning, and editing and writing of material. Print Services included professional printing of all material, color copying and printing. Forms Management/Conference Proceedings provided forms management, forms analysis/design (paper and electronic) and inventory/distribution, conferences/proceedings, and format definition, and author kits for conference proceedings.

Protective Services

Protective Services was responsible for safety within the LTS Division, and SSCL-wide support for the protection of life, property, and the environment.

Safety Group

LTS Safety consistently provided the employees of LTS/EG&G with a safe work environment while complying with all applicable State and Federal Environment, Safety and Health regulations. LTS developed and implemented the following safety training courses for LTS: ladder safety, forklift safety, back injury prevention, welding and cutting safety, lock-out/tag-out procedures, and injury reporting. Lock-out/tag-out was subsequently adopted by several other divisions including Environment, Safety & Health. Coordinated training was done in the following safety related areas: Confined Space Competent Person, half face- and full face-respirator, confined space entry, permit required, Hazardous Material First Responder, portable fire extinguisher, and Self Contained Breathing Apparatus (SCBA).

The Safety group developed a method for procuring safety shoes and prescription safety glasses which became the basis for the program used by the ES&H Department for Lab-wide procurement of these items. The group developed a process for tracking safety inspections and following up on corrections, and for inspections performed by the safety coordinators, managers, and department heads. The group was among the first from the SSCL to join DOE's Training Resources and Data Exchange (TRADE) organization, becoming members of the Procedures Special Interest Group (PRO SIG), Occupational Safety Special Interest Group (OS SIG), and the Advanced Training Technologies Special Interest Group (ATT SIG). They met regularly with members from other DOE facilities to exchange information. They also developed and presented a safety orientation video for new EG&G employees and the SSCL Subcontractor Safety Guidelines.

Security Services

Security Services provided physical security for all SSCL facilities, property, and real estate, maintained access to all facilities through the use of the access card system and lock and key control, and provided VIP escort support for visiting dignitaries and for professional conferences held at the SSCL.

Emergency Services

The Emergency Operations Center/Dispatch provided 24-hour emergency response through the use of the 1313 Emergency Notification System. Dispatch monitored all security alarm systems, closed-circuit television systems, emergency distress signals, fire and oxygen deficiency hazard alarms, and severe weather alarms, and they activated the appropriate response group to react to emergencies on SSCL property. Emergency Medical Services provided construction site emergency medical response for treatment and stabilization of injured personnel. Emergency Response Services/Fire Department provided rescue and fire protection for the SSCL. Hazardous Material Emergency Response provided a Laboratory-wide emergency team to respond to all hazardous material spills, working with division and SSCL ES&H personnel.

Training Programs

LTS Training contributed greatly to all the SSCL Training Programs. The initial coordination of SSCL training was begun by this Division. Laboratory-wide instructors were organized into a working group that shared ideas and lessons learned. LTS produced 90% of the first SSCL Training Manual, used its own resources to create and put into production the first phase of the SSCL Training Data Base, developed training forms, and made them all available for Laboratory use.

Within the LTS Division, a central Training Office was established that coordinated and documented all training activities within LTS, used LTS personnel as subject matter experts and instructors, and wrote RFPs for vendor training. Each Department within LTS had a direct line of communication to the Training Office. Reports of completed training were issued to employees, supervisors, managers, and corporate officials. LTS was the first Division to distribute a signed Training Policy and Training Standard.

LTS was the only SSCL unit to present any training materials at the DOE Training Resources and Data Exchange (TRADE) Conference. Two presentations on Heavy Equipment Training were given during the 1993 TRADE National Conference. It was because of the efforts of LTS Training that the SSCL was scheduled to co-host the 1994 TRADE Conference with Pantex before the project was terminated.

Quality Assurance

LTS QA developed the division Quality Implementation Plan, assisted each operating element in developing quality assurance plans and practices, provided for quality training and consultation, and participated in supplier qualification, Lab-wide audits, development of Lab-wide QA and engineering documents, standards, and procedures.

Chapter 28. Environment, Safety, and Health and Quality Assurance

(L. Coulson, S. Galpin, and S. Baker)

This section briefly describes the major Environment, Safety and Health (ES&H) accomplishments at the Superconducting Super Collider Laboratory (SSCL), with particular emphasis placed on innovative contributions to the ES&H needs of a high energy physics lab. Senior staff members who were involved with the technical ES&H development of the SSCL were interviewed and asked to submit written summaries of what they considered to be the most important developments of ES&H. Tape recordings made during the interviews and the unedited written contributions are preserved in ES&H Summary History.[1]

A summary of the key ES&H accomplishments include: the introduction of System Safety methods used in construction safety, safety analysis, and readiness reviews; DOE concurrence with a safe design for tunnels with egress points 2.7 miles apart; background radiation monitoring stations which can also be used in schools for educational purposes; a comprehensive and site specific groundwater activation/transport model and innovative electronic designs for safety interlock systems and oxygen deficiency detector systems. The material presented in each section below, summarizes the primary accomplishments in the category. There is some overlap of subject material in the various disciplines; for example, material expected in the environmental protection section may appear in the radiation safety section.

Organization and Management of ES&H

The Laboratory organization of ES&H as a line function was documented in Chapter 1 of the ES&H Manual.[1] To support the line organization several ES&H entities were created. The ES&H Oversight Office provided oversight and policy recommendations to the Director. The ES&H Department, reporting to the General Manager, provided ES&H program development, ES&H personnel as a matrix function, and some direct ES&H support (e.g., dosimetry, hazardous waste management, etc.) as a line responsibility. Each Division had its own Division Safety Lead, generally a professional in one of the ES&H disciplines.

ES&H documentation reflected this hierarchy,[2] i.e., all policy statements were approved by the Director. ES&H Programs and Lab-Wide Procedures were approved by the General Manager. Division leaders approved Program Implementation Plans and Practices at the division level. A system of committees provided additional ES&H support. Internal committees included: the ES&H Committee and associated subcommittees.[1] Standing external committees included the Underground Technical Advisory Panel (UTAP),[3] External Radiation Control Advisory Panel,[4] and the Ellis County Citizen Advisory Committee.

Construction Safety

The Superconducting Super Collider (SSC) was to be a massive 10 year design and construction project. The importance of ES&H in design and construction was emphasized from the beginning. The SSCL policy to build excellence into the construction ES&H program started with the selection of the Architect-Engineering/Construction Management (A-E/CM) firm using ES&H as an important criterion to be considered in the review of written proposals and interviews of the A-E/CM candidates. The SSC objective was to construct the facility to meet all applicable design requirements. The primary source of ES&H design criteria was DOE 6430.1A (General Design Criteria). More specific requirements, primarily related to the life safety aspects of fire protection, were also established.[1]

The initial construction ES&H program met the most rigorous construction industry standards. Parson Brinckerhoff and Morrison Knudsen (PB/MK), the chosen A-E/CM, was required to have a detailed Construction ES&H Management Program approved by the SSCL. This Program was quite specific on the entire range of construction ES&H issues. The PB/MK Program required their subcontractors to have written ES&H programs of their own, approved by PB/MK. Smaller companies were permitted to adopt the PB/MK manual while larger companies generally had programs of their own. PB/MK performed inspections of every subcontractor activity every shift, providing written notification of significant violations, including stopping any work posing an imminent danger to personnel or the environment. Subcontractors were required to document regular inspections by their own safety personnel. After the tunneling fatality in January 1993, it was decided that the construction safety effort would be strengthened through the use of job hazard analyses for all underground tasks. Recognized high hazard activities were subjected to readiness reviews (see System Safety Section).

The SSCL was supported in the underground construction ES&H program by the independent oversight and advice from the Underground Technical Advisory Panel (UTAP).[2] UTAP members were internationally recognized experts in underground construction. Although its primary mission was technical advice in underground construction, the Panel also made some valuable contributions to ES&H; for example, UTAP subpanels reviewed the accident reports and planned mitigation resulting from the fatality near the N15 site, and again on the occasion of rock falling in the chalk tunnels.[3] Their expertise gave the Lab and the DOE confidence in the underground ES&H program.

A wrap-up workers compensation insurance program was implemented for the SSCL project. The insurance company assigned a full time claims manager to the site office to work directly with the SSCL Risk Management Office and the safety and medical staff. Future self-funded insurance programs (OCIP) should be structured to share rewards of good performance with the top performing contractors and to penalize those contractors whose work results in excessive losses to the insurance program.

Emergency Preparedness

Emergency Preparedness planning and implementation at the Laboratory presented several new challenges, both due to the size of the Laboratory site and to the combination of construction and operations taking place simultaneously. The site covers twelve separate fire zones, presenting challenges in coordinating offsite rescue and fire support services for a 54-mile ring with two campus locations, shafts to the surface every 2.7 miles, and several remote support facilities. Logistics is further complicated by the fact that the majority of these emergency response agencies are not full-time paid departments. These conditions presented challenges in developing communications capability across the site to provide effective emergency reporting systems, warning to SSCL workers and visitors of emergency events, and consistent quality communications for emergency response purposes. The open campus policy of the Laboratory presented challenges in ensuring personnel accountability during emergency events. The Emergency Preparedness Plan[1] developed initial criteria to address these issues. The criteria were later redefined based on the operational status of the Laboratory with issuance of the Emergency Warden Procedure[2], Emergency Awareness Guide,[3] and Emergency Dispatch Practice.[4]

The combination of construction and operations activities presented challenges in developing emergency preparedness that would meet all of the Laboratory's needs. The off-site fire and rescue services only provided surface fire and rescue support. Their entry into construction areas such as shafts and tunnels was prohibited as defined in the contracts with the cities of Waxahachie and Ennis. Emergency medical support demands were considerably higher than at other DOE facilities, due to the construction activities spread over 54-miles area. Accelerator facilities' hazards are generally less than other DOE facilities, and yet, they present challenges in coordinating hazard information with offsite response agencies. In particular, the quantity of hazardous materials on site did not require an Emergency Planning and Community Right-to-know Act (EPCRA) to be filed with local governments. However, the SSCL did maintain a chemical inventory in HazMat Boxes to provide local emergency responders with hazardous materials information. Because of the construction and remote locations, proper directions to an emergency event location were critical. Many access roads were new and sites were unmarked. The division of emergency responsibilities between construction contractors and Laboratory personnel presented challenges as well. These issues were addressed in a letter to the DOE Superconducting Super Collider Project Office,[5] and the report prepared by the Emergency Preparedness Subcommittee.[6]

In response to these challenges, the Laboratory instituted an emergency reporting "1313" call system and obtained space on local towers for repeaters to provide site communications and data links. Contracts were established with two off-site paid response agencies to coordinate within their districts and provide response for the Laboratory. In addition, Emergency Medical Services were contracted and Emergency Medical Service Stations were established around the Collider ring to provide site-wide coverage. In response to hazardous materials issues, HazMat Boxes were mounted on poles at the entrance to each Laboratory site. Each box contained the chemical inventory for the facility and provided hazard information directly to local response agencies as they arrived at the scene. An Operational Emergency Plan[7] was developed to meet all Laboratory emergency response needs and to identify the Emergency staff and responsibilities.

Environmental Protection

During SSC site selection, the DOE, with the help of the Central Design Group (CDG) prepared a Final Environmental Impact Statement (FEIS)[1] that evaluated the environmental impact for the seven site finalists. After the Texas site was chosen, the National Environmental Protection Act (NEPA) process was used to evaluate the chosen site in detail, including the impact of the design modifications specified in the Site-specific Conceptual Design Report (SCDR)[2] and final site footprint definition.[3] Thus, a draft Supplemental Environmental Impact Statement (SEIS) was prepared, followed by the Final Supplemental Environmental Impact Statement (FSEIS).[4] The Record of Decision,[5] signed by the Secretary of Energy in February of 1991, called for a Mitigation Action Plan (MAP).[6] This was the first time such a plan was required for a DOE facility. The MAP had two noteworthy features. First, it called for Environmental Compliance Plans for activities that had potential environmental impacts. This required all construction contracts under the direct supervision of the Architect-Engineering/Construction Management (A-E/CM) to have an Environmental Compliance Plan. As explained below, this facilitated the environmental permitting process. Second, the MAP would not to be modified to report progress on mitigation actions. Any modification of the MAP would have required review and approvals by DOE resulting in delays. These delays were avoided by agreeing that progress on mitigation actions would be reported in the annual Site Environmental Reports,[7] including actions anticipated for the following year.

To maintain the construction cost and schedule, it was critical that all required permits be identified as early as possible and the permit applications be coordinated and expedited by and among the many organizations playing a part in the construction (DOE, SSCL, Texas National Research Laboratory Commission (TNLRC), and PB/MK). The primary tool used for this purpose was the Regulatory Compliance Plan.[8] This Plan lead to the creation of the Environmental Compliance Committee composed of representatives of DOE, SSCL, TNRLC, PB/MK. This Committee held regular meetings to identify permit requirements, to develop technical requirements necessary to fill out the permit applications, and to coordinate meetings with regulatory authorities. This process, supported by quick turn-around by the State agencies, succeeded in greatly reduced the permitting time. A proposal[9] was prepared to pursue site-wide permitting with the Department of Energy to reduce the permitting time and administrative cost of obtaining multiple construction and operation permits.

The Environmental Monitoring Plan[10] was created to establish a reliable environmental baseline and to accurately monitor the effects of construction. This Plan included: groundwater monitoring for water levels and water quality starting in May 1989; surface water monitoring for water quality at 14 sites starting in May 1993; logging of meteorological data, noise level and air quality (24-hour particulate) at two locations at the N15 site, starting in the autumn of 1990; and, environmental radiation measurements using TLDs, starting in July 1993, at five sites each on the East Complex, the Linac area of the West Complex, and the boundaries of the West Complex. The water monitoring part of the Plan was developed from information prepared by the Texas Bureau of Economic Geology (TBEG).[11]

The large site size and multiple detector locations needed to collect background radiation data made it necessary to develop remote radiation background monitoring stations that could transmit data to a central location. A background monitoring station was developed which contained a NaI(Tl) scintillator, an energy-compensated Geiger counter, and a computer controlled energy spectrum pulse height analyzer. A prototype system was assembled in 1991. During the development of the prototype it was realized that a few minor modifications would allow the same stations to serve an educational purpose in the high schools while also satisfying the SSC need for background data. Modifications made for the high school systems allowed the teacher to use a single key to stop SSC background data acquisition and use the system for educational purposes. Striking another key allowed the system to return to background data acquisition for the SSC.[12, 13, 14] Four units were constructed to place in local high schools throughout Ellis County and one for the West Complex.

The Lab took innovative steps in its efforts to identify existing environmental problems on the land parcels being acquired by the TNRLC. Many hundreds of separate parcels of land, mostly rural, had to be acquired for the 16,600 acres needed by the project. To maximize the likelihood that existing environmental problems would be identified, landowners were asked to complete a Landowner Questionnaire. The questionnaire included questions about known environmental problems, wells, and cultural resources. A number of problems were thus voluntarily revealed and mitigated before taking possession of the land.

The Cultural Resources Programmatic Agreement (PA)[15] was created as a guidance document to ensure that adverse effects on cultural resources would be properly analyzed, documented and mitigated. DOE delegated the responsibility to TNLRC for the impact analysis and mitigation of Historic structures,[16] along with the public information program, leaving DOE responsible for the archeological impact mitigation.[17] The firm ArchiTexas/Solamillo/Hardy-Heck-Moore was contracted to perform the mitigation on historic structures. They won an "Award of Excellence in Historic Architecture" for significant contributions to the preservation of Texas' architectural heritage from the Texas Historical Commission.

The Ellis County Site is at the southern tip of the tall grass prairie. Because of the Lab's desire to enhance the environment, a program resembling the Fermilab prairie restoration project was initiated to reintroduce the plant species in the natural habitat of the tall grass prairie, thus preserving the prairie gene pool. A prairie burn was conducted in the spring of 1991 on a prairie remnant located in Ennis as a management technique to improve prairie seed quality and quantity. That site and three other nearby sites were harvested in the fall of 1991. A Prairie Restoration Program[18] was developed and 30 acres of land on the West Complex was planted with prairie plant seed in the fall of 1992.

Since the SSCL was the first DOE research facility built since implementation of the strict environmental protection standards, waste generation and minimization concerns were considered as integral parts of all ES&H construction and operations plans and procedures. The difficult task of managing waste at the 26 non-contiguous waste generating sites was handled with the Hazardous Waste Management Procedure.[19] Communication of these requirements to the operational and working levels was accomplished via a Satellite Accumulation Area Management program[20] which designated and trained key people to manage the generation of hazardous waste within their assigned areas. A Waste Minimization/Pollution Prevention Program[21,22] was developed while the SSC was in a preoperational state, thus allowing the program to optimize the potential for source waste reductions, a philosophy that is key to the new regulatory pollution reductions strategy.

Disposal of hazardous and radioactive (mixed) waste is costly and time consuming. To minimize the generation and therefore disposal of the mixed waste caused by the build up of radioactivity in resins used to remove impurities from the accelerator cooling water systems, a special study was conducted at Fermilab. Normally, regeneration of resin produces radioactive salt would be treated as mixed waste. The Fermilab study showed that a carbon filter preceding the resin tank could remove the same radionuclides as the resin tank. The test also showed that it may be necessary to use a string filter in front of the carbon filter to prevent clogging. The carbon filter is inexpensive and can be disposed of as low level radioactive waste, mitigating the requirement for disposal of mixed waste.

Experimental Safety

ES&H considerations were an integral part of the detector design discussions from the beginning of the SSCL. An international meeting on detector safety was held in May of 1990 and included representatives from all the DOE high energy accelerator labs and CERN to discuss the important features of a good detector/experiment safety program.[1] That working group addressed not only the safety issues for the existing detector proposals but also lessons learned by other labs about safety organization, administration, and procedures. It was intended to develop a program which built on their strengths while avoiding their weaknesses.

The most challenging technical ES&H issues of the project were associated with the detectors and the experimental halls. Because of the size, complexity, experimental requirements, and underground location, safety issues were a great challenge. For four years, numerous national and international working groups were established, enlisting the best experts to address specific and broad technical and administrative issues surrounding both the SDC and GEM detector groups. Results of these meetings were crucial in guiding the evolving detector and experimental facility designs.

Day-to-day ES&H challenges were handled by a subcommittee of the Laboratory ES&H Committee. The subcommittee, composed of SSCL physicists, engineers, and ES&H personnel, met on demand to address design issues, documents, etc. Formally, the subcommittee advised the Physics Research Division (PRD) head as well as periodically reporting its activities to the Lab Director at quarterly ES&H Committee meetings. Although two detectors were under design, many of their ES&H problems were similar in nature if not in scope. The reader is referred to the summary paper "GEM Project ES&H Close-Out Summary"[2] and to "SDC ES&H Final Report"[3] for a distillation of ES&H issues and solutions being considered.

Fire Protection

The unique features and locations of the facilities under construction at the SSC Laboratory provided many challenges to the conventional wisdom in fire protection. Primary among these issues was the need for safe egress features from the main Collider tunnel where the exits were 2.7 miles apart, rather than the standard 400 ft apart.[1] A milestone was reached with the DOE approval of SSC Egress Provisions and Features for Evaluation of Equivalency.[2] This was the first "official" recognition for an accelerator facility that because of the unique design features (an underground concrete structure) and unique nature of the occupation and use (to be accessed very rarely by a small number of very well trained and physically fit persons) it was reasonable to conduct a hazards analysis and build in mitigation measures for a safe facility as opposed to "code compliance at all cost." This "analyze and build safe" concept was extended to the other tunnels and underground operations.[3,4 5,6] The experimental halls provided even greater challenges with their multitude of complex structures and unusual hazards. Solutions to the unusual and complex fire protection needs in the experimental halls were explored during three fire protection workshops with representatives from other Labs.[7,8,9]

The administration and organization of the SSCL Fire Protection Program were formally established in June 1993 with the development of the Interim Fire Protection Program.[10] Fire protection design requirements and standards were developed in several areas: the Fire Protection Design Manual[11] detailed fire protection design criteria for all facilities above and below ground; a fire protection standard for wire, cable, and fiber optics was also include in this manual;[12] and global fire detection and alarm signaling system requirements, in conjunction with the Communications Task Force, were also defined.[13]

Fire protection design criteria for the accelerators, and the surface and underground facilities, equipment and systems, were determined by conducting Fire Protection Design Analyses (FPDAs). The analyses proceeded from the Linear Accelerator to the Low and Medium Energy Boosters through the Test Beam Area and N15 - N25 Shafts and Main Collider Tunnel FPDAs.[14] The West and East Campus water supply analyses addressed the design and limitations of the fire protection water supply and distribution systems configured with small rural and municipal water companies.[15,16] Other analyses/evaluations address unique features associated with the North and South Detector Assembly Buildings and control and instrumentation rack systems for the Accelerator Systems String Test (ASST) Facility.[17]

Industrial Hygiene

Key industrial hygiene issues at the SSCL included chemical hazard communication,[1] chemical management,[2] and maintenance of positive control of oxygen deficiency hazards[3] caused by the extensive use of cryogenics. The SSCL took a pro-active approach to maintaining control of the chemicals used on site and to ensuring employee awareness of hazard information using the Material Safety Data Sheet (MSDS) program.[4] Chemical management was initiated with the purchase request,[5] with "follow through" labeling from receipt, to storage, to the end user, and through material consolidation and disposal as a waste product.[6] Other industrial hygiene concerns, such as noise,[7] exposure to lead,[8] and respiratory protection,[9] were addressed in the overall industrial hygiene program.[10]

To ensure personnel safety, oxygen monitors were employed where there was extensive use of cryogenics to alert personnel to oxygen deficiency hazards (ODH). The oxygen sensors provided input into the safety systems; these sensors were part of the Personnel Access Safety System (PASS). A large number of sensors were needed to provide adequate coverage at the SSC, resulting in conflicts between reliability and cost. The problem was resolved by choosing inexpensive electrochemical cells and made reliable by an innovative design. The design used a two out of three voting scheme.[11] Three proximate sensors were part of one circuit which would alarm only if two of the three cells detected a problem. In this way, false alarms were significantly reduced. This system also provided fault tolerance and ease of maintenance. Should a single cell fail during a running period, the cell need not be replaced immediately. This system was very reliable, operating with a 19.5% oxygen alarm threshold during the year at the Accelerator System String Test (ASST) and associated refrigerator buildings.

Industrial Safety

A challenge for the SSCL was the clarification of the applicability the Occupational Safety and Health Administration (OSHA) standards during the construction and preoperational phases of the SSC accelerators. The conflict arose between use of the operational[1] or construction[2] standards as they apply to equipment installation and preoperational testing of the accelerators. The Tunnel Safety Working Group findings[3] concluded that both standards apply for equipment installation and testing, with the exception of underground construction.[4] Underground construction standards do not apply directly as this activity is not considered civil construction. The Working Group recommended continued use of the standards for underground construction because of the "common sense" guidelines they provided.

Given that the superconducting magnets were to be code stamped,[5] a major hurdle stood in the way: the ASME Boiler and Pressure Vessel Code (B&PV) code did not cover application of the Code at liquid helium temperature. Use of 304LN stainless steel for the cold mass shell at liquid helium temperature, made it necessary to submit a Code Case to ASME. A formal request was made to ASME, along with supporting data showing that material properties are actually improved for 304LN as the temperature decreases below liquid nitrogen temperature. The Code Case was approved by ASME.[6] While the Code Case grants the use of 304LN, some additional testing is required to ensure material composition and fracture toughness, per (h)(5) of the Case.

Discussions were also held regarding the applicability of OSHA construction standards versus Mine Safety and Health Administration (MSHA) standards,[7,8] no final decisions were made. Day to day industrial safety, such as occurrence reporting, etc., was formalized and implemented in accordance with ES&H policy as established in the ES&H Manual.

Medical Program

The SSCL Medical Office opened in June 1990 with the hiring of one nurse, followed in November 1990 by a physician specializing in Occupational Medicine, as Medical Director. From the beginning the Occupational Medical Program as described in the Site Occupational Medical Plan, General Policies, was pro-active, emphasizing injury prevention rather than treatment. It included a heavy emphasis on wellness programs. Programs and accompanying documentation were developed over the following three years and were still in an evolutionary state when the project was canceled. Nevertheless, most elements of a sound occupational medical program were in place by the time of the cancellation.

The Site Occupational Medical Plan[1] was composed of a set of hierarchical documents consisting of Medical Policies, Medical Standards, Medical Procedures, and Medical Office Clerical Procedures. The Medical Policies represented the core of the Plan, defining the interaction of the Medical Office with the rest of the Laboratory. Medical Standards defined the scope of each type of medical examination and the criteria necessary for determining that the individual was medically fit to perform assigned duties safely. Medical Procedures including student nursing protocols provided the medical and nursing staff with detailed steps for performing procedures within the Medical Office.

Special attention was given to the oxygen deficiency hazard (ODH) Respirator and ODH Certification[2] criteria. This standard was developed to set exact criteria for medical clearance for use of respirators (including SCBA) and for clearance for work in ODH areas. A provision was also made for a variance procedure to allow for accommodation under the Americans with Disabilities Act.

The documents of most importance among those developed by the Medical Office are those related to compliance with the Americans with Disabilities Act. These consisted of the procedure "Work Activities Evaluation Process," [3] its associated Work Activities Evaluation forms, and SSC Laboratory Policy "Reasonable Accommodations." [4] Most recently, a form was developed to provide the Medical Office with complete information on respirator use, to enable proper medical evaluation of individuals using respirators. This also entailed changes to the Work Activities Evaluation forms that was in process at the time the project was canceled.

Quality Assurance

To integrate research and development practices, quality assurance principles and DOE contract requirements, a cooperative effort had to be exerted. To accomplish this task without limiting the creative nature of the scientists involved, the Program Management, Safety, and Quality organizations focused on the Laboratory program and contract compliance issues. Quality involvement helped provide consistency in the Laboratory's interpretation of administrative and contract requirements for the project. The SSCL Quality Assurance (QA) Program provided not only a graded approach to quality but the development of a strategy to determine how the graded approach should be applied within each organization.

The original contract imposed a DOE Order covering Quality Assurance[1] which adopted QA Program Requirements for Nuclear Power Plants[2] as a *preferred standard*. While the *basic* requirements of this standard were acceptable, the *supplemental* requirements were onerous, and totally unsuitable for the SSC. As a result, the Laboratory and the DOE Superconducting Super Collider Project Office agreed that only the *basic* requirements of Nuclear Power Plant QA program were required for the SSCL, and a Lab-wide QA Plan was implemented in 1991.

The issuance of a new DOE Order[3] with an implementation guide for research[4] represented tremendous progress in terms of integrating the quality principles from industry into philosophical underpinnings of how quality was done in DOE environments. The Research Guide contained two major sections—one for research and one for facility construction. The issuance of the DOE QA implementation guide for research provided an opportunity for affected organizations to tailor a QA program to the individual needs of the user rather than adopt a strict, across-the-board compliance system.

In order to meet schedule and performance milestones with a project as technologically advanced as the SSC, many activities had to be coordinated simultaneously without the luxury of conventional design review processes. Because a design may change several times prior to the delivery of a one-of-a-kind or prototype component or subsystem, close verification and monitoring of design, manufacturing and test processes were needed on a real-time basis. This verification and monitoring was performed on two levels. In the divisions, continuous monitoring of design, procurement, manufacturing, installation, and testing activities was performed. At the General Management level, quality program development and implementation was evaluated within each division. Critical suppliers involved in system design, manufacturing and testing are evaluated against contract and program requirements to assure that systems safely perform their intended functions.

Responsibilities for quality were extended by the participation of the SSCL Quality Assurance Office in Accelerator Readiness Reviews (ARR) previously known as Operational Readiness Reviews (ORR) for each major machine developed and designed at the Laboratory. Quality Assurance promoted continuous awareness of DOE contract requirements, SSC Laboratory Quality Assurance requirements, and the Safety Analysis Report requirements—not an easy task in the scientific community. The process developed into a cooperative attitude in which physicists, scientists, engineers, safety and quality professionals worked together towards a common goal.

As stated earlier, the SSCL QA Plan complied with the DOE contract and DOE Orders[1,3,4,5] covering both basic and applied research activities at the SSCL. The QA Plan was supplemented by Laboratory QA Procedures (LQAPs) that constituted the Laboratory Quality Assurance Manual. Each division prepared and implemented a Quality Implementation Plan (QIP) for the activities performed by the division. During the development of the QIPs each requirement of the SSCL QA Plan was evaluated for applicability. The extent of application was determined by the nature, scope, scale, complexity and hazards associated with the technical, cost, and schedule performance of the activity. Each phase of the activity (design, fabrication, transportation, installation, and operation) was also evaluated in determining the extent of application. The divisional QIPs were supplemented by Laboratory and divisional plans, standards and procedures. Each division could use the LQAPs originated by the SSCL QA office or the division could develop its own QA procedures. The SSCL Quality Assurance Office categorized the applicable orders into the ten criteria of DOE QA Implementation Guide. The resulting matrix (similar to the Fermilab list) of orders also identified the organizations having primary implementation responsibility.

Radiation Safety

The nature of the radiation protection issues at the SSC was not unique. However, because of the accelerator size and beam energy some traditional accelerator health physics problems were more complex and needed innovative solutions.[1,2] Particularly challenging were muon shielding and groundwater protection. The potentially delicate situation of having a site spread throughout Ellis County, intermingled with the public—literally below their homes—was handled by developing very stringent environmental radiation design criteria[3] and a sophisticated hydrodynamic independent model for groundwater activation limits. These criteria set more strict standards than what had been normal practice at accelerator laboratories, reflecting the SSCL policy for As Low As Reasonably Achievable (ALARA) goals. Also, included in the radiation safety design criteria was the expectation that regulatory bodies would continue to lower radiation exposure limits from the time the design was begun through the projected life of the accelerator—and yet it was unlikely that the accelerator shielding (especially for the main Collider rings) could be modified after completion of initial construction.

SSCL design criteria limited the annual "off-site" dose equivalent to 10 mrem or less from all sources of radiation.[3] One of the Director's goals for the SSCL was to keep the site as open to the public as possible, therefore, outdoor barriers and fences erected for radiation protection were to be used only as a last resort. For this reason, all the accelerator shielding was designed to reduce the dose equivalent in open areas, including the top of shielding berms, to less than 20 mrem per year, based on expected beam losses. For the possibility of an unlikely event such as a catastrophic beam loss, open areas were shielded to 10 mrem per event. Controlled areas, typically inside service buildings near the accelerator, were shielded to a dose equivalent of less than 200 mrem per year, and 100 mrem per accidental beam loss.

The shielding calculations were based on hadronic cascade Monte-Carlo shielding codes that have been modified to extend up to SSC energies.[4,5,6,7] The source terms for these calculations were based on expected beam losses and upgraded beam intensities. For some of the accelerators, the upgraded intensities represent a factor of 10 over the nominal annual design intensities. Shield thicknesses were determined from these calculations.[8] Software quality assurance was another concern addressed at the SSCL. This is especially important when calculations are performed by people at separate facilities. A proposal to address this problem that not only insured that proper versions of the codes were available for use, but also provided guidance on using the codes was advanced.[9] This proposal was under discussion when the project was terminated.

Muons produced by the high-energy beams caused unique shielding problems for the HEB Collider rings.[10,11] For example, muon beams are created downstream of proton beam loss points, such as the collision regions, scrapers, and beam backstops. For distances of 5 km or more the annual dose in the beam could exceed the 10 mrem limit. The radial beam size at the 10 mrem/year contour grows to only a few meters at the widest point. Therefore, because the 10 mrem/year contour line remains well below the surface, it was not necessary to purchase the land surface to ensure the off-site dose limit would not be exceeded. In areas where it was not necessary to own the surface, a volume of rock, known as stratified fee, was purchased at the elevation of the accelerator. Where stratified fee was purchased, the site boundary was interpreted to mean the boundaries of the underground purchased volume. The volume of rock defined was shaped to contain fully the 10 mrem/year contours. For simplicity, the cross section of the volume was defined as 100 ft high and 1000 ft wide. The length was adjusted in each case to ensure that at the end of the purchased volume the limit of 10 mrem/year would never be exceeded. At half the length of these vectors and at the ends it was planned to install muon monitoring stations to certify that nowhere outside the stratified fee volume did the annual dose exceed 10 mrem.

The design guideline for air activation was intended to limit the dose equivalent at the site boundary due to activated air to less than 0.1 mrem per year. This is the limit at which the Environmental Protection Agency requires monitoring of air emissions. To achieve this goal, air in the accelerator tunnel was to be circulated when beam was present instead of releasing it to the atmosphere. Also, the High Volume Air Circulation (HVAC) system for the experimental halls was to be designed to allow no more than 2–3% release of air into the environment when the beams were colliding.

One of the most important issues in the environmental arena is ground water protection. Therefore, it was very important to develop a process for calculating the amount of radioactivity produced in the underground rock and soil by beam losses and predicting the subsequent leaching and transport of the radionuclides in the groundwater. Prior to a site selection, an elementary hydrological model of a shallow well in proximity to the tunnel was used to determine the isotopic concentration in the water pumped from a well.[10] After the Texas site was chosen, the compatibility of this model with the site specific geology was evaluated. The Texas site hydrology is not compatible with the original model since water does not permeate uniformly from the surrounding rock into local wells. Since the host rock for the facility has low permeability, groundwater movement in the proximity to the tunnel must be through fractures. Realistic quantitative predictions of radionuclide concentrations in groundwater depend on understanding beam losses, radionuclide production, and on establishing a model which reflects the hydrology surrounding the accelerator enclosures.

A study of the geology and hydrology was undertaken by the Texas Bureau of Economic Geology (TBEG). Radionuclide production and leachability were studied by direct measurements. Samples of Austin Chalk, Taylor Marl, and Eagle Ford Shale, were collected from the coring operations and irradiated using a high energy proton beam at Fermilab. The results of a similar study of Fermilab soil in the early 1970's[12] are considered a bench mark, the results of the Ellis County study were compared to the earlier Fermilab study. The results of the SSC study[13,14] indicated that locating the SSC in the rock in Ellis County was a good choice from the standpoint of radionuclide production and leachability in the medium surrounding the tunnel.

The groundwater transport aspect of the model was based on the average radionuclide concentration produced in an "activation zone" surrounding the accelerator enclosures.[15] This zone, which extends 4 meters into the formation surrounding the accelerator, contains 99.9% of the induced activity produced in the ground. The average activation concentration is approximated by the radionuclide concentration one meter from the tunnel wall. This model has the advantage over well models because it is applicable for both point and distributed beam losses. Using this model, predictions of the radionuclide production and transport were made for all accelerators at the SSC based on expected beam losses. These calculations showed that the beam loss which could be allowed was well within the operating envelope of the injectors and collider with local shielding at expected loss points.

The key to protecting personnel from exposure to accelerator beams is the personnel access safety systems, also known as safety systems, or at some facilities, as radiation safety interlocks. Heretofore, such safety systems have relied heavily on relay logic due to the system's inherent high reliability and fail-safe nature. However, the size and in particular the distances involved in the SSC mandated the use of newer technologies. A prototype safety interlock system, known as the Personnel Access Safety System (PASS),[16] was developed for the entire accelerator complex and installed for use at the Accelerator System String Test (ASST) facility. The PASS design was based on Programmable Logic Controller (PLC) technology. Two complete programmable logic controllers referred to as PLC A and PLC B, were on line at all times using 1-out-of-2 voting scheme, meaning any one system can cause the system to shutdown, or conversely both systems must be running for the system to be operational. Each PLC was programmed independently by different programmers. The concepts of "fail-safe" and "redundant" were employed whenever possible. These systems operated for over a year, providing electrical and oxygen deficiency safety to personnel entering specified areas. Very few problems were encountered. There was complete confidence to proceed with this design for the entire accelerator complex.

One of the final SSCL shutdown and closure activities included the compilation and cataloguing of radiation protection and shielding documents into a Radiation Special Collection.[17] This collection includes additional information (i.e., notes, files and documents) used in determining shielding needs, and developing the radiation protection program.

System Safety

Perhaps the biggest challenge, from the ES&H perspective, in the design, construction, occupation, installation, commissioning and operation of the various parts of the project was the identification and mitigation of all hazards, compliance with all ES&H requirements, and satisfying all other bureaucratic demands—on time, the first time. There was neither time or resources to build any facility which could not be occupied on schedule. Everything had to be designed and built right the first time and the approval process had to be so smooth that no delays were encountered. The solution to this challenge was one of the most important ES&H developments at the SSCL. A formal systematic safety analysis and review process was created.

The qualitative safety process is consistent with the techniques taught at the University of Southern California (USC), which is endorsed by the System Safety Society. The process used at the SSC was similar to Department of Defense (DOD)[1] and National Aeronautics Space Agency (NASA)[2] system safety programs and processes, but with a scope appropriate for an accelerator laboratory, meeting the requirements of DOE.[3] SSC Laboratory Hazard Analysis Instructions[4], Procedures for Safety Report Selection and Development,[5] Hazard Reporting, Hazard Tracking, and Risk Resolution[6] were developed and were successfully used by the ES&H System Safety Engineers and line organization engineers to facilitate the implementation of the systematic safety process. For each major subsystem the systematic process was begun with the development of a formal plan, such as the SSC System Safety Program Plan for the Linear Accelerator (Linac).[7] Such plans specified the safety task requirements, responsibilities, subsystems to be analyzed, and the schedule for completing hazard analysis and safety assessment reports.

The next task was to develop the Preliminary Hazard Analysis (PHA). The hazard analysis process used a collaborative team effort of cognizant physicists, design engineers, and safety engineers who performed the hazard analyses and safety assessments of their system/subsystem designs and operations. Emphasis was placed on safety relating to facilities producing radiation or containing cryogenic liquids or high energy sources. Delegating detailed hazard analysis tasks to the professional experts and individuals closest to potential safety problems was the best method of detecting and identifying potential hazards and in implementing hazard prevention, elimination, and mitigation methods. During the hazard analysis process, engineers generated a complete system, subsystem, and equipment list prior to conducting a PHA. Hazards were identified and classified into low, medium or high risk categories based upon hazard severity, probability of occurrence, and consequence per the risk assessment chart.[4] An example of a comprehensive hazard analysis to the subsystem and major component level can be found in Accelerator Systems String Test (ASST) Safety Analysis Report,[8] Appendix A. The next step in the process was to eliminate the hazard by design modification or other mitigation techniques. Appropriate mitigation was often largely a matter of cost-benefit tradeoffs. The ultimate objective was to identify and eliminate or control all hazards by ensuring the hazard was indeed a low risk. Decisions on risk reduction were made by line organizations with concurrence from ES&H professionals.

Documentation was vital to the success of this safety process. Paper trails were very important to connect the hazard analysis, safety assessment, and hazard tracking/risk resolution system, but most importantly to help ensure hazards and mitigation actions are tracked and resolved in a timely way. A basic system for hazard tracking was created using a computer database to ensure that each hazard was documented and traceable from its initial identification until it was reduced to lower risk. This system verified that "as built" system hazards were mitigated and that risks were reduced to an acceptable level. For example, the Linac Lab Hazard Tracking Log[9] provided evidence to line management and readiness review personnel that all previously identified hazard analysis items and recommended actions were documented and traced, and that mitigation actions were actually put in place and the items verified as closed. This process lead to successful accelerator readiness reviews and to obtaining permits from the DOE to operate accelerator facilities in a timely manner.

The last formal step in the systematic safety analysis and review process, prior to obtaining a permit to operate and commissioning, was to conduct a formal Accelerator Readiness Review (ARR) using a graded approach to validate that accelerator facilities could be operated with acceptable risk. The process for readiness reviews relied on the line division personnel presenting technical design information, and evidence of hazard mitigation, best engineering and management practices, and compliance with applicable requirements, to an independent team of experts. This team determined that mitigation was in place, and that systems could be energized with acceptable low risk. Independence was interpreted as including personnel from divisions other than the one doing the work. Technical presentations and readiness review checklists were an integral part of ARRs.

In summary, among the global and tangible benefits of the system safety process were that it followed an effective risk-based approach, and used a powerful safety management tool to drive and influence development of specific safety requirements for design specifications, safety systems, safety devices, safeguards, operational safety procedures, safety training, and other methods to mitigate hazards and risks. This process contributed significantly to ensuring a safe system the first time, on time.

PART VII. SPECIAL TOPICS

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Chapter 29. Survey and Alignment

(L. Ketcham)

It is essential to establish roles and responsibilities in the area of survey and alignment at an early stage of a project to avoid repetition of work and to coordinate the compatibility of diverse efforts. This was particularly true for the Department of Applied Geodesy (DAG), which had a global role requiring interaction and compatibility with many other groups throughout the Laboratory. The task is documented in the DAG Management Overview Document (MOD).[1] The baseline WBS structure had many limitations from the DAG point of view. The estimate ignored certain activities, in particular detector alignment, and was certainly not the result of a comprehensive bottoms-up cost estimate based on the roles and responsibilities described in the MOD. A reworking of the DAG cost estimate was in progress when the SSC project was terminated.

Budgeting Alignment Tolerances

Misalignment errors acceptable from a beam dynamics perspective must be distributed in the most cost-effective manner among various contributors. The contributors include magnet fiducialization, survey, and operational impacts on alignment. The adaptation of physics requirements to the tangible world has caused problems on successive projects. The long, thin geometrical figure of the control network used to align an accelerator gives poor absolute position to the level of millimeters. This is clearly not compatible with sub-millimetric physics requirements. The SSC approach, as had been the approach on previous accelerators, was to establish the theoretical beam line as the magnetic center lines of quadrupoles.[2]

The alignment error distribution for an SSC quadrupole is illustrated in Figure 29-1. The distribution of the physics alignment requirements between fiducialization and survey errors was established and documented in the 3B specifications of each machine [e.g., 3]. The conceptual design needed to meet the requirements was to be documented in the conceptual alignment plan for each machine [e.g., 4]. The fiducialization error budget is the uncertainty introduced by the need to relate the reference from a physics point of view (magnetic field, electronic center of a diagnostic device) to a tangible reference on accessible surfaces of the component. Because the reference system for the alignment is the magnetic field of the quadrupoles, the fiducialization error appears "twice" in the error propagation (see Figure 29-1).

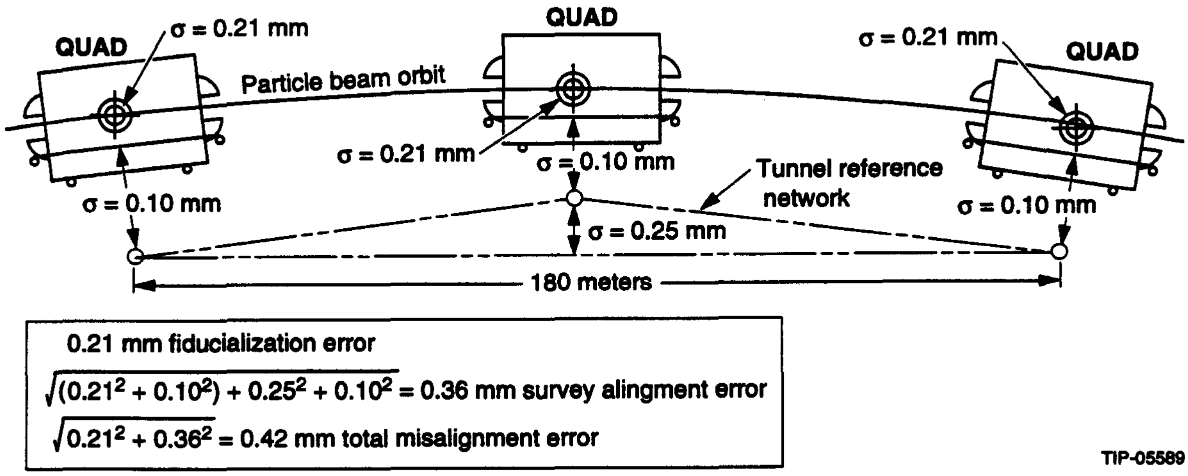


Figure 29-1. Quadrupole Alignment Error Sources.

The survey error budget arises from two major sources: first, the error accumulated during the measurement of the tunnel reference network; and second, the error associated with the measurement process to transfer position between the tunnel reference network and the components. The order of magnitude of the two error sources for the Collider quadrupole is illustrated in Figure 29-1.

As part of the process of choosing an adjustment mechanism, DAG performed a series of mechanical measurements on a couplet of Collider dipoles supported by a six-strut system. The aim was to detect eventual distortions introduced by the support mechanism and to verify the appropriateness of this technology. The software package DSRUT was developed to compute the changes in strut lengths required to adjust a component from a current location to a desired theoretical location.[5,6] For efficiency of production it was essential that fiducialization measurements be performed while the component was "warm." A series of tests were instigated using resources of MSD and DAG to ensure that the warm-to-cold correlation was sufficiently predictable to allow this method of fiducialization.[7]

Civil & Tunnel Construction Surveys

DAG produced a QA/QC plan to support the Conventional Construction Division.[8] Covered in the plan are the following topics as they pertain to the civil construction survey: coordinate transformations, design document reviews, data handling, and field surveys. The coordinate transformations involved the verification of the transformation of Site Cartesian Coordinate System (SCCS) coordinates into geodetic coordinates, the reverse transformations, and the verification of tunnel construction line data contained in the design packages. Reviews of the design document involved the review and approval of all A-E/CM conceptual survey designs and field and office procedures before they were implemented. The data handling involved the validation/verification of implemented software, the data capture and processing, and data acceptance and storage. The field surveys comprised the verification of fiducial networks, shaft locations, surface to tunnel transfers, and primary tunnel construction reference networks.

All proposed changes to the machine lattices were processed by DAG to verify that any movements in Virtual Survey Monuments were understood.[9,10] All alignment information provided by PB/MK to the subcontractor was verified by DAG to ensure that software employed by A-E/CM met requirements.[11]

The primary and most labor intensive QA/QC function in the civil construction survey effort was to verify that the bored tunnels met project requirements. The conceptual design of this activity is detailed in [12]. Three distinct activities are outlined in this document: verification of documented procedures, independent data processing, and independent field measurements. The verification of documented procedures involves the in-field/office checking that the approved procedures put forth by the A-E/CM are being followed. The independent data processing comprises the reprocessing of portions of contractor collected data to ensure that there are no biases, systematic errors caused by software, or undetected glitches in the processing of final coordinates. The independent field measurements involved DAG crews going into the tunnels and gathering data and processing it to independently verify tunnel orientations. The procedures for DAG field activities are described in [13].

The intent in software development was to produce a software package integrated across tasks. The general packages used for the QA/QC of the civil construction activities, namely PPROC, REDOB, ADLIB, are described in the discussion of software below. The program TCENT, which offsets and computes SCCS coordinates of the tunnel construction line from the lattice SCCS coordinates, was used to verify tunnel alignment information produced by the A-E/CM.[6]

All QA/QC activities were completed with the generation of a verification report. For independent tunnel verifications, the reports were sent to the CCD QA/QC officer, but most of the reports remained in the DAG document system. No mechanism, except for independent tunnel verifications, had been set up to handle the dissemination of verification reports. However, when discrepancies were encountered, appropriate measures were taken to have them resolved.[11,14]

Tunnel Reference Network

A precision reference network was required in each tunnel to support installation and alignment of the machine components. The tunnel reference network was a sequential series of monuments whose positional interrelationships were determined in a common coordinate system prior to component installation and alignment. Once in place, the tunnel reference network would provide the framework necessary to align and/or accurately define the position of machine components and other supporting hardware that would be location dependent. It would also supply the infrastructure required for the Facility Information System.

The difference between global and local requirements should be stressed. As an example, the requirement that the invert of the Collider tunnel differ at most -0.5 inches from grade should be interpreted as a deviation from the local datum (survey monument) and not as a maximum deviation from a sitewide theoretical plane. The concepts for the tunnel reference network could be divided into the surface densification, the surface to tunnel transfer of coordinates, and the tunnel reference network survey.

The role of the surface densification was to extend coordinates from the project fiducial control system to the locations where coordinate transfers would take place. The surface-to-tunnel transfer of coordinates was performed by plumbing the densified 3D reference points at the tops of the sight pipes, down through each pipe into the tunnel. Three dimensional coordinates had to be transferred into the tunnel at each end of the tunnel segment being surveyed (if the tunnel did not close on itself) to allow for tunnel survey closure. The survey of the tunnel reference network was required before installation of components could begin, and it required continuous access to the tunnel section being surveyed. A monopod system was designed to allow quick and very precise mechanical forced centering of the orientation and distance measuring instruments above the monument reference marks.[15] With the exception of some transfer lines and the utility regions of the Collider, network designs for all the machines had been completed.[16] The network for Linac had been installed, surveyed, and processed, and the results agreed very well with the theoretical design.[17] The current-at-termination-state of concepts (~50% complete) is contained in the document "Collider conceptual plan."[4]

Machine Installation Alignment

This can be defined as the alignment necessary for the make-up of the interconnect region between components. The process is explained in more detail in the conceptual plan for Collider alignment.[4] The machine installation and alignment could be subdivided into the support/adjustment mechanism installation and the actual component alignment. The survey for the support/adjustment mechanism could be performed using the tunnel reference monuments and by locating stand footprint templates in the tunnel, within the range of the adjustment mechanisms. The stand footprint would show all the required markings for bolt holes, stand base, etc., that would be required for installation. Obviously for the cold machines, the component alignment would occur before the interconnects were made up. The first step in any alignment system would be to make a quick check on component stability by measuring the relationships between the primary and secondary fiducials on the installed component in the tunnel and comparing them with the given "pedigree." The concept developed employs a minimum of one laser tracker. In the case of quadrupoles (with more stringent alignment requirements), two trackers were to be used. The tracker(s) were interfaced along with electronic tiltmeters to a control computer that would guide the entire process. The location of the tracker(s) could be determined by a 3-D resection from the tunnel reference network. Once positioned in the system, measurements could quickly be made to the fiducial reference fixtures on the components to determine the amount of adjustment required to position the component into its desired location. With the use of the six strut mounting and adjustment system, required changes in each of the strut lengths to obtain alignment could be computed and displayed to the operator. The technicians only had to measure independently the amount they were changing each strut length to adjust the component. Tests on prototype systems had shown this to be a very efficient method of performing the alignment. The same system could have been used on the resistive machines, but the tiltmeters would probably have been replaced by computing roll from the knowledge of additional fiducial locations. The concept worked in theory, but there was still much work to do in evaluating the robustness and capabilities of the laser tracker. This was, by far, the largest unknown in the process.

Machine Smoothing Alignment

The last activity before commissioning is the final beam path "smoothing," which can be simply defined as the bringing of the relative component alignment into specification. For the cold machines, active fiducial fixtures (a fiducial where an instrument can be mounted) would be deployed on the quadrupoles because these are the components that define the beam orbit.[3]
A network with a reasonable amount of redundancy could be established between quadrupoles to determine their locations relative to each other. The principle behind the network measurements is that although systematic errors will bias the measurements, as long as the systematic effects are

reasonably consistent, they can be removed from the final computation results. This is accomplished by fitting smooth curves to the quadrupole locations and analyzing the discrepancies between the curve and the computed position to determine the amount of misalignment. Any misalignments that exceeded the specifications would require readjustment of the component by the amounts of the computed discrepancies. The readjustments would be performed by making relative movements using the secondary fiducials and a laser tracker. Various designs of active fiducial fixtures and fiducial platform mounts had been looked at, but no final decisions had been made as the project ended. The analysis and design of how the network was to be measured and the type of curve fitting to be used were still in the beginning stages. The resistive machines were to use a very similar process except that network measurements would be made to the primary fiducials because no active fiducials existed.

Large Detector Assembly & Alignment

General activities related to experiment alignment largely dealt with the definition of the survey system to be adopted for the SDC and GEM experiments. The conceptual plan for the SDC detector was at a very preliminary stage. The main focus prior to Laboratory shutdown was to establish fiducials on the detector component when appropriate as part of the manufacturing process. The status of the process is documented in the SDC Conceptual Alignment Plan.[19] Other noteworthy activities undertaken for the SDC Collaboration were geometrical pre-analysis work for the Range Only Monitoring system[20] and the QC measurements performed on the toroid prototype blocks at Atommash in Russia.[21,22] The GEM experiment installation sequence and concepts were not sufficiently advanced to start work on alignment concepts. Interface Control Documents were established between DAG and the detector subsystems.[23]

Preliminary designs of fiducials for the detector components were drafted, along with proposals for interchangeable targets to be deployed at the fiducials. Other monumentation remained to be detailed, although designs of wall brackets employed at CERN were felt to be adequate, with minimal adaptation, for use at the SSCL. Monumentation developed for SSCL machine alignment activities was also likely to be adapted for experiment alignment activities.

Available measurement techniques had been identified, although, as indicated above, specific applications were still to be decided. Triangulation and optical tooling were two of these techniques, both of them being employed at other labs and in industry. Polar observations with the aid of the "Laser Tracker" were showing promise, and the application and testing of this instrument during the early machine alignment activities were being closely followed. Developments in photogrammetry (especially digital photogrammetry) were also being monitored for potential use at the SSCL.

The specific experiment alignment activities were initiated with the design of a minimal control reference network for the experimental hall. The exercise allowed the definition of conceptual interface requirements for survey wall brackets and a minimal set of essential "lines-of-sight." The documentation was included in the experimental facilities requirements for the experimental caverns. A particular problem unique to the SSC was to assure the alignment interface between machine and experiment. The problem arose because of the length of time required to install the experiments and the limited lateral adjustment of the ensemble in the detector design. The concept was to use geotechnical instrumentation (inverted pendula) to provide a stable datum independent of movements caused by the cavern and the weight of the experimental apparatus.[18]

Data Management System

It was decided early in the involvement of the group at the SSCL, that a database would be required to manage the large quantities (by survey standards) of data that would be generated. An initial assessment of the needs of the group was documented in the Data Management and Processing Plan,[24] which detailed data to be stored, software interface and user interface requirements, and a schedule for the whole project. Owing to a general lack of experience and resources in the field, Information Services were asked to aid in the development of a data management system, using an Oracle relational dataBase.

A number of software applications were developed for the processing and analysis of geodetic survey data. Testing and documentation of the applications had begun as the project shut down but were far from complete.[6,25] A Software Management Support Document[26] detailing a management system for software version control, together with software documentation requirements and guidelines, was completed. It was to be supported by a number of technical documents on general geodetic subjects detailing the mathematics on which the software development was based.[27,28]

Documentation of the database development as of termination consisted of the project notebook and other accompanying background information. Completion and compilation of these notes were in progress.[29] A Data Flow Diagram depicting a generalized view of the DAG processing system was developed, and a Project Requirements Specification providing information about the identified processes was written. Sufficient detail for development of appropriate software and user interfaces was absent from the documentation as the project ended.

The design of the database was initiated following the identification of the processing system. A data dictionary was developed. Subsequently a prototype system permitting the upload of field data, the browsing of data, and the integration of several DAG software applications was developed. As a result of the prototype development, a more complete data dictionary, listing the entities and their attributes, and Entity-Relationship Diagrams showing the relationships between those entities for the three sub-systems were generated. As they now stand, these documents are complete, but the reasoning behind the choices and the decisions made could not be included before the Laboratory closed down.

Software

Because the aim was to minimize hand editing of files, output files from one program were designed to be input files for the next program in the chain. Software development as the project ended focused on a set of programs to perform basic tasks, namely, data capture, coordinate transformation, observation preprocessing, observation adjustment, and result post processing. The data capture software was called DTCAP.[6] It was designed to work on data collectors or PCs (e.g., Paravant and laptops) for automating and QA/QC of the "in field" data collection process. All electronic survey instruments in use in DAG (i.e., Leica: ME 5000, T &TC 2002, 3000, 1600, 1610; and DMT gyro theodolite) can be interfaced and have collected data using this program.

Two coordinate transformation software packages exist: LATTC[25, 28] and LATCV.[6,28] LATTC transforms coordinates between all the different geodetic systems being used on the project, including geoidal information. Version 2.4.0 of this program is fully documented and verified. LATCV, which transforms coordinate covariance data as well as coordinates, was designed to replace LATTC. Currently, it is fully coded but has only been partially tested and verified.

Observation preprocessing is performed by PPROC[6] followed by REDOB.[6,24] PPROC computes, and applies meteorological and calibration corrections to the observations. REDOB was created to reduce observations to the datum where the least squares adjustment is to be performed. Gravimetric, geometric, and projection to a mapping plane are all rigorously computed and applied. Observation adjustment is performed by ADLIB,[6] which is a software program created to obtain an estimate by least squares of 1D, 2D, and 3D coordinate values. Many observation types are accepted by this program, including horizontal and slope distances, directions, azimuths, angles, horizontal offsets, zenith distances, and leveled heights.

The following post processing software packages were being developed by DAG as the project ended: PRJ1D, PRJ2D, and XFORM.[6] The programs PRJ1D and PRJ2D were created to compute the "best" 1D and 2D datum independent displacements from two independent epochs of observations. A full rigorous error propagation is performed with the displacements tested against a user defined confidence interval for significance. The full documentation for these programs had not yet been completed. XFORM was designed to estimate by least squares the parameters for a Helmert transformation between two Cartesian coordinate systems.

Chapter 30. Collider Cold Bore Tube Vacuum

(W.C. Turner and A.W. Maschke)

The problem encountered in the Collider cold bore tube vacuum is how to deal with the combination of superconducting magnets and the gas desorbed by synchrotron radiation produced by the circulating protons. Refer to Chapter 8 for a brief overview of the Collider vacuum issue at the SSC. The cryosorbing bore tube is effectively a quasi-closed system; tightly bound gas is steadily converted to loosely bound physisorbed gas by photodesorption. The desorption coefficients of the tightly bound gas, and therefore their contribution to beam gas density, decreases with continued photon exposure. However, the build-up of physisorbed gas leads to two sources of beam gas density increasing in time: the isotherm density of the physisorbed H_2, and the density due to photodesorption of physisorbed gas. If the average or local gas density limits are exceeded, then the beam tube would need to be warmed up (to ~20 K), the physisorbed H_2 pumped out, and the beam tube cooled back down to resume operations.

For the Collider, the basic question was whether the frequency of beam tube warm-ups required for a simple 4.2 K beam tube, as envisioned in the baseline design, would be low enough not to be unduly disruptive of operations. Otherwise, some type of liner, or distributed pumping system, may have had to be installed. To answer this question it was necessary to re-start an experimental photodesorption program and develop a beam tube vacuum model. Together these would allow one to predict the frequency of beam tube warmups without a liner and to specify the conductance of holes if a liner were needed. Because of schedule pressure from the magnet production program it was also necessary to start a prototype liner design activity in parallel with the experimental program in the event that a liner was necessary. In addition, a number of other activities were started: electron desorption experiments, measurement of the H_2 depth profile, measurement of 4.2 K sticking coefficients, alternative beam tube plating techniques and measurements of the pumping speed, and pumping capacity, of various cryosorber materials.

During this new era of Collider vacuum work, two technical meetings were hosted at the SSCL devoted to the common vacuum problems of the SSC and the LHC at CERN. Collections of vugraphs presented at these meetings were distributed to the attendees.[39,40] A bibliography of papers that have been written describing progress in these areas is given at the end of this chapter. To group the papers according to subject matter, the bibliography is subdivided into sections paralleling the organization of this report: overviews, vacuum modeling, photodesorption experiments, ancillary experiments, beam tube resistivity, liner options, and alternative beam tube vacuum options. Technical overviews of the Collider cold bore tube vacuum problem can be found in Refs. [1-4].

The vacuum requirements and their derivation are discussed in the introduction to Ref. 1. The global requirement is that the vacuum limited luminosity lifetime due to beam gas scattering exceed 150 hrs. This limits the average beam gas density inside the Collider beam tube to 3×10^8 H_2/cm^3, 3.3×10^7 CO/cm^3, etc., for molecular species taken separately. The local requirement on gas density comes from the maximum power that can be deposited in the magnet cryostats before increasing temperature causes a runaway increase in beam gas pressure and/or a magnet quench. The local gas density limits are 4×10^{10} H_2/cm^3, 4.3×10^9 CO/cm^3, etc. The third requirement is that beam tube warm ups for vacuum maintenance not be too frequent so that excessive loss of operation time is avoided. For design purposes approximately one beam tube warm up per year has been taken as a goal.

The primary vacuum experiments still needed before a complete modeling of the Collider vacuum could be done are: measurements of molecular sticking coefficients, measurement of the mean molecular speed of photodesorbed molecules (or equivalently direct measurement of gas density inside the 4.2 K beam tube), and long-term exposure measurement of the photodesorption coefficients. Measurements of sticking coefficients have begun at BNL and are likely to continue. At the time of writing this report, it appears that direct measurement of density inside a 4.2 K beam tube will be done at BINP, Russia, with an H^-/H^+ beam before termination of their contract with SSCL in June 1994. "Long term exposure" means approximately one year of integrated photon flux at design intensity, or ~2×10^{23} photons/m. Current measurements at 4.2 K extend to ~10^{22} photons/m, or ~ten days of operation at design intensity (10^{16} photons/m/sec). A high intensity synchrotron radiation beamline was constructed at BINP a 2×10^{23} photons/m experiment. It was intended to include a task in the BINP contract to perform this measurement once an understanding of how to do cold tube photodesorption experiments had been achieved. This understanding is now in hand, but the BINP contract was not modified to include such an important task before termination of the SSCL. However, the interest in doing this experiment is high at BINP and they may do it without funding from the SSCL.

The outstanding issue with the Collider cold bore tube vacuum was whether to proceed with the baseline concept of a simple 4.2 K beam tube identical with the superconducting magnet bore tube or to install a liner. Recent cold tube photodesorption experiments on electrodeposited Cu [1,8] favored the liner approach. The SSCL was awaiting long-term exposure ~2×10^{23} photons/m photodesorption results before reaching a final conclusion. Two outstanding technical issues for the liner were: demonstration of a cryosorber with sufficient H_2 pumping speed and pumping capacity, and understanding the contact heat transfer characteristics of sliding supports between the liner and the 4.2 K bore tube. The need for a cryosorber could be eliminated by lowering the cryostat temperature to reduce the saturated H_2 isotherm density to the required range. For the SSC the required temperature would be ~3 K and a decision was made early on not to pursue this route. A critical concern for the "4.2 K" liner is the uniformity of the synchrotron radiation heat load transferred to the 4.2 K cryostat and the possibility of localized heat transfer inducing a quench of the superconducting magnets. For the 80 K/20 K concepts, the concern is instead the possibility of thermal shorts to the 4.2 K cryostat.

The pumping speed of the cryosorber should be chosen to be large compared to the conductance of the liner holes so that the cryosorber is not the limiting factor. One choice is to locate the cryosorber on the 4.2 K magnet bore tube. However, utilization of the very high effective area of charcoal due to the matrix of very fine pores depends on the surface mobility at 4.2 K. If the surface mobility is not high enough, there is technical risk that the enhanced capacity compared to a bare metal surface may not be realized. A contract was in place with CEBAF to do these measurements over a temperature range of 4 to 20 K, and an appropriate experimental apparatus had been assembled. However the basic measurements of pumping speed and capacity had not yet been made for charcoal and other candidate materials at the time of this report. Barring unforeseen difficulties, CEBAF intends to complete these measurements over the next couple of months. Another possibility is to apply the cryosorber to the outside of the liner, and this is attractive from a fabrication viewpoint. If the temperature of the liner increases somewhat above 4.2 K when exposed to synchrotron radiation, the pumping characteristics of the cryosorber could even be improved because of increasing surface mobility. The caveat is that the liner temperature must remain low enough not to thermally desorb the hydrogen, (probably below 20 K). The liner temperature depends on the critical issue of what can be achieved for the contact thermal conductivity of the sliding supports with reasonable mechanical loading. Measurements of thermal conductivity were made for the 80 K liner concept[23] and were being planned for the "4.2 K" liner when the SSCL was terminated.

Collider Vacuum Modeling

Modeling of the Collider beam tube vacuum is described in Refs. [5 to 7]. The emphasis in Ref. [5] is on the cryogenic impact of beam gas scattering. A maximum local beam gas density requirement is derived there and corresponds to about 0.6 W/m of power deposited in the magnet cryostats due to shower products from beam gas interactions. Ref. [6] describes fits of the measurements of desorption coefficients with a diffusion model parametric dependence. Ref. [7] describes model equations for computing the Collider beam tube vacuum pressure, including the photodesorption coefficients of tightly bound and physisorbed gas and the H_2 isotherm.

Simple 4.2 K Beam Tube Without a Liner

As described in Ref. [7], the H_2 density in a simple 4.2 K beam tube, long enough that axial diffusion can be neglected, is a sum of three terms due to photodesorption of tightly bound molecules, photodesorption of physisorbed molecules, and thermal desorption of physisorbed molecules. The tightly bound molecules are converted to a steadily increasing surface density of physisorbed H_2. Too high a surface density of H_2 can lead to degradation of luminosity lifetime, or to exceeding the local density maximum, due to either of the last two terms. Ref. [7] also considers the case of short beam tubes where axial diffusion is not negligible. This is important for the interpretation of photodesorption experiments and for defining the maximum axial length of beam tube that can be effectively pumped from the ends.

Liner

The gas density in a liner configuration depends only on the desorption coefficient of the tightly bound gas and, perhaps somewhat surprisingly, not on the desorption coefficient of gas physisorbed to the liner, and not on the equilibrium isotherm density of H_2. For this reason it is simpler to specify conservative parameters for a liner that will give adequate vacuum performance than it is to demonstrate that a simple beam tube without a liner will or will not meet the vacuum requirements. The origin of this result is that the inside surface of the liner is not a closed system and the surface density of physisorbed gas reaches a quasi-steady state. A consequence of this analysis was the realization that the best way to measure the desorption coefficient of tightly bound gas is with a liner configuration, and the best way to measure the photodesorption coefficient of physisorbed gas is with a simple 4.2 K beam tube. This idea was applied with success in the cold beam tube experiments at BINP. The photodesorbed gas accumulates behind the liner out of the view of the synchrotron radiation photons. Sufficient cryosorber capacity (e.g., charcoal) must exist in the annular region behind the liner to keep the H_2 density below the requirement and well below the isotherm saturation density. The purpose of the cryosorber is to increase the effective surface area for absorbing H_2 well beyond that of a bare metal surface, and the time between beam tube warm ups well beyond that required to desorb a monolayer of H_2.

Photodesorption Experiments

During the last two years of the project, photodesorption experiments had been done with approximately 20 candidate beam tube samples for the Collider. Experiments had been done at room temperature (294 K) at 77 K and at 4.2 K. Most of the room temperature experiments were done on the BNL NSLS UV ring. All of the 77 K and 4.2 K experiments were done on the VEPP2M storage ring at BINP, Russia. The emphasis of the simpler room temperature experiments was to survey a large number of different materials with photon dose 10^{23} photons/m, equivalent to half a year of Collider operation. The 4.2 K experiments are much more difficult because of the need for a LHe cryostat that can be continuously filled and the problems of determining the gas density inside a cryosorbing beam tube. Consequently, the 4.2 K experiments concentrated on establishing a valid experimental procedure with a single beam tube material, electrodeposited Cu produced by Silvex. This was accomplished with the cold tube photodesorption experiments completed at BINP in August 1993.[8]

At the time the SSCL was terminated, the plans for future cold tube experiments were: to develop methods of direct gas density measurement inside a cryosorbing beam tube, to duplicate the BINP cold beam tube cryostat apparatus at the BNL NSLS to increase the throughput of cold tube experiments, and to extend the integrated photon flux to the equivalent of one year of Collider operation, 2×10^{23} photons/s, with an electrodeposited Cu beam tube. In addition, it was planned to bring a small scale 4.2 K beam tube experiment online at the NSLS UV ring to do quick turnaround exploratory experiments. The large cryostat and small scale experiment would have shared the same beamline at NSLS. At the time of SSCL termination, a company had begun design work for fabrication of the large cryostat, the beamline for the small scale apparatus was in place, and an initial look at photodesorption indicated that the basic apparatus was working properly.

Photodesorption Experiments at Room Temperature (294 K)

The results of 294 K room temperature photodesorption experiments are described in Refs. [11, 12 and 13]. Experiments on Silvex electrodeposited Cu were done with and without magnetic field, with and without a 350°C vacuum bakeout, and with thermal pretreatment (700°C for 5 hrs.). Photodesorption coefficients were measured for H_2, CH_4, CO and CO_2 up to $\sim 10^{23}$ photons/m. Experiments were also done with high purity bulk Cu, with Fluhman electrodeposited Cu, and with Au coated electrodeposited Cu. All these experiments used the same standard NSLS cleaning procedure (degrease, alkaline cleaner, hot deionized water rinse, alcohol rinse and air dry) prior to installation in the vacuum system. High purity bulk Cu and electrodeposited Cu from the two manufacturers had the same photodesorption yields within ± 50%. A 350°C vacuum bake and a thermal pretreatment (700°C, 5 hrs.) both reduced the photodesorption yields by approximately a factor of two. Au coating over electrodeposited Cu produced no change in the H_2 desorption yield but decreased the yields of CO and CO_2 by a factor ~2.5. Magnetic field had only a small effect on photodesorption yield, indicating that photoelectrons leaving the surface play only a small role in photodesorption yield. When the SSCL was terminated, plans were in place to test photodesorption yields of several additional types of Cu plating, including chemical vapor deposition and physical vapor deposition. However, the general impression that was emerging from these experiments was that the photodesorption yields were relatively constant (within a factor of ~2) and independent of the method of manufacturing. The conclusion was especially evident in the similarity of high purity bulk Cu produced by Hitachi with the electrodeposited Cu. The conclusion is reinforced by the electron desorption experiments and measurements of hydrogen depth profiles described below.

Photodesorption Experiments at 4.2 K

Photodesorption yields were measured for one meter lengths of Silvex electrodeposited Cu beam tubes at 4.2 K. Some data were also taken at 77 K. (The results are described in Refs. [1, 8 and 9].) Earlier experiments during the CDG era are described in Refs. [10 and 11]. Subsidiary experiments measured the adsorption isotherms of H_2 and He at 4.2 K. The physisorbed H_2 was found to be ~100% desorbed when the beam tube was warmed to 20 K. Two configurations were studied: a simple beam tube and a liner. Analysis of the liner experiment gave the 4.2 K desorption coefficients of H_2 and CO, while the simple beam tube experiment gave the photodesorption coefficient of physisorbed H_2. This was the first time this information had been obtained in a beam tube geometry. The photodesorption coefficient of the physisorbed H_2 was found to be large and to depend linearly on the surface density of adsorbed H_2 up to approximately one monolayer, ~3×10^{15} H_2/cm^2. At one monolayer surface coverage, the number of desorbed H_2 molecules per incident photon is of the order of unity. For comparison, the 4.2 K desorption coefficient of tightly bound H_2 was measured to be initially 3×10^{-3} and at 10^{22} photons/m ~4×10^{-4}. This was considerably smaller than the desorption coefficients measured at room temperature. After less than one hour of exposure at ~10^{16} photons/m/sec, gas density in the simple beam tube configuration was dominated by photodesorption of physisorbed H_2. At ~10^{22} photons/m, the total desorbed H_2 at 4.2 K was 3.4 monolayers. The extrapolated total desorption yield for 2×10^{23} photons/m, or one year of Collider operation, is 10–20 monolayers of H_2. Desorption yields of this magnitude and the large desorption coefficient of physisorbed H_2 favor the liner approach to the Collider beam tube vacuum system, unless some practical means can be found that reduces the desorbable hydrogen by at least an order of magnitude. A byproduct of these experiments is that the liner concept was demonstrated to effectively shield the physisorbed molecules from the photon flux.

New Methods of Gas Density Measurement in Cryosorbing Beam Tubes

Direct measurement of gas density inside a 4.2 K beam tube is difficult. Two new methods were under development at BINP and BNL for use in photodesorption experiments. The concepts are briefly described in Ref. [1]. BINP has developed a method depending on neutralization of H^-/H^+ beams. This method has very high sensitivity and should be able to measure H_2 density well below the 3×10^8 H_2/cm^3 range of interest.[1] Initial experiments are planned to be conducted at BINP before termination of the SSCL contract in June 1994. A second method under development at BNL uses annihilation of positronium. A low energy positron beam, ~30 eV, near the maximum cross section for formation of positronium, is created by moderation of positrons from a ^{22}Na source in a tungsten foil.

Electron Desorption Experiments

A series of carefully controlled electrodesorption experiments were done at the SSCL and at the University of Texas at Arlington (UTA), under contract with the SSCL. The experiments led to two important conclusions. In the first instance, it was shown that the bulk diffusion was a negligible contributor to the total amount of desorbed hydrogen. The other conclusion was that the desorbable hydrogen came from the immediate area of the surface, and was largely independent of the metal surface used. For instance, there was very little difference between a clean gold surface and one made of OFHC copper. Typical surface coverages were around 3–5 $\times 10^{15}$ molecules/cm^2. A surface that had been exposed to air for a considerable length of time, or rinsed in tap water, would typically have about ten times more desorbable hydrogen on the surface. Ten different copper electroplating techniques were tested, and the desorption rates turned out to be largely independent of the technique used, even though there were orders of magnitude differences in the amount of bulk hydrogen in the material. Polishing the surfaces made no discernible difference in the desorption, either. This led to the conclusion that the Collider must either have a distributed pumping system (a.k.a. a liner), or that a method must be found to clean the surface before operation. Studies were ongoing at the time of project termination to determine whether or not an electron beam "scrubber" would work satisfactorily. As this report was written, results were inconclusive.

One of the suggestions that had been put forth early on was the notion that the desorbed hydrogen came from the bulk, by a diffusion path. Therefore, because the surfaces in the Collider would be near 4.5 K, diffusion would not be possible and desorption might not be a problem. This was not the case however. In fact, the experiments done with electrodesorption at low temperatures were consistent with desorption rates at room temperature, a not so surprising result because almost all the desorbed hydrogen was coming from the atomic layers nearest to the surface.

Ancillary Surface and Vacuum Experiments

H_2 Depth Profile with Nuclear Reaction Analysis

The depth profile of H_2 has been measured at SUNY-Albany for various beam tube materials using nuclear reaction analysis.[1,14] The results of these experiments are that all materials examined so far have < 100 Å surface layer containing a significant fraction 30–50% of the hydrogen observed in photodesorption experiments with exposure up to 10^{23} photons/m. The densities of hydrogen at the surface and extending into the bulk material were practically identical for Silvex electrodeposited Cu and high purity bulk Cu Hitachi 10100, perhaps surprising given the very different methods of production. The inference is that all materials acquire a similar hydrogen rich surface layer owing to exposure to atmosphere and/or the cleaning process. If it is possible to reduce the surface concentration of hydrogen in some way, the photodesorption will be reduced also.

Sticking Coefficients

An apparatus has been assembled at BNL for measurement of molecular sticking coefficients on beam tube surfaces.[1] The experiment uses a variable temperature gas doser and secondary electron emission spectroscopy to measure the surface build up of physisorbed gas. Preliminary results have been obtained for room temperature H_2, D_2 and CO on a 4–5 K clean Cu surface. It is likely that this work, started with a SSCL contract, will continue at BNL.

Microstructure Analysis, Thermal Pretreatment

Scanning electron microscopy has been used at VPI to examine cross sections of electrodeposited Cu beam tube samples. It was found that the Cu had a porous columnar structure with grain size ~5 µm and porosity ~20%. With heat treatment (700°C, 5 hrs.) the porosity was reduced to ~10% and the grain size increased to ~20 µm. Two thermally pretreated Silvex electroplated Cu tubes were prepared for photodesorption tests at the BNL NSLS UV ring. After thermal treatment the tubes were flash coated with 200–500 Å of Au to stabilize the Cu surface before venting to atmosphere and shipping to BNL. Thermal pretreatment (700°C, 5 hrs.) was found to reduce the H_2 and CO_2 photodesorption yields by a factor of two and CO by a factor of three compared to an untreated tube.

Beam Tube Resistivity

Low Frequency Resistivity

The low frequency resistivity (~kHz and below) of the beam tube wall must be low enough that it is practical to stabilize the resistive wall instability by feedback control. In the CDR the low frequency resistivity was specified to be equivalent to a 100 mm thick layer of Cu with residual resistivity ratio RRR = 30 at 4.2 K and B = 6.7 T. The specification was unchanged in the SCDR. In the 3B Specification for the Collider Arcs, the low frequency resistivity specification was revised to reflect the fact that it is the product of thickness *(t)* and conductivity (σ) that matters; the new specification was $\sigma_t > 2 \times 10^5$ Ohms^{-1}. The CDR is a special case of the new requirement. The effect of low frequency resistivity on liner designs including the Lorentz force and heating during a magnet quench are discussed in Ref. [16]. An additional consideration for the resistivity specification is that the resistive wall instability growth rate depends on the inverse cube of the beam tube inner diameter. The final thickness of Cu, the inside beam tube diameter, and the measured Cu resistivity should be chosen to be consistent with the resistivity growth rate originally specified in the SCDR: ~134 turns at 2 TeV injection. The low frequency resistivity of samples of electroplated Cu tubing were measured at 4.2 K with magnetic field in Ref. [17] and without magnetic field in Ref. [18].

High Frequency Measurements and Anomalous Resistivity

The high frequency resistivity (~GHz) should be low enough that parasitic heating of the beam tube wall by beam image currents is a negligible heat load to the 4.2 K refrigeration. In the CDR and SCDR the high frequency resistivity was assumed to be the same as at low frequency. Recently, the resistivity of 4.2 K samples of electrodeposited Cu at 1, 7 and 12 GHz were measured without magnetic field and reported in Ref. [18]. The measured resistivities were found to be significantly less than the low frequency values due to the anomalous skin effect, but still low enough that image current heating would not be a problem. This work was done at LANL under contract to the SSCL. It was intended to extend the measurements to include the effect of magnetic field at one of the short dipole magnet test stands at the SSCL. The SSCL was terminated when preparations for these experiments were under way and they were never completed.

Liner Options

Work related to liner concepts is contained in Refs. [3] and [19–30]. Additional work on the impedance of liner structures is contained in Refs. [31 to 37] and discussed below in the section "Impedance of Liner Structures." When design work on a liner was initiated in 1991, analysis and extrapolation of the very limited 4.2 K photodesorption data indicated that 4.2 K and 20 K liners could not meet the beam stability impedance budget and the vacuum design goals, whereas an 80 K liner met the requirements; the number of holes required to achieve an acceptable beam tube pressure was too large at the lower temperatures.[30] A collection of 27 reports describing the technical work done on the 80 K liner concept is contained in Ref. [29]. The original goal of this work was to design a prototype liner for the Collider that could be assembled on a half cell of the ASST. The purpose of the ASST test would have been to give a full system demonstration of solutions to the critical engineering issues: acceptably low thermal heat leak to 4.2 K, absence of thermal shorts, quench survivability, cryosorber performance and regeneration, interface with a beam position monitor, and recovery from a vacuum accident. In addition, the ASST tests were to demonstrate assembly and operating procedures. During the year following initiation of this design effort it became clear with the new photodesorption data that extrapolation of the earlier data to large photon fluxes was too conservative, and that 20 K and 4.2 K liner options could be specified that simultaneously satisfied vacuum and impedance requirements. Because of the perceived reduction in complexity, cost and risk of a 4.2 K liner compared to 20 K and 80 K liners, a management decision was made to redirect the liner design effort to 4.2 K. Some conceptual work and design calculations had started when the SSCL was terminated.

Cryosorber Development

Cryosorber development was crucial for pumping H_2 in any of the liner concepts. Basic data on pumping speed and capacity did not exist for a reliable design. It was intended to place contracts with experienced workers in this field and in particular to take advantage of the large amount of previous work done by the fusion research community. A contract was in place with CEBAF and a special purpose cryostat assembled there for measuring isotherms, pumping speeds, and pumping capacities of various cryosorbers. The apparatus achieved an unprecedentedly low H_2 background by using an extractor ionization gage housing immersed in LHe at 4.2 K to reduce H_2 outgassing from the wall materials. Isotherms were measured for bare metal surfaces down to background H_2 density ~10^5 H_2/cm^3, and work was beginning to measure the pumping characteristics of charcoal, anodized aluminum and porous metals. Contracts with LLNL, SAES Getters and Grumman were ready to be put into place in FY93.

Monte Carlo methods were used to examine the dependence of cryosorber performance on the number and width of cryosorber strips, on the location of cryosorber strips relative to the perforations in the liner, and on the annular gap width between the liner magnet bore tube. The results are reported in Ref. [19].

Impedance of Liner Structures

A liner would increase the impedance seen by the circulating proton beam because of the perforations and because of the decrease in the inner wall diameter. It was therefore imperative to gain a complete experimental and theoretical understanding of liner impedance to be sure that a liner could be designed that was compatible with the vacuum requirements without undue reduction of the safety margin for instabilities. An experimental apparatus was assembled for measuring the impedance of a 1m length of beam tubes with varying numbers and sizes of holes and slots,[35] analytical work was extended from circular holes to slots[33,37], and extensive numerical calculations were done with the computer codes MAFIA[31,32] and HFSS.[34] At the time of SSCL termination, this work was in good shape; the agreement between experimental and theoretical impedances was excellent, and the magnitude of photodesorption coefficients allowed the number of liner holes to be chosen small enough to allow adequate impedance safety margin. High frequency coaxial TEM modes propagating in the annular region between the outside of the liner and the magnet bore tube were also studied; up to 30 GHz, no coupling was observed between the inside and outside regions of the liner, so that it was concluded that the impact of these modes would be insignificant.[32]

Alternative Beam Tube Vacuum Options

Almost all the work on the Collider beam tube was done with electroplated Cu on a stainless steel tube. In 1993, an aluminum tube was proposed as a lower cost alternative.[38] The basis for this proposal was that an aluminum alloy could be specified that met the beam stability requirements and was strong enough to withstand quench forces with reasonable wall thickness. Considerable cost savings would occur because of eliminating the need for plating. Extruded configurations with perforated chambers for pumping photodesorbed gas out of the view of synchrotron radiation, thus fulfilling the function of a magnet bore tube plus liner, are also possible. The SSC termination occurred before this proposal could be given serious consideration.

Chapter 31. Ramp Rate Issues in HEB Magnets

(J. Tompkins, C. Haddock, G. Snitchler)

This section describes performance issues created by the ramp rate sensitivity displayed by the first 50 mm prototype Collider dipoles and the efforts undertaken to understand and decrease that sensitivity. Eddy currents, generated by the changing magnetic field during ramping, are a key factor in understanding these effects. The HEB, designed to operate at 62 A/sec, would be much more sensitive to ramp rate dependent phenomena than the Collider ring which was designed to ramp at 4 A/sec. While the ramp rate sensitivity is of greatest concern to the design and performance of HEB magnets, most of the performance data is from tests of the ASST dipoles and the discussions are largely about ASST magnet behavior. The observation of rapidly decreasing quench currents with ramp rate was the first indication of significant eddy current effects in some of the 50 mm dipoles. A second indication was the observation of the anomalous behavior of magnetic multipoles measured in hysteresis loops for the same magnets. A third indication came from measurements that looked at the total energy deposited in a magnet during a complete current cycle as a function of the ramp rate.

The study of the ramp rate sensitivity of the recent magnets focussed first on understanding the eddy current effects. The decay time constant for cable eddy currents is largely determined by the inter-strand resistance. The ramp behavior of one class of magnets was clearly dominated by eddy currents and is consistent with a very low average inter-strand resistance. The inter-strand resistance obtained in the final magnet assembly is the result of many aspects of the magnet fabrication, including the strand composition and processing (purity of the Cu, annealing steps, etc.), condition of the strand surface (oxidized, coated, etc.), coil molding (pressure and temperature; sequence; duration), collaring pressure, etc. The coil molding process is dictated in large part by the cable insulation and adhesive employed. Control of all of these parameters is necessary to ensure that the interstrand resistance is not too small. However, there is also the possibility that too high an inter-strand resistance might lead to quench instability since it prohibits current sharing in the conductor. Thus the issue of ramp sensitivity has potentially many variables to understand and control.

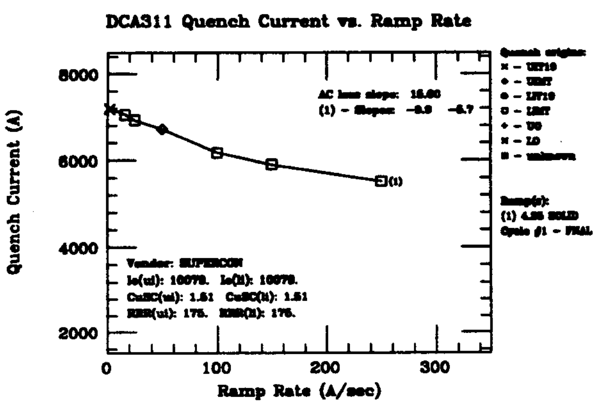
The discussions below include an overview of the results from the tests of ASST full length dipoles, the results of tests of early vendor produced model (short) dipole cold masses, a brief discussion of the program to solve the ramp rate issues (in which a major role was assigned to Westinghouse, the HEB dipole vendor), results from *in situ* inter-strand resistance measurements, and finally a discussion of the physical models developed to explain the observed behavior.

Ramp Rate Effects in ASST Dipoles

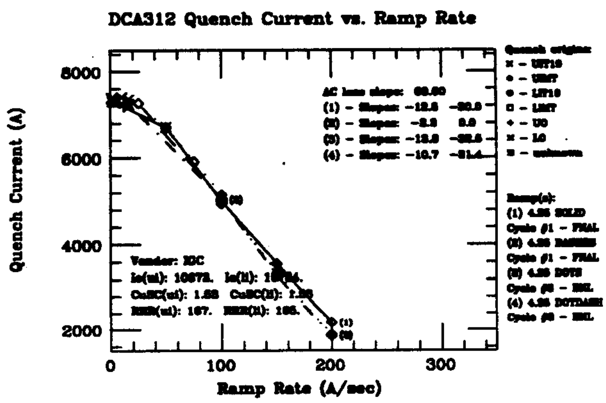
Quench Performance

The early ASST dipoles showed a sensitivity to current ramp rate (dI/dt) that had not been observed in the 40 mm magnet program.† During ramping, the changing magnetic field (dB/dt α dI/dt) causes eddy currents to flow in the conductor. If the resistance between strands in the cable is sufficiently low the time constant associated with the eddy currents is correspondingly large and the eddy currents can cause significant heating, raising the conductor temperature and thus lowering the quench current. The existence of low interstrand resistance points along the cable could also lead to one (or more?) strands carrying considerably more current (the sum of transport plus eddy currents) than the average and thus cause quenching at lower than the expected short sample limit. The influence of the eddy currents on the quench performance of the magnets was identified with the test of the first prototype at Fermilab, DCA311. The quench current reached a plateau below that expected from short sample calculations and the quench origin was not at the high field point on the pole turn. It was then observed that lowering the rate of the current ramp to quench increased the quench current and the quench origin moved to the pole turn.

Once the sensitivity of the ASST dipole magnet quench currents to ramp rate was identified, systematic studies of the quench current (I_q) vs. the ramp rate were made for all magnets.[1-4] All magnets were tested at ramp rates between 4 and 250-300A/sec at 4.35 K during their initial test cycle. On a few magnets, additional ramp sequences were performed during a second thermal cycle and at lower temperatures. The quench current versus ramp rate data for all of the full length 50 mm dipoles are displayed in Figures 31-1(a) through 31-1(s).[5] Multiple ramp sequences were run for several magnets: DCA312, DCA317, DCA322, DCA323, and DCA213. In general, the ramp rate results were very reproducible with only DCA213 showing some lack of consistency in the range ~20 < dI/dt < ~150 A/sec for the different measurement sequences. In tests at lower temperatures, similar slopes were observed with offsets in quench currents consistent with that expected from the change in temperature.



(a)



(b)

Figure 31-1.(a) thru (t) Quench Current vs. Rate Ramp.

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† The increased sensitivity to ramp was first observed at BNL in tests of short (model) 50 mm dipoles which had an all kapton-polyimide insulation scheme which was cured at a higher temperature than the standard kapton-fiberglass/epoxy insulation.

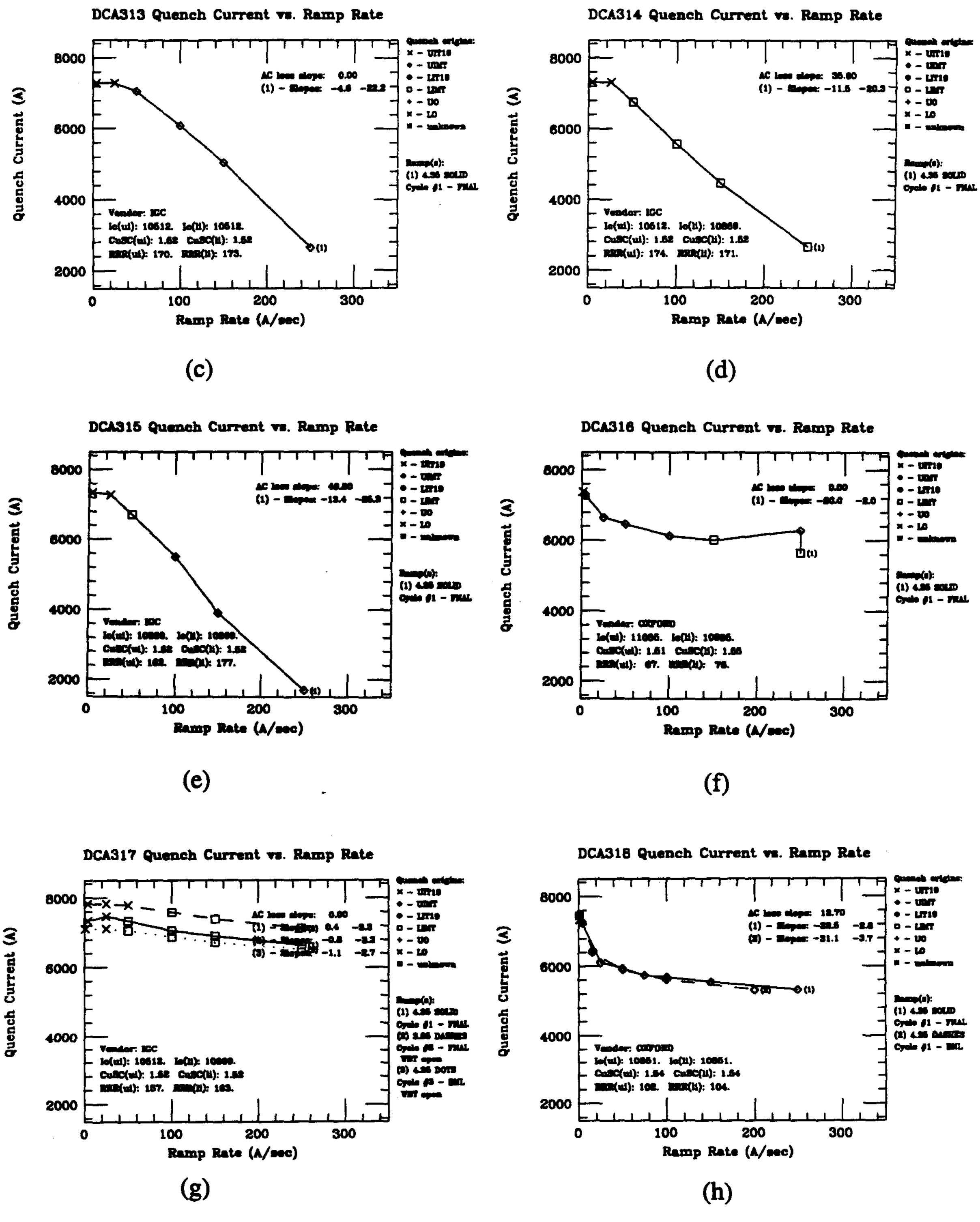


Figure 31-1.(a) thru (t) Quench Current vs. Rate Ramp (cont).

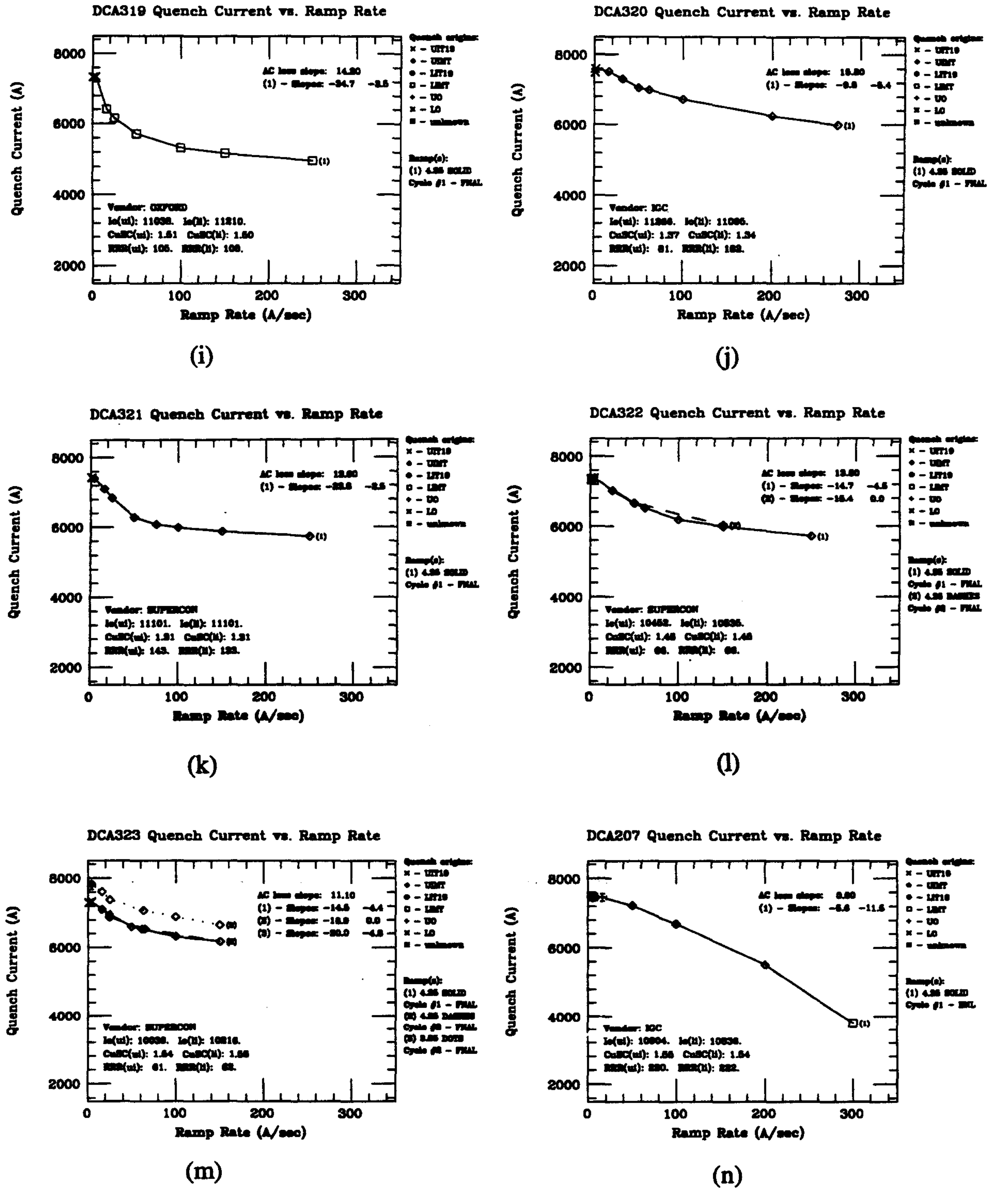


Figure 31-1.(a) thru (t) Quench Current vs. Rate Ramp (cont).

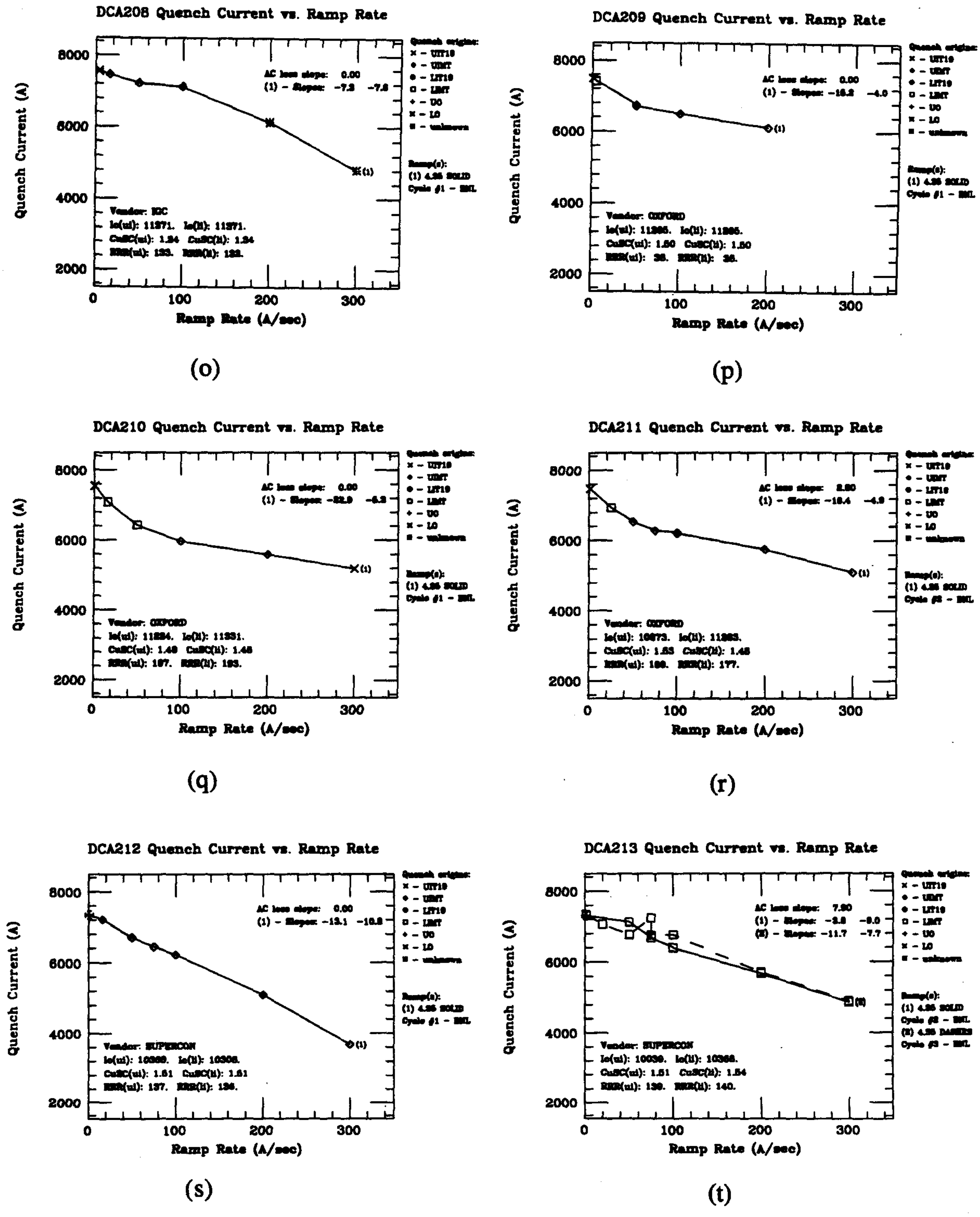


Figure 31-1.(a) thru (t) Quench Current vs. Rate Ramp (cont).

Figure 31-2 compares the quench current versus ramp rate for all of the magnets built at Fermilab. (For clarity, the BNL magnet results are not included in this figure because their tests were performed under significantly different cooling conditions owing to higher helium flow rates and an internal cooling scheme;# the same general behavior applies, however.) Examination of the data reveals an interesting pattern: at least two distinct classes can be identified. The first class of ramp rate dependence included magnets in which the quench current at low ramp rates was only slightly lowered but the current dropped precipitously at high ramp rates (above 50 A/sec). This class has been dubbed "Type A" magnets. The second class of magnets demonstrated nearly opposite behavior, having the quench currents drop dramatically at low ramp rates, up to about 50 A/sec, and then only gradually at higher ramp rates. This second class has been dubbed "Type B" magnets. There were also a few magnets that didn't fall into either of these classes, showing less overall sensitivity to the ramp rate. The Type A magnets—high sensitivity at high ramp rates—can be explained by models of the coil which have very low interstrand resistance and generate large eddy currents when ramped. The Type B magnets—high sensitivity at low ramp rate—are not as easily explained; detailed models of the superconducting cable behavior are being developed.[6-7] In both cases, the contact resistance between strands in the cable is considered to be a critical variable.

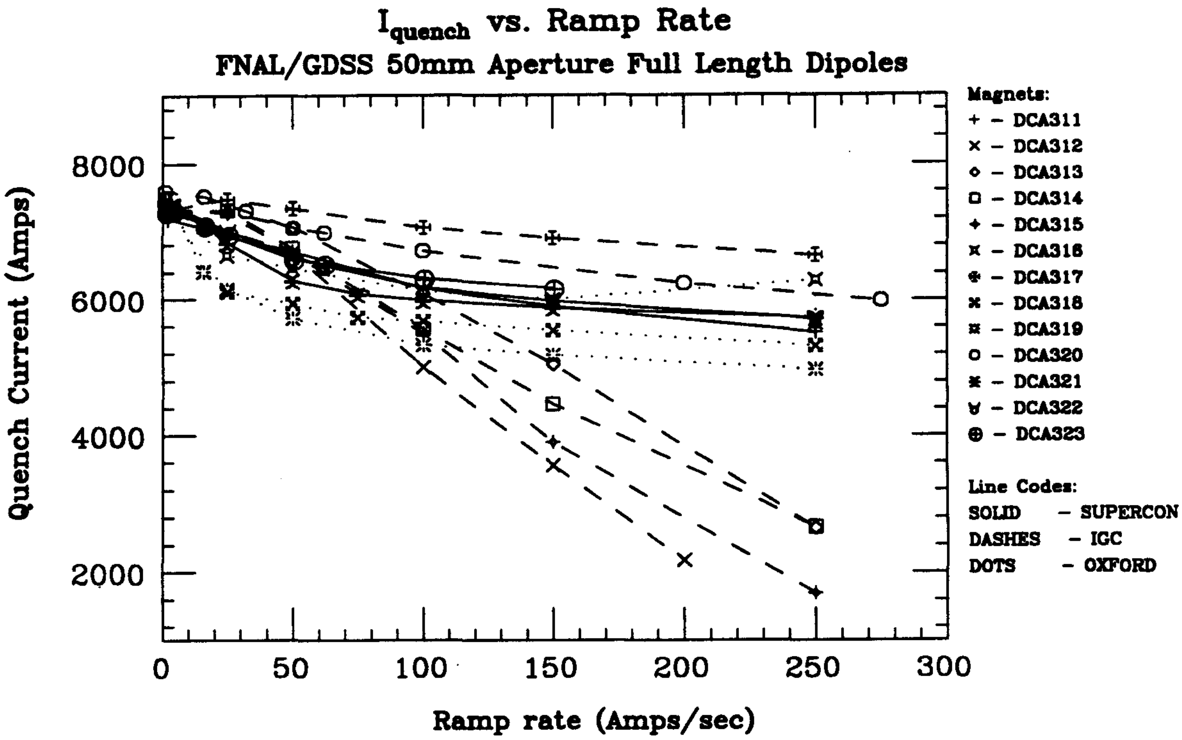


Figure 31-2. Quench Current vs. Ramp Rate for General Dynamics Magnets Built at Fermilab.

The magnets built and tested at BNL incorporated a modified helium circulation scheme known as "cross flow cooling." By blocking part of the parallel helium flow paths in the cold mass, cross flow cooling magnets have a large fraction of the flow directed transverse to the magnet axis and hence provide significant mixing with the helium in the annular region between the coil and the beam tube.

If the Fermilab magnet data are sorted by inner coil superconductor vendor, an interesting pattern appears. (See Figures 31-3 through 31-5.) There is a significant correlation of the different classes of behavior with conductor manufacturer: Type A - IGC (with magnets DCA317 and DCA320 showing decidedly less sensitivity) and Type B - Oxford and Supercon. However, the origin of the differences between manufacturers is not yet explained; there are differences in the details of the strand manufacturing that are being investigated. A summary of the ramp rate sensitivity investigations is given in Ref. [8].

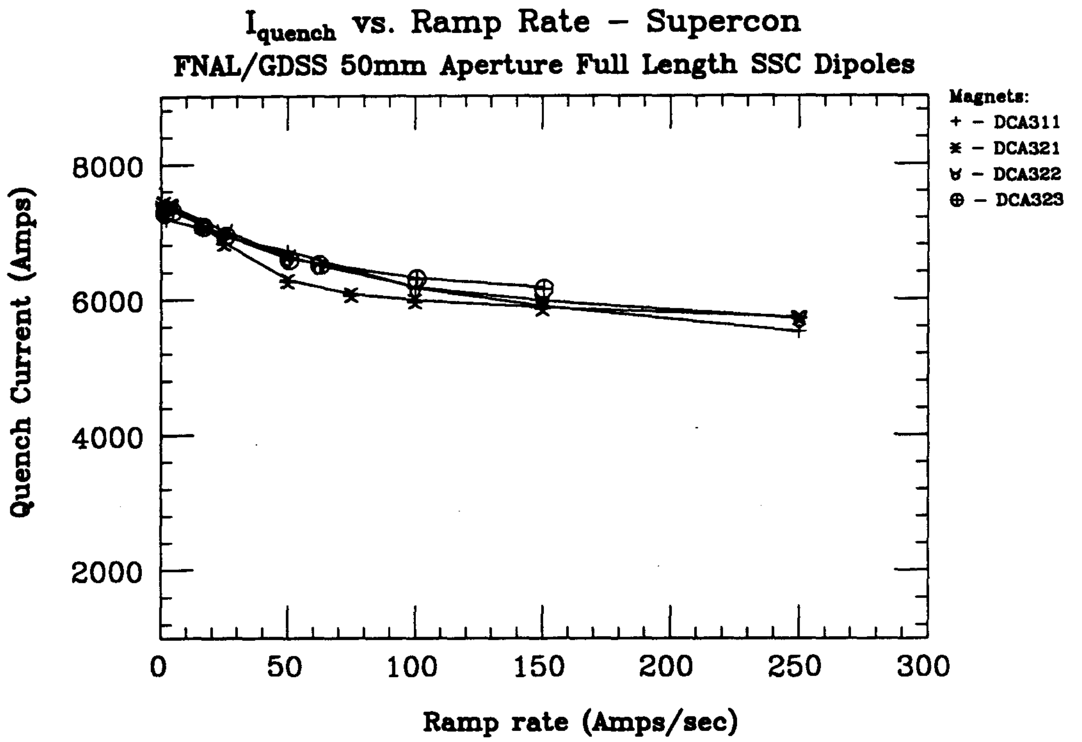


Figure 31-3. Quench Current vs. Ramp Rate Supercon Brand Inner Coil Superconductor.

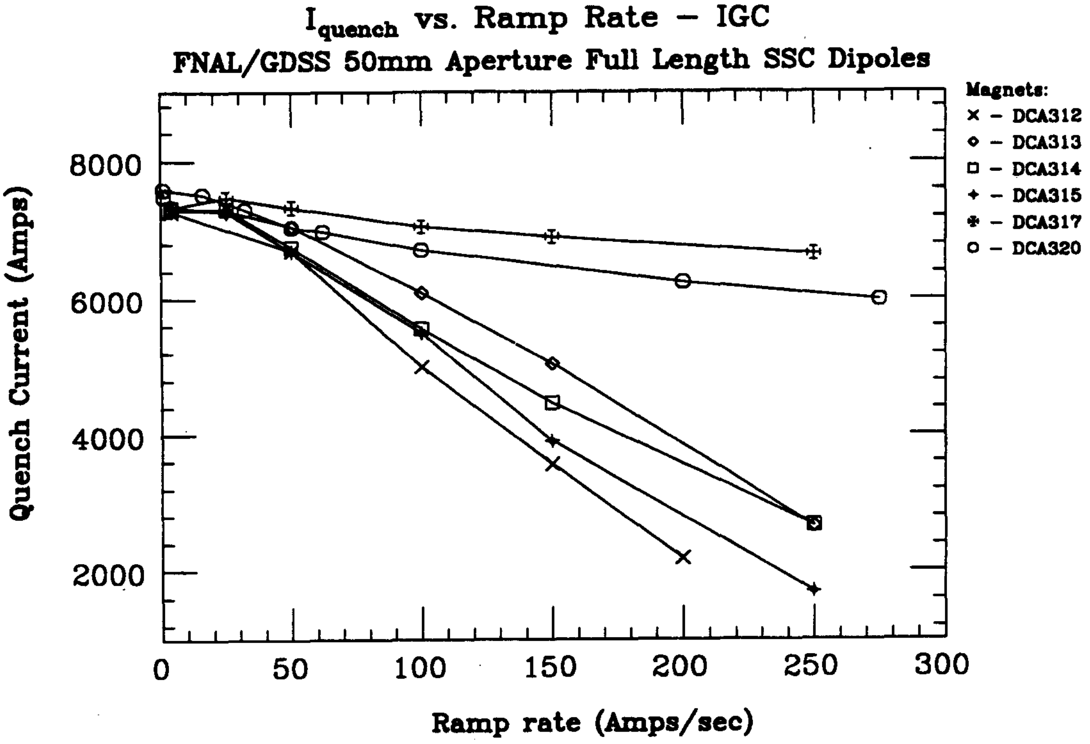


Figure 31-4. Quench Current vs. Ramp Rate IGC Brand Inner Coil Superconductor.

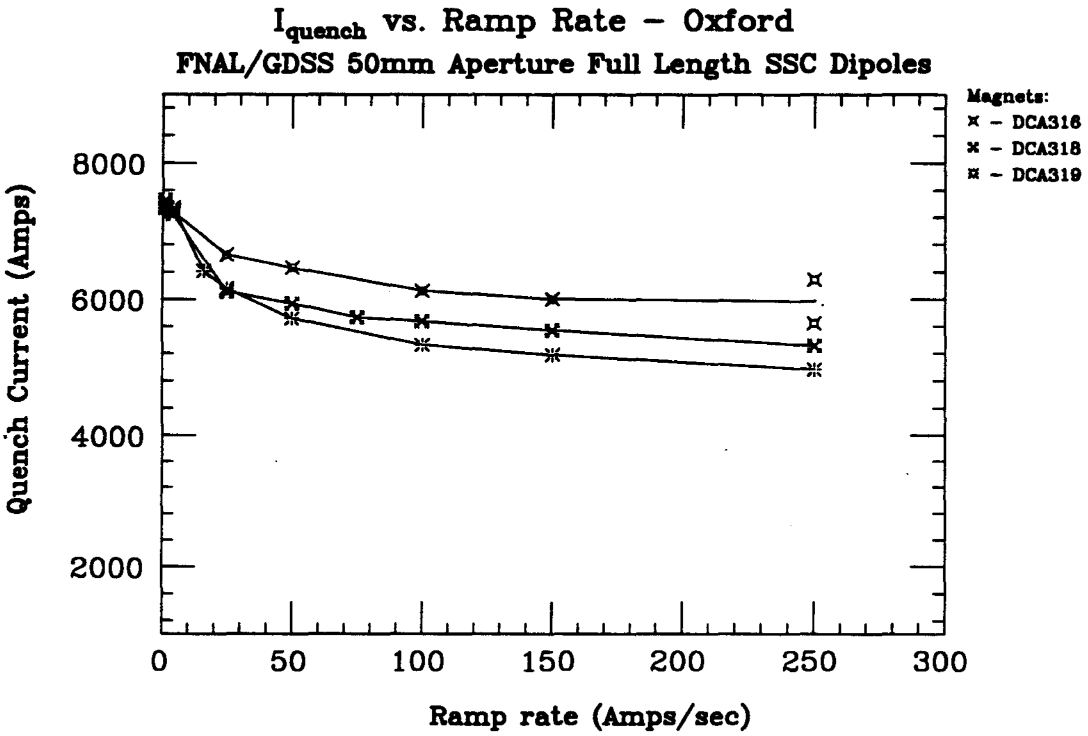


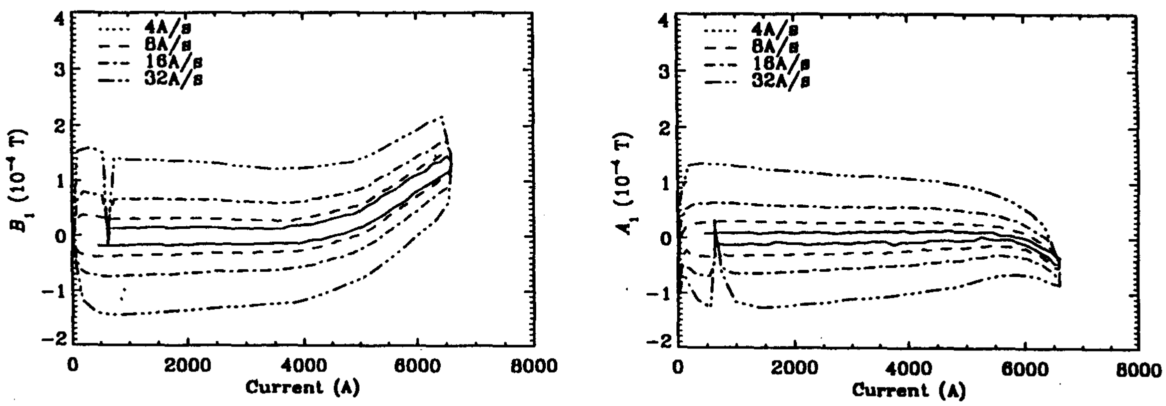
Figure 31-5. Quench Current vs. Ramp Rate Oxford Brand Inner Coil Superconductor.

The 4 A/sec ramp rate for collider operation does not present a quench current problem in the face of these data. The HEB, however, must operate at ramp rates of 62 A/sec, and the observed ramp rate sensitivity would be of concern. The quench data taken at 4 A/sec demonstrate plateaus well above the operating current which satisfy the Collider "margin" requirement of 10%. Studies of the down ramp behavior (ramping the magnet down from the operating current level at rates of 200 A/sec to 300 A/sec which could occur during Collider operation) indicate that there is sufficient margin to avoid quenching.

The issue of AC losses/ramp rate sensitivity in superconducting magnets has been dealt with at previous accelerators by controlling the surface of the conductor: the Tevatron coated alternate strands with either a resistive or a conductive coating; HERA employed conductive coatings; at IHEP/UNK, a resistive coating was developed by controlled oxidation during cable fabrication. These and other methods are presently under investigation for the SSCL cable, primarily for application in the HEB dipoles.

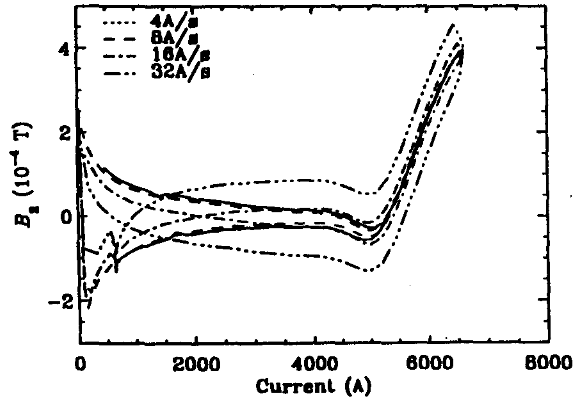
Eddy Current Induced Multipoles

The magnets that were most sensitive to high ramp rates also displayed anomalous behavior in aspects of their magnetic field measurement data. Hysteresis loops for several of the multipoles showed unpredictably large up-down ramp differences, and in some cases, the signs of the up and down ramp multipoles were opposite to what was expected from magnetization currents. (See Figures 31-6(a) through 31-6(d).) The width of the curves (up ramp versus down ramp) increases nearly linearly with ramp rate while staying nearly constant as a function of current. These are clearly characteristic of eddy current domination of the hysteresis loops. Note that the field strengths A_n,B_n, are plotted in T not the usual "units" which are normalized to the normal dipole component (e.g., $b_n = B_n/B_0 \times 10^4$). Discussions of the field harmonics and eddy current effects in ASST dipoles are found in Refs. [9-12].

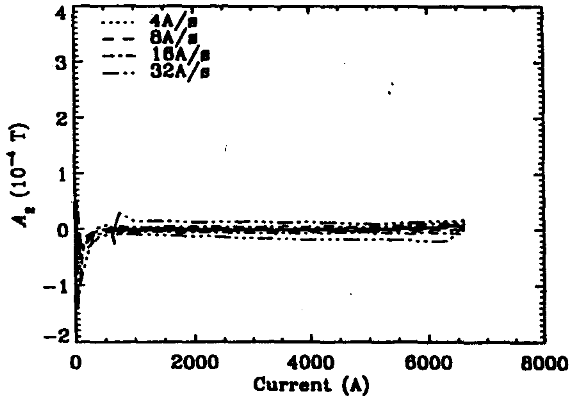


(a) (b)

Figure 31-6. (a) thru (d) DCA312 Low Order Multipole Components Measured at Ramp Rates from 4 to 32 A/sec.



(c)



(d)

Figure 31-6. (a) thru (d) DCA312 Low Order Multipole Components Measured at Ramp Rates from 4 to 32 A/sec (cont).

A detailed analysis of these data by Ogitsu[13] was able to explain the behavior in terms of eddy currents generated in the conductor. The analysis subtracted the known geometric and magnetization components to the multipoles and determined that the remainder was constant in magnitude over the current loop, changing sign when the ramp direction changes. This behavior is characteristic of eddy currents which depends only on dI/dt, not the magnitude of the current. A model was developed which used the strength and distribution of the eddy current multipoles to extract the effective inter-strand resistance. Results from this model are displayed graphically in Figure 31-7 for one position of the magnetic measurement coil, where the inter-strand conductance (1/R) is plotted versus the cable position in the two dimensional cross section. Extracting the interstrand resistance from data at one ramp rate yields consistent results at the other ramp rates which helps to provide confidence in the model. There are further discussions of models of the conductor behavior in the section on AC loss models.

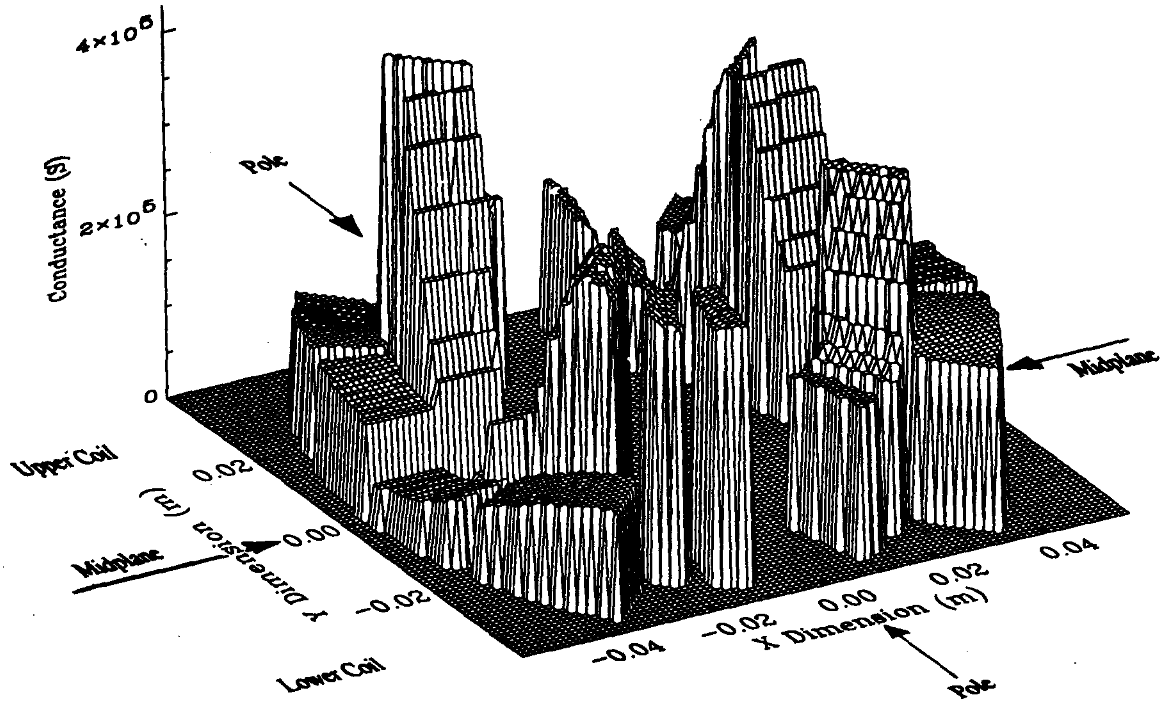


Figure 31-7. DCA312 Inter-Strand Conductance.

Energy In/Energy Out Measurements

As discussed in the quench performance section above, the observed sensitivity of the 50 mm dipoles' quench currents to the ramp rate (dI/dt), was an indication of eddy current heating. The rapid fall-off of the quench current with ramp rate for some dipoles implied large eddy currents within the conductor. However, the observed quench behavior could be a local phenomenon: it is possible to imagine situations where one section of the conductor might have high local heating or one strand having excess current due to a loop caused by low inter-strand resistance at isolated points, while the rest of the magnet would be relatively insensitive to the ramp rate. A measurement of the total energy deposited in the magnet can be made by "energy in - energy out" (EIEO) measurements: the difference between up ramp and down ramp energies as determined from direct measurement of the current and voltage of the magnet. The EIEO measurement characterizes the behavior of the bulk properties of the conductor and magnet.

High accuracy measurements of magnet current (I) and voltage (V) were made for "sawtooth" current ramps from 500 to 5000 amps at ramp rates of from 25 A/sec to 150 A/sec. (This version of EIEO measurements was developed by J. Strait, J. Ozelis, and M. Wake at Fermilab.[14,15]) The energy loss per cycle is plotted versus the ramp rate: a linear fit to the data yields a slope, energy loss/cycle/A/sec, which is related to the dynamic (eddy current induced) losses, and an intercept, energy loss per cycle, which is due to the hysteretic losses in the iron and the superconductor.† Figure 31-8 displays the EIEO measurements for magnets at Fermilab. There are clearly two classes of magnets: those with large dynamic losses (large slopes) and those with small dynamic losses (small slopes). The agreement among all magnets for the intercept (hysteretic losses) is quite good. The large dynamic losses occur in the same magnets that displayed the strong dependence of quench current on ramp rate. If the slope of the quench current vs. ramp rate data for ramp rates greater than 50 A/sec versus the slope of the energy loss per cycle vs. ramp rate is plotted, a clear correlation is visible: these data are presented in Figure 31-9. The magnets with high EIEO losses also have large quench current decrease with ramp rate. The agreement between the EIEO measurements and the quench current data at high ramp rates indicate that the eddy current heating affecting the quench currents in these Type A magnets is characteristic of the entire magnet, not a local effect.

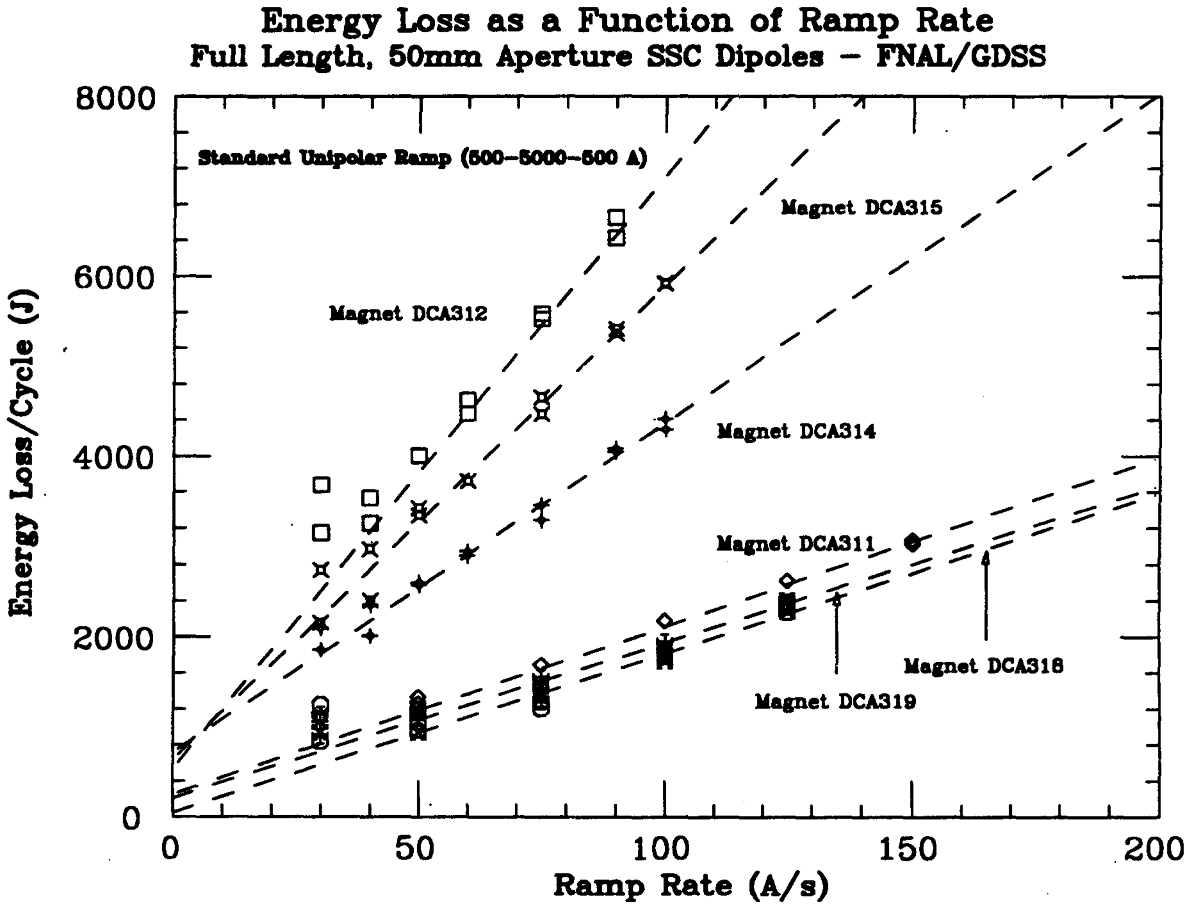


Figure 31-8. Energy Loss as a Function of Ramp Rate Full Length, 50 mm Aperture SSC Dipoles produced by General Dynamics at Fermilab.

† The Fermilab analysis, references [14,15], uses a nonlinear (quadratic) form for the fit; the analysis here is restricted to the linear form. See Ogitsu, Ref. [16].

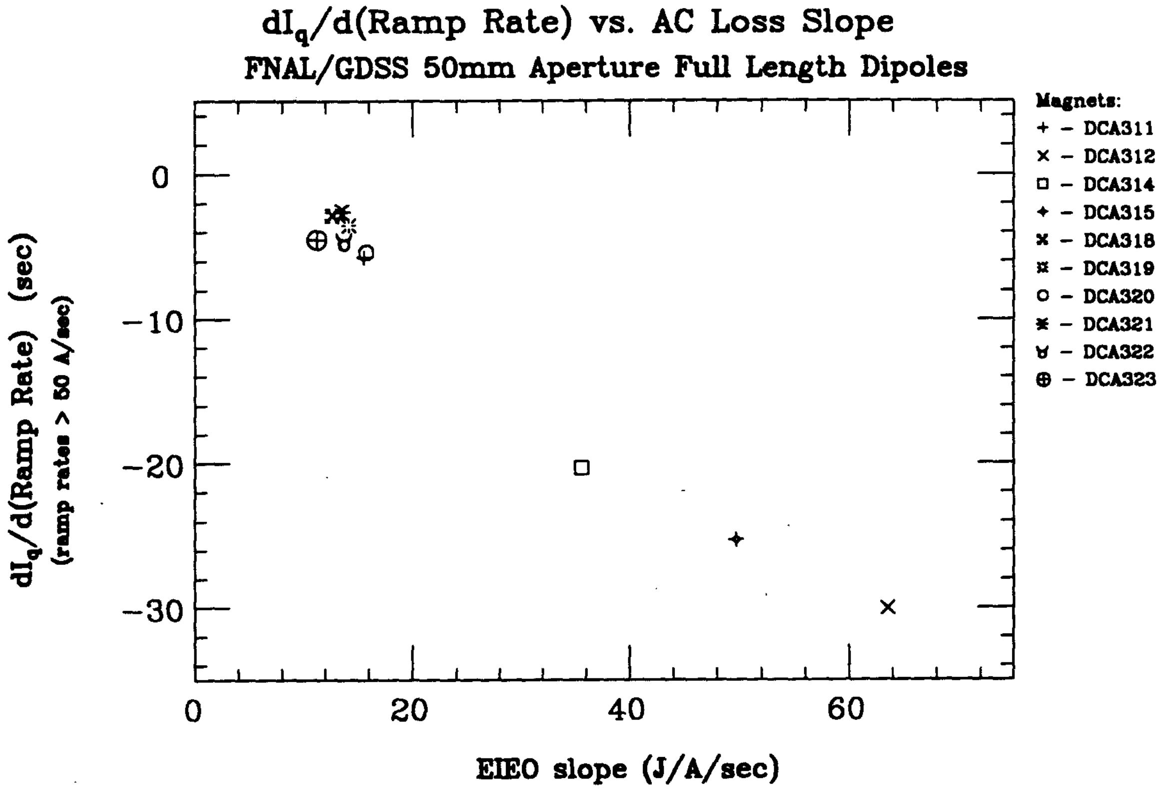


Figure 31-9. Quench Current vs. AC Loss Slope, 50 mm Aperture SSC Dipoles produced by General Dynamics at Fermilab.

Special Ramp Sequences

Toward the end of the ASST test program, as the initial deliveries of magnets to the ASST were completed and schedule pressure was reduced, more time was to devoted to tests. Various special current ramp sequences were developed and run to attempt to gain more information about the underlying causes of the ramp sensitivity.[16,17,18] Magnets were tested more extensively at this point and several Fermilab magnets were re-tested at BNL. The special ramps were composed of individual segments consisting of a starting and ending current and a ramp rate; "dwell times"—when the magnet sits at a constant current without ramping—were inserted a various points between ramp segments. By varying the ramp parameters—sequences of ramp rate, target currents, and dwell times—attempts were made to determine the various time constants associated with the eddy currents. Two of the more interesting ramp sequences are discussed below.

For Type A magnet DCA312, a simple ramp sequence was used to examine the thermal time constants. In a direct ramp to quench at 100 A/sec, the magnet quenched at a current of about 5000 A. Subsequent ramps were performed in which the magnet was ramped to 4800 A at 100 A/sec, and then held for a dwell, or "cooling" time which was varied from 2 to 600 seconds before resuming a ramp to quench at 100 A/sec. Figure 31-10 shows the quench currents versus the length of cooling time between the arrival at 4800 A and the re-start of the ramp to quench. The data are fit with two exponentials with time constants of roughly 3 and 120 seconds; these are in good agreement with calculations of the thermal time constants in the cold mass.[16]

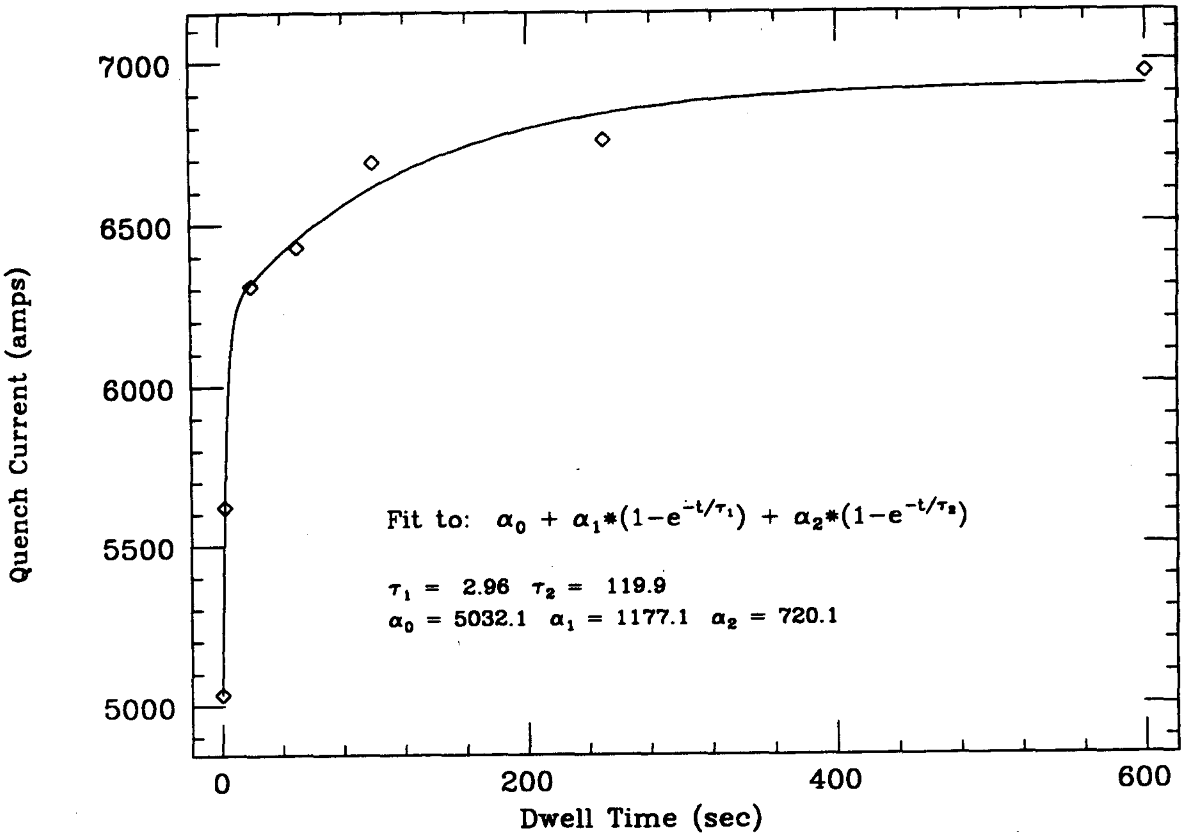


Figure 31-10. DCA312 Cooling Experiment.

For Type B magnet DCA323, a more complicated sequence of ramps is used to elucidate features of the Type B behavior. First, in a direct ramp to quench at 100 A/s, the quench current obtained is 6320A. On a second ramp sequence, the magnet is ramped at 4 A/s to 6320 A (the direct 100 A/s quench current) and then allowed to cool at this current for 600 seconds. It is then ramped to quench at 100 A/s and obtains a quench current of 6970 A. In a third ramp, the magnet is ramped to 6970 A at 4 A/s, and allowed to cool at this current for 600 seconds. It is then ramped down to 6320 A at 100 A/s and, without any dwell, then ramped upward at 100 A/s reaching 7350 A when it quenches; this has been dubbed a "V-ramp." If heating were the quench mechanism, one would expect the magnet to quench before it reached 6970 A on the last part of final ramp sequence since the heating depends only on the time ramping, not the direction, and it has been ramping longer than in the second ramp sequence. The eddy currents, however, are sensitive to the ramp direction: they are generated in opposite directions on the down ramp and up ramp portions and hence tend to cancel. This yield a smaller eddy current contribution and thus results in a higher quench current for the V-ramp. For this to be a valid interpretation, the eddy current time constant must be long compared with the time required to the 13 seconds required for the V-ramp. The test summary reports for all the ASST dipoles are listed in Refs. [19-42].

Recent Short Model Magnet Tests

During 1993, seven vendor-produced, dipole "model" magnet (1.0 – 2.0 m) cold masses were cold tested. They consisted of four 50 mm aperture dipoles (DSD series, for CDM) designed by General Dynamics and fabricated on SSCL tooling by GD personnel. Three 50 mm aperture dipoles (DSB series, for HEBDM), employing an SSCL "technology transfer" design, were fabricated by Westinghouse at their Round Rock facility. The primary intent—in addition to technology transfer—in building these models was to show that the cross sectional and end designs would provide performance which meets the basic requirements of training performance, ramp rate behavior, and AC loss behavior. The models were also intended to provide magnetic field quality information to be used in iterating the cross section to meet the required field harmonics and transfer function specifications. As more information about the ramp sensitivity of the ASST magnets became available, modifications were made to the last DSB models to incorporate changes that would increase the inter-strand resistance. Described below is the measured performance of each group of magnets.

DSD Series Dipoles

The test results highlighted two problem areas in the design, the first was caused by a weakly supported splice between inner and outer coils, consequently, almost all of the training quenches were located in the splice region. The second problem was of extreme ramp rate sensitivity, believed due to a low inter-strand resistance caused by high temperatures and pressures used in the cure cycle. The effect also results in extremely high AC losses approximately ten times those observed in ASST magnets. Quench testing at lower temperatures ("sub-cooling") resulted in more training, or, in the case of DSD104, subcooling appeared to degrade the mechanical stability of the splice further. At ramp rates greater than 16 A/s, the quench origin moved from the splice region to the inner coil windings near the mid-plane, because of the induced eddy current effects. A complete description of the test results, including splice resistance measurement, and quench protection heater tests is given the individual test reports (see Refs. [1,2,3, and 4]).

The DSD series used an all kapton insulation scheme with polyimide adhesive as the bonding agent. The cure temperature for the polyimide was 225°C which is much higher than the 135°C temperature used with the kapton/fiberglass-epoxy system employed in the ASST dipoles. BNL designed a curing schedule which separated the high pressure steps (needed for coil sizing) from (brief) the high temperature step required for the adhesive to set up. The extremely large eddy current effects observed in the DSD models are believed to indicate that there were problems in controlling the temperature and pressure during the coil molding process.

DSB Series Dipoles

The first two cold masses of the series were constructed with "bare" cable while the third, commandeered for use the ramp sensitivity program, used an "All Ebanol" coating of CuO on the cable. The first cold mass had several training quenches at the top of the ramp splice on the outer coil, and did not reach a conductor limited plateau on the first thermal cycle. Retraining was evident on the second thermal cycle. DSB702 reached a stable quench current plateau after 3 training quenches located in the return end turns. One thermal cycle was performed. DSB703 showed a marked improvement in performance with two training quenches in the end turns before reaching a conductor limited plateau. Ramp rate performance and AC loss behavior were much improved over the previous two cold masses, the quench origin did not move toward the mid plane as was the case for the first two cold masses. A complete description of the test results is given in Refs. [5,6, and 7].

The performance of DSB703, constructed with the all ebanol coated cable, was very interesting from two aspects. The ebanol coating clearly had the result of increasing the interstrand resistance: neither the quench behavior nor examination of the magnetic measurement data indicated the presence of significant eddy currents. A interesting fact was that the quench performance in terms of training and stability was very good: the lack of current sharing capability between strands due to the higher resistance did not appear to adversely affect the quench properties of this magnet.

Summary

The initial training performance of the vendor models magnets is displayed in Figure 31-11. As described above, the first General Dynamics model magnet, DSD101, had a problem with an internal splice between the inner and outer coils and was limited to currents of about 3300 A. The second model magnet, DSD102, also was limited in its quench performance by the splice. The last two magnets in the sequence displayed significant training but reached currents well above the operating current.

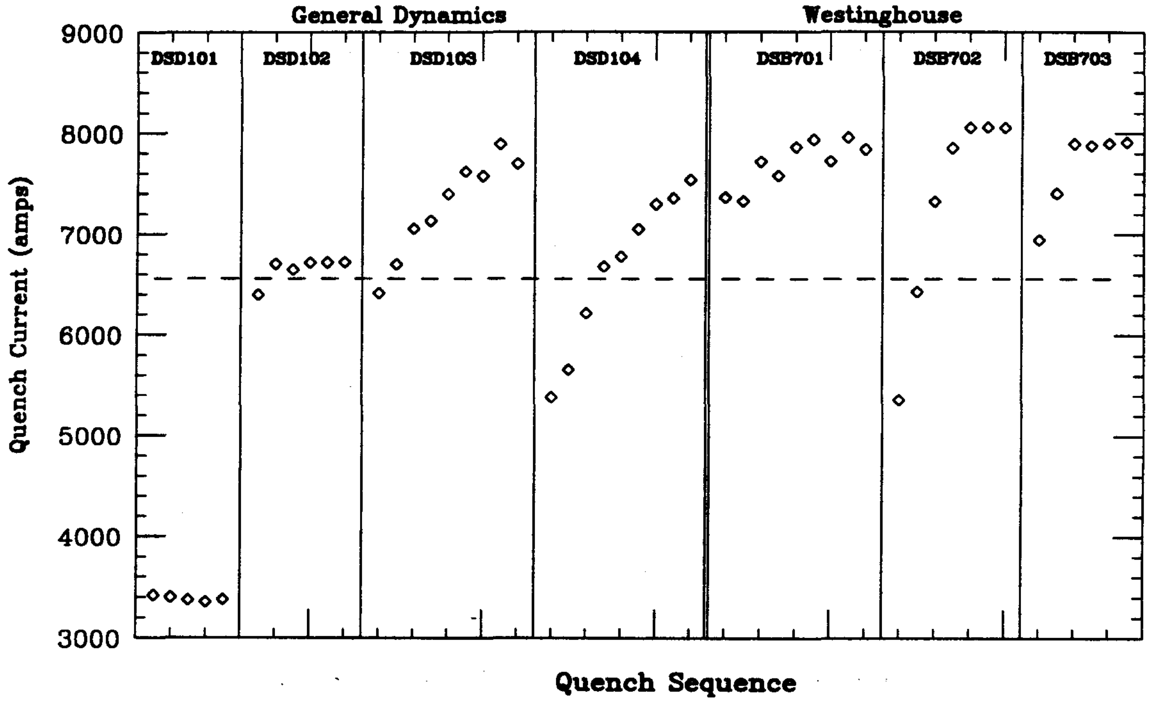


Figure 31-11. 4.35 K Quench Performance Vendor 50 mm Model Dipoles General Dyamics and Westinghouse.

The Westinghouse models displayed significantly better training performance; all models reached currents well above the operating current. As discussed above, the last model, DSA703, which had an ebanol coating applied to the strands to increase the inter-strand resistance, had the best training performance of the models. DSB703 had two training quenches before reaching a current plateau above 7900 A.

Comparisons of the two series of model magnets display a significant difference in ramp rate sensitivity. Figure 31-12 compares the quench current versus ramp rate for the three DSD magnets that reach plateaus and the three DSB magnets. The ramp sensitivity of the DSD models—strongly Type A behavior—is among the highest observed in any of the 50 mm SSC dipole magnets; the HEB models show a much lower sensitivity. As discussed above, the difference in sensitivity can be attributed to the different insulation schemes and corresponding differences in curing cycles. The last DSB magnet, DSB703, displays a clear Type B behavior, although the effect is much smaller than observed in the full length magnets.

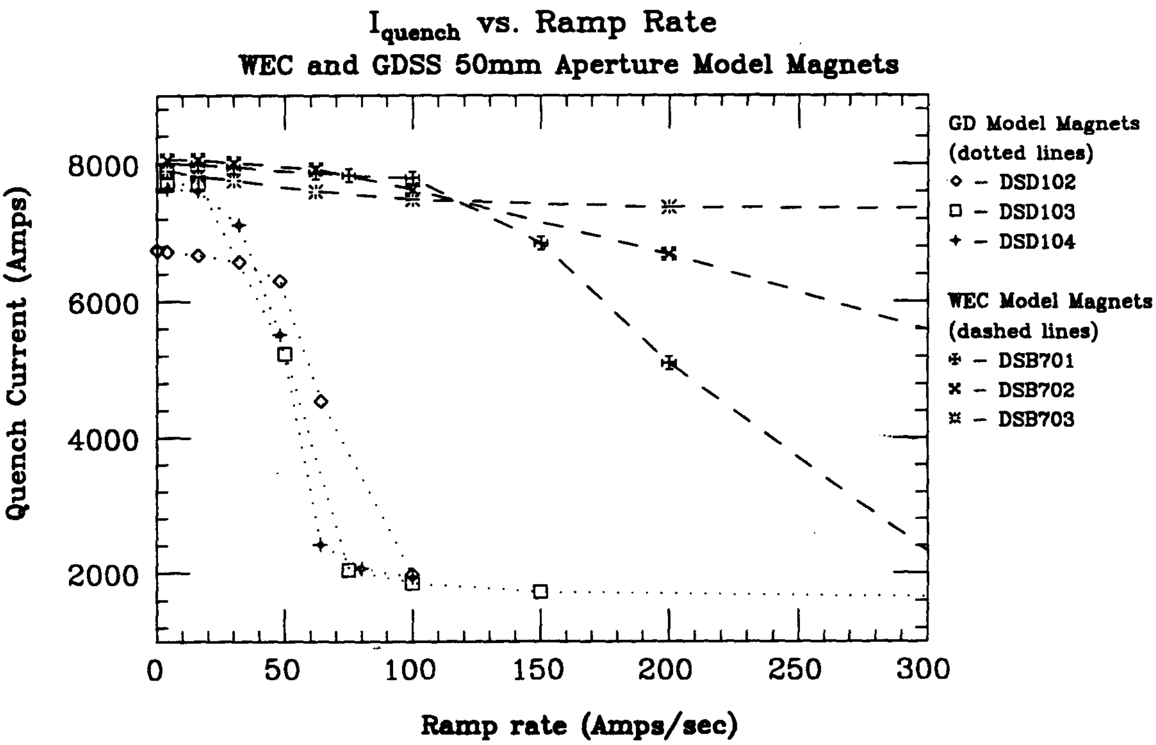


Figure 31-12. Quench Current vs. Ramp Rate: Westinghouse and General Dynamics 50 mm Aperture Model Magnets.

The success of the Westinghouse model DSB703, with the all ebanol coated strands, and the lower temperature curing cycle with the kapton/fiberglass epoxy insulation system, indicates that high inter-strand resistance can be used to solve the Type A behavior problem. However, reservations exist in using this approach due to its effect on current sharing (and the potential problem for quench stability), cost and handling problems with the conductor, and the long term reliability of the coating. The success of one model does not immediately translate into a solution for the HEB. Another key reservation is that DSB703 clearly demonstrates Type B behavior, which although small in the short model magnet, may emerge as a significant problem in a full length dipole. The test conditions of a long magnet differ significantly from those of a short magnet since the cooling is different (pool boiling versus super-critical helium). Also, the lengths of current loops could be quite different, as well as the fact that they are typically fabricated on different sets of tooling. A definite test of this scheme would have to include full length magnet fabrication and test.

HEB Dipole Ramp Rate Sensitivity Program

The High Energy Booster was designed to be a dynamic machine with eight bipolar cycles at approximately 60 A/s to fill the Collider ring. This ramp rate was sufficiently large to have an impact on quench performance and an impact on cryogenic performance. The dynamic or ramp rate performance was considered to be an AC loss related phenomenon. The primary heat generation terms are superconductor hysteresis and cable eddy currents. The AC loss program began with a trade study for the SCDR. A more expanded study was published and a cooling study was performed.[1,2] The primary focus was on the filament diameter and therefore the hysteretic losses, which was justified because the 40 mm CDM program had demonstrated little eddy current AC loss sensitivity. This low eddy current prediction was also supported by evidence from Brookhaven on cable samples.[3] The trade study concluded that a 50 mm HDM would be adequate under the presumption that hysteresis losses was the dominant term and the Brookhaven data reflected the eddy current contribution.

A strand sample contract was established directly with Westinghouse (WSTC) to measure hysteresis and eddy current losses in cables. At the same time a collaborative effort was established with KEK to study both samples and model magnets with both 6 μm and 2.5 μm filaments.[4-7] The KEK 6μm and 2.5μm filament model magnets were ramp insensitive and AC loss measurements were made with limited success. A significant contribution from the KEK collaboration was the cable studies that were carried out on a wide variety of cable samples under a range of temperatures and pressures.[8] The KEK data demonstrated a strong dependence on the curing temperature and pressures. There was also considerable eddy current loss dependence on the strand configuration and specifically a low loss for strands with a CuMn barrier. There is currently work in progress to confirm this result.[9] Westinghouse Magnet Systems Division (WMSD) elected not to complete the WSTC cable magnetization studies as part of their program and only limited information was generated from this program.[10]

Recent Activity

As was discussed above, the ASST magnets built at the Fermi and Brookhaven National Laboratories demonstrated unexpectedly high dynamic quench sensitivity and could not meet the HEB specifications. The magnets performed in two classes: high AC loss or Type A magnets and low loss or Type B magnets. (A summary of the relevant ASST AC loss data is given in Ref. [11].) The prototype Type A magnets quench current vs. ramp rate plot characterized by a drop of quench current with nearly a constant slope that approximately corresponds with the energy deposition associated with the AC losses. The Type B magnets quench current vs. ramp rate plot displays nearly opposite behavior: dropping quickly at ramp rates below approximately 50 A/s and leveling off to a low slope at higher ramp rates. The Type B behavior can be described by models with a "trapped current" (current loop between strands caused by low inter-strand resistance contact points) with a long time constant, but this behavior is still not well understood. This type of model will be discussed below.

WMSD was given a lead role to embark on an AC loss program. WMSD developed a program around the DSB technology transfer model magnet and an "autopsy" plan for ASST prototype magnets. The program included two Fermilab cure profile, glass-epoxy 1.5 m magnets (DSB701-2) and one all-ebonal 1.5 m magnet (DSB703). The DSB coil-on-coil design required two curing cycles for the inner coil that could make the DSB more susceptible to higher AC losses. The results of these magnets are summarized in the short magnet section and Refs. [12-14]. DSB701and DSB702 both demonstrated classic Type A behavior while DSB703 demonstrated Type B behavior. The only autopsy information available at the time of publication is the interstrand resistance measurements of DCA312 performed by V. Kovachev, which are discussed in the following section. These measurements confirmed very low interstrand resistances in DCA312 which was the highest loss magnet in the ASST program. It also demonstrated that adjacent strands have a lower interstrand resistance than standard strand crossings.

The AC loss program was clearly terminated at a critical time in its development. The Type A behavior could be mitigated by producing a cable or process that insures a relatively higher interstrand resistance; this was discussed in the preceding section. The AC loss evidence from the ASST magnets and the results from DSB703 suggest that a high interstrand also plays a key role in the problematic Type B behavior. The ramp behavior of magnet DCA317, which displayed low ramp rate sensitivity and no anomalous multipoles, is at least an existence proof demonstrating that there is an acceptable interstrand resistance which mitigates Type A and B quench current degradation.

In the waning months of the project, several proposals were made on strand coatings to provide an inter-strand resistance intermediate between that displayed by the worst ASST magnets and that inferred from the behavior of DSB703. Westinghouse proposed a copper-nickel jacket around the copper can of the strand.[15] This would insure that the strand cross-over contact areas ("spoons") had a higher resistance. A modified proposal to nickel flash existing strand was made because of the long turn-around times for strand matrix changes.[16] Another proposal was to implement "Zebra cable" which is a cable of 50% ebanol strands and 50% "stay-bright" strands. The penalty of Zebra cable is a higher eddy current AC loss and its impact on the cryogenic system. It has not been proven that Zebra cables do not form trapped current loops although there is some speculation that the mutual inductance of the adjacent strands damp out the trapped currents.[17] Another proposal is to use an all "stay-bright" strand cable where the solder contains a higher resistance material.[18]

There is evidence from KEK sample studies[8] and from the GD model magnet program (DSD101-4) [11, 19-24] that the curing process is a key factor in determining the interstrand resistance in standard uncoated Rutherford cable. More specifically that temperature, pressure, and dwell time are key factors. The DSD10x series of magnets were made from IGC cable and were cured at 250°C under at least 15 KSI pressure. This represented extreme temperature and pressure relative to the baseline glass-epoxy insulation that was cured at 135–150°C at 10 KSI. The GD model magnets had approximately 50–100 times higher eddy current losses than the worst ASST magnet, DCA312. This AC loss performance extreme re-iterated the need to take the materials and process into account when planning a solution for Collider Ring harmonic requirements and HEB ramp rate and harmonic requirements. The insulation section discusses plausible lower temperature, pressure, and duration material selections that can meet radiation requirements.

Interstrand Resistance Measurements

Much of the discussion of eddy current phenomena assumes that the inter-strand resistance is very small (on the order of a few micro-ohms per crossover) in the magnets displaying the most dramatic effect. As part of their program to investigate ramp sensitivity, Westinghouse performed an "autopsy" of magnet DCA312, the lossiest of the ASST dipoles. One of the important aspects of the magnet autopsy plan was the in-situ measurement of interstrand resistance in collared magnet sections. Four sections of DCA312 were designated for interstrand resistance measurements. Two of those sections contained quench sites (occurring during the 100 A/s and 200 A/s ramps, respectively) and two of them were sections representative of the magnet where quenches did not occur. The sections were sent to the SSCL where the inter-strand resistance measurements were performed.

The aims of the DCA312 interstrand resistance study was to measure and analyze the interstrand resistance in each quadrant of these four sections and to find a correlation between the measured interstrand resistance, the actual resistance of individual interstrand contacts, and the quench performance of the magnet. The following conclusions have been drawn from this study.[1]

The entire inner coil of DCA312 has relatively very low interstrand resistance. The adjacent strand contact resistance for one cable pitch length is typically in the 0.1 –1.0 $\mu\Omega$ range, but in some turns it can be as low as 50 $\mu\Omega$. The crossover resistance is typically in the range of

1-100 $\mu\Omega$. These low interstrand resistances result in strong electromagnetic coupling between the strands and large cable eddy current losses during the field/transport current ramp. Low interstrand resistances obtained in this work are qualitatively consistent with the EIEO measurements results of DCA312 discussed above.

The crossover resistances in the high ramp rate quench sites are typically much lower than those in non-quench sites of the coil, while the adjacent strand resistance is essentially the same for the entire coil. The ratio of the crossover resistance to the adjacent strand resistance for the quench sites is normally between 1 and 10. This ratio for the non-quench regions is usually an order of magnitude higher. The average interstrand resistance decreases from the pole turn and increases again towards the midplane. The interstrand resistance distribution obtained in this work is reminiscent of the U-shaped curve evaluated for the interstrand distribution from multipole decay measurements.

The interstrand resistance distribution curve for DCA312 displays some irregularities in the interstrand resistance around the wedges. Such irregularities were observed in the inner coil of DSA328 (a Fermilab built model magnet.) Clearly, the coil preparation technology and/or coil assembly procedure affect the interstrand resistance in the coil around the wedges. The interstrand resistance in some cable turns can vary along the magnet axis by an order of magnitude. This can probably be attributed either to an initial non-uniformity in the cable and/or to non-uniformity of coil preparation and assembly.

The results of DCA312 interstrand resistance measurements correlate very well with the finding and optical observations performed at WMSD after the magnet autopsy.[2] The DCA312 results are also in a good agreement with the adjacent and non-adjacent strand contact resistance behavior previously observed in the inner coil of DSA328, a short model magnet built at Fermilab.[3] The interstrand resistance results from both the DCA312 and the DSA328 studies have led to an extension of Carr's anisotropic continuum model of electromagnetic coupling in superconductors which includes Rutherford type of cables.[4]

AC Loss Models

The initial AC loss estimates for a 50 mm HEBDM magnet were included in the SCDR. The underlying assumptions were published in a more detailed report.[1,2] The primary focus was on the supposition that AC heating required proper cooling. This is certainly a reasonable supposition from the cryogenic requirements aspect but was proven to be only a contributor to the total problem in the ASST program. Steady state thermal models were generated to predict HEB cell performance.[3] The ASST prototype ramp rate data demonstrated a much higher AC loss sensitivity than anticipated. As discussed above, the magnet performance was characterized into two classes designated Type A and Type B. The Type A magnets demonstrated a near linear but usually a large slope of the quench current vs. ramp rate curve and the Type B magnets revealed a more subtle non-linear behavior with a fast drop in quench current below 75 A/s and a low slope curve at higher ramp rates.

The thermal models were modified to reflect the transient behavior of the heating profile during a ramp to quench. These models reflected the general behavior of the Type A magnets but under predicted the quench behavior when calibrated with integral AC loss data collected at Fermilab.[4,5] An analysis technique based on the eddy current or dynamic field harmonics was developed by Ogitsu.[7] This model was based on the Morgan model for Rutherford cable and was extended to included non-identical cross-over resistance. The Ogitsu model was successful in localizing the low interstrand resistance near wedges in the inner coil of DCA312. It provided valuable information for the quench mechanism in Type A magnets. The thermal models[6] were later calibrated to the localized losses extracted from the Ogitsu model, but little change was associated with the more accurate heating profiles.

The obvious conclusion from the initial transient thermal studies was that the heating itself was not the driving factor in Type B behavior. There were several efforts to construct stability models. A pulsing eddy current model assumed a trapped current caused by local low interstrand resistances in a global matrix of high interstrand resistances. This model required short time constants for the pulsing effect which was not consistent with the long time constants in Type B magnets.[8] This model did stimulate the V-ramp test (discussed in the Special Ramp Section, above) which further clarified the time constants observed in simpler ramps sequences. A dynamic stability model was constructed based on the current carrying capacity of a multifilamentary strand under dynamic conditions. This stability model assumed that the current could not properly transfer into the copper in an AC ramp situation. This model produced Type B curves but did not explain why superconductor produced by different vendors had such a wide variation in performance.[9]

The most plausible class of models for Type B behavior were long time constant trapped current models. The idea of a trapped current came from the observations made in HERA magnets of periodic field harmonic variations which occurred at the cable pitch length spacing.[10] The first trapped current model was the steady state Stiening model.[11] Other more elaborate models included transient LR circuit effects and multiple coupled diamonds.[12,13,14] The most compelling model contained the argument that the driving term was net flux in a strand pair diamond.[15]

The Westinghouse model magnet program would have provided the perfect avenue to substantiate the relevant parameters for the trap current model. The all ebanol magnet DSB703 demonstrated classic Type B behavior.[16] This result was anticipated because the strands cannot current transfer significantly and the low interstrand resistances at the ramp and midplane splices provide the required trapped current loops. If DSB703 was modified to contain iron end laminations, the driving term could be augmented by a maximum of 20% and a higher trapped current should reflect in the quench current. The second modification to DSB703 would be a change in the midplane "bus" splice to significantly increase the resistance of the circuit and damp out the depth of the Type B behavior.

Chapter 32. General Superconducting Magnet R&D

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In this chapter, various efforts are discussed that were made in magnet program and were supported by superconducting magnet R&D funding. The topics include the development of the Magnet Test Laboratory, development of new systems for magnetic measurements, and brief discussions of materials and insulations studies as well as end part development for superconducting magnets.

The Magnet Test Laboratory

The Magnet Test Laboratory (MTL) is a test facility built specifically to evaluate the performance capabilities of superconducting accelerator magnets prior to their installation in the HEB or Collider ring. A detailed description of the facilities and its capabilities can be found in Ref. [1]. Further details of the facility design can be found in Refs. [2,3, and 4].

MTL Status

At the time of project termination, the MTL was nearly ready for operation. The principal technical component, a 3.8 KW liquid helium refrigerator ($12M value), had been installed.[5,6] Acceptance testing was complete and remaining punch list items (all minor) have since been completed. However, many items "repaired" by PSI (the refrigerator manufacturer) require running the system in order to check them out. To go back "on line," helium and liquid nitrogen must be procured. For example, the feed and end cans require cold testing to prove out their capability for satisfactory operation. Without powering the vapor cooled leads, that part of the feed can cannot be proved out.

The first four single magnet cold test stands and a three magnet "string" test stand have all been delivered and were on the floor of the MTL; the first single magnet cold test stand was in the process of being readied for the first cold test to take place in the fall of 1993. The design of the cold test stands is described in Refs. [7] and [8].

The facility electrical instrumentation design for the testing of magnets is essentially complete. The concept for the operation of the test facility envisioned a distributed control system whereby Sun workstation hosts control VME-based control blocks.[9,10] Various control blocks are responsible for the control of the power supplies, the acquisition of rapidly changing data such as voltage tap readouts and pressure sensors, the high accuracy acquisition of slowly changing data (temperature and flow), and the system safety data. The system safety block is allocated to a semi-autonomous computer module that had the ability to log potential problems, act on the potential problems without direction from the host computer system, and shut down the system in a safe manner if the monitoring system itself had problems. A separate computer monitor checked the magnet for indications of a quench condition, to safely shut the system down before the superconducting load would be damaged.[11] (This system concept has been the subject of a patent application.) The slow data acquisition module currently has 140 input channels with the ability to determine input values with an error of less than one part per million. Included in the design of the slow data acquisition modules is a fairly flexible ability to provide sensor excitation to operate temperature and pressure transducers. The high speed acquisition module currently has 96 channels capable of recording data at up to 20,000 samples per second for each channel, and saving the most recent 60,000 samples of each channel. All these modules currently exist and have been tested. At termination, the module controlling the power supply was under design. The design parameters had been determined, the hardware configuration had been determined, and a first pass at the controlling software had been written. With the inclusion of this last module, a state-of-the-art integrated test facility could have been operational.

The SSCL has six 8000 Ampere power supplies, five 10,000 Ampere power supplies and one 15,000 Ampere power supply for powering superconducting magnet-type loads. All these power supplies are water-cooled SCR units with active or passive filtering. The output power is up to 400 KW. The supplies operate under varying control schemes and are therefore not completely interchangeable without some modification to the control modules. Power supply specifications are given in Refs. [12-15]. The MTL was designed so that the power supplies could be connected via a "link box"[16] to adjacent test stands to reduce the number of power supplies required while maintaining a level of flexibility and redundancy.

A new design for 10 kA vapor-cooled power leads was developed by the SSCL and Fermilab.[17,18] Tests of these leads were performed at Fermilab in the Lab 2 vertical dewar test facility. The feed and end cans for the first cold test stand are at the Laboratory.[18,19,20] The end can has had an electrical inspection and the electrical inspection of the feed can was ~ 95% complete (the high potting was finished).[21] On hand were more than 90% of the materials required to connect the dipole magnet DCA207 to the feed and end can. Some procedures remained to be written, but many of them could have been adapted from existing ASD procedures. The U-tubes required to connect the feed can to the distribution box had all arrived. The hardware for the slow scan data acquisition system was complete though significant cabling remained to be done. About 80% of the programming required to drive that system was finished, and the remaining 20% was not felt to be difficult. The quench detection system and the high speed data acquisition system were finished and had been demonstrated. Significantly, the hardware backup to the quench detection system was not complete. The first version of the top level operator interface software was essentially done. The LCW plant was finished and had been received from the supplier. All vacuum equipment had been delivered.

Software for the MTL resided in two main hardware architectures. Data acquisition and instrumentation were performed using VME based 68030 processors; computation and the man-machine interface utilized SUN SPARC workstations. The data acquisition real-time operating system was Wind River's VxWorks augmented with SSC code for device drivers and communications to the host. The host system ran SunOs (Unix) and used X-Windows as the primary windowing system. Control panels and displays used the DynaGraphX graphical user interface (GUI) builder and widget library based on Motif.

Applications were designed using a distributed client/server paradigm. This approach allowed operation of a test to migrate from workstation to workstation as needs demanded. System availability was also greatly improved by this distributed solution. Data were passed between machines using the ISTK "software bus" model. An extension of the GLISH sequencing language was used as the control mechanism. Data were contained in SDSs which provides an efficient and machine independent file system. SDSs containing test results were stored in a catalog database implemented with the Sybase DBMS. The ISTK software is described in Refs. [22-26].

Sufficient software was on hand to be able to operate all of the principal functions associated with magnet testing—cool down, quench test, magnetic measurement, and warm up—with varying levels of automation. More work was required to make the system suitable for "non-experts" to operate. It was anticipated that much of the development in the next two years would be directed towards refinements in the graphical user interfaces, enhancement of the data base management and report generation, integration of the magnet test software and the refrigerator control software, the development of extensions to the exception handler system, and the possible utilization of artificial intelligence techniques to address exception handling during facility operation.

The safety reviews and associated analysis required prior to the commencement of MTL operation were nearly complete. The MTL ODH report had been finished and approved. More than 90% of the interim procedures associated with this system were in place. All but about 100 of the SAR mitigations required for a cryogenics test were complete and verified. Those that remained were mainly associated with procedures and personnel training. Roughly 50% of the personnel training was complete as was approximately 75% of the procedures and test plans required for a cryogenics test. The acceptance test reports on items such as the feed and end cans, DCA207, data acquisition system, etc., still had to be written, but most of the information was available, and this would have been easy to complete.

Magnetic Measurement Systems

The "Mole" Harmonic Measurement System.

The Test Department is in possession of 9 "moles," i.e., the magnetic measurement apparatus developed principally at BNL for use in determining the field quality of the superconducting magnets. Also, three transporters that can be used to position a mole anywhere along the length of the magnet are also at the Lab. There have been some modifications by the SSC to the basic design developed by BNL. The length of the measurement coil has been altered from the 1 meter value used in the original BNL systems so that some of the moles have an active length of 946 mm (11 transposition pitch lengths of the inner conductor). Also one mole has been built with a 250 mm length (3 pitch lengths), and one has been built with a 43 mm active length (one-half pitch length so that it is optimally sensitive to the axially periodicity of the field multipoles generated by the non-uniform current distribution within the conductor). The short coil is also useful for studying the rapid variation in the magnetic field quality near the end of a magnet. Four of the coils were built using alumina ceramic coil forms. This allows very high accuracy placement of the induction coils on the form. Typical manufacturing tolerances are approximately ±10 microns. These coils are expected to have systematic measurement uncertainties that are considerably smaller than the forms made from G10 or filament wound epoxy with a G10 overcoat.

Data acquisition systems of a unique SSC design have also been built to control each mole system. Features that distinguish these systems from the original BNL system are as follows: (1) The system incorporates low noise preamplifiers, which are used to reduce the random uncertainty of the measurement due to electronic noise. (2) The system includes provision for "two-stage bucking" which allows the induced coil voltages to be acquired with less demanding requirements on digital voltmeter performance and which also provides a further reduction in the random uncertainty of the measurement. (3) The system replaced several different electronic modules with a single custom VME controller board which triggers the digital voltmeters used to acquire the voltage signals from the mole. The controller board also measures the time between successive encoder pulses and records this information in a dual-port memory accessible over VME (so that velocity corrections to the measurement can be made). Additionally, it provides closed loop velocity control to either the pneumatically or electrically driven moles, reads out the gravity sensors, and provides the oscillator for the field angle measurement and the temperature stabilization of the gravity sensor. (4) The data acquisition is accomplished using a VxWorks realtime kernel running on VME in a MVME147 board. The software is hosted on a SUN workstation. All raw data is saved, in contrast to the BNL system where only averaged multipoles are accessible. The UNIX OS makes possible remote operation or observation of data taking, which is a nice feature when test facilities are far from those interested in the data or remote servicing is required. Communication is via ISTK formalism, which allows the data to be transported, stored, or displayed in a platform independent way. (5) The MVME147 board also controls the operation of the transporter using off-the-shelf VME boards (in contrast to the custom electronics in the BNL stand-alone system).

Other Measurement Systems

A stretched wire system has been developed that uses the voltage induced on a single wire, moving sinusoidally in a magnetic field, to determine the center and field orientation of a quadrupole magnet operating at a current of as little as approximately 10 amps. The wire motion is controlled using the precision oscillator from a lock-in amplifier and the signal is synchronously demodulated using the lock-in amplifier to determine its voltage and phase. Very high precision mechanical actuators were purchased for this apparatus, as was a theodolite, so that the fiducials of the wire actuator system could be precisely aligned relative to one another.

A fluxgate magnetometer system was also developed to determine local field center within the aperture of a quadrupole magnet. The device operates at fields up to about 10 gauss (or currents of around 3 amps in an SSC Collider quadrupole magnet). Two fluxgates separated by a fixed radial distance are used to calculate the gradient and the distance to the field center.

A 32-channel pulsed NMR array system has also been built for the SSCL by Gil Clark at UCLA. This apparatus uses NMR techniques to determine the magnetic field quality at fields of either 0.6 or 2 Tesla ± 20%. The device consists of 32 individual 1 cm long NMR coils placed circumferentially on a one-inch-diameter circle. The apparatus depends on the fact that the variation in field intensity is, to a very good approximation, a variation in the vertical component of the dipole field, and thus the individual amplitude measurements about the circumference can be used to determine the multipole expansion of the field. A $\pi/2$ RF "tipping" pulse is applied to the sample and then the precession frequency of the NMR spins due to the main field of the magnet is measured as a series of induced pulses on the excitation coils of each NMR sample. The time between successive pulses is digitized for each channel. This time is a measure of the field intensity at that point. The same principle has been used to develop an ESR array that can be used to measure field quality at approximately 100 gauss. The devices allow a cross check of the mole measurements and provide some insight into the overall systematic uncertainties of the magnetic measurement program, since the mole and NMR or ESR systems are expected to have much different sources of systematic error.

Materials and Insulation Studies

The search for the best electrical insulation materials to wrap around the superconducting cable has led away from a first layer of polyimide film and a second layer of glass tape impregnated with epoxy adhesives toward an all polyimide film system with an adhesive coating of either

Cryorad (by Allied Signal), 3P (by Sheldahl), or a low temperature version of XMPI (by Dupont). Test programs were set up to determine what combinations of film wraps would yield the lowest stress relaxation measured as creep and the best compressive breakdown characteristics with two kilovolts applied. Radiation tolerance studies were also performed on these films and adhesives.

The general direction being taken by the Magnet Development Group at the MDL was to use a high tensile modulus film such as Apical NP with no adhesive, 0.001" thick, wrapped with a 50% overlap as the first layer. This was followed by a n butt wrap of a second layer of the same film but with a .0002" thick layer of Sheldahl 3P adhesive on the top side of the film. This appeared to be the best combination of high compressive strength versus voltage breakdown, low stress relaxation, good radiation resistance, moderate curing temperature (about 165°C), and moderate cost.

Oak Ridge National Laboratory and CERN have carried out radiation tests on polymeric materials used in magnets and other programs. The materials were used as end part and insulation materials. The results indicated that most of the epoxy materials degraded under radiation of 10^8 Rads. Tests were carried out at BNL and General Atomics on composites, films, adhesives, and thermoplastics. Epoxy G-10 CR and low temperature cure epoxy used for insulation degraded at low levels. Polyimide adhesives, thermoplastic imides, and films withstood the radiation with minimal loss at 10^9 Rads. The film adhesives required two stage curing to provide good radiation resistance.

End Part Development

The end part design techniques implemented by make magnet and vendor programs were developed in the Fermilab ASST program. The mechanical conceptual design of the end parts was generated by a computer code called BEND. The code was developed to determine a constant perimeter path for the cable that minimizes the stress introduced in it by the requirements of the end geometry. The magnetic design was generated in a computer code called ENDS3D from the output of BEND. The materials program was the key factor in meeting the radiation, stiffness, and conformance requirements. The materials and manufacturing programs are reviewed briefly below.

Machining with Convolute Wound Tubes of G10 CR, G-11CR, Spaulrad

These parts were fabricated using five axis machining of composite tubes. The convolute wound tubes offered better strength than filament winding but less than compression molding. The bend program was used in the design of the parts, which were machined in house using liquid coolant.

Parts using Resin Transfer Molding(RTM)

RTM parts using preform of end parts were made with Cryorad resin. The preform was made by 3 dimensional stitching. Other resin systems could be used for part fabrication, such as Isopreg epoxy resin. The RTM method provided good end part conformance to the compressed conductors. Problems remain in fiber bunching, resin rich regions, and difficulty in making thin sections. The more recent parts showed promise in resolving resin rich regions.

Compression Molding of Prepreg

The final shape can be compression molded from precut prepregs. Hard shells rather than tubes were compression molded using prepregs and were machined into final parts in five axis machining. Also the compression molding technique could be used to mold the hard core of the part in the Hard core-soft shell system. Half shells were compression molded with G-10, G-11, and Spaulrad-M materials and machined on a five axis machine.

Hard core-Soft shell Approach

The basic principle behind this process is to provide the necessary strength and radiation resistance to the core of the material. The shell will be of a softer material that conforms to the shape of the coil during molding. A similar approach was used in the modification of end parts to fit the coil. The choice of core and shell can be developed depending upon the magnet requirement. The hard core can be compression molded and the core can be insert molded onto it in a second operation. In terms of cost and performance, this approach offers the most advantages.

Chapter 33. ASST Program

History of Program

(P. Kraushaar)

The Accelerator Systems String Test (ASST) complex is located at the N15 site. The complex was initially constructed in 1991 to demonstrate the operation of a standard half cell of the Collider machine lattice using prototypical superconducting magnets for a Congressionally mandated milestone for the SSCL. The milestone was scheduled for completion by October 1, 1992. The ASST half cell consisted of five 50 mm aperture dipoles, one 40 mm aperture quadrupole, and three spool pieces. The dipoles were assembled at Fermilab by technicians from General Dynamics using Laboratory-developed designs and tooling. The spool pieces were manufactured in industry from an SSCL design. The quadrupole magnet was built at Lawrence Berkeley Laboratory. The magnets were cold tested, prior to installation in the string, at Fermilab. The milestone test (Run 1) was completed with the successful powering of the half cell to 6520 amps on August 14, 1992.[1] This was not, however, the first effort by the SSCL to operate a Collider-prototypical magnet string. A magnet string of earlier prototypes from the Collider magnet development program, which consisted of 17 m long, 40 mm aperture dipoles, was tested at the ER4 service building site at Fermilab prior to the ASST effort. The Fermilab test is referred to as the ER string test and is described in Refs. [2–4].

The completion of the August 1992 milestone marked a transition point for the ASST management structure. The task force organization used for the milestone effort focused on accomplishing a single task. With the milestone completed, the task force was dissolved and the ASST entered a new phase. The planning for this transition started well in advance of the completion of the milestone. The new organization was to focus on the operation of a test facility rather than accomplishing a single task. The philosophy behind the new organizational structure adopted for the ASST was that the SSCL required a facility where technical components could be integrated into Collider prototypical systems and subsystems for testing and run under various operational scenarios. Without this capability, the SSCL's superconducting machine groups could not verify by test the design parameters contained in the superconducting machines' (Collider and HEB) Level 3B specifications.[5,6] In addition to providing a test bed for accelerator systems, personnel training, and the development of procedures for operations, the ASST test program needed to provide for testing critical component parameters that could not be verified in single component testing. Examples of this would be the heat leak to the 4 K cryogenic circuit in the magnets, and the response of spool piece components to conditions generated during magnet quenches.

The ASST Test Group was formed within the Collider Machine Group from experienced task force members and was responsible for the management and operations of the testing facility. This core group utilized and directed technical resources drawn from both the Accelerator Systems Division (ASD) and Magnet Systems Division (MSD). To assist the ASST Program Manager, two committees were formed drawing on expertise from across the Laboratory. One committee was the ASST Program Steering committee, which was responsible for the review and approval of test requests submitted by SSC staff. The other was the ASST Safety Review committee whose responsibilities included the operational safety reviews of the test program and facility prior to startup of a test run. Additional information on the ASST organization can be found in Ref. [7].

Facility Description and Capabilities

The ASST complex consisted of the ASST string, the refrigerator, the magnet power supply, and the refrigerator compressor buildings. The last three areas were part of the N15 Utility complex designed to serve during Collider operation. The ASST building consists of a large, 29 m by 98 m laydown area for the receiving and checkout of string components, and the magnet string enclosure, which is 200 m long and 5.2 m wide. The string enclosure was built with the same curvature as the Collider tunnel. A niche area was provided to contain the quench protection system and other test electronics. Located adjacent to the niche were two trailers. One was configured to provide office space for technical personnel, and the other served as the ASST control room. The remote operation of the string subsystems and the monitoring of the technical components under test was accomplished from this control room. These systems included cryogenics, magnet power, quench protection (QPS), controls (data acquisition and process), and personnel safety.

The primary refrigerator was called the Plan A unit; the smaller, backup unit was called Plan B. The initial cryogenics system for the ASST was built around a small 550 watt helium refrigerator that could provide 135 liters/hr of liquid helium. The system delivered 50 g/s mass flow of helium to the string.[8] The refrigerator was adequate to cool and operate a half-cell string and was purchased as a backup to the primary refrigerator. Plan B was used in Runs 1 and 2 when the primary system was delayed. The Plan B refrigerator was removed from the ASST and would have been used at the SSCL's Central Facility as part of the spool piece test stand if the project had not been canceled.

The Plan A refrigerator was commissioned and used to support the ASST test program for Run 3. This refrigerator was initially planned to be part of the N15 Arc Sector Refrigerator. However, improvements in refrigerator design resulting from the Plan A design effort, provided a more cost-effective alternative for the Collider cryogenic system. The Plan A system was tested at 4500 watts of refrigeration with 0 g/s of liquefaction. During normal operations, the system could provide 2200 watts of refrigeration and 22 g/s liquefaction. The maximum liquefaction rate was 40 g/s. The nominal mass flow of helium was 100 g/s with a minimum flow capability near 20 g/s. The minimum operating temperature was 2.8 K. The operating pressure of the string was 4 bar. The system was used at the ASST for the first time in August 1993 to cool down and operate the full cell being tested in Run 3.

The magnet power system consisted of a high current DC power supply and an energy dump or extraction subsystem. The DC power supply was capable of supplying a maximum of 8000 amps of current (at 40 volts) with a total output deviation of ±100 ppm. This supply did not meet Collider requirements but was adequate for the ASST program. A small low-conductivity water (LCW) supply system was assembled to provide cooling water for the power supply system. The energy extraction subsystem consisted of a dump resistor, which could be switched in series with the magnets, and a dump switch. The dump resistor had a maximum resistance of 40 mΩ with taps at 10, 20, 30, and 40 mΩ. These taps corresponded to the nominal values required for a half-cell, full cell, one and a half cells, and two full cells respectively. The resistance values were selectable in 2 mΩ steps. The dump switch consisted of a SCR in series with and backed up by a mechanical switch. The switch was rated for currents in excess of 7500 amps.

The magnet power system was controlled by a local processor, named the Collider Excitation Controller and Regulator (CECAR), and monitored from the ASST Control Room. The operators could select the type of ramp, ramp rate, and current value. The console display provided a schematic of the string under test and displayed key electrical parameters in real time. The observables were stored in data buffers that could be read out and also stored in the ASST database.

The quench protection system (QPS) worked in conjunction with the magnet power, and personnel safety systems. During Runs 1 and 2, the system had one quench protection module (QPM), which monitored quarter coil voltage taps on the string's magnets. This system was expanded for Run 3 to include a second QPM to allow for tests that require QPM to QPM operations. Like the power system, the QPS was controlled and monitored in the control room. The console displays allowed for the monitoring of the voltage taps and other diagnostic information. During a quench event, the voltages and currents that occurred in the magnets and the bypass circuits were recorded in data buffers for later display and analysis. The magnet power and quench protection systems used at the ASST are discussed in Ref. [9].

The ASST had an integrated controls and data acquisition system that recorded data from the numerous sensors monitoring the string components and the subsystems supporting the test operations. The Research Instrumentation Data Acquisition System (RIDAS) was the primary data acquisition system for test data. RIDAS was divided into a VXI based data logging system and a VME based transient data recording system. To support the tests requested for the full cell configuration, RIDAS logged data from over 420 separate sensor channels. The periodic data logging was performed at a sample rate of five minutes. The transient data system could accommodate up to 320 channels with its ten A/D modules and a wide range of sampling rates and collection times. During the half-cell tests, sampling rates and collection times varied from 2000 samples per second for 30 seconds to 10 samples per second for 30 minutes. In addition to RIDAS, the controls system contained the cryogenic process controls, which monitored 80 sensor channels from the string and controlled 25 remote devices. There was also a vacuum process controls system, which had approximately 40 sensor channels.

Test Program

The ASST Test Group developed a procedure by which technical staff could submit a request to conduct a test at the ASST using the available basic string configuration. Basically, the requester submitted to the test group a one-page form outlining the test objectives, string configuration required, including specialized sensors, and the importance of the test to the overall program. The request was reviewed by the principal members of the test group for completeness and then referred to the ASST Program Steering Committee for review. The steering committee met monthly, and the actions taken were recorded in the committee minutes. Test requests approved by the steering committee were returned to the test group to be scheduled and conducted. For additional details on the test request submittal and evaluation process consult Ref. [11].

At the time of project termination, approximately seventy (70) test requests had been submitted to the ASST test group. Of these, 20% were thermal related measurements, 36% power systems related, 23% component tests, 10% mechanical systems related, and 11% involved other types of testing. Of the requests submitted, 76% were approved, 11% were either rejected or withdrawn, and 13% were pending committee action. Because of the change in priorities that resulted from project termination, not all the approved tests for Run 3 were executed.

Major Technical Results

The ASST testing program had three testing runs. The first two runs were conducted on a half-cell configuration, and the third run utilized a full cell. The initial half cell was composed of the following components in the order listed: half a collider prototypical feed spool (HSPRF) manufactured by Meyer Tool, five 50 mm dipole magnets (DCA313, DCA314, DCA319, DCA315, DCA316), a prototypical spool piece with a recooler (SPR1) manufactured by Cryenco, a 40 mm quadrupole (QCA403), and a special end spool (HSPRF) manufactured by Consolidated Vacuum Industries.

The Run 3 full cell consisted of the following components in the order listed: the HSPRF, five dipoles (DCA313, DCA314, DCA315, DCA323, DCA322), quadrupole QCA406, SPR2 manufactured by Meyer Tool, five dipoles (DCA316, DCA319, DCA320, DCA210, DCA212), quadrupole QCA405 and the HSPRF. The 300 series dipoles were manufactured at Fermilab by General Dynamics, and the 200 series were made at BNL by Westinghouse. All spool pieces were equipped with quench valves. The quadrupoles used in the full cell were equipped with an internal quench bypass bus to allow them to be in the nominal Collider sequence relative to the dipoles and yet quench protected separately. The detailed technical results from these runs are available in a number of references [12–19] and are only summarized in this section. In addition, test reports for completed test requests are contained in the test request files for the ASST.

Thermal Measurements: One of the more critical measurements that could be done at the ASST on the magnet string was the heat load determination for each of the cryogenic circuits, 80 K, 20 K, and 4 K. The heat leak budgets are basic to the sizing of the refrigerator system for the Collider, and because of their small value on a per-component-basis, they are nearly impossible to measure accurately on a single component test stand. Even in the string environment, the measurement was difficult owing to high heat leak end effects from the spools. The magnitude of the spool heat leak was unexpected and believed to be the result of poor quality control during the manufacturing process and the large number of penetrations for R&D instrumentation connectors. The static heat load budget for a 50 mm dipole magnet cryostat with interconnect was 0.36 watts for the cold mass (4 K), 5.06 watts for the 20 K shield, and 37 watts for the 80 K shield. The measured values from Run 2 are 1.4 W ± 28% for the cold mass, 5.59 W ± 2% for the 20 K circuit, and 24.5 W ± 16% for the 80 K shield.[12,18] Thermal data from the full cell Run 3 were taken and will be reported in a future publication.[19] To assist in the understanding of the heat loads data from the earlier runs, a specially instrumented dipole (DCA323), which had an array of thermal sensors mounted on the shields, support posts, and MLI blankets, was installed in the first half cell for Run 3. Analysis of that data was in progress as this report was prepared.

Quench Voltages and Pressures: During the power testing program at the ASST, no natural quenches were observed in the half cell during Runs 1 and 2 up to the full current operation of 6500 A. To test the performance of the quench protection system, quenches were induced in the string by firing a particular quench (strip) heater in one of the magnets or one of the spot heaters. Quench heater tests provide data on the magnet string's response to the quench protection system or beam induced quenches. Spot heater related tests provided data indicative of the string's response to localized quenches.

The peak voltage developed in a magnet string is a concern because the dielectric strength of the components in the system must withstand it without failure. The peak voltage is influenced by circuit inductance, string temperature, RRR values of the magnets, and the method of quench initiation. (The RRR is the residual resistance ratio: the ratio of the resistivity at 300 K to the resistivity at 10 K.) The maximum voltage observed during quench heater testing was 1700 V to ground from a quench at 6000 A. The projected voltage to ground at 6500 A was about 2150 V, which was above the operational limit of the string. At 6000 A, the measured MIITs was 9.4 with projected value of 9.8 at 6500 A. (The MIITs value is defined by the integral over time from quench initiation to infinity of the square of the time varying current, in amps^2–sec, times a 10^{-6} scale factor.) For spot heater tests, the maximum voltage to ground was 1232 V from a quench at 6500 A. The MIITs value for this quench was 10.99. These maximum voltages were observed in DCA319 and indicated a possible operational concern. DCA319 had a much lower RRR than the other two dipoles in its quench protection quarter cell (96 compared to about 175). This meant that DCA319 had a higher resistance at 10 K than the other two dipoles and, as a result, developed higher voltages and absorbed more energy than the other dipoles in the quarter cell.[13–15,20] For Run 3, the quarter cells were reconfigured to use similar RRR magnets to check if this would minimize the voltages to ground developed during quenching. The peak pressure observed in a quench event during Runs 1 and 2 occurred in the ASST half cell configuration during a strip heater induced event. The peak pressure was 1.41 MPa (about 205 psia). The typical full current quench pressure was about 1.24 MPa (180 psia). The magnet string had been certified to 1.84 MPa (295 psia) with the operational limit safety valve set at 1.47 MPa (235 psia).

Splice Joint Resistance: The superconducting power bus that powers the magnets runs through each magnet and spool piece. At each interconnect, the power bus must be spliced together, and the resistance of this splice is an important technical parameter. Excessive resistance results in increased heat load to the system which can result in unwanted quenches. The splice joint resistance was measured for a number of splices in each run. The data from Run 1 gave an average splice resistance at 6.5 kA of 0.99 ± 0.18 nano ohms, while measurements from Run 2 gave 0.76 ± 0.16 nano ohms. The maximum relative variation of resistance from splice to splice was 60% with the average being 20%.

Magnet Ramp Rates: During single magnet testing, some ramp rate dependent quench behavior was measured. The ASST was limited in the up ramp rate that could be produced during excitation by the quench protection system and the power supply. The maximum value exceeded by several times the planned rate in the Collider. However, by varying the dump resistor value, the quench behavior with respect to rapid down ramps could be bracketed. The maximum half cell down ramp rate that did not result in a quench was between 275 and 340 amps/sec when starting at 6.5 kA at 4.6 K. That range exceeded by 50% the nominal down ramp rate of 188 amps/sec planned for Collider operation.

Bypass Leads: The bypass leads are located on the SPR spool and are used to conduct current from the superconducting magnet bus to the bypass diodes during a quench. These leads represent a superconducting to resistive transition and are vapor cooled to reduce the recovery time constant. They represent a heat leak to the system and are composed of stainless steel to minimize this leak. The leads are designed to withstand the MIITs developed during a quench related energy dump. For nominal Collider operation, this value is 1000 MIITs. The string was configured to allow various levels of MIITs to be dissipated in the bypass leads. One bypass lead was tested to 1400 MIITs and another to 2040 MIITS with no ill effects. The conclusion drawn from these tests was that the lead was over designed and could be reengineered to further reduce the heat leak.

Operational Experience

Over the almost two years of its operation, the ASST facility and test program provided technical data on the string systems and components. Besides technical data, the ASST program acquired useful operational and organization experience on providing a testing facility for scientists and engineers within the organizational scope of a large DOE funded project. The sometimes cumbersome and time consuming procedures and practices mandated by DOE for controlling a multibillion dollar scientific project like the SSC were often not applicable, in a pragmatic sense, to an operating testing facility established within the project scope. This disconnect was pointed out by the results of a quality assurance audit conducted on the ASST by the General Management Office (GMO) in January 1993, three months after the ASST test group assumed the responsibility for the ASST facility. Although the audit team found that the ASST management and technical staff conducted business in accordance with sound scientific research practices and produced a high quality product (good test data), it was not apparent that these practices were in strict compliance with SSCL project plans.[21] In response to the audit report, the ASST management developed a series of ASST specific plans to document formally how the ASST was to conduct and document the testing program. These documents—the ASST Program Management Plan, Configuration Management Plan, Operations Plan, and Quality Implementation Plan—were in draft form at the time of project termination and are represented by Refs. [22–25]. In addition, numerous other documents were developed for the ASST which included equipment checkout procedures, safety procedures and checklists, and operational procedures and checklists. A document tree drawing was developed to show what procedures were available and their inter-relationships.[28] In addition, a spreadsheet based index of drawings and controlled documents generated at the ASST was maintained on a run-by-run basis.[29]

The configuration management of the ASST program represented a major task because of the number of systems and technical components provided and maintained (to a large extent) by the technical divisions. A base configuration was established for each testing run, after which modifications to it for each experiment or test had to be tracked and documented with the data taken. The original philosophy adopted was to base the configuration management on an electronic database that maintained the hardware configuration of the string (including all sensor information) on a run-by-run basis. The database was to contain all system level drawings and be capable generating loop level drawings for R&D sensors in the string components.[26] The effort was eventually expanded to a point where the data acquisition system would have accessed the hardware database to determine sensor location and parameters during testing. The work was to be completed for Run 3, but it was cut short by project termination. A summary of the system requirements and the progress made is contained in Ref. [27].

Technical Issues Not Resolved

The test data and operational experience gained at the ASST using the prototype Collider magnets and spools were to be integrated into a vendor-based design for the industrial, mass produced components. The project cancellation left many issues unresolved because the next iteration of design was neither completed nor tested. It is not possible to discuss all of them in this document, but a few illustrative examples can be given.

One such issue was the importance of the RRR range of the finished magnets that would be acceptable to the operation of an accelerator. For example, can the RRR range be adequately controlled during manufacturing (what process variables determine the final value)? Or is it necessary to measure the RRR (a cold measurement and thus costly) of each magnet and then sort them for installation?

The heat leak questions for both the dipole magnets and spools is another example. The magnet cryostat heat leak to the 4 K circuit was a factor of three over budget. The heat shield stability and multi-layer insulation (MLI) bunching was a possible problem, but the source of this excessive leak was left undetermined. Additional design work was indicated. The spool pieces had large, unexplained heat leaks that could only partially be accounted for by the extra R&D instrumentation leads they contained. The quench valves originally specified for the spool pieces had unacceptable performance and operational lifetimes.

Concluding Remarks

The ASST was an operating test facility for superconducting magnet strings at the SSCL at the point of project termination. Runs 1 and 2 had been completed using prototype magnets in a half-cell configuration. Run 3, the first using a full cell of magnets, had completed the thermal testing portion of the test plan when operations were suspended. A proposal was submitted to DOE to approve a modified electrical testing program of six-weeks duration to be conducted as part of the shutdown activities.[30] The proposal was approved, and the results of the testing effort will be reported in [19].

The test group had a comprehensive and aggressive test program planned for approximately three years after 1993 using a full cell configuration of Collider prototype and preproduction magnets. The program was based on the requirements and priorities established by the Collider Machine Group with input from the technical divisions. The results of the program would have been fed back into the engineering effort for the superconducting components in the accelerator lattice to improve their operational performance and lifetime. A full cell test using preproduction or low rate initial production magnets was being planned for Run 4. The effort would have provided an early check on the system level performance of the industrially designed and manufactured magnets. The test would have also provided technology transfer to, and installation experience for, the Collider installation contractor prior to in-tunnel work. The basic Collider test program would have culminated with the Early Cryo Loop Test, which was another major milestone for the SSCL. The Early Cryo Loop Test was planned as an in-tunnel test using the first four cells of the Collider lattice to have been installed at N15. After that point, the HEB Machine Group would have used the ASST surface facility to conduct an HEB magnet string testing program. Once the planned testing program was complete, the experienced test operators and ASST test group personnel would have formed the core group responsible for the commissioning of the ten arc sectors as they were installed and brought on-line.

Chapter 34. Ion Source and RF Quadrupole

(W. Funk and K. Saadatmand)

Volume-produced, low-temperature (< 2 eV) H^- ions can be directly extracted from a multicusp plasma source to form a low-emittance and high-brightness beam. A pulsed RF-driven (2 MHz) volume H^- source was developed for the SSC by LBL.[1] Currently, two RF volume sources are operating. An R&D source has been under study on a test stand since May 1992, and an injector source has been providing beam for the SSC linear accelerator (Linac) since April 1993.

Figure 34-1 is a functional diagram of the SSC Linac injector showing the H^- Ion Source, LEBT, and RFQ. Figure 34-2 shows the Injector at its temporary location at the R&D laboratory. The injector was scheduled to be moved to its permanent tunnel location later in 1994. First beam was successfully accelerated through the injector on April 8, 1993. With 30 mA from the 35 keV ion source, the injector output current was 18 mA. After a brief description of the Injector subsystems, details of experimental results from the injector output beam characterization will be presented below.

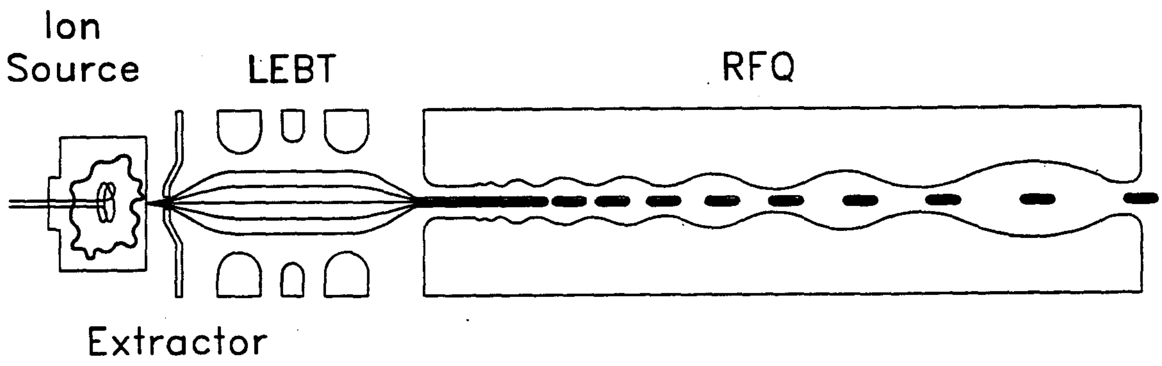


Figure 34-1. Functional Diagram of the SSC Linac Injector.

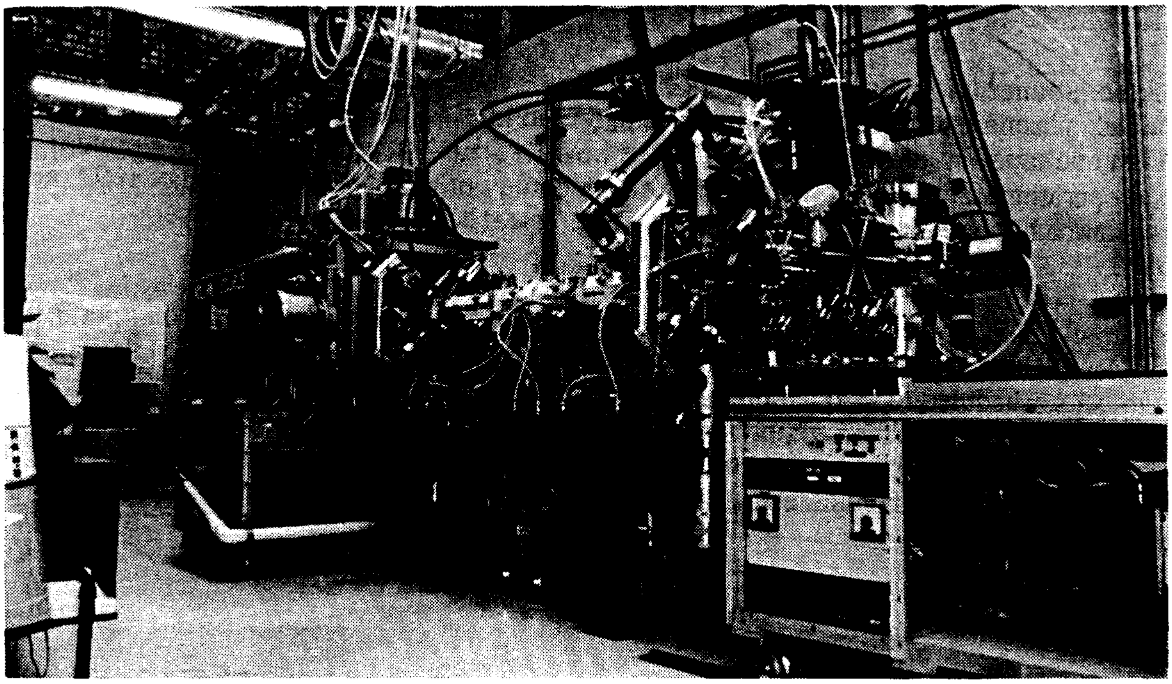


Figure 34-2. SSC Injector at its Temporary Location.

Injector Subsystems

SSC H^- RF Volume Source

Multicusp plasma sources provide volume production of low energy (<2 eV) H^- ions leading to low emittance, high brightness beams. An RF driven volume H^- source, based on RF induction discharge, was developed for the SSC by LBL.[1] A schematic of the SSC RF volume ion source is shown in Figure 34-3. The plasma is confined by the longitudinal line-cusp field produced by samarium-cobalt magnets that surround the source chamber and back flange. A pair of water-cooled permanent magnet filter rods placed near the plasma electrode creates a narrow region of transverse magnetic field that divides the source chamber into discharge and extraction regions. The 2-MHz RF power, uses electrons supplied by a hairpin tungsten filament plasma starter to excite and ionize the hydrogen gas molecules in the discharge region. The RF power is inductively coupled to the mixture via a two-turn ceramic-coated copper antenna. The magnetic field of the filter rods prevents the energetic plasma electrons from entering the extraction region. Cold electrons, the positive and negative ions, and the vibrationally excited hydrogen molecules can drift across this magnetic field forming a plasma in the extraction region with a low electron temperature. The cold plasma enhances the formation of H^- ions by dissociative attachment[2].

Extracted H^- beam currents as high as 40 mA at 35 kV have been achieved. The volume source has a high extracted electron to H^- ratio (30:1). The unwanted electrons are separated from the H^- beam by a 4-cm-long magnetic spectrometer at the extractor electrode exit (Figure 34-3). The spectrometer's magnets are housed inside a soft iron envelope to prevent the fringe field from penetrating the extraction gap and the volume source. Figure 34-4 is a close up of the RF volume source as part of the Injector assembly (the LEBT vacuum shell and portions of the RFQ are also shown).

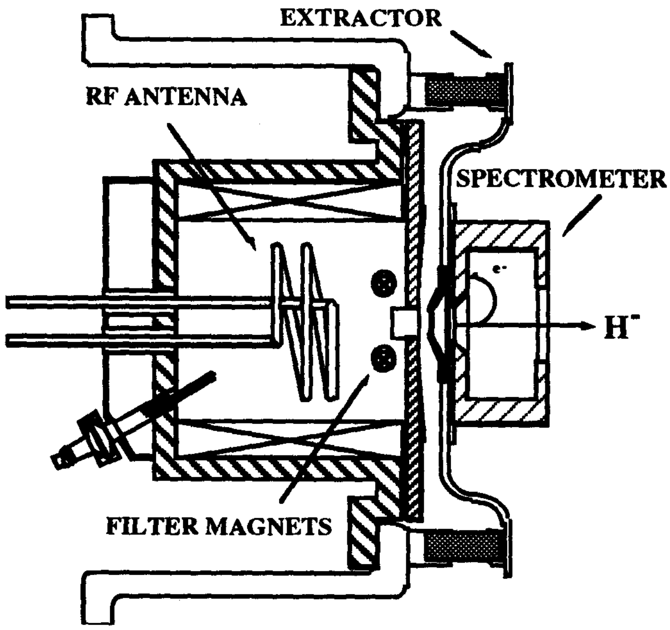


Figure 34-3. Schematic of SSC H⁻ RF Volume Source.

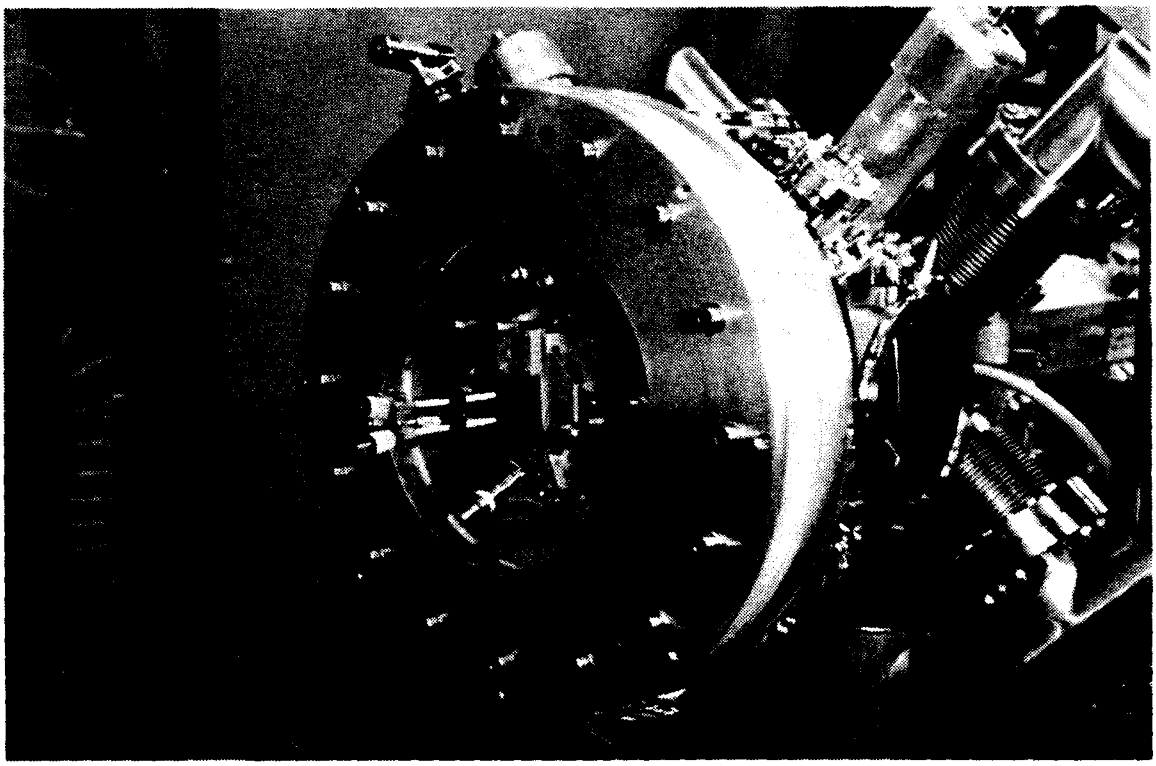


Figure 34-4. Close-up of RF Volume Source.

Emittance measurements, made at an axial position corresponding to the LEBT entrance (~ 5 cm downstream of the extractor electrode), yield $\varepsilon_{t\text{-}n\text{-}rms}$ (rms normalized emittance extrapolated to 100 % of the assumed Gaussian beam[3]) of 0.10–0.15 π mm-mrad. A smaller emittance,[4] $\varepsilon_{t\text{-}n\text{-}rms}$ = 0.06 π mm-mrad, has been measured in the presence of Xe neutralizing gas, which minimizes space charge effects. The actual H^- beam emittance out of the ion source is believed to be closer to 0.06 π mm-mrad. Figure 34-5 shows a typical horizontal phase-space emittance contour plot of beam out of the volume source. The beam is highly diverging and is about 0.8 cm in radius.

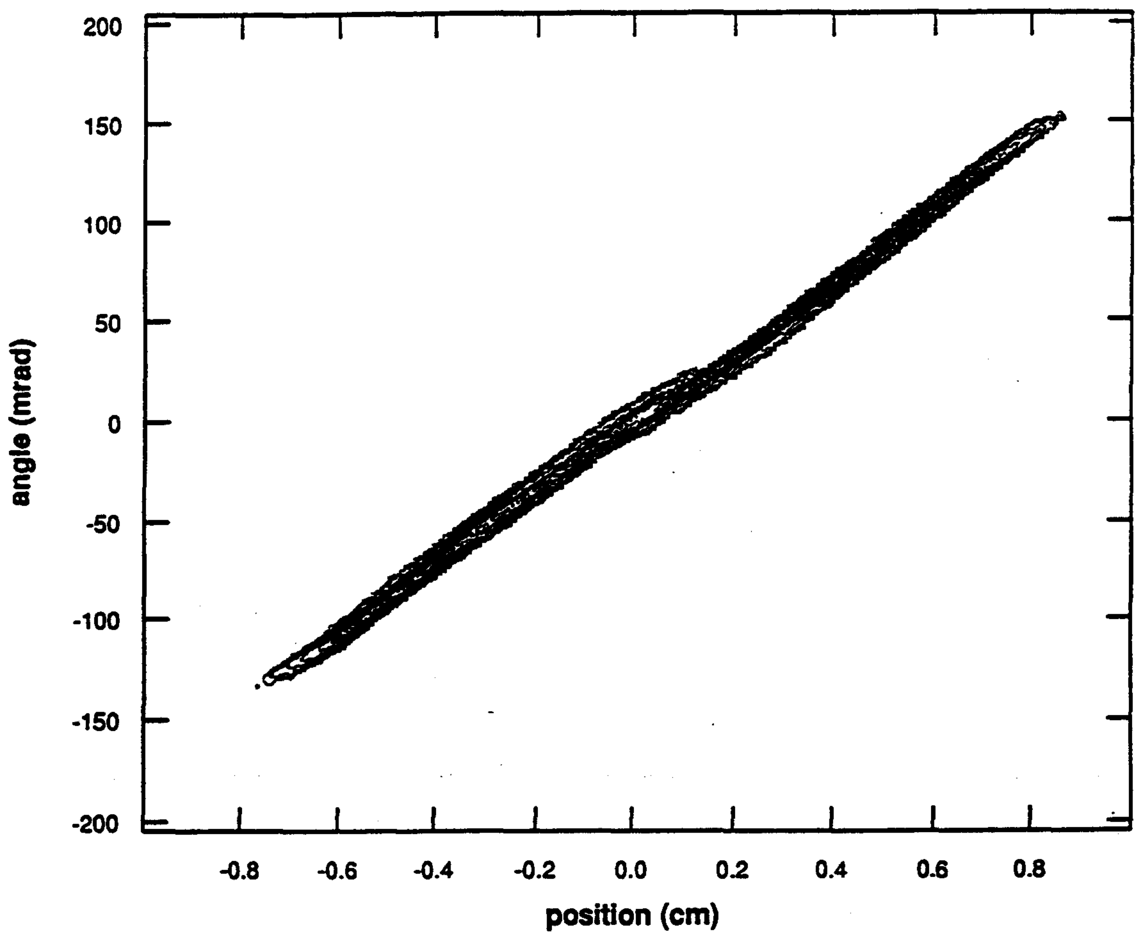


Figure 34-5. Typical Horizontal Phase-space Emittance Contour Plot of Beam out of the Volume Source.

Low Energy Beam Transport (LEBT) Systems

The divergent ion source beam is matched into the RFQ by the LEBT. The LEBT housing also contains source diagnostics and provides the differential pumping between the source and the RFQ. The SSC RFQ requires a highly convergent input beam. The Twiss parameters for the design input beam are $\alpha_{x,y}$ =1.26 and $\beta_{x,y}$ =0.018 mm/mrad (140 mrad convergence and~4 mm in diameter).

A gas neutralized LEBT is not an option for the SSC, because the neutralization time (~50 μs) is longer than the SSC pulse length. Thus, electrostatic LEBTs were the only viable option. The 30 mA operating current is low enough that several electrostatic focusing concepts can be considered. The einzel lens and helical electrostatic quadrupole (HESQ) lens were the leading candidates for the SSC Linac, and their characteristics were being evaluated. Also the University of Maryland is investigating a straight electrostatic quadrupole (ESQ) LEBT concept[5] for the SSC, and LBL is investigating a very compact single ring lens concept.[6]

The einzel lens is probably the most mature technology for this application. Unfortunately this LEBT requires voltages similar to the source voltage; this results in nonlinear aberrations. For the initial commissioning of the Injector, an existing dual einzel lens LEBT was being used optimized to meet the SSC magnetron ion source requirements. The choice was not the most technically desirable one but, in the interest of meeting the schedule, it was the logical one.

The 30 mA output beam of the volume source and einzel LEBT configuration was characterized at 35 keV. Figure 34-6 shows a typical horizontal beam phase-space emittance contour plot out of the einzel lens at an axial location corresponding to the RFQ entrance. Nonlinear aberrations are quite pronounced. However, the shape of the vertical and horizontal phase-space emittance contour plots are similar. The measured $\varepsilon_{t\text{-}n\text{-}rms}$ ranges between 0.38 π mm-mrad in the vertical plane to 0.79 π mm-mrad in the horizontal plane. This is 3 to 5 times the ion source emittance. However, most of this LEBT induced effective emittance growth is due to the large, low particle-density, phase-space wings. As shown in Figure 34-6, the converging core of this beam, which contains the majority of particles, fits within the nominal acceptance space of the RFQ. Computer simulations[7] have indicated a 40 to 65% transmission of this beam through the RFQ. A 50% transmission would provide a more than adequate Injector beam (15 mA) to commission the following stages of the SSC Linac. Figure 35-7 is a close up of the einzel lens housing assembly as installed in the injector. The ion source extractor and magnetic spectrometer are also shown in this figure.

Radio Frequency Quadrupole (RFQ)

The SSC RFQ is a four-vane structure designed and built for SSC by LANL.[8] The design parameters of the SSC RFQ are given in Table 34-1. The SSC RFQ has two unique features. First, the design included the effects of higher multipoles by using an 8-term electric field potential to optimize transmission. Second, the intervane voltage is ramped along the length of the RFQ to minimize beam losses and structure length.

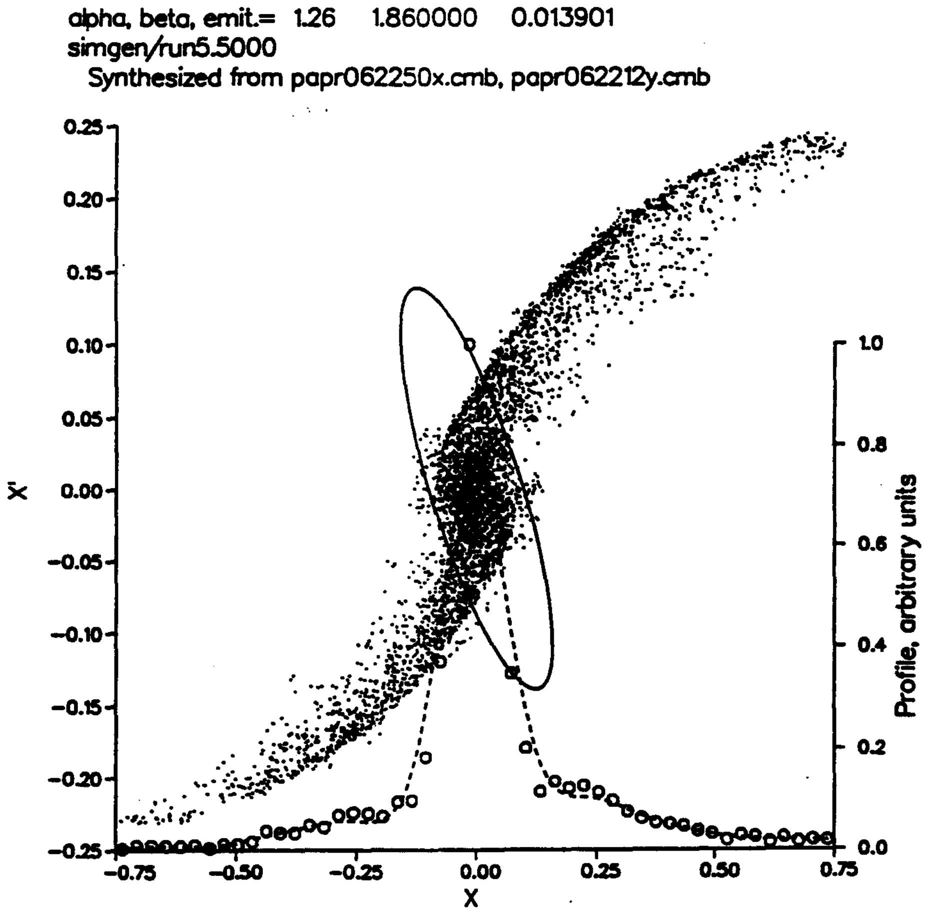


Figure 34-6. Typical Horizontal Beam Phase-space Emittance Contour Plot out of the Einzel Lens at an Axial Location Corresponding to the RFQ Entrance.

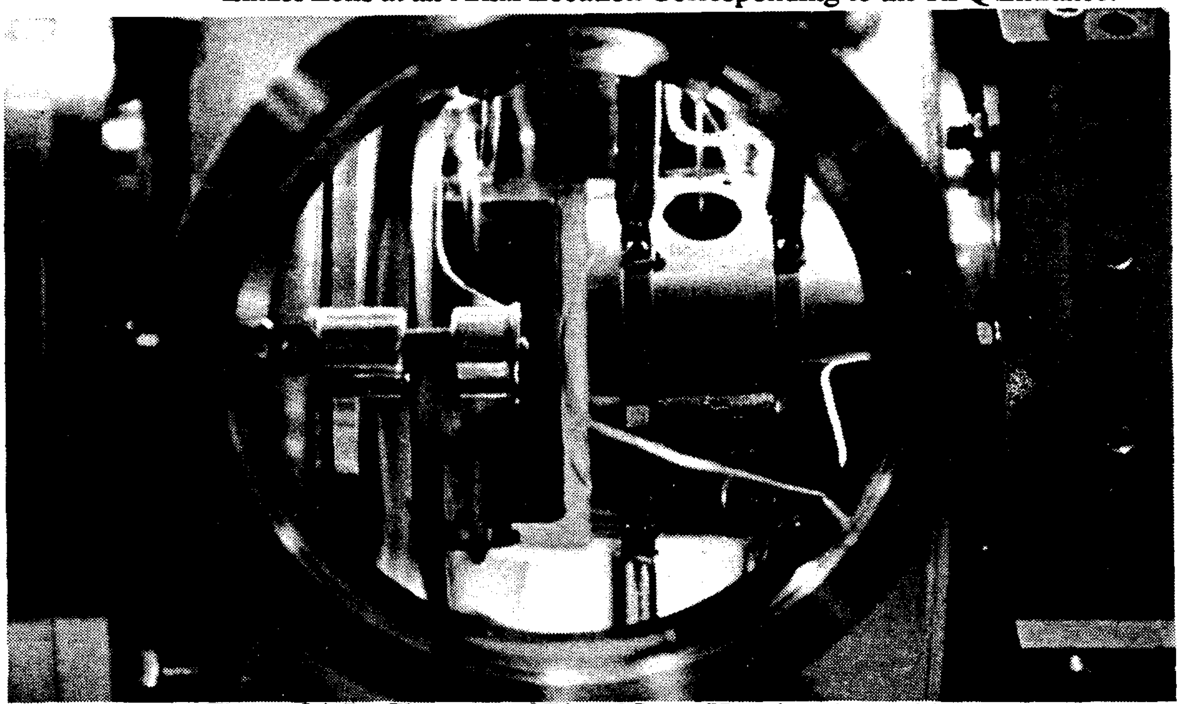


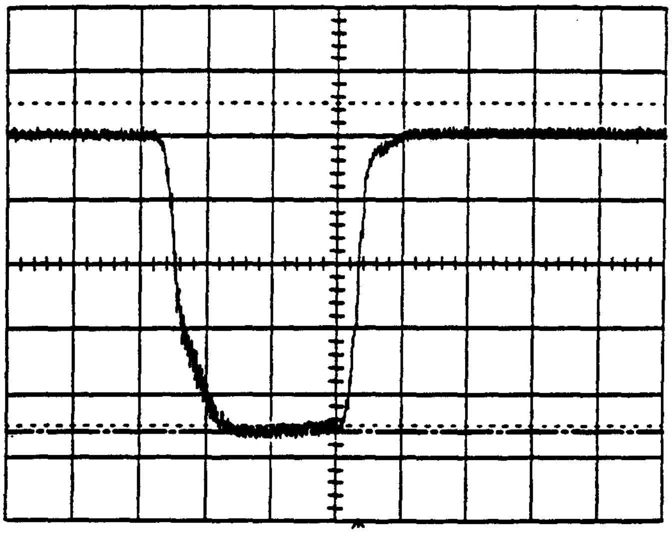
Figure 34-7. Close-up of Einzel Lens Housing Assembly.

Table 34-1. SSC RFQ Design Parameters.

Frequency	428 MHz
Injection Energy	35 keV
Output Energy	2.5 MeV
Injection current	30 mA
Output current	28 mA
RFQ length	218 cm
Input aperture radius	0.198 cm
Final aperture radius	0.240 cm
Final modulation factor	1.93
Intervane voltage	54.82 to 88.5 kV
Peak surface field	36 MV/m (1.8 K)
Cavity rf peak rf power	<300 kW
Input $\varepsilon_{t\text{-}n\text{-}rms}$	<0.2 π mm-mrad
Output $\varepsilon_{t\text{-}n\text{-}rms}$	<0.2 π mm-mrad
Output ε_1	<0.82 × 10^{-6} eV-s
Output beam radius (rms)	0.75 mm

Injector Output Beam Characterization

A set of toroids and Faraday cups (FC) placed in various axial locations along the injector are used to measure the output beam current and beam transmission through the RFQ. A Faraday cup can be inserted between the ion source and the LEBT to measure the ion source beam current and to block the beam from the rest of the Injector. A non-intercepting toroid in the LEBT measures the RFQ input beam current. At the RFQ output, the injector current is measured by a toroid and a downstream FC. The injector output beam current, as measured by the RFQ output FC, is shown in Figure 34-8. The measured output beam shape is similar to the measured ion source output beam current (Figure 34-9). The highest injector output beam current achieved to date is 20 mA (for 30 mA input); this translates to a 66% transmission through the SSC RFQ.



Vertical Axis : 4 mA/div
Horizontal axis : 20 μs/div

Figure 34-8. Injector Output Beam Current.

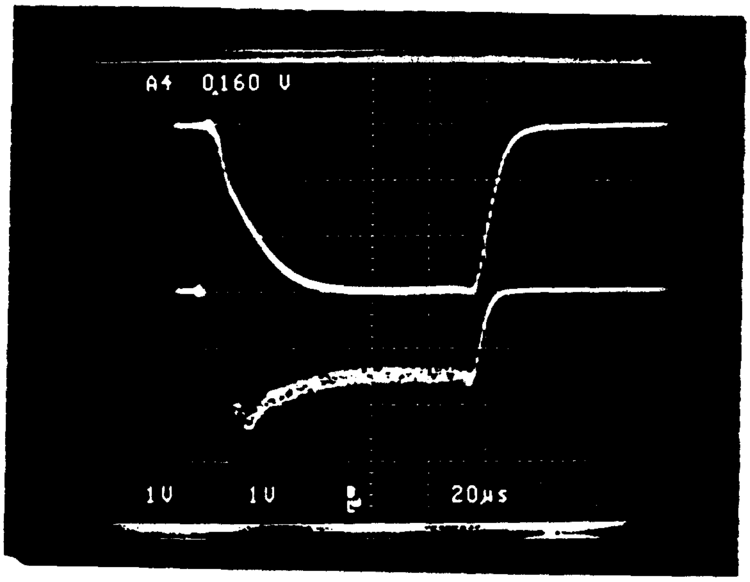


Figure 34-9. Ion Source Output Beam Current.

An absorber-collector experiment has bracketed the output beam energy to a value between 2.1 MeV and 3.3 MeV. In this experiment, a 2.1 MeV range-thick foil, placed upstream of the output F.C., allowed the whole injector output beam to be collected, while a 3.3 MeV range-thick foil stopped the entire beam. The experiment also indicated a 100% accelerated beam at the nominal RFQ design field.

A Rutherford scattering experiment[9] confirmed the results of the absorber-collector experiment and measured the injector output beam energy to be 2.5 MeV, within 50 keV accuracy. The transverse emittance of the injector output beam was measured by a slit-and-collector diagnostic system. Typical horizontal and vertical phase-space emittance contour plots of the injector output beam are shown in Figures 35-10 and 35-11, respectively. These measurements have yielded transverse emittance measurements of $\varepsilon_{x\text{-}n\text{-}rms} = 0.2\ \pi$ mm-mrad and $\varepsilon_{y\text{-}n\text{-}rms} = 0.19\pi$ mm-mrad, 21.6 cm downstream of the injector (output current of 20 mA; 67% transmission).

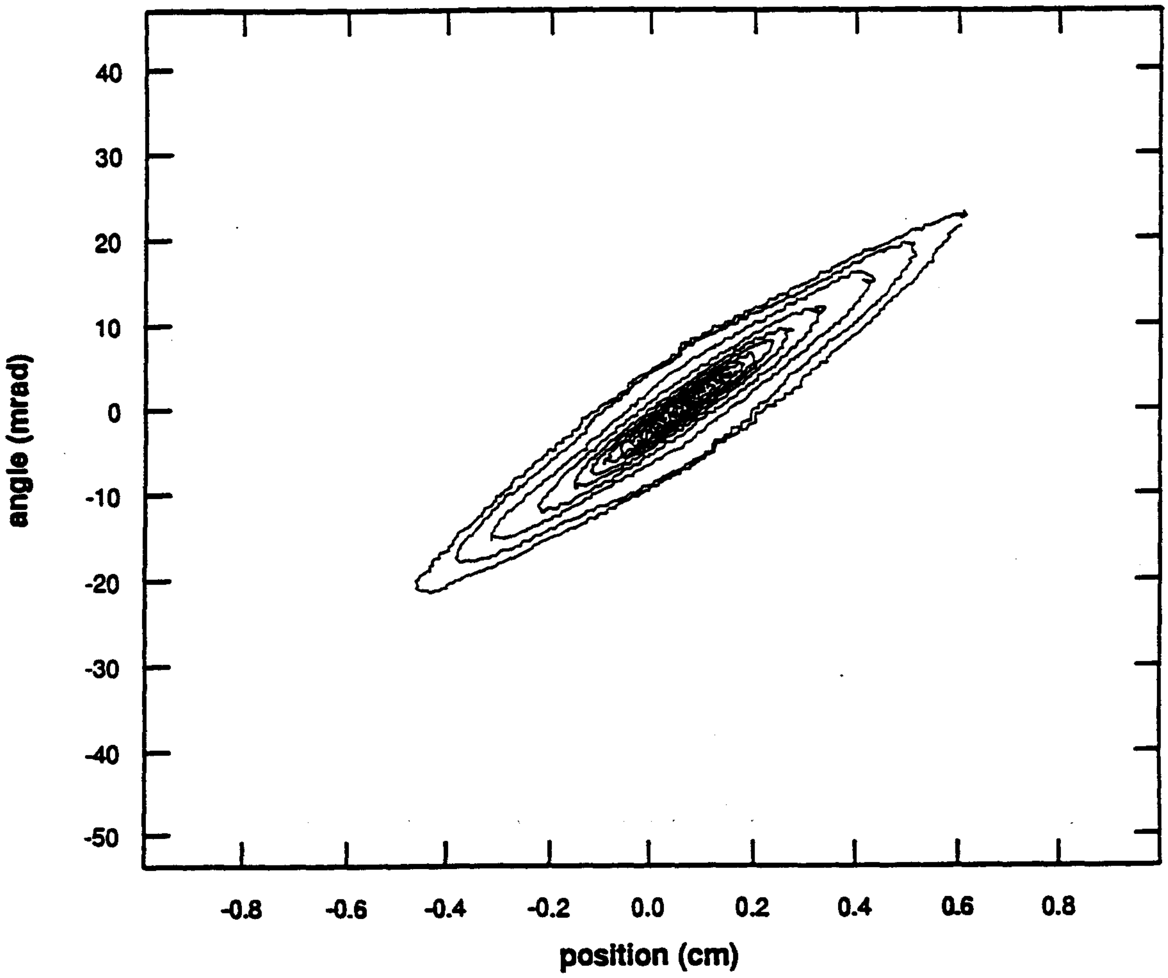


Figure 34-10. Horizontal Phase-space Emittance Contour Plot of Injector Output Beam.

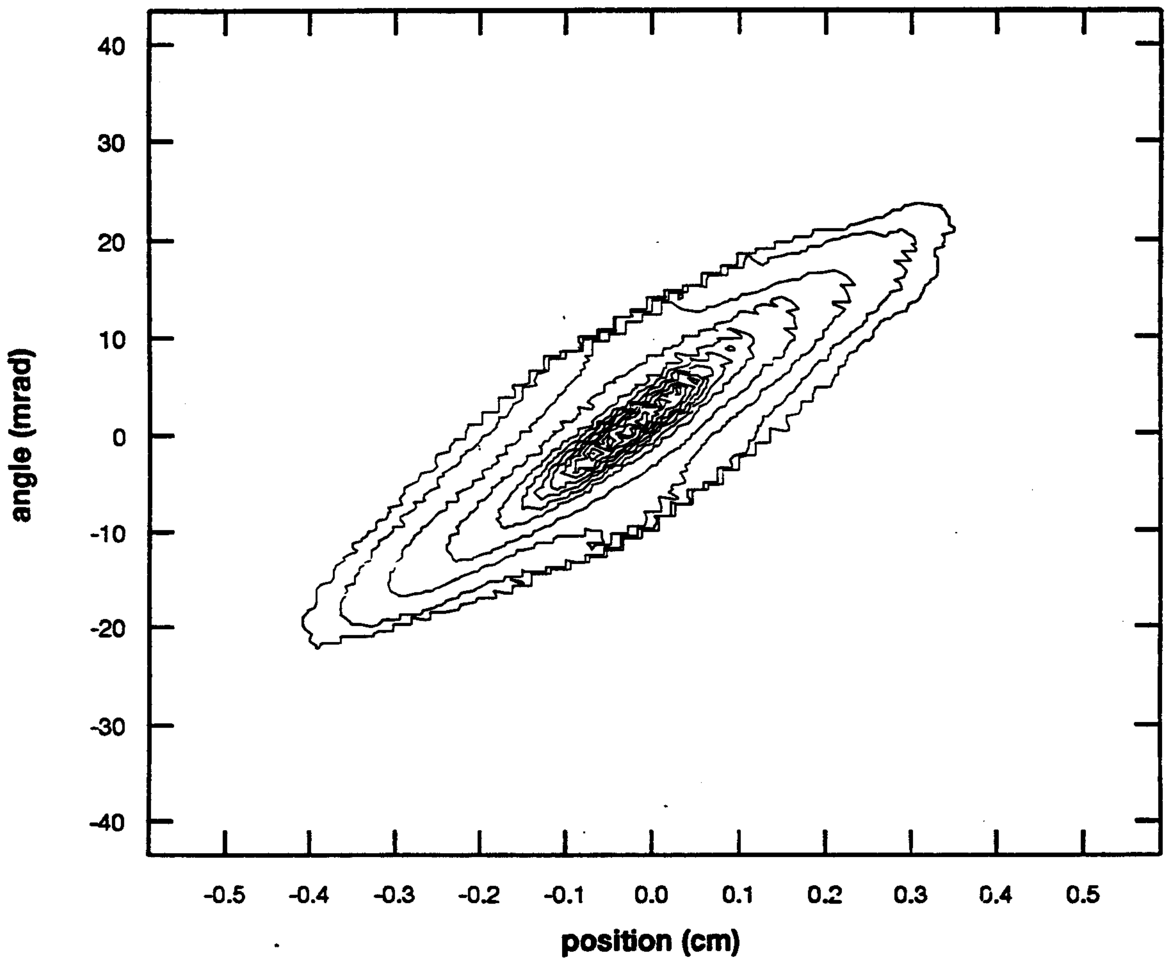


Figure 34-11. Vertical Phase-space Emittance Contour Plot of Injector Output Beam.

A bunch shape monitor diagnostic built by INR[10] was used to determine the micro-bunch longitudinal phase profile. The beam hits a thin wire at a 10 kV potential, and secondary electrons are emitted proportional to the beam intensity. The electron beam is collimated and "time stamped" with an RF deflector. The deflector phase (w.r.t. the output beam phase) is scanned, measuring the intensity of the electron beam at different times during the micro-pulse to produce an intensity versus phase profile. The first measurements of the bunch shape monitor are in good agreement with theory. Figure 34-12 shows a comparison of measured results with the theoretical model at nominal RF power, 15 cm downstream of the RFQ. The measurements indicate a well bunched beam with an rms micro-bunch length of 10 degrees.

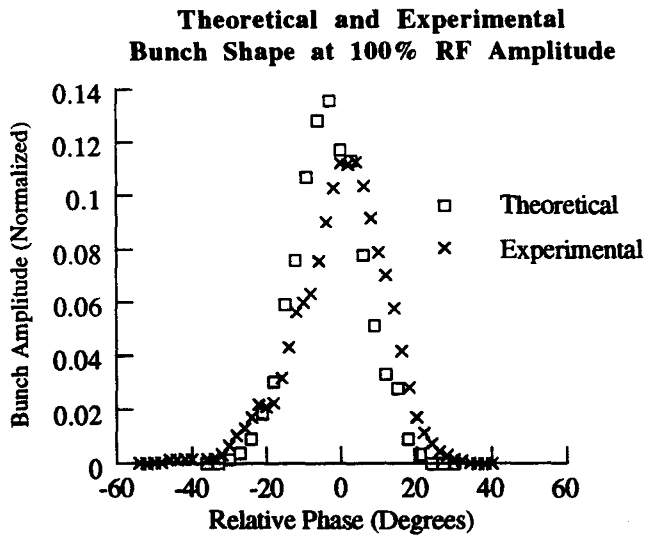


Figure 34-12. Theoretical Bunch Shape Predicted by PARMTEQ Simulation and Experimental Data as Measured by the Bunch Shape Monitor for Nominal Vane Voltage. The Intensity is Normalized for a Unit Area.

Chapter 35. Machine Lattice Files

(G. Bourianoff)

Description of Lattice File Archives

This section will describe the machine lattice file archive. The first part is a description of the archive organization as a UNIX directory tree. (Additional archive data accessible through World Wide Web is under consideration.) This is followed by a description of the physical location of the archive as well as instructions for accessing it.

The second major part of this section will describe the revision level of each lattice. This will be more than a simple label such as Rev 2.1; it will include a verbal description of the principal features of that particular revision, which will help identify it for the people closely associated with development of that lattice. The description will of necessity be inexact and subjective, but it will nevertheless be quite useful. The exact contents of each lattice are contained in the specified file.

UNIX Directory Structure

The lattices are stored in the form of a UNIX hierarchical file structure, which will reside on several different media at sites that include BNL and possibly other DOE laboratory facilities. The lattice information is contained in database tables, and ASCII input files that are ready to be run by at least one standard simulation code; e.g., TEAPOT, MAD, or TRANSPORT. The output file(s) corresponding to the input are also saved as part of this archive.

The file structure is shown schematically in Figure 35-1. The top level (level 1) directory is labeled Lattice, and it is anticipated that a parallel directory labeled codes will be created as part of a separate effort. The second directory level identifies one of 9 lattices in the SSC complex. The directory labeled Collider will contain 4 lattices corresponding to the top and bottom rings at injection and collision optics. The subdirectories labeled "M to H Xfer" and "H to C Xfer" also contain 2 lattices each since there are 2 lines going into the HEB and 2 lines coming out of the HEB. The level 3 subdirectories are empty placeholders and are present only for the sake of organizing the other files. The subdirectories in level 3 correspond to accelerator simulation codes in common use within the community. The subdirectory SRC corresponds to database tables used by the lattice database.

The actual lattice information is contained in the files in level 4. In general, they consist of an input file for a specific simulation code and the output file(s) generated by the input. Again in general, the input file will contain the lattice information in the form required by the individual simulation code plus the commands necessary to assemble the lattice information, calculate the optics functions of the bare lattice, and set the tune and chromaticity to the desired values. A separate file will contain anticipated alignment errors and magnetic field errors, and the commands necessary to correct for those errors using routine operational procedures.

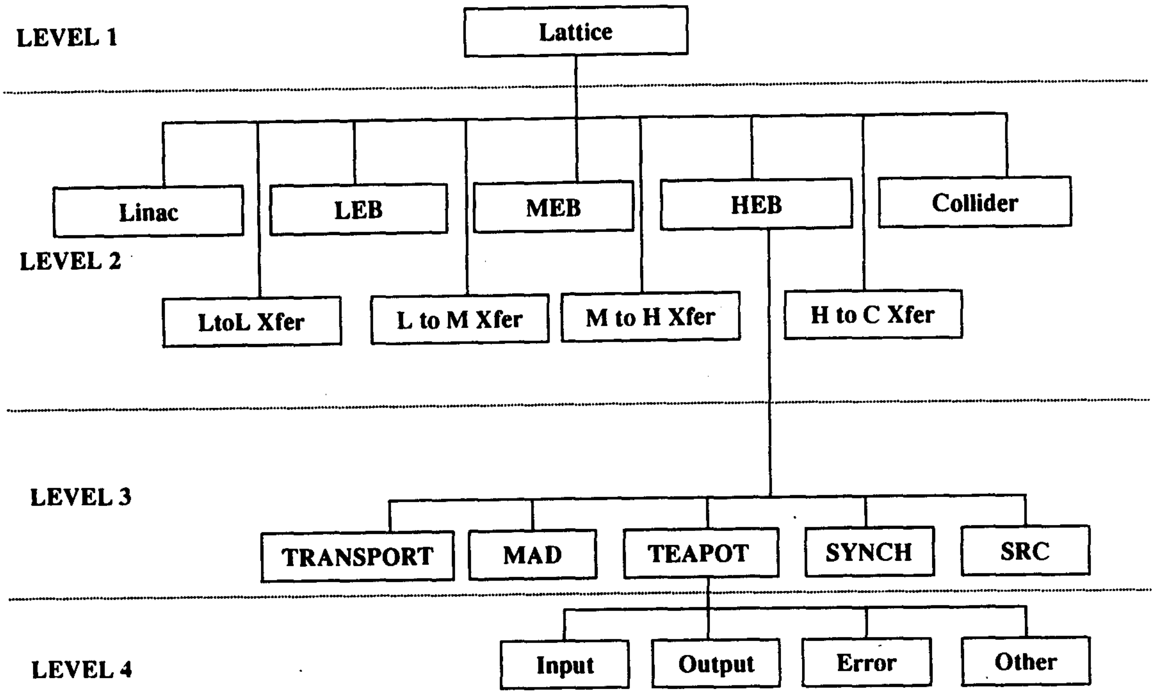


Figure 35-1 Schematic Representation of UNIX File Structure.

Archival Media

Simulation models have been developed for the lattices of the SSC circular machines, that have been used for the evaluation of machine performance owing to the presence of simulated errors, the study of correction systems, and the determination of dynamic and linear apertures. Although there are obvious differences in the design and parameters of the three injector machines and the Collider, there are some common features in the models developed for these accelerators. The general characteristics of the simulation model and tools will be discussed first, followed by information specific to the individual lattice files describing every machine model.

Model and Tools

The main tool used for the lattice performance analysis is the TEAPOT code suite, that consists of the TEAPOT code itself, VECTRAC, the parallel extension of its tracking core, and a set of postprocessors used for visualization and analysis of the results. The starting point of the simulation is the "ideal" lattice, i.e., the linear lattice with the main magnetic elements represented by thin lenses. The number of thin lenses depends on the accelerator described and the nature and location of the magnetic element itself. The lattice is tuned to its nominal fractional tunes, and normally the linear chromaticity is corrected.

Alignment and field errors are then added to the relevant elements in the machine. The model assigns a random distribution of alignment errors to bending magnets, quadrupoles, sextupoles, and beam position monitors. Main dipoles and quadrupoles are assigned random and systematic field errors, specified as multipoles up to order nine. The multipoles reflect the specification assumed for the magnet design in the various machines. The model simulates realistically the correction procedures necessary to improve the control of the machine with errors. The main correction procedures are the control of the closed orbit (by a set of beam position monitors and correction dipoles), decoupling (by skew quadrupole correctors), retuning (by trim quadrupoles), and compensation of chromaticity (by sextupole correctors). Further correction procedures are simulated in some particular machines, such as the local chromaticity correction system or the crossing angle system in the Collider lattice.

In general, the single particle dynamics behavior of the lattice with errors is evaluated after a satisfactory level of correction is achieved. Typically, the dynamic and linear apertures of the machine are determined on the basis of short-term tracking directly with the TEAPOT code, while long-term tracking is performed with the VECTRAC code on a parallel platform.

Lattice Error Files

For each circular lattice, a TEAPOT file with the description of the errors and corrections for that particular machine, is stored in the subdirectory ERROR under the directory TEAPOT. The error assignments and specifications match the teapot "ideal" lattice that is stored in the parallel subdirectory INPUT. The error files contain also a set of standard initial conditions that can be used for tracking runs. The suffix _inj and _top label error sets used for the particular machine at the injection and top energy configurations, respectively. A README file stored also in the ERROR subdirectory contains detailed information associated with the simulation model of that particular machine.

Description of Status of Each Lattice

Each accelerator design has been maintained in the SSC Lattice Database in the form of relational database tables. This disk archive contains various output files generated from the database, which will be more useful from the point of view of the usual accelerator application codes such as MAD, TRANSPORT or SYNCH. The database tables are stored, along with the original source in electronic form. The database tables can be utilized by anyone (if they have the LAMBDA Collaboration software) to reconstruct any of the lattice databases defined here. Only the latest (or last) version of each accelerator lattice provided by the various machine groups to the lattice database has been archived. A list of each of the designs stored and comments on them are given below. For more complete discussions of the lattice designs archived, please see the chapters on each machine in this document.

Linac

The SSC Linac was designed using the TRACE3D and PARMILLA codes. The version stored here is named lin_rev1. The first section of the Linac contains the H^- ion source and beam transport systems. Following this are the Drift Tube Linac (DTL) and Coupled Cavity Linac (CCL). Between each of these major components of the Linac are matching sections containing beam instrumentation and steering equipment.

Low Energy Booster (LEB)

The version of the LEB in the archive is named leb_rev2. This lattice was designed using the code DIMAD. The LEB is composed of three symmetric sections for a total length of 570 m. Each of these three sections contains an arc and straight section. The straight sections are composed of three FODO cells each and are used for injection from the Linac, extraction to the MEB, and for the RF systems. The basic FODO structure of the LEB arcs consists of four superperiods, each composed of three FODO cells. The central cell of these three contains no bending magnets. The structure facilitates chromatic stability because the dispersion can be high and positive in the empty cell while being low or negative in the bending cells.

Medium Energy Booster (MEB)

The MEB was designed using the code SYNCH. The version of the lattice stored here is named meb_rev0_4, which includes correction and beam instrumentation packages. The MEB lattice is composed of 8 sections, each section including an arc and an insertion region for a total length of 3960 m. Five of the straight sections are used for injection (1), transfer to the HEB (2), transfer to the MEB test beam lines (1), and the MEB abort line (1). There are two types of insertions, long and short. The short insertion is used in the injection area, and the long insertions for 200 GeV extraction. Each arc section is made of 14 FODO cells containing four 6m dipole magnets.

High Energy Booster (HEB)

The HEB was designed principally using the code SYNCH. The HEB lattice stored here is named heb_rev1. The HEB is composed of 6 arc sections (1001.32 m), 2 long straight sections (390.83 m), and 4 short straight sections (233.31 m) for a total length of 10.8 kilometers. The total HEB arc contains 256 half cells of length 32.5 m each, composed of 2 dipoles and a quadrupole. The long straight sections are designed for beam transfer to the Collider rings and 2 TeV test beams. The short straight sections are designed for injection of beam from the MEB as well as for the HEB beam abort lines. Dispersion suppresser cells connect arc and straight sections.

Top Collider Ring (TOP)

The last version of TOP Collider ring lattice was designed using the code MAD. The version stored here is known as top_rev2. The Collider ring consists of two major arc sections (north and south) and two straight sections (east and west) containing the interaction regions and utility areas used for injection from the HEB as well as for beam abort. The full length of the Collider is 87.120 kilometers.

Transfer and Test Lines

The MEB test beam lines were designed using the code TRANSPORT. The test beams are extracted from the MEB at 200 GeV, transported down a common primary line of length 491 m, after which the beam is separated into three (ultimately to have been six) secondary lines of length 447 m. The versions of the lattice archived are named kb1_rev2, kb2_rev2, and kb3_rev2. The preliminary design of the other three lines (kb4, kb5, and kb6) are also stored in the src directory. The HEB abort lines were designed using the code TRANSPORT. The versions stored here are known as hebabtt_rev1 and hebabtb_rev1, respectively. The MEB abort line was designed using the code TRANSPORT. The version stored here is known as mebabt_rev1.

The Linac absorber lines, one for the Linac itself and the other for the Linac to LEB transfer line, were designed using the code TRANSPORT. The Proton Therapy Line was designed using TRANSPORT. The Linac transport and Linac to LEB transfer lines were designed using the code TRANSPORT. The version stored here is named ll_rev1_1. The first half of this line (Linac transport section) is composed almost entirely of FODO cells with a 90 degree phase advance, and it is about 100 m in length. The second half of the line (transfer section) contains two eight degree and one four degree bending sections, and it is about 110 m in length. The transfer section contains three regions for beam scraping, two H^+ absorber lines, and one for emittance measurement. The injection girder at the LEB end contains four identical bump magnets that move the LEB closed orbit 47.2 mm off axis during the transfer process.

The LEB to MEB transfer line version is named lm_rev2. This transfer line was designed using the code TRANSPORT. The transfer line is about 249 m long. Between the LEB extraction straight and MEB injection area, the transfer line is composed of ten 2 m dipole and 24 quadrupole magnets divided into three sections. The first section is responsible for matching LEB and MEB vertical dispersion, the second for matching horizontal and vertical beta functions, and the third, a 120 m FODO section, transports the beam into the MEB injection straight.

The two MEB to HEB transfer lines, MT (for MEB to HEB to the TOP Collider ring) and MB (for MEB to HEB to the BOTtom Collider ring), were designed with the code TRANSPORT. The lattices archived are named mt_rev1 and mb_rev1. The shorter (MT) of the two lines is 850 m in length while the longer (MB) is 2.2 kilometers in length. The extraction and injection sections of the two lines are similar in structure. Beam is extracted from the MEB using fast kicker magnets that move the beam horizontally from the MEB closed orbit. This is followed by a section of Lambertson and C magnets that move the beam vertically away from the MEB and down to the transfer line proper. Injection at the HEB is roughly the inverse of extraction: C magnets and Lambertsons followed by fast kickers position the beam at the HEB closed orbit. The MB line is composed of two vertical bending sections, an 800 m FODO section containing horizontal bends, a 400 m FODO matching section used to modify the 51.5 m β peak to a 36.2 m peak, and two final vertical bend sections. The MT line is composed of a vertical bend section and a 500 m FODO section with horizontal bends continuing into the final vertical bend section.

The HEB to Collider transfer lines were designed using the code TRANSPORT. The versions stored here are named ht_rev1 and hb_rev1 for HEB to TOP and BOTtom Collider rings, respectively. These transfer lines are 637 m long, excluding the extraction and injection regions. The transfer line itself is composed of three sections. The first and third are vertical bending regions containing Lambertsons, C magnets, and vertical bending dipole magnets. The middle section has a pseudo-periodic FODO structure used to provide optical flexibility for matching the HEB and Collider closed orbits, dispersion and beta functions.

Access Instructions

Once compiled at the SSC laboratory, the lattice archives will be transported to one or more other sites, where they will be placed on disk. The directory structure will then be made available through the UNIX File Transfer Protocol (ftp). The system will be configured to accept "anonymous ftp," that is, any person with access to the Internet will be able to access the files. The exact location in the directory structure where the SSC lattice archive will reside will be determined in conjunction with the system administration personnel of the other site(s). One commonly used directory structure is as follows:

```
/
|
|
|---------------|
|               |
|               |
 (other              pub
 filesystems)   |
                |---------------|
                |               |
            (other        SSC_lattices
             ftp
            filesystems)
```

SSC_lattices is the top directory of the tree discussed in the remainder of this document. In this directory, in addition to the other files and directories discussed herein, would be the file ssc_lattices.tar.Z. This file, created using the UNIX tar (Tape Archive and Record) and compress utilities, would contain the entire ssc_lattices filesystem.

Any researcher on a UNIX computer attached to the Internet will be able either to obtain a portion of the lattice archive, or to re-create the entire lattice archive directory tree easily on his or her own machine. Below is a sample session for a person working on a machine performing this process. The session is indented, while editorial comments begin at the left margin.

The user begins at his machine prompt by typing "ftp" followed by the location of the archive on the Internet.

> my_machine> ftp ftp_machine.site.somewhere.net
>
> Connected to ftp_machine.site.somewhere.net
>
> 220 site FTP server (Version 2.1aWU(1) Thu Jun 3 23:00:04 EDT 1993) ready.
>
> Name (ftp_machine.site.somewhere.net:me) anonymous

In the line above, ftp_machine has asked the user what his name is, and he has replied "anonymous." This merely means that he is a user who does not have normal access to ftp_machine. The system replies

331 Guest login ok, send your complete e-mail address as password.

Password:

The user enters his e-mail address at the above line, but it does not echo, being a password field. A log is kept of these, however, for use in determining who is accessing the machine and how often.

230 Guest login ok, access restrictions apply.

ftp>

This merely means that not all files may be accessed via ftp. The ftp session is initialized in the pub directory. The user enters:

ftp> cd SSC_lattices

ftp> bin

200 Type set to I

ftp> get ssc_lattices.tar.Z

200 PORT command successful.

150 Opening BINARY mode data connection for ssc_lattices.tar.Z (NNNNNNN bytes)

The system now transfers the file to the user's machine, placing it in the directory on the local machine from which the ftp session was started. When complete, the user sees

226 Transfer complete.

local: ssc_lattices.tar.Z remote: ssc_lattices.tar.Z

NNNNNNN bytes received in NN seconds (NN kbytes/s)

and types

ftp> quit

221 Goodbye.

my_machine>

Assuming that the directory the user started from on his local machine is empty, ls will now return

my_machine> ls

ssc_lattices.tar.Z

Now the user unpacks the file by first typing my_machine> uncompress ssc_lattices.tar.Z

my_machine> ls

ssc_lattices.tar

This file may now be converted into the component directories and files using tar as follows:

my_machine> tar -xf ssc_lattices.tar

my_machine> ls

SSC_lattices ssc_lattices.tar

SSC_lattices is the top directory of the lattice archive directory tree. All files described in this document are now on the user's machine.

Chapter 36. Physics Detector Simulation Facility

(L. Cormell)

Off-line computing systems were developed by the Computing Department (CD) of the Physics Research Division (PRD) to provide resources needed by the Collaborations for reconstruction, analysis, and simulation of SSCL detector data. The systems were to be several orders of magnitude larger in capacity than those in operation at other laboratories at the time. Estimates from GEM and SDC indicated a need for nearly a million SSCUPs (SSC units of performance which is approximately 1 VAX 11/780 equivalent) of CPU capacity to meet their needs. In addition mass storage capacities in excess of 1×10^{15} bytes (peta-bytes) per year and data transmission rates in excess of 1 Gbps were required. The details of the activities of Experimental Systems Computing can be found in the bibliography. The foremost references are the Computing Project Management Plan, R40-00002[1] and Experimental Systems Computing, SSCL-N-814.[2]

The mission for Experimental Systems Computing was to define, plan, design, procure, install, implement, and operate off-line computing systems required to support detector design and construction, and the SSCL experimental programs. These off-line components included Simulation, Mass Storage, Analysis, Reconstruction, Communication, and Data Distribution Systems. Additional activities in support of detector computing would include system software development, core applications development, computing and networking R&D, and hardware and software evaluation and testing.

Off-line computing systems included resources required during the Laboratory's construction period for simulation of detector design, software development, testing of off-line systems concepts, support of experimental programs conducted outside the SSCL during its construction, and hardware and software systems needed for carrying out computer and network-related research and development programs. Off-line systems also included resources needed by physicists for production, analysis, and simulation of experimental data during the SSCL operation.

Work Plans, Project Accomplishments, and Status

Work Plans, Strategy, and Approach

The mission of the Physics Research Division Computing Department was carried out in conjunction with Collaboration computing personnel and commercial developers where appropriate. In general, the Collaboration management was more involved in the generation and validation of requirements, and in the development and implementation of detector specific software. CD management was more involved in long range R&D, in promoting common computing solutions, and in the implementation of specific HW and SW computing subsystems and projects. However, both Collaboration and CD management played significant roles and shared the responsibilities in all aspects of off-line computing. The implementation of major hardware subsystems and systems software was performed by CD. Development of the core elements of the software systems was a joint effort, but the overall integration was performed primarily by CD. Detector specific or subsystem specific modules including analysis, reconstruction, and simulation algorithms were normally developed by user/developers in the Collaborations.

Systems' requirements for production off-line computing dictated that events be reconstructed at a rate that would keep pace with the recording of experimental data. Each major detector would require a minimum of a 100 HZ trigger rate and 1 MByte maximum event size. That data rate would require systems that could support the storage and accessibility of data sets of about 1 peta-byte per year. Production and analysis of these data would require off-line computing resources with the equivalent power of about 1 million VAX 11/780 computers in total for the two large detectors. A large Computing Center for the storage and analysis of detector data was planned. This facility would house the major systems for off-line computing as shown in Figure 36-1. Data from the detectors would be stored in a robotic Mass Storage System capable of handling data rates in excess of 200 MB/s for a total of several peta-bytes per year. Event data would be reconstructed in a large Reconstruction Ranch to produce data summary tapes that would be stored in a Mass Storage System. A distributed Analysis Facility would provide physics analysis capabilities for the physics users. All data would be organized under a data base management system and a DBMS Server. As necessary, tapes could be copied or distributed over the network to the regional centers. All elements of the off-line Computing Center and the experimental halls would be interconnected by high speed networks in excess of 2.4 Gbps.

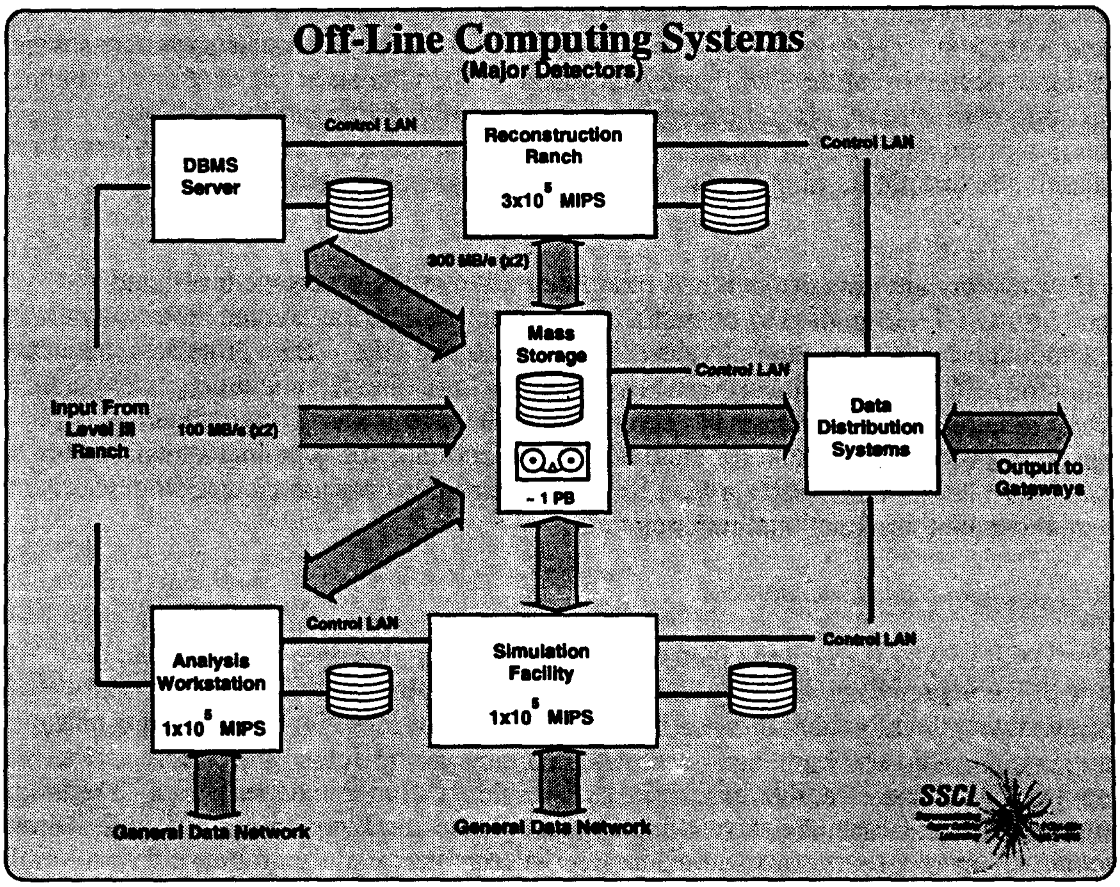


Figure 36-1. Facility for Major Systems for Off-line Computing.

The strategy for off-line computing systems development at the SSCL was to take advantage of available commercial technologies of the 1990s which make effective use of UNIX architectures, open systems, and industry standards. Development projects using these criteria resulted in the implementation of computing systems that minimized risk and internal development, so that available resources could focus on technology selection and applications. The SSCL thus took advantage of industrial capability to deliver computer technologies that have a price/performance ratio allowing the SSCL to meet the projected off-line computing requirements at least cost and greatest technological advantage.

The development and implementation of these systems was planned to be phased for several reasons: to minimize costs and risks, to maximize personnel resources, to optimize staff training, to meet increasing demands, and to capitalize on technology advances. Initial requirements were for detector modeling and simulation. Later, preoperational and operational capabilities would be developed and brought "on-line" to meet the computing requirements of the detector collaborations in a timely fashion. The Physics Detector Simulation Facility (PDSF) is an example of the phased development of off-line resources. Each of these phases could be used as a prototype for the final operational off-line systems. The development of subsystems, such as mass storage, was tied to the development phases of the PDSF. In general, milestones, goals, and deliveries for each subsystem were to be tied to each new phase of the PDSF. Some subsystem prototypes were to be developed independently of the PDSF and later integrated. In the later stages of development of the PDSF and other subsystems, a target (final) platform or configuration would be chosen. Common integrated software for these platforms would be finalized. The major systems were to be purchased and installed during the last two years of the development cycle prior to SSC operation.

Hardware and software projects and their integration into systems were planned and developed through the formation of project teams. The project teams executed the development and implementation tasks necessary to meet the deliverables of the WBS. Project leaders reported administratively through the standard PRD management structure. Development tasks were in all cases responsive to the requirements of the experimental collaborations, and project leaders reported for purposes of requirements validation to the corresponding project leaders within the Collaborations. The Collaboration project leaders were responsible for ascertaining whether the implementations met the functional requirements.

Computing Development Environment

The SSCL PRCD, SDC, and GEM Collaborations were in a unique position to take advantage of the leap in computer engineering efficiency and potential for improvement with favorable software development cost-to-benefit ratios. The lack of legacy constraints of outdated hardware, uncontrolled software, and immovable bureaucracy provided the opportunity to plan and implement the most cost-effective, scientifically feasible solution for the long term. The unique environment at the SSCL set the stage for an unprecedented combination of physics Collaborations and Laboratory computing department resources. Recognizing the need for an innovative solution to the problems of insufficient funding, limited personnel resources, and tight schedule constraints, PRCD had long championed a confederated approach to maximizing commonality in the solutions to the computer engineering and software development problems facing the collaborations. An effort was made to establish and prioritize software development requirements shared by the two collaborations. Among those prioritized requirements were requirements for a software framework environment and for an integrated Computer Aided Software Engineering (CASE) environment.

The PRCD, SDC, and GEM computing subgroups agreed to develop a Memorandum of Understanding for management of joint projects between PRCD and the two Collaborations. The Experimental Computing Management Committee (ECMC) was established to oversee initiation, assignment prioritization, and allocation of resources to projects.

Projects, Accomplishments, Status

The status of the activities as the project ended is summarized here. PDSF: Phase III completed providing nearly 7000 MIPS of computing power, 200 GB of disk storage, and more than 500 GB of robotic tape storage. PRIDE (Physics Research Integrated Development Environment): The initial environment was implemented providing an integrated set of debuggers, CASE tools, and word processing. Later phases would have incorporated project planning and tracking systems. Fermilab Test Beam: A storage and analysis facility was developed for data to be collected at the Fermilab test beams. The project, scheduled for FY95–96, involved the transmission of detector subsystem data from Fermilab to SSCL at 45 Mbps. Several tera-bytes of data would be collected and stored in a robotic system for retrieval and analysis. Multi-media and Desktop Televideo Conferencing: Working with the ESNET, the Desktop Video Task Force had successfully conducted internal tests and conferences with LBL and ANL. Shared whiteboard and other multi-media message techniques were implemented in the PRCD environment. Several "movies" depicting detector simulation were developed. Framework Software: Working with SDC, GEM, and IBM PRCD had begun development of a framework of software services under the PRIDE umbrella that would facilitate the development of an integrated software system for physics users' applications. PASS (Peta-byte Access and Storage Systems): This joint project with ANL, LBL, and UIC was partially funded by the High Performance Computing and Communications initiative. Goals of the project were to use modern data base techniques such as object-oriented data bases to organize, store, and retrieve HEP data. Mass Storage: There was a joint project with Ampex, Inc., to develop a 15 MB/s device driver for D2 tape drives. TTR Storage and Analysis System: PRCD developed a data storage and retrieval system for the Texas Test Rig. Data was stored in a Sybase managed data base. A graphical user interface was developed to provide access to analysis tasks, event displays, and data base browsers.

Physics Detector Simulation Facility

Several Computing Advisory Groups were formed during the start-up of the SSCL to advise the PRD on computing strategies and requirements that were deemed necessary to provide a base at the SSCL to support detector development activities. The Computer Planning Committee recommended that 4000 VAX 11/780 equivalents be available at the SSCL to support experimental physicists worldwide in the simulation of physics events in various proposed detector geometries, aiding the design of large detectors. The PRD was tasked to develop this facility, which was the first major off-line computing resource at the SSCL. This resource, called the PDSF, has recently completed its third phase of development and has the equivalent capability of nearly 4000 SSCUP or 7000 MIPS of computing power.

The PDSF features a series of integrated workstations, which have been utilized to support the modeling and simulation of the design of the GEM and SDC detectors. With the $500M price tags, the incredible complexity, and the long lead time for construction of these detectors, up front modeling and simulation takes on a significant role. Before construction of the SSC detectors could begin, several critical design studies must be performed. Many of these studies are carried out by constructing computer models of the detectors and by simulating the interactions they will study to determine how well proposed designs will work. The PDSF has been built to provide computing resources for this purpose. About 750 scientists from around the world were using the facility to plan experiments and design SSC detectors in 1993. The PDSF has been quite successful and has proven popular with high energy physicists at major universities and laboratories around the world. The system averages 60–80 "users" every 24 hours, seven days a week, and runs at full capacity. By using high performance workstations, the SSCL has been able to mount the world's largest computing facility of its type at a fraction of the cost of mainframes or super-computers.

The PDSF employs a parallel processing architecture that is powerful, economical, and scalable to larger sizes. The facility employs a novel concept of computing invented by the SSCL Computing Department that uses an integrated network of distributed RISC/UNIX workstations. The networked workstations have been integrated to provide mainframe services in a client/server architecture, such as system-wide batch and tape handling and user-accessible job monitoring services. System accounting utilities for tracking disk, CPU, and tape usage have also been developed that provide system-wide data by user, group, or system. The PDSF enables SSC physicists to perform computations at a rate unimaginable and unaffordable just a few years ago. The facility provides computing power equivalent to about 100 mainframe computers at a small fraction of the cost. Computational tasks are organized into many separate subtasks which are worked on in parallel and simultaneously by many individual computers of the network. The technique takes advantage of powerful and less costly RISC/UNIX work stations, which use open (non-proprietary) systems and conform to industry standards that permit the integration of equipment of different manufacturers.

The facility, shown in Figure 36-2, provides batch and interactive processing from a "ranch" of computers networked by fiber optics and organized into three "corrals." One corral contains 32 SUN Sparcstation 10s. A second corral contains 32 Hewlett Packard Model 9000/720 and 735 work stations. A third corral contains Silicon Graphic Model 360s used as computer servers. Silicon Graphics Challenge L multi-processors act as the "gate" or data server to the ranch's three corrals. The PDSF is the world's most powerful high energy physics computing facility.

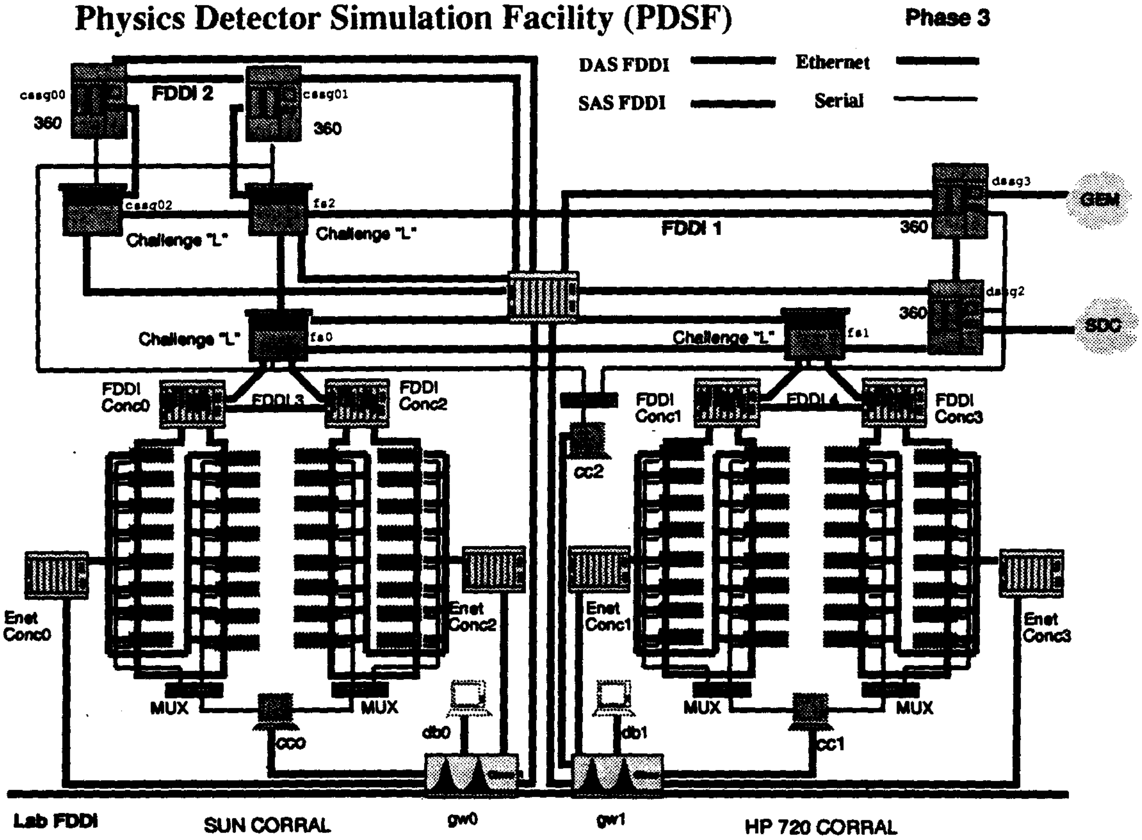


Figure 36-2. Facility Providing Batch and Interactive Processing.

Among the near-term benefits of the SSC project are the substantial technological advances made by the nation's computer industry as it worked with the Computing Department to develop the systems, hardware, and techniques for meeting the challenges. For example, commercial computing systems similar to the PDSF design have been developed by IBM, DEC, and by a joint HP/Convex endeavor.

Chapter 37. Computing, Information, and Data Systems

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The Information Services (IS) Department of the Office of the General Manager provided comprehensive support for Laboratory administrative and scientific computing. Support included design, development, configuration, operation, maintenance of hardware and software resources, coordination of planning and acquisitions, and design, installation and operation of a sophisticated data communications network. Figure 37-1, below, shows computing resources developed and supported by IS as of September 1993.

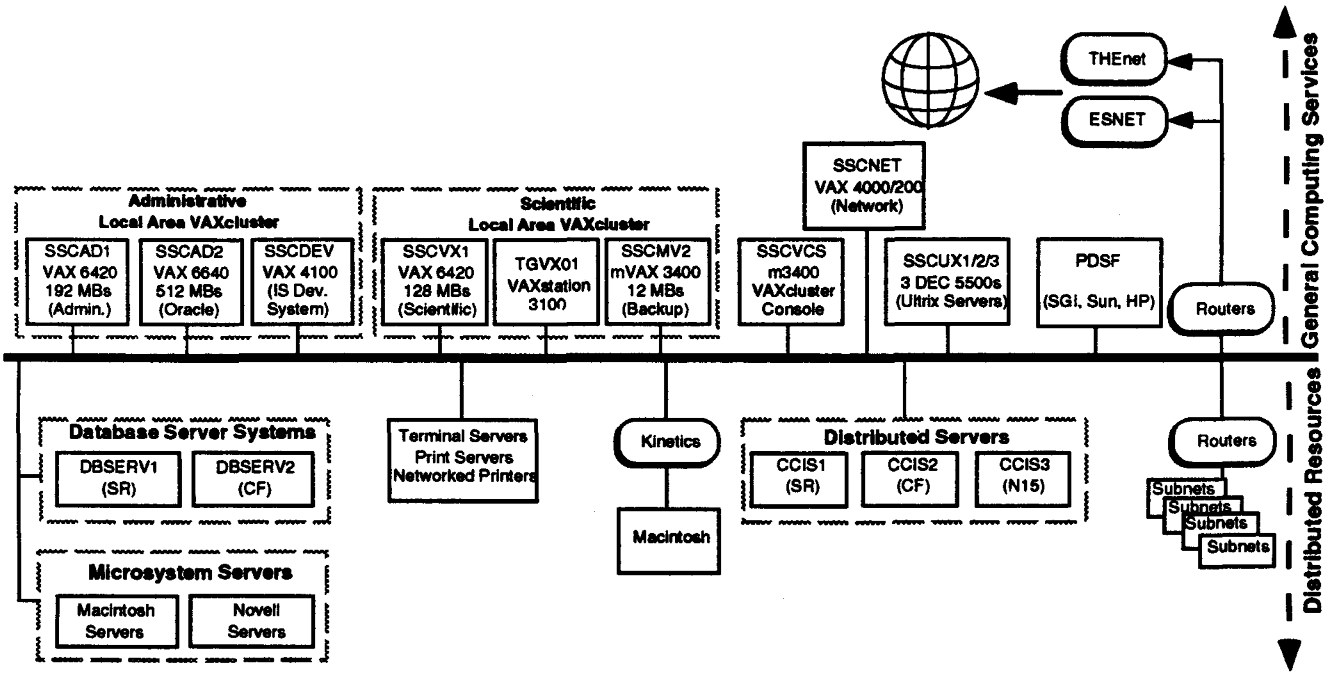

Figure 37-1. SSC Laboratory Computing Resources, September 1993.

The Distributed Computing Environment

The hallmark of the Laboratory's computing environment was its variety. The user community was a diverse group from widely different backgrounds and institutions. IS strategy was to provide users wherever possible with the computing resources that would enable them to be most productive. That strategy was implemented through the development of a heterogeneous, distributed client/server computing environment. In that environment, the individual scientist, engineer, or administrator had access from the desktop to a wide range of computing resources. Table 37-1 shows various systems supported in the SSC Laboratory computing environment.

Table 37-1. Systems Supported in the SSC Laboratory Computing Environment.

Server Platforms	Desktop Systems	RDBMS Products	Network Protocols	Electronic Mail Systems
VAX/VMS	Macintosh	Oracle	TCP/IP	QuickMail
SUN OS, Solaris	PC-DOS	Sybase	AppleTalk	cc:Mail
DEC/Ultrix	PC-Windows	Informix	DECnet	SMTP
HP	UNIX		IPX	VMSmail
Novell				Bitnet
SGI				

Relational Database Technology

Relational database management technology is central to the development of integrated information systems in a distributed computing environment. Its table structure provides a data repository that can be used by many applications. It minimizes redundant data entry, provides more reliable data integrity, and does not require users to learn lengthy and elaborate file paths in order to query the systems. RDBMS software is commercially available for multiple hardware platforms and operating systems, and data in the databases is also accessible using multiple hardware platforms and operating systems. Three RDBMS products, Oracle, Sybase, and Informix, were in use in the Laboratory

Administrative Resources

The various financial, human resources, and management information systems were housed on the administrative VAXcluster, located in the Computing Center in Stoneridge Building 4. Early interim systems were based on the Deltek financial system, supplemented by programs developed in the PowerHouse fourth generation programming language. In the summer of 1993, the Laboratory was completing the process of converting from interim information systems to comprehensive, integrated systems based on the Oracle RDBMS. Oracle was chosen because it is a mature product, in use at other DOE installations, with a robust suite of applications. In October 1993, Deltek- and PowerHouse-based systems still in use were housed on a VAX 6420, SSCAD1, with 192 MBs of memory and 15 GBs of storage. Oracle-based systems were housed on the VAX 6640, SSCAD2, with 512 MBs of memory, and 68 GBs of storage. The third node in the administrative VAXcluster was SSCDEV, a VAX 4100 with 64 MBs of memory and CD-ROM for software distribution. SSCDEV was a test area for IS applications and developers.

Information Systems

IS, in close collaboration with user groups, provided design, development, and maintenance support for a large suite of financial and management information systems. As of October 1993, the Laboratory was completing the transition from the legacy Deltek systems to Oracle RDBMS-based systems. Plans called for a fully integrated suite of financial and procurement systems, and a new, integrated human resources system. The development of reporting databases for major systems was under way. Major systems supported in October 1993 are described briefly below.

Financial and Procurement Systems

Oracle Government Financials modules included Accounts Payable, a payment management system, General Ledger, the primary cost allocating and financial reporting system for the Laboratory, and PO (Purchase Order), a resource for managing the purchasing system. Deltek General Ledger, used by subcontractor EG&G Science Support Corporation, provided feeds to Oracle General Ledger. The Open Commitments system for tracking outstanding purchase orders provided information used by both the Finance and Procurement organizations. Property Accounting, a PowerHouse system, provided fixed asset accounting for Laboratory assets.

Travelmaster is a stand-alone COBOL-based accounting system that provides trip numbers and reconciles and reports trip expenses. It was enhanced by a suite of PowerHouse utilities (Travel Accounting System, TAS) that provided menu security, specialty reporting, batch processing, and trip number authorization.

Human Resources Systems

STAR (System for Tracking Applicants and Requisitions) was developed in PowerHouse for the Laboratory Personnel Department. The system manages applications, resumes, and personnel requisitions. Deltek Payroll manages the payroll payment process for the Laboratory. The payroll system includes a MAP file to match the 26 character Oracle charge codes to the shorter Deltek codes. Payroll Direct Deposit Download, a PowerHouse system, provides batch interface between the payroll system and a local bank.

The PowerHouse Benefits system was developed to manage all employee benefit information. TIAA/CREF is a powerhouse system designed to interface with the external Teachers Insurance and Annuity Association/College Retirement Equities Fund, which covers URA employees only. It extracts appropriate employee payroll information from the payroll system and creates a tape for distribution to the retirement fund manager.

Material and Logistics Systems

The Master Equipment Records System (MERS, also called the Property Management System) tracks all bar-coded capital equipment and equipment classified as sensitive by the DOE. MINX consists of several Informix programs that provide parts-based configuration management and inventory control. It also provides the MRP (material resources planning) system used by Magnet Systems Division to track the as-built configuration of magnets built at the Laboratory. MTS (Material Tracking System) uses Oracle PO tables and allows for receipt and tracking of all equipment and supplies purchased by the Laboratory. It tracks stored items and was to be used to track and control excessed property, including non-bar-coded items.

Document Management Systems

DTASS (Document Tracking and Storage System), developed in Sybase for the Physics Research Division, is a tracking system and repository for scientific papers. DCC (Document Control Center) is a Sybase system used for document tracking and version control by the Laboratory Document Control Center. As of October 1993, all preliminary work had been completed, and the Laboratory was preparing to purchase a comprehensive document management system.

Cross Platform Applications

As systems matured, cross platform applications designed to optimize Laboratory-wide access to information were developed by IS staff. The first to be brought on line was PhD (Phone Directory), a client/server application with two basic elements, a sophisticated graphical user interface (GUI), and the database access mechanism behind it. The latter included an automated time-out/reconnect feature to minimize impact on data repositories and on the data network. Developed entirely in house, PhD uses information from the Human Resources database, and displays a Laboratory employee record with fields for first, last, and preferred names, division affiliation, extension, mail stop and physical location, and e-mail address. PhD allows users of Macintosh, UNIX and DOS-Windows systems to search on any field and read information from the screen, print it, or save it to a text file.

Two other cross-platform GUI applications were in development as of October 1993. A PR/PO lookup application allowed Mac, PC, and UNIX users to track the status of their own requisitions and purchase orders. This application was not distributed to users, but it was successfully tested on Macintosh, UNIX, and DOS Windows platforms. ROC (Registry of Correspondents) would have provided SSCL scientists with comprehensive biographical information about members of the international high energy physics community.[1]

Integrated Laboratory-Wide Data Access and Reporting System

Query and reporting functions are critical to the overall effectiveness and value of information systems. Because the information systems supporting administrative and business functions are hosted on a variety of operating systems and database platforms, methods for accessing the underlying data for reporting purposes were initially limited to the tool set provided by the primary data capture system on the host platforms. By June 1993, Information Systems had begun to address ad hoc query and reporting needs through an integrated, widely distributed, client/server Data Capture/Distribution System (DC/DS).

Implementation began during the first quarter of FY1993 with the acquisition of two database servers configured with Oracle software. The servers were placed in the two most populous locations: Stoneridge (900 people) and Central Facility (900 people). These primary servers act as reference repositories for information systems data, and provide ready access query, and reporting capability to the local (site) user community. As the Laboratory expanded geographically and personnel were assigned to new sites, additional database servers were planned using architecture compatible with network design strategies that minimize inter-site general data traffic.

Figure 37-2 is a schematic representation of the distributed reporting architecture. The central repository consolidates subsets of data from the various primary data capture systems and distributes these data sets to the reference repositories. The architecture allows for unified administration of the large databases on a tightly controlled centralized computing system. Security and data integrity issues can be addressed efficiently and economically because users who require read-only access to data will not have direct access to the data capture and production system. Production processing can take place more efficiently because the central system is not required to respond to ad hoc queries and reporting requirements.[2]

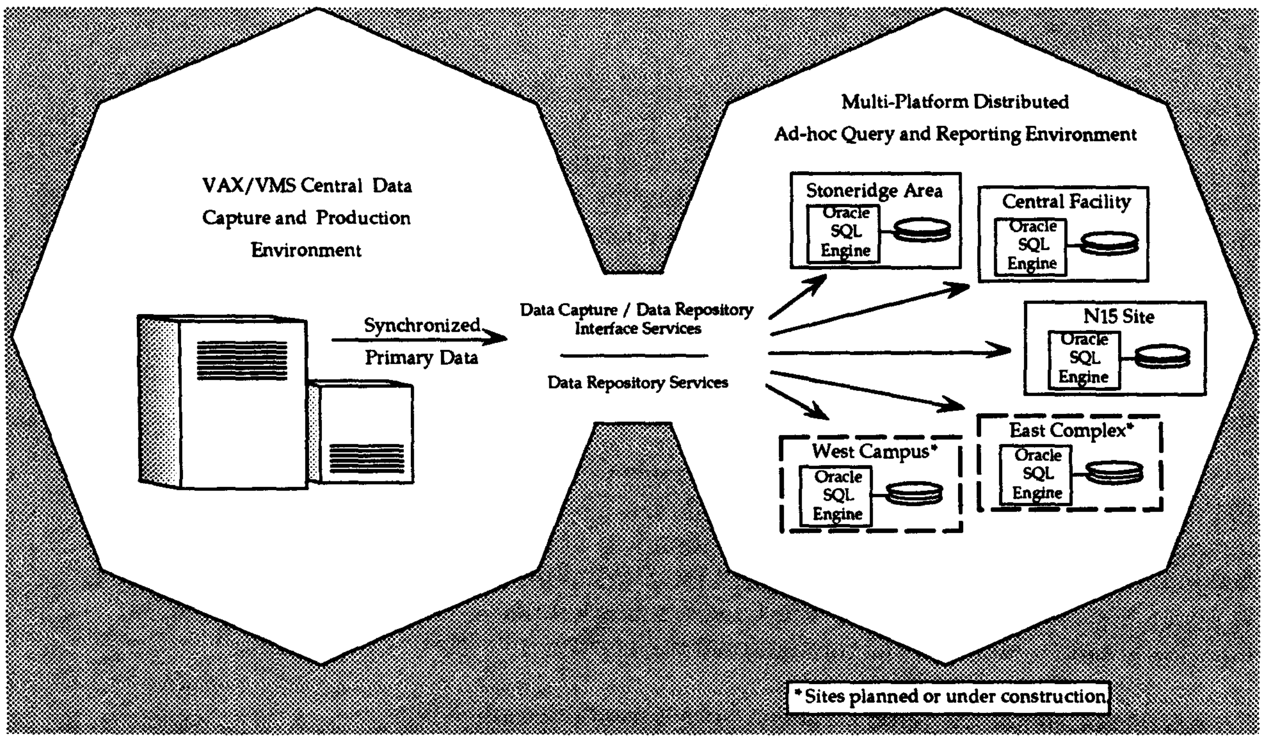

Figure 37-2. SSC Laboratory Planned Distributed Data Access and Reporting Architecture.

Distributed UNIX Resources

IS operations has configured and maintained a robust system of distributed UNIX servers. Some of these servers directly support technical and scientific personnel, most of whom rely on UNIX-based workstations. Many servers, however, provide cross-platform, Laboratory-wide functionality in support of file service, print service, database reporting service, name service, and access to Usenet.

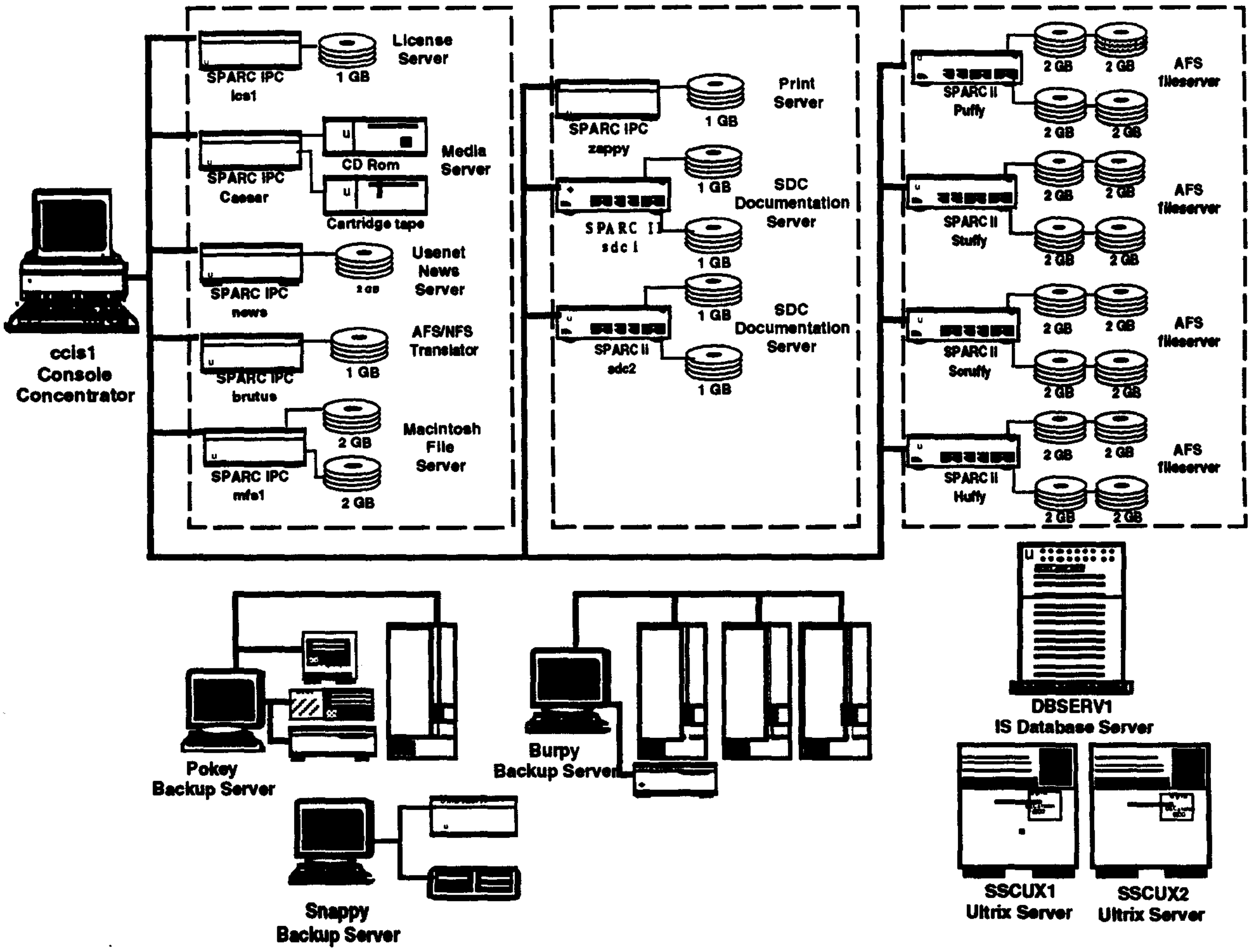

Figure 37-3. Stoneridge 4 Distributed Server Architecture.

Typical hardware configuration at each site consists of one workstation that serves as the console system for one to ten additional rack-mounted machines without separate monitors or keyboards. Console communications for each server are handled through a built-in serial port to the local console server system. The configuration allows one system administrator to monitor all server consoles and respond to most problems from a remote location. Other benefits include savings in costs and computer room space and reduction of environmental impact. Figure 37-3, above, and Figure 37-4, below, show the distributed server configurations at the three major Laboratory sites: Stoneridge, Central Facility, and N15.

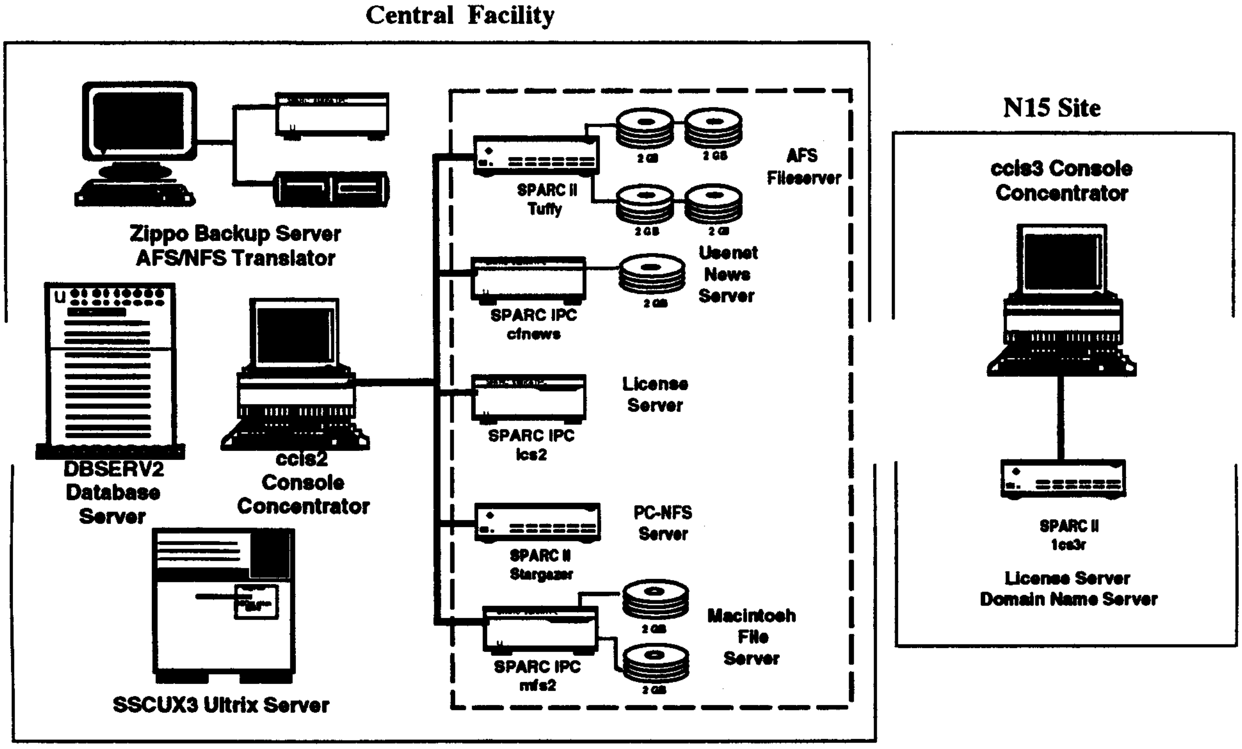

Figure 37-4. Distributed UNIX Server Architecture[3] at Central Facility and N15.

UNIX Application Server

To provide one general area for commonly used UNIX software and application programs, IS undertook the UNIX Application Server project. After investigating several alternatives, the Andrew File System (AFS) was chosen to implement the application server. AFS is a distributed file system that supports multiple computing architectures. For each workstation (client) that uses AFS, a link /usr/ssc is created, which points directly to all available software for that specific architecture. Workstations that do not support AFS can access the application server using the AFS/NFS translator. The application server eliminated program duplication for similar system architectures, thus saving resource time spent building and maintaining software and monitoring disk space. This approach made it easier to support existing programs and introduce new versions.[4]

Shared Microcomputer Software Facilities

To minimize Laboratory investment in microcomputer applications software, software sharing facilities were incorporated into the distributed computing environment. These servers provided users with access to applications software on an as-needed basis, greatly reducing the requirement for individual application licenses. The first such facility was a Macintosh server that housed a library of Macintosh applications configured with KeyServer™ metering software. The Laboratory was licensed for a specific number of concurrent users for each application. KeyServer™ tracked the number of licenses in use for each application, maintained waiting lists, notified users of availability, and timed out applications not actually in use on the desktop. Applications could be run from local systems to minimize network impact. As of October 1993, Macintosh applications servers were on line at Stoneridge, Central Facility, and the N15 Site. DOS-based applications servers were in the process of being configured.

Scientific Facilities

SSCVX1, the "scientific VAX," was the first large computing resource on line at the Laboratory. It served as an electronic home base for Laboratory physicists and provided computing resources for visiting scientists and scientists who participated in Laboratory work from remote locations. At peak usage, the scientific VAX supported over 2500 user accounts. SSCVX1 is a VAX 6420 with 128 MBs of memory and 16 GBs on line storage. It supports general purpose scientific computing, electronic mail, and network connectivity to HEPnet. TGVX01 is a VAXstation 3100 with 12 MBs memory and 5 GBs on line storage, which supports MSD code development and maintenance efforts. The third node in the scientific VAXcluster is SSCMV2, a VAX 3400 used for backup.

SSCNET, a VAXserver 4000/200 with 32 MBs of memory and 1 GB of on line storage, is a stand alone VMS system that supports various network services, such as Bitnet routing, IP nameservice, and electronic mail delivery (PMDF). IS also provided installation, implementation, and operational support for the Physics Detector Simulation Facility (PDSF).

Data Communications Network

The general data network provides connectivity at the desktop for the Laboratory distributed computing environment, both within the Laboratory and to external consultants, collaborators, and subcontractors. As of October 1993, the Laboratory data network served a total of six sites spread over 150 square miles. Connectivity among remote sites was provided by leased T1 circuits. Plans had been made to begin interim support to an additional site (the East Complex, where detector sites were under construction) using leased lines and microwave-generated circuits.

The three principle laboratory sites—Stoneridge in south Dallas County, Central Facility in Waxahachie, and the N15 Site at the north end of the West Complex—are configured with FDDI backbones with Ethernet segments routed through network concentrators. Remaining sites were configured with routed Ethernet. Connectivity to the desktop was provided using unshielded twisted pair. Subnets were provided for working groups to optimize network traffic. At its peak, the network comprised 750 miles of twisted pair copper wire, 113 miles of fiber, and 47 miles of Ethernet. Figure 37-5 shows the general configuration of the Laboratory data network.

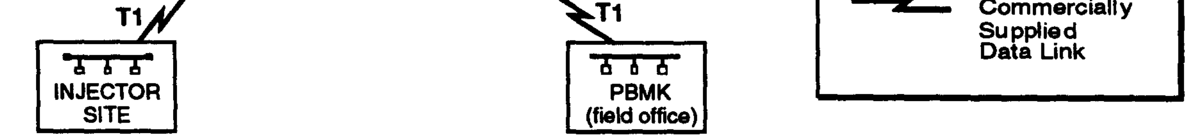

Figure 37-5. SSC Laboratory Data Network, October 1993.

The network was designed to minimize the effects of equipment failures and other problems on Laboratory work flow. Traffic was automatically diverted around a failed router. Each major Laboratory site had an independent nameserver so that a major outage at one site would not affect the other two. Network management systems provided monitoring capability at the Network Operations Center located in Central Facility. The operations center also served as a focal point for troubleshooting and dispatching.

Local networks supported included AppleTalk, Ethernet, Novell, Banyan, and FDDI (Fiber Optic Distributed Data Interface). Wide-area connectivity was through ESnet, THEnet, and Sesquinet, using TCP/IP and DECnet protocols. The data communications network was designed to support phased migration to OSI/GOSIP standards as equipment became available.

Chapter 38. Reliability, Maintainability, and Availability Activities

(DOE and Contractors)

Reliability, maintainability, and availability (RMA) requirements on the SSC were the responsibility of URA in terms of overall SSC Laboratory RMA management and control. The SSCL augmented their RMA capabilities via a subcontracting relationship with Lockheed Corporation.

The Department of Energy (DOE) had the overall program RMA responsibility. DOE augmented its RMA capabilities with participation from its support contractor KIRA, Incorporated and one of KIRA's subcontractors, Research Analysis Corporation (RAC). This enabled DOE to take an active role in the conduct of RMA tasks and provide hands on guidance regarding the establishment of RMA design requirements, the evaluation of design impact and achievement of those requirements, and the assessment of the final design. The following text details noteworthy RMA accomplishments prior to the cancellation of the SSC Project.

Design Reference Mission

SSCL Design Reference Mission

The SSC operational availability requirement of 0.80 in the Level I Specification[1] was an area of major concern, and was judged by the Central Design Group to present sufficient risk such that use of modern RMA engineering tools would be essential to program success. Experience had shown that as accelerator beam availability fell below about 80%, efficiency of the physics experiments degraded rapidly due to an inability to maintain coincident accelerator and detector operation.

The intent of the SSCL Design Mission Profile[2] was to demonstrate how RMA allocations could be derived for the collider and its subsystems that met both the physics requirements and the planned three-month annual shutdown. Including a basic SSCL requirement to limit the number of total Superconducting Magnet System Failures to 6 per year, and applying available information from other collider projects, a design reference mission was developed. The Injector Complex availability was assumed to be approximately the same as the FNAL Tevatron. With an annual shutdown of three months assumed, the remaining hours were assigned as fill/tune time, stable beam time, unscheduled maintenance time, and magnet replacement time. The allocation model provided the information detailed in Table 38-1.

Table 38-1. Annual Allocations from the Design Reference Mission

Annual shut down	2190 hours
Weekly Preventive Maintenance	132 hours
Magnet Replacement	1506 hours
Unscheduled Maintenance	427 hours
Fill/Tune	417 hours
Stable Beam	4088 hours

However, the small time allotted for unscheduled maintenance (427 hours) placed a significantly high Mean Time Between Failure (MTBF) requirement on all collider subsystems, demanded short downtimes, and placed .999 type availability requirements on most collider subsystems. This was clearly unrealistic in terms of design achievement.

As a result, a re-evaluation of the impact on collider RMA allocations was performed by utilizing most of the available annual calendar time as scheduled uptime while still meeting the high energy physics goal of 3754 hours of annual stable beam at design luminosity. (This goal is consistent with an integrated luminosity of 10 fb^{-1} per year.)

The Design Reference Mission profile[3] was a bottoms up approach. Most of the three months annual shutdown was removed from the number of annual hours the collider would be unavailable. Scheduled downtime for this Design Reference Mission included a one-month annual shutdown, 8 hours per week for planned periodic maintenance, 210 hours annually for gas desorption, and 6 annual magnet (cold piece) system failures. A Mean-Down-Time (MDT) for each collider subsystem was estimated, and the relative complexity for each subsystem determined. An MTBF was then calculated for each collider subsystem (based on their relative complexity), and the unscheduled downtime and fill/tune time was derived to meet the physics requirement of 3754 hours of stable beam. The results were presented to SSCL personnel.[4] This study clearly indicated that lower MTBFs and longer MDTs could be tolerated at the collider subsystem level if the annual shut-down was revised from three months to one month. This RMA allocation model provided revised annual allocations which are shown in Table 38-2.

Table 38-2. Annual Allocations from the Revised Design Reference Mission

Annual shut down	720 hours
Weekly Preventive Maintenance	312 hours
Annual Gas Desorption	210 hours
Magnet Replacement	1506 hours
Unscheduled Maintenance	1161 hours
Fill/Tune	1097 hours
Stable Beam	3754 hours

The re-evaluation effort clearly indicated the need for new and innovative thinking in terms of reliability and maintainability performance parameters, and as such became the catalyst for the development of both a Top Down and Bottom Up Design Reference Mission model. For the Top Down Model,[5] equations were developed to take a specific SSC annual operational profile and determine solutions to MTBF, MDT, Unscheduled Downtime, Operating Time, Availability, and Tune/Fill Time. The results of this model's equations allowed for a specific solution for a given collider MTBF and MDT. For the Bottom Up Model,[6] equations were developed to use complexity factors and Mean Down Time for each collider subsystem, along with the Annual Operational Profile to determine a unique solution for collider and collider subsystem MTBFs, collider MDT, number of fills/tune, number of annual failures, and collider availability. The results of this model's equations allowed for a specific solution for any number of operational scenarios.

Linac Special Project

One of the most noteworthy tasks initiated by the DOE in the area of RMA was a special project, conducted to demonstrate to SSCL design personnel the analysis process that needed to occur at each accelerator machine level in order to gain the necessary insight to effectively analyze and drive the evolving design for achievement of allocated RMA parameters. In March 1992, it was decided by DOE and the SSCL, that due to the commissioning schedules of each accelerator, this RMA Pilot Project[7] would be the most beneficial if the candidate for RMA analysis was the Linac. This project's objective was to determine through analysis and modeling predictions (both steady state and Monte Carlo), the Linac reliability, maintainability and availability parameters based upon the current design, for both the specified and commissioned versions. This effort resulted in the publication of an SSCL Engineering document with nine attachments, the first being the final briefing[8] that summarized the project's purpose, background, approach and results. This briefing was prepared and presented to the machine leaders and their personnel covering all areas analyzed during the three month long project.

There were five specific fundamentals identified in this briefing to develop a practical approach for implementing an RMA program on accelerators. First, a high machine availability is needed to achieve the SSC physics goal of 3754 hours. Second, one must design for availability at each machine level to actually achieve it in use. This means that the machine seldom fails, it is repaired quickly, equipment status indicators are incorporated to replace long down time items prior to failure, and the maintenance/spares concept is well defined. Third, the design reference mission must be the basis for both the design and the RMA assessment. Fourth, one must consider the impact on the total system to maximize any increase in availability for the dollars spent on alternate designs, improvements, and decisions on spares. Finally, one must consider design and manufacturing disciplines as part of the acquisition strategy in selecting vendors for high reliability components.

The briefing provided both the Steady State and Monte Carlo simulation results, the top five unavailability and unreliability critical component leaders, the long downtime items (top 19) and the availability projections. The Monte Carlo simulation technique[9] and the Steady State technique[8] yielded the following figures of merit as shown in Table 38-3.

Table 38-3. Special Project RMA Results for Linac.

For the	Availability	MTBF (hours)	MDT (hours)
Monte Carlo SPEC Configuration	0.94	47	2.7
Monte Carlo Commissioning Configuration	0.96	55	2.5
Monte Carlo Alternate RF Volume Only	0.94	56	3.4
Steady State SPEC Configuration	0.92	47	3.9

One of the first steps in the performance of this project was the preparation of Reliability Block Diagrams[10] in various serial and redundant configurations that simulated a given Linac configuration for purposes of calculating various RMA figures of merit. These Reliability Block Diagrams with their associated individual input parameters (i.e., MTBFs and MDTs) enabled the calculation of the Linac availability, MTBF, and MDT.

Reliability data[11] were prepared for the Linac by performing failure rate predictions through the application of the parts count method and the part stress analysis method (both cited in MIL-HDBK-217F), the application of AVCO's Failure Rate data, and from various commercial vendor data sources. These reliability predictions were performed down to the replaceable component indenture level for all the Linac subsystems, and were then aggregated up to the subassembly level for purposes of input to the Monte Carlo (TIGER) simulation model. In addition to the reliability data, a reliability report[12] on the Linac Monitor and Control Cabinets was prepared by using an assumed configuration of each cabinet.

A Linac maintenance concept[13] was also prepared by reviewing various Linac published documents and having technical interchanges with Linac subsystem physicists and engineers to determine feasible options for levels of maintenance and activities to be accomplished at each level. It postulated three levels of maintenance to be implemented with the Linac: On-line (at the Linac), off-line (at West Campus), and Depot (at Central facility or an equipment supplier's facility). The maintenance concept addressed Reliability Centered Maintenance (RCM), various maintenance scenarios, and other elements of supportability (software, technical data, support equipment, supply, training, personnel, and facilities). Maintainability Data[14] was prepared for the Linac by estimating active and inactive time through querying Linac physicists and engineers in a maintainability questionnaire. The questionnaire was used to document individual knowledge regarding past experiences with repairing either identical or similar equipment on previous projects (FNAL, LAMPF, BNL, CERN, DESY, etc.). Downtime predictions in the form of active and inactive delay times were made down to the replaceable component indenture level for all Linac equipment, and were then aggregated up to the subassembly level for purposes of input to the TIGER simulation model.

Besides the maintainability data, Mean Down Time (MDT) data[15] for Linac was also prepared by aggregating the active (MTTR) and inactive (logistics and administrative) times, for each of the replaceable components, by their weighted quantities and failure rates. Both normal and Log normal underlying distribution assumptions were taken into consideration and MDTs were calculated accordingly, for both Linac and its subsystems. This data is shown in Table 38-4.

The final step in the performance of this project was the preparation of a Normalized Unavailability Ranking[16] for the Linac. In this ranking, the higher the value, the less available that component will be. It was determined that the items in the Linac most likely to not be available for operation when required were as follows: klystron modulators, triodes/tetrodes, klystrons, ion pumps, magnets, and solid state drivers.

One last event emphasized the importance of conducting similar special projects on the remaining injector accelerators, the collider, and the detector systems. This occurred in January of 1993, when personnel from DOE, ROMAR, KIRA and RAC decided to establish a Linac Critical Parameters List[17] for the express purpose of tracking the Linac design progress from a Reliability, Maintainability, Availability, and Quality performance perspective. This list was constructed by determining the most critical design parameters and their nominal values for purposes of tracking the design progress at various milestones such as PDRR, PDR, CDR and ATPR. At those times, design margin assessment would be accomplished. For the Linac, the following parameters were determined to be the most critical, and therefore the ones to track: (1) output energy, (2) output transverse emittance, (3) output longitudinal emittance, (4) RF peak output power, (5) spectrometric analysis, (6) chemical analysis, and (7) number of failures. The benefit of such a critical parameter listing and tracking is realized when the system is commissioned and it meets or exceeds its RMA requirements and expectations.

Table 38-4. Linac Mean Down Time (MDT) Data.

Subsystem	Normal (hours)	Log Normal (hours)
Ion Sources	5.86	3.63
LEBT	4.29	3.37
RFQ	8.11	4.83
RFQ/DTL	6.79	5.16
DTL	3.97	3.38
DTL/CCL	3.89	3.37
CCL	4.98	3.92
Transport Line	6.75	4.55
RF Generation	3.02	2.97
Linac	5.03	3.87

Klystron Modulator RMA Design Support

Part of the DOE RMA plan was to take one of the reliability/availability critical items from the Linac study and conduct in-depth RMA analysis for that particular equipment manufacturer's design, to determine as early as possible in the design process, whether RMA allocations and requirements were being met. In direct response to this objective, DOE assigned Research Analysis Corporation (RAC) in October 1992 to help Maxwell Laboratories Inc. (the DTL/CCL Klystron Modulator designers) apply Reliability and Maintainability design tools and techniques to their evolving Klystron Modulator designs. The purpose of this was to determine, through the performance of FMECAs, Reliability/Maintainability Predictions and a Safety Analysis, whether the designs were capable of achieving their allocated MTBFs and MTTRs, and where undesirable failure modes or safety hazards might existed in the proposed design. The results of this successful study are presented in Refs. [18] through [23].

RMA Design Standards/Guidance Papers

Design Standards

The first SSCL Electronic Parts Derating design standard document[24] was intended to establish guidelines to be used in the selection of parts and the packaging of equipment that was designed or purchased by the RF Group within ASD. Those guidelines were intended to enhance equipment reliability and minimize equipment failures by establishing minimum component derating requirements and providing a reliable guide for high voltage package design.

In June 1992, a second Electronic Parts Derating design standard[25] was released by DOE/KIRA for SSCL application. The objective of this derating manual was two-fold: the first was to provide a derating criteria for commercial electronic part types that would achieve reliable operation of these commercial parts in the long life requirement of the SSCL. The second objective was to provide the design engineer with sufficient information about each part such that the engineer could make an intelligent decision with respect to which part should be used in the design. This information, which was a departure from most part derating criteria documents, included the manufacturer's name, part number, and major part parameters including applicable tolerances and mechanical configuration. The manual was published in a partially complete form to allow its use by the SSCL design team for the part types completed, as opposed to waiting until all the part categories were completed.

In 1993, a third document for Electronic Parts Derating[27] was developed by DOE/RAC for application during the design of the electronics portion of the SDC Detectors. It is a condensed version of a more extensive Naval Sea Systems Command derating requirement document (TE000-AB-GTP-010, Rev. 1). It also removes all references to Military Part Specifications, and it is directly applicable to commercial parts and commercial hybrid devices.

A design standard for Custom Integrated Circuits (IC's)[27] was also developed. This design standard provided internal chip design requirements to be used in conjunction with electrical parameter requirements for the design and constructions of custom ICs. Finally, a redundancy design standard was developed which laid out the design considerations and the mathematical relationships for determining system reliability when the design employs the use of redundant equipment.[28]

Guidance Papers

Numerous guidance papers were also prepared and disseminated amongst the design groups for consideration during their iterative design process. This included all contractors and subcontractors to the SSCL. The first design guidance paper[29] provided a systematic methodology for the selection and application of parts to assure their proper usage in a manner suitable for application within the SSCL designs. These methods would minimize the number of different styles and types of parts, assure that the integrated circuits selected were not an obsolete technology or soon to be obsolete, assure that adequate electrical and thermal derating was achieved, and assure that parts were not damaged during the manufacturing process. The process emphasized four major areas for consideration. They were: part selection, part application, part manufacturing, and part documentation. Another specific design guidance paper[30] provided a list of current integrated circuit technologies, and described which ones were recommended for use. Most of these concepts were in place within the SSCL at various levels, at the time of SSC Program cancellation.

Failure Reporting, Analysis, and Corrective Action

A sound Failure Reporting, Analysis, and Corrective Action System (FRACAS) is an integral part of any good RMA program. The original FRACAS guideline, when applied by operations personnel at the ASST, was considered too time consuming. RAC, on behalf of DOE, examined methods that would allow timely review of failure events. The method developed was to take the summary raw data from the ASST Run 2 and determine which operational anomalies were in fact failures, what if any corrective action was accomplished, and whether further corrective action was warranted. As a result, a four page document entitled Operational Problems and Corrective Action (OPACA)[31] was generated and sent to the ASST operational personnel for their review and consideration.

Chapter 39. Cost Chronicle Summary

(T. Elioff)

Projected Costs

The first consideration of the design of a pp collider in the 20 TeV range began in workshops and summer studies during the period 1978 to 1983. Some very preliminary estimates indicated costs in the range of $2 to $3B. In early 1983, a HEPAP subpanel on new facilities was formed. The subpanel unanimously recommended a project (designated the SSC) to design and construct a multi-TeV, high luminosity collider. In August 1983, at the request of DOE, another HEPAP subpanel was set up to make recommendations for a 1984 R&D effort that would focus on SSC goals. This subpanel provided advice on the details of the R&D effort, particularly with regard to accelerator physics and superconducting magnet development needs.

In November 1983, a group of senior scientists from the nation's high energy physics community presented a petition to the directors of four U.S. high energy physics accelerator laboratories in which they proposed, in the interest of early initiation of SSC design work, a plan for the creation of SSC Reference Designs. In December 1983 the laboratory directors responded to the petition and, together with DOE, chartered the National SSC Reference Designs Study (RDS) to review in detail the technical and economic feasibility of various options for creating an SSC facility. The objective of the study was to help DOE, the high energy physics community, and the scientific community as a whole to decide how best to proceed with R&D directed toward improving the cost effectiveness of accelerator technology applicable to an SSC. Primary emphasis was on estimating the range of costs within which SSC construction could confidently be expected to fall.

The RDS was centered at LBL from February through May 1984 and involved more than 150 scientists and engineers from national laboratories and universities. Construction costs were estimated for a 20 TeV collider with consideration of three different superconducting magnet types for the main ring dipoles, namely, a 6.5 tesla cold-iron design, a 5 tesla iron-free design, and a 3 tesla injectors of $2.72B, $3.05B, and $2.70B (all in FY84$), respectively, for the above three magnet types. The RDS also concluded that the effort could be accomplished within a 6-year construction schedule. The results were then reviewed in detail by a special DOE committee.

As a result of the success of the RDS, URA in the fall of 1984 formed the SSC Central Design Group (CDG) to direct and coordinate the national R&D work. Headquartered at LBL with Maury Tigner as Director, the CDG technical staff members were drawn from high energy physics and accelerator and technical groups across the country, representing both universities and national laboratories. The work of the many contributing institutions, firms, and individuals was focused first on R&D leading to a Conceptual Design Report (CDR).

The principal activities for FY85 involved a diversified effort on model magnet and cryostat R&D to provide the technical basis for selection of one of the superconducting magnet designs then under study. A detailed cost analysis was made for each magnet style. The technical aspects of field quality, R&D requirements, production and assembly methods, and reliability were studied in detail. Cost vs. aperture studies were also made for each magnet. Many technical reviews were conducted during the year in these areas. Upon the recommendation of a special magnet selection advisory panel, a 1-in-1, cold iron, 6.5 tesla design was selected as the choice for the collider magnets. This design was to be evaluated and costed in the CDR.

The CDR effort in 1986 drew on prior R&D efforts, including the work of many different groups assembled by the Central Design Group to address specific technical issues. The CDR included both a conceptual design for the SSC and a cost estimate—for the construction portion of the project—of $3010M (FY86$). A schedule duration of 6-1/2 years was estimated leading to a completion date of mid-FY94. Because no site had as yet been selected, conventional construction costs were examined for three "example" sites from around the country and averaged to arrive at a cost estimate. In separate reports the CDG documented estimates of the additional costs for R&D, pre-operations, operations, and a range of costs for the initial complement of detectors and computers. Thus the estimate developed in the CDR and related documents represents the first TEC estimate for the SSC (see Table 39-1 column one).

Formation of the first budget request for SSC construction project funds was in progress early in 1987. In preparing the request for the FY88 period, DOE decided to base its initial request to Congress on the CDG construction cost estimate of $3010M (FY86$) which equated to $3210M (FY88$). An allowance was adopted for detectors and computers of $664M (FY86$) which equated to $719M (FY88$). DOE used an allowance of $446M (FY88$) for research and development and pre-operations. These considerations led to a total project cost estimate of $4375M (FY88$). The schedule duration was extended by 1 year from that envisioned by the CDG to present a less aggressive funding profile. With escalation added, the first total cost estimate submitted to Congress totaled $5320M (AY$). No cost increase was estimated based on the extended schedule (see Table 39-1, column two).

In 1988, concurrently with extensive site selection efforts, DOE sought the services of a contractor to manage the design, construction, and research program at the SSC Laboratory. It was announced in January 1989 that URA, in conjunction with its partners EG&G Intertech and Sverdrup Corporation, had been selected. URA named Roy F. Schwitters as the Director of the Laboratory. With the selection of the near-Dallas site and the assembling of the design team, one of the first efforts was directed toward a revised conceptual design. The overall physics objectives of the SSC remained as they were in the 1986 CDR. However, certain system parameters were modified and optimized to meet the goals. The revised design reflected: an updated assessment of the physics to be explored by the SSC; advances in accelerator and detector design and technology; recent experience with other high energy physics facilities around the world; and the characteristics of the Texas site.

Somewhat more conservative than the design proposed in the 1986 CDR, the revised design focused on reducing the commissioning time for the Collider, ensuring highly reliable operation, and maintaining flexibility in experimental capability. The primary design changes can be summarized as follows:

- An increase in energy for the injector accelerators from 1 TeV to 2 TeV for the HEB, along with related increases in the energies of the MEB and LEB.
- A change of the magnetic focusing strength in the Collider ring, requiring an increase in the circumference of the Collider ring.
- An improvement in the field uniformity and design margin of the Collider superconducting dipole magnets, related to an increase of the coil inner diameter.
- Adaptation of the facility to the site, including the depth of the Collider tunnel.
- Incorporation of flexibility in the design to make possible later installation of beam bypasses.
- An increase in the size of the experimental halls in view of the latest understanding of the size, complexity, and technical sophistication of the detectors.

The SSCL completed documentation of the Site-Specific Conceptual Design Report (SCDR), total project cost, schedule, and funding profile in June 1990. The estimate reflected an increase in total project cost to $7837M (AY$) and a 9-year schedule that extended project completion to the end of 1998. The SCDR, along with documentation presented to DOE and its review teams in June 1990, formed the basis for the SSCL cost and schedule baseline (see Table 39-1, column three).

To ensure a thorough evaluation of design, cost, and schedule, DOE organized three reviews: the customary DOE program office review, the Department's Independent Cost Estimating staff review, and a third special review by HEPAP. The base SCDR costs developed by the SSCL together with the review recommendations formed the cost and schedule baseline for the project. The revisions resulting from the reviews and the final cost estimates are provided in the fourth column of Table 39-1. While the baseline showed certain increases over the SCDR for technical systems, a significant part of the increase was due to an extension in schedule from 9 to 10 years and the inclusion of R&D costs from FY88 and FY89 as indicated in Table 39-1. The values in Table 39-1, converted to FY93$, are plotted in Figure 39-1.

In the area of projected operations costs, more detailed estimates were developed in 1992. An operations and commissioning report (SSCL-SR-1210) was completed in April 1992. The purpose of the report was to present a plan for the sequential commissioning and operation of individual accelerators and other technical facilities of the SSC. A central objective of the plan was to describe activities at the SSCL that are not included as part of the construction project TPC, even though they occur during the overall project construction time frame. Examples of such activities include the operation of general Laboratory facilities and services not specifically related to construction, the operating costs for the individual accelerators in the injector chain once they were commissioned, and the costs of SSCL physics research groups. The Operations and Commissioning Report provided detailed costs for the operations of each of the following SSC Laboratory facilities and research areas: injection accelerators, test beams, experimental facilities, magnet research laboratory, and physics research. The report projected total operations costs of $493.6M (FY91$) for the period FY91 through FY99.

In response to a DOE request in July 1992, a draft report on operations in FY2000 and beyond was provided in September 1992 and extensively reviewed by a DOE Task Force in October of that year. The report summarized the physics goals for detector operations during the first five years. The Physics Division operations were described in terms of in-house physics research, the support functions for users, and operations functions for the experimental halls and associated facilities. All the tasks associated with the Accelerator Division operations of the injectors and the Collider were discussed, and a detailed manpower analysis for each task was provided. Finally, the Laboratory support areas were described and needs of manpower estimates were made.

The final report estimated a total annual operations cost of $317.2M (FY91$) for the year 2000. The total included costs for all Laboratory manpower (2428 FTEs), materials and supplies, power and utilities, cryogens, equipment, accelerator improvements (AIP), and general plant projects (GPP) (see Table 39-1, column five).

Table 39-1. Summary of the Evolution of SSC Program Costs (M$).

	1986 CDG (86$)	FY88 DOE Request (88$)	1990 SCDR (90$)	Jan 1991 Baseline (90$)	Nov 1992 (91$)
Project Costs (TPC)					
Construction	3010	3210	5288	5487	-
R&D	150	236	356	322	-
Accel. Equip.	40	40	40	-	-
Pre-Ops	113	170	131	131	-
Detectors	629	719	752	760	-
FY88 & 89 Costs	-	-	-	133	-
Total	3942	4375	6567	6833 [1]	
Construction Period	(6.5 years)	(7.5 years)	(9 years)	(10 years)	
Annual Operations					
Operations	176	190	-	-	258
AIP	10	11	-	-	10
GPP/GPE	7	7	-	-	5
Accel. Equip.	25	29	-	-	4
Physics Equip.[2]	15	32	-	-	40
Total	233	270	-	-	317

[1]This equates to 8,249M$ in AY$.

[2]Includes detectors and computers.

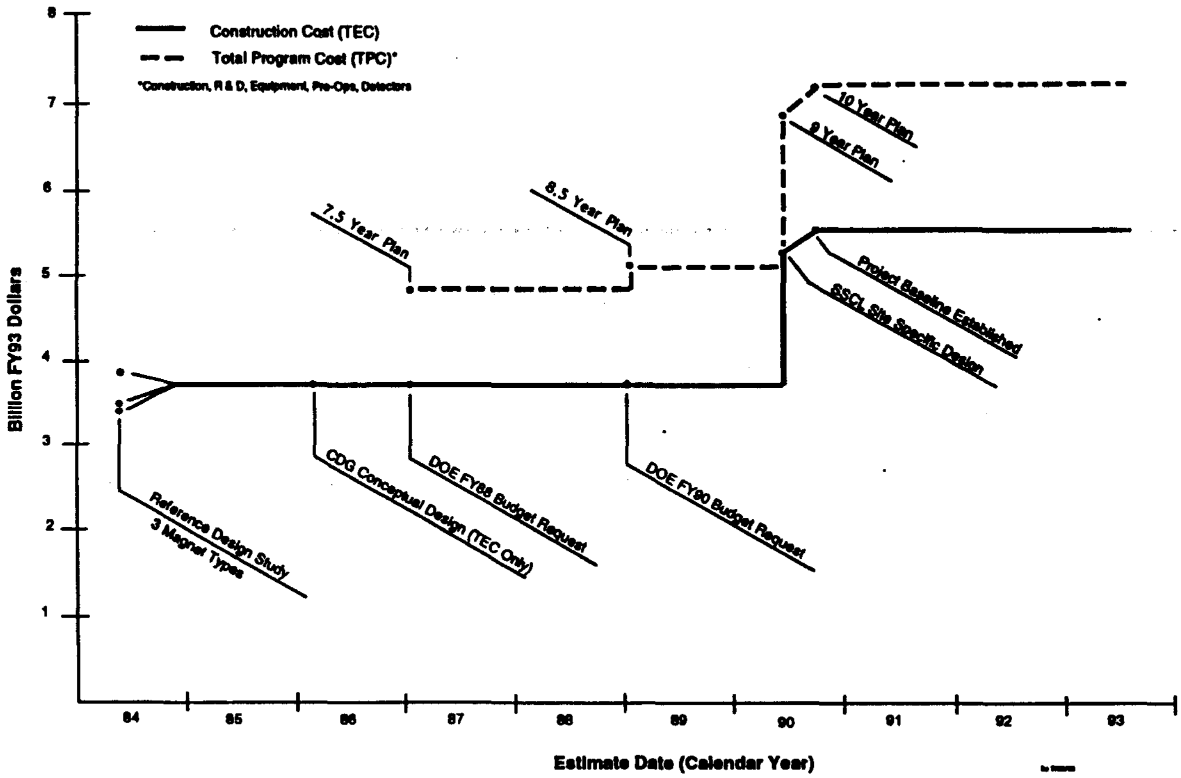

Figure 39-1. SSC Cost Estimates in FY93$.

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To accommodate the reader who wishes to investigate further a particular subject or event discussed in summary fashion in this report, a major effort was made under the direction of Tom Prosapio to locate, collect, and consolidate as many of the references listed below as possible. The collected documents were transferred to the archives of the Milton White Library of Accelerator History at the Fermi National Accelerator Laboratory in Batavia, Illinois, as the SSC Laboratory shut down.

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