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SSC DEVELOPMENTS*

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I. Introduction.

In less than four years the Superconducting Super Collider (SSC) project has gone from the initial realization that 40 TeV collisions were feasible to the present serious consideration for multibillion dollar funding by the Department of Energy (DOE). We here trace this remarkable history and project it to its central place in high energy physics in the 1990's. We describe the Conceptual Design Report which defines the SSC as it is presently envisioned. Finally we review recent task force studies of SSC detector development and summarize recent workshop conclusions on the physics capabilities of the SSC.

II. History and proposed scenario.

By the time of the 1982 Snowmass workshop[1] it was realized that the physics of the TeV mass scale was the key to the development of an understanding beyond the Standard Model and was now within reach by U.S. technology. A radical reexamination of the long range priorities of high energy physics was begun. The Lawrence Berkeley Laboratory high-rate detector workshop[2] confirmed the feasibility of operating at high luminosity with a hadron-hadron collider; the Cornell high-energy accelerator workshop[3] confirmed that a 20 TeV on 20 TeV hadron collider was technically possible with present technology. In mid-1983 the Fermilab Tevatron came on the air demonstrating that operation of nearly 1000 superconducting magnets was now reality.

In that climate, HEPAP was led to the proposal[4] that construction of the delayed CBA facility for proton-proton collisions at 800 GeV center-of-mass energy be bypassed and that the U.S. proceed directly to a 40 TeV proton-proton collider with luminosity $10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. The spectacular discovery of the intermediate gauge bosons at the CERN SP$\bar{\mathrm{P}}$S 540 GeV collider and the fact that the 1 TeV Tevatron $\bar{p}p$ collider would soon be in operation were important factors. A strong consensus of support within the high energy community helped to persuade the DOE to support SSC research and development (R&D) starting in the fall of 1983.

This was followed by the formulation of a program of R&D for the SSC and a reference designs study was initiated by the high energy laboratory directors. The University Research Association (URA) was accepted as manager of this program; the Chicago $\bar{p}p$ workshop[5] confirmed that there was little physics

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advantage to $\bar{p}p$ collisions and that the higher luminosity of pp had priority; the Ann Arbor accelerator workshop[6] addressed a broad spectrum of accelerator questions. In May, 1984, the Reference Designs Study,[7] a first detailed definition of the technical requirements and comprehensive cost analysis ($3B in 1984 dollars for construction of the SSC), was submitted to the DOE. The DOE then approved the proposal for a three-year R&D program to be directed by Maury Tigner, who was appointed by the URA Board of Overseers.

In parallel with that year of development and definition of the SSC accelerator program an intensive study of the SSC physics prospects was carried out in a series of workshops known as Physics at the SSC (PSSC).[8] Meetings were held at Fermilab (FNAL), Brookhaven National Laboratory (BNL), Woodlands, Texas, and Stanford Linear Accelerator Laboratory. In addition a Lawrence Berkeley Laboratory (LBL) workshop was held on the physics of the Standard Model at SSC[9] and a cross section document, EHLQ,[10] was prepared. This process culminated in the June, 1984, Snowmass workshop on physics at the SSC.[11]

October 1, 1984, marked the formal beginning of a three-year SSC R&D project designed to produce a realistic proposal for construction of the machine. Major work was to be carried out by BNL, FNAL, LBL and the Texas Accelerator Center (TAC) as well as by universities and private industry. The activities were to be coordinated by a Central Design Group stationed at LBL. Major milestones have been successfully met on schedule. Principal have been the Siting Parameters Document[12] in April, 1985, the magnet type selection on September 13, 1985, and the Conceptual Design Report[13] in March, 1986.

The workshops have continued with emphasis on detector issues (Madison muon detector workshop,[14] Fermilab SSC trigger workshop,[15] IEEE radiation damage conference,[16] LBL workshop on silicon detectors,[17] and LBL workshop on wire-chamber radiation damage[18]) as well as those in which an increasingly refined treatment of the Standard-Model and new SSC physics is being confronted by the constraints of realistic SSC detector facilities (Eugene,[19] UCLA,[20] and Madison[21]). Notable among recent task force charges have been the discussion of SSC detector development[22] and cost,[23] and the detailed examination of the cost and physics limitation of a $\bar{p}p$ alternative.[24]

At the present time, a recommendation to fund SSC construction is under serious consideration by DOE and we may consider the proposed scenario for its construction and first operation as envisioned in the Conceptual Design Report. If forwarded to President Reagan by Secretary Herrington, the project could be included in the FY88 budget presented in January, 1987. If Congress does not reject it outright, initiation of a site search could begin that Spring. The site selection process is expected to take 18 months with proposal review by a joint committee of the National Academies of Science and of Engineering which will forward a small number of outstanding possibilities to the Secretary of the DOE. Given FY88 authorization, beneficial occupancy of one cluster of experimental areas would take place in Winter, 1993, and of the second in Summer, 1994.

We could hear those magical words "SSC beam on!" in Fall, 1994. I have been told that the following are too fancifully optimistic, but in my scenario the horizontal gauge boson is discovered in Winter, 1995, an unexpected new kind of event is found to be flooding the detectors in Winter, 1996, and not too long after that two Higgs, the fourth generation, and SUSY are discovered. But we now return to present realities.

III. Conceptual Design Report.

The Conceptual Design Report[13] is a bulky report, with even bulkier appendices, which was delivered to DOE on March 31, 1986. It is not an engineering design from which the accelerator could be constructed, but it is a design sufficiently thorough to insure that the SSC is well within the capability of present technology and to provide the basis for a detailed and accurate cost estimate.

Of the 37-page parameter list, we cite just a few that summarize the essential character of the machine. It is a 20 TeV on 20 TeV proton-proton collider 82.944 km around as shown in Figure 1. It has two clustered interaction regions (IRs).

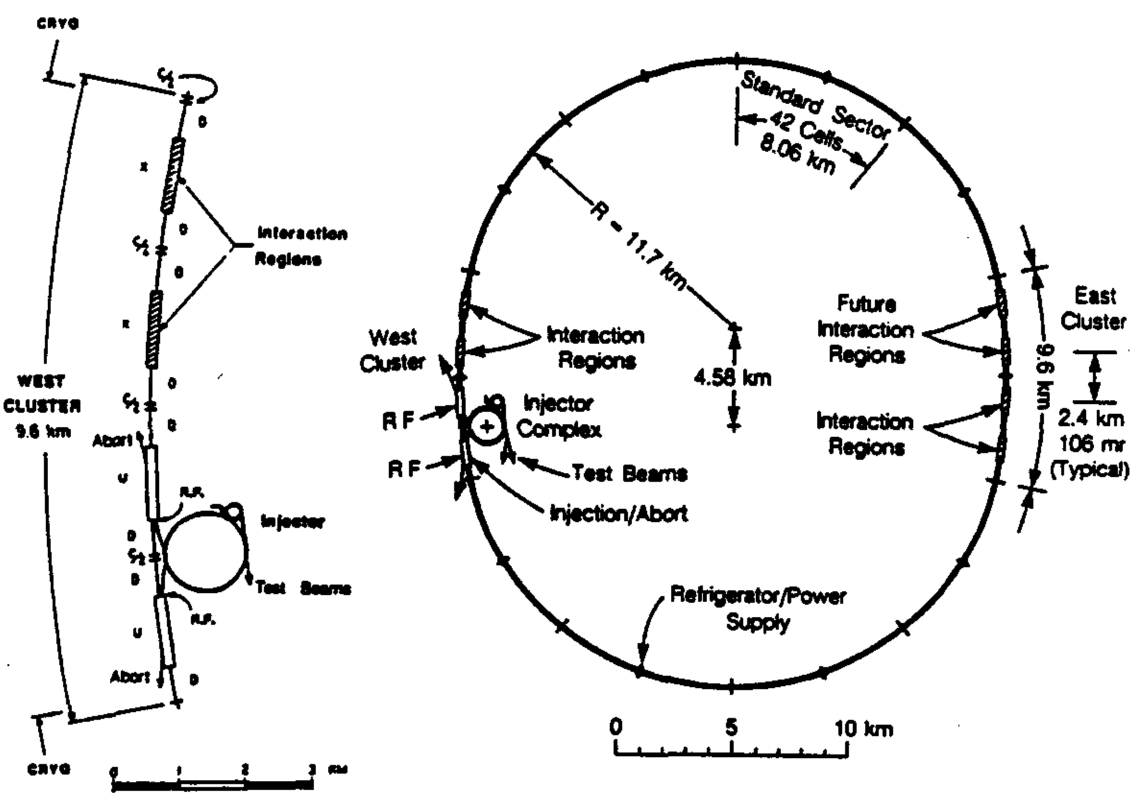

Figure 1. Layout of the 83 km SSC collider ring and West cluster detail showing the 1182 meter experimental (X) and utility (U) straights, the 576 meter three-cell dispersion suppressors (D) and 96 meter half cells (C/2).

One cluster contains the injector/abort complex and two experimental facility IRs. The other cluster contains four IRs, of which two are for future development. Of the four initially instrumented IRs two will have maximum luminosity $10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ with ± 20 meters space for experimental equipment between beam quadrupoles and the other two will have maximum luminosity $5.6 \times 10^{31}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ and a ± 100 meter space.

Beam intensities correspond to 405 megajoules of stored energy per beam and fast abort is required to protect the superconducting magnets. For a cross section of 90 mb there will be a 90 MHz interaction rate in the high luminosity IRs. With a 4.8 m bunch spacing there will be 1.4 interactions per bunch crossing with a rms beam size of 5 μm at a crossing angle of 75 μrad.

Adjacent IRs will be separated by 2.4 km with 106 mrad of horizontal bend in between. Injection is accomplished with a sequence that traces the remarkable accelerator development of the past few decades: a 50 KeV H^- source, 2.5 MeV RFQ, 0.6 GeV Linac, 8 GeV low energy booster, 100 GeV medium energy booster, and a 1 TeV high energy booster. In the final 20 TeV rings there are 7680 horizontal dipole superconducting magnets of length 16.54 m and with full field of 6.6 T.

The SSC parameters are the result of many man-years of detailed study, simulation, experimental tests, research and development, together with essential experience with the Tevatron I and other accelerators and colliders. They describe a machine which is technically well understood and which can be built with the confidence that it will provide through the 1990s and into the next century a source for new understanding of the fundamental forces of nature.

The cost, in 1986 dollars, for the construction of the SSC, exclusive of experimental detectors and with the assumption that the site is provided by the host, is summarized in the table below. It is based upon some 2000 technical items entered into the Work Breakdown Structure tables found in the Conceptual Design Report and perhaps as many more items for the conventional facilities.

SSC Cost Summary, FY 86 M$	
Technical components	1,424
Conventional facilities	576
Systems engineering and design	288
Management and support	192
Contingency	530
Superconducting Super Collider	3,010

By far the largest cost item is found within the technical components category: $1,001M for the magnets. Of this sum $746M is for the 7680 horizontal dipoles; and the latter cost is dominated by a 78% materials cost! It is not surprising that a great deal of effort has gone into R&D on superconducting wire with the result that very impressive progress has been made. As shown in Figure 2 the critical current density achievable in production-size NbTi billets has increased dramatically from the 1800-2000 A/mm^2 to the 2750 A/mm^2 in the Conceptual Design Report. Present indications are that values well above 3000 A/mm^2 may prove to be feasible for improved performance at less cost.

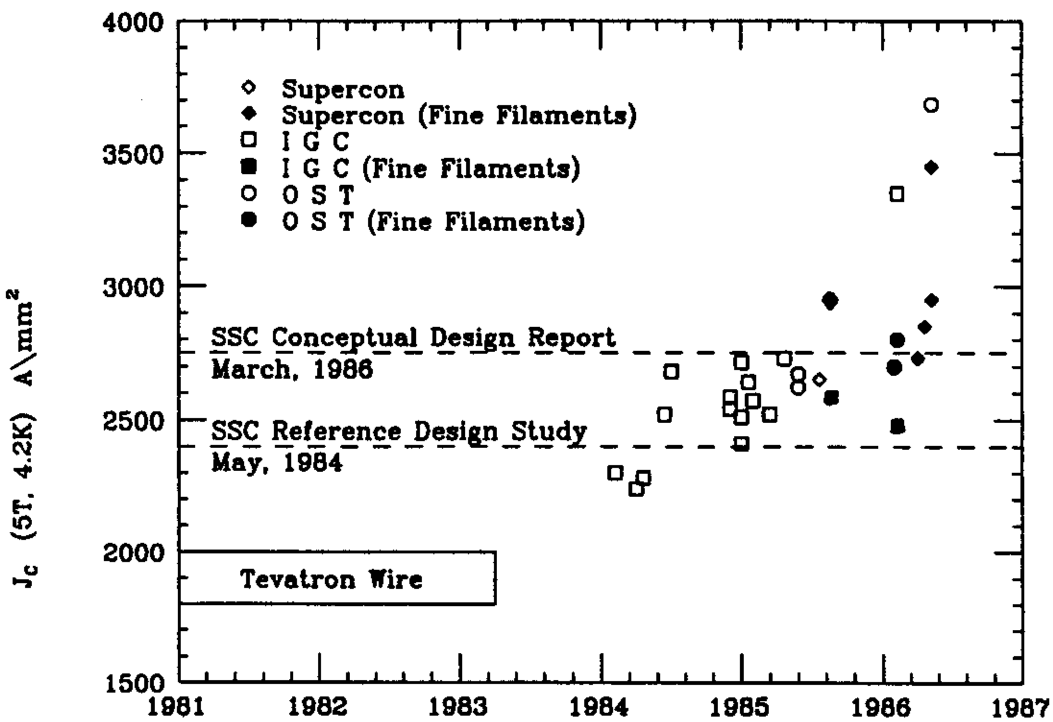

Figure 2. Critical current density for NbTi superconductor from U.S. vendors.

It also is not surprising that great effort has gone into superconducting magnet R&D. The chief competition was between the "collared, cold-iron," 6.6 Tesla type and the "superferric" 3.0 Tesla type which was developed by the Texas Accelerator Center. The unanimous recommendation was for the former, and Tigner's choice of the 6.6 Tesla magnet fixed the length around the accelerator to be some 52 miles. The validity of the choice was reaffirmed by a HEPAP subpanel during the week before this Vanderbilt Conference.

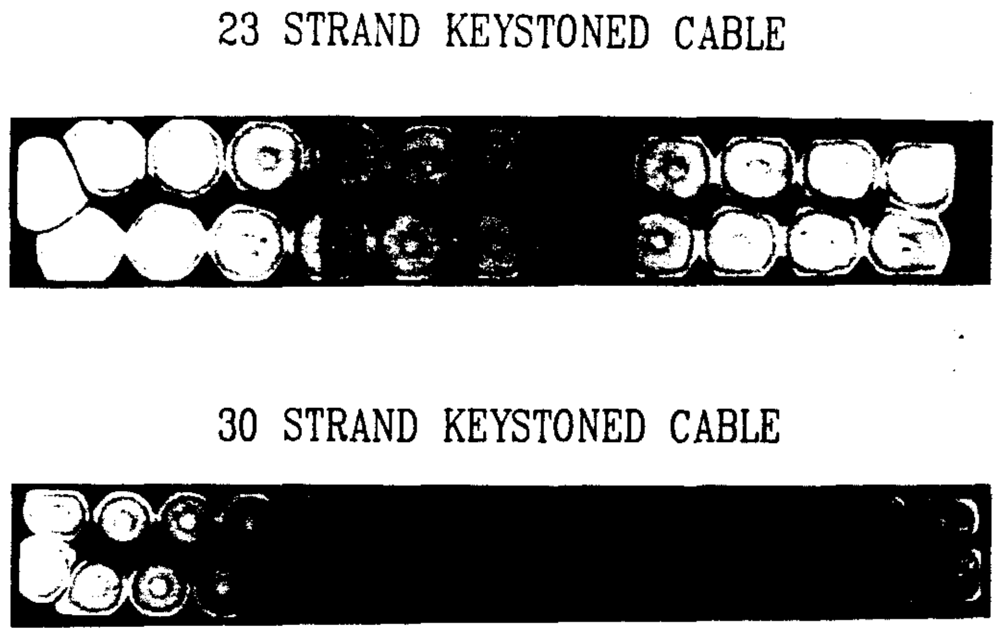

Figure 3. Cross sections of inner/outer 23/30-strand keystoned superconducting cable.

Figure 3 shows the configuration of the superconducting wire packages. Each strand contains thousands of copper-clad NbTi filaments with diameter 5 microns or smaller. Their arrangement in the "*cosθ*" winding in the stainless steel collar for a magnet dipole is shown in Figure 4. The collared coils are mounted in a 27-cm diameter flux-return iron yoke to form a cold mass assembly shown installed in the cryostat in Figure 5. Great design care and test experience has made possible the very low cryostat heat budget of 25 Watts to 80° K, 2.5 Watts to 20° K, and 0.3 Watts to 4.5° K for each dipole.

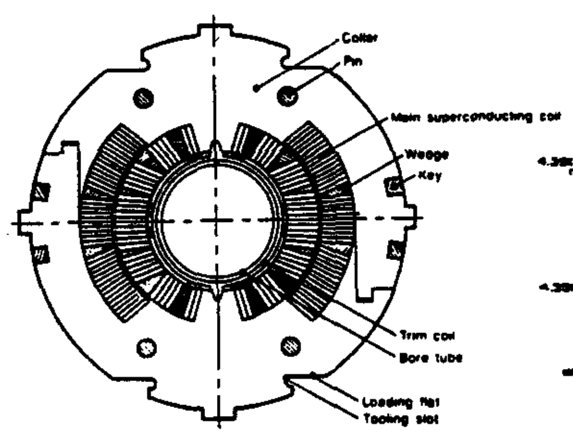

Figure 4. Coils and collar.

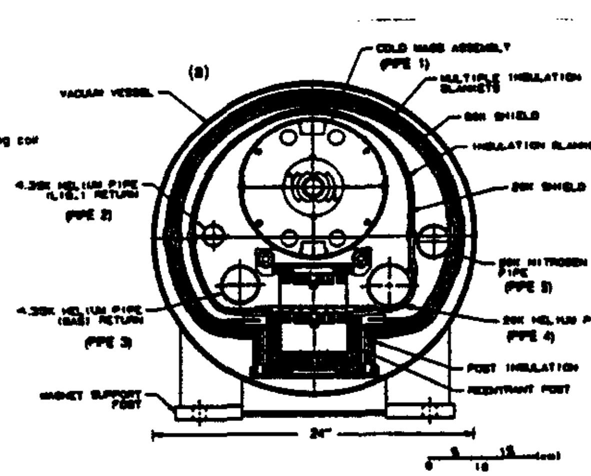

Figure 5. Magnet in cryostat.

The first full-length prototype dipole magnet, Figure 6, has been shipped from BNL where it was produced to Fermilab where it has been installed in its cryostat. The Fermilab magnet test facility is now coming into operation with a magnet string test scheduled for the coming fall.

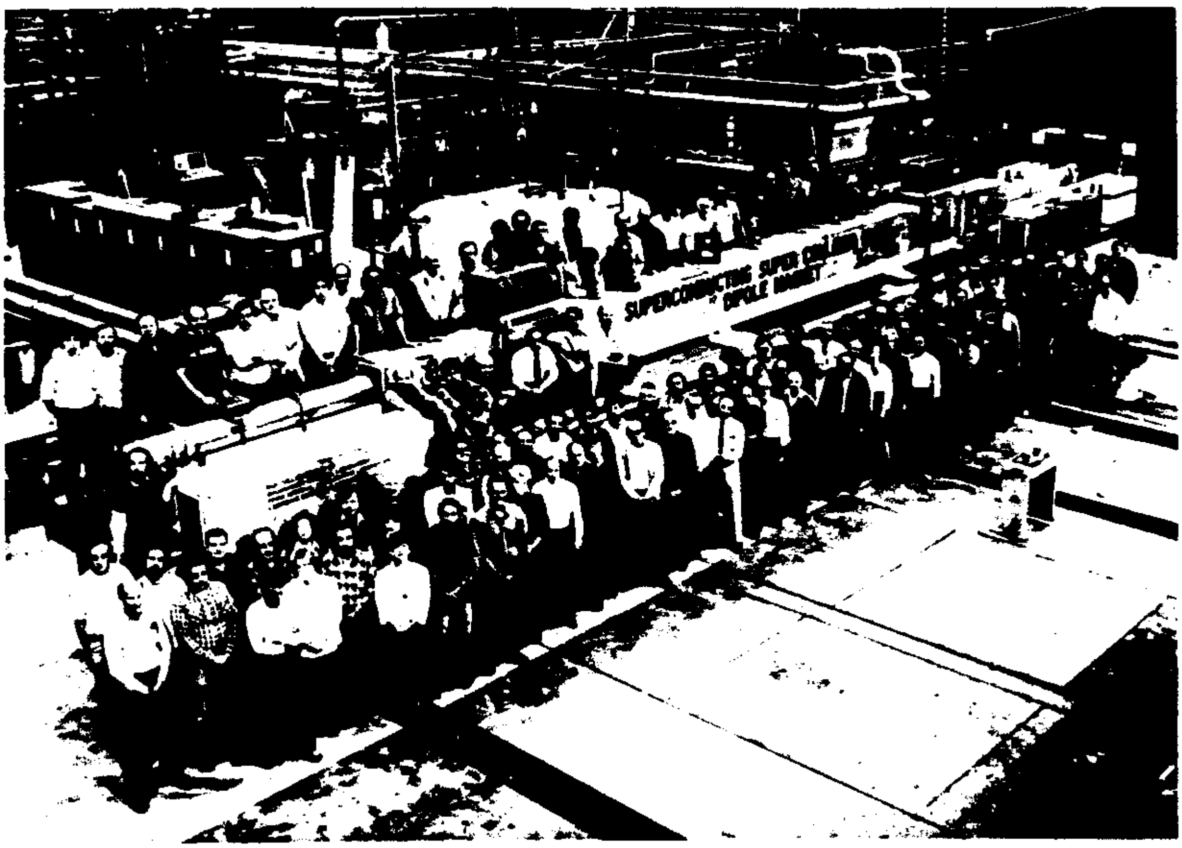

Figure 6. First full length prototype dipole ready for shipment from BNL to Fermilab.

The dipole magnets will be placed in the SSC tunnel, Figure 7, so that the two counter-rotating proton beams will be separated vertically by 70 cm. Figure 8 shows the first of two vertical steps to bring the beams into collision at the high-luminosity interaction point.

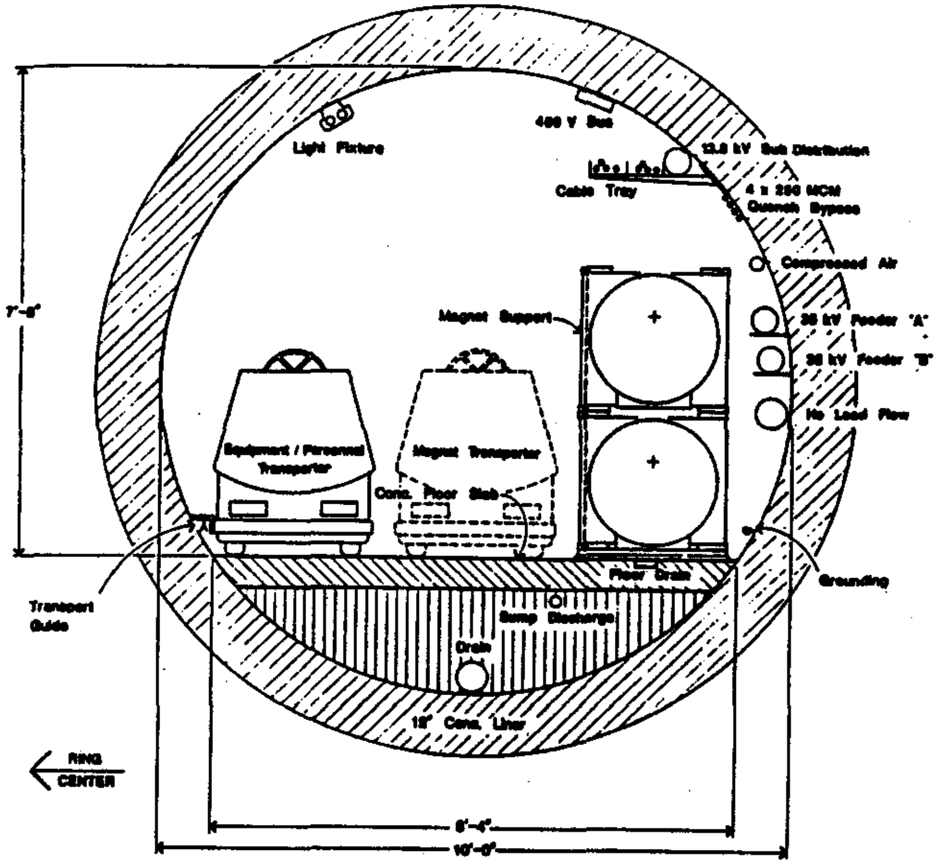

Figure 7. Tunnel cross section showing 70 cm vertical beam separation and magnet transport scheme.

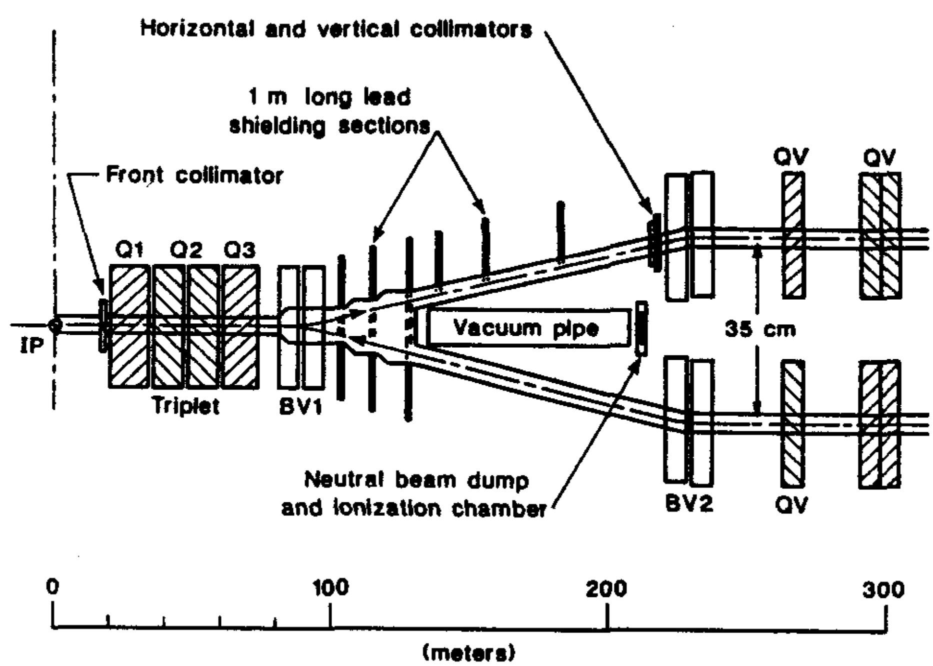

Figure 8. Arrangement of quadrupoles and vertical bends near the high luminosity interaction point, IP.

IV. Workshops and Other Activity.

The SSC presents new detector challenges because of the increased complexity of interactions, the higher particle energies, and the much higher event rates. A fine review of current detector development which is pertinent to the SSC has been made by the task force on Detector R&D for the SSC.[22] It concludes that substantial R&D is required in (1) radiation resistance, (2) faster time response, (3) improved granularity, (4) improved performance of electronics systems, (5) improvements in computing, and (6) improved performance for measurement of momentum and energy in the TeV range. In addition, a continued development of Monte Carlo simulation programs is needed. Within the context of those broad requirements the task force made specific recommendations for vigorous programs of basic R&D related to SSC detector needs. These include the investigation of wire chambers, silicon detectors, and scintillating fibers as tracking devices, and the testing of major calorimetric systems based on liquid argon, warm liquids, silicon sampling and heavy scintillating glasses. Particle identification considerations first require Monte Carlo studies for optimization of the muon spectrometer configuration and for the evaluation of the need for the development of fast RICH (ring imaging Čerenkov counter) detectors for hadron identification. Very-large-scale integrated circuit (VLSI) design centers are recommended to develop improvement in the performance and reduction in the cost of electronics. Advanced triggering and computing developments for major new and upgraded collider experiments will provide valuable experience for the SSC. Finally, there is an urgent need for increased manpower in the development of Monte Carlo programs to simulate high energy pp collisions and to parameterize detector response reliably in the TeV region. Many of these topics have received recent attention at workshops and conferences and an intensified attack is indeed needed. The LBL workshops on new solid state detectors[17] and on radiation damage in wire chamber detectors[18] examined recent work in critical areas.

A first attempt to estimate the cost of the experimental facilities has been done[23] by the Detector Cost Model Advisary Panel (G. Trilling, chair), the Detector Cost Evaluation Panel (R. Schwitters, chair), and the Off-line Computer Advisory Panel (S. Loken, chair). As an example, one of the generic 4π magnetic detector which they considered in their modelling is shown in Figure 9. It covers up to 6 units of rapidity with a 20% charged track momentum resolution 1 TeV, electromagnetic and hadronic energy resolution of 15 and 50 % at 1 GeV, and muon momentum resolution 20% at 1 TeV. While the task force models cannot in any way be taken as proposals, they represent a natural evolution of the instrumentation in use today and can be used for estimates of the total costs as is shown in the table below.

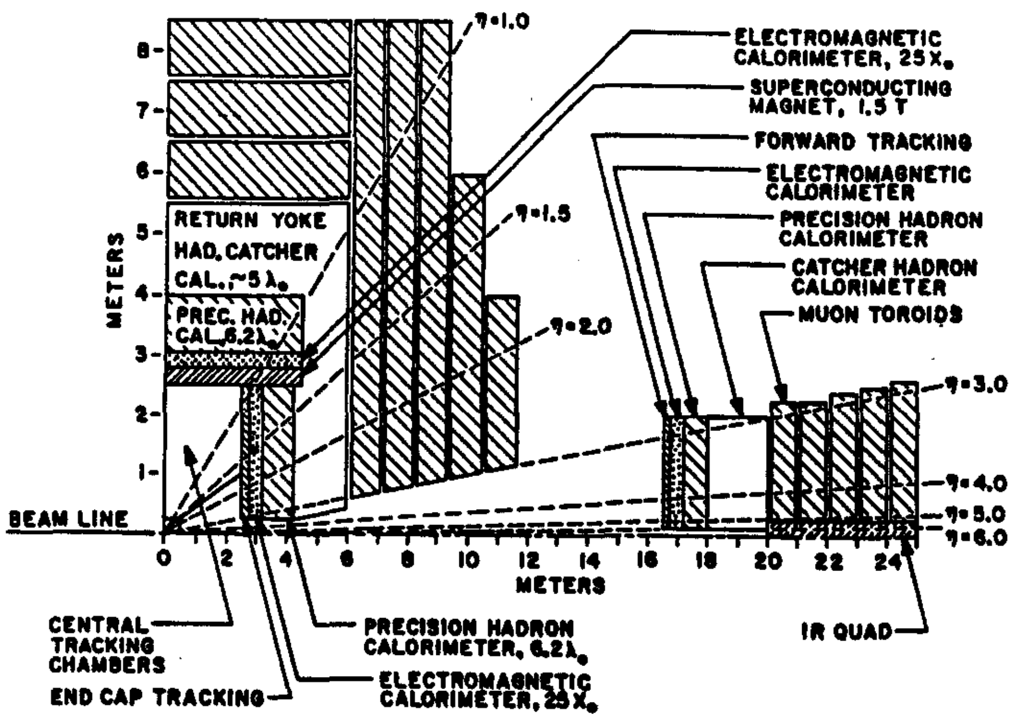

Figure 9. One of the SSC 4π magnetic detector facility models.

Detector Costs	
4π Magnetic Detector	\$290M - \$334M
Spectrometer for High Energy μ's	159M - 174M
Upgraded Existing Detector	90M - 125M
Additional Forward/Intermediate Detector	95M - 102M
Specialized Detectors	less than 20M
Total after ± 15% inclusion	\$558M - \$865M
Off-line Computer Costs	
Hardware Costs	\$64.6M
Software	5.0M
Total	\$69.6M

Since the 1984 Snowmass workshop, several physics simulation programs have undergone increasing sophistication and improvement by incorporating new theoretical input and by matching new results from the CERN SP$\bar{P}$S collider. They agree on the QCD processes and all include initial and final state gluon radiation, but differ in the treatment of the fragmentation process. Two popular Monte Carlo programs are ISAJET[25] with independent fragmentation, and PYTHIA,[26] a Lund-based Monte Carlo with color-string fragmentation. These and similar programs are being used to evaluate prospects for the study of interesting physics processes at the SSC. Three examples will serve as illustrations: the search for an intermediate mass Higgs particle, the search for supersymmetric gluino pairs, and the search for horizontal gauge bosons.

Above about 200 GeV mass the decay $H \to W^+W^-$ dominates. Production and decay rates are known from the Standard Model for given Higgs mass and the issue becomes one of the generation of QCD background and of direct W pair production, together with an evaluation of the detector trigger and event-analysis capability. The process has been studied extensively.[15,19,20,21] For example, a trigger strategy has been developed[28] which successfully reduces the event rate from the raw 100 MHz to 1 Hz of recorded data and retains 1/3 of the Higgs events for a mass of about 200 GeV:

Summary of Trigger Strategy and ISAJET Results for $H \to W^+W^-$			
Trigger Selections	Rejection Factor	Remaining Cross Section (nb)	$H \to W^+W^-$ Efficiency
First Trigger Level:			
a) Electron candidate, $E_T > 25$ GeV	10,000	30,000	0.86
b) Event $P_{T,miss} > 40$ GeV	4	7,500	0.43
Second Trigger Level:			
a) Electron candidate isolation	1.5	5000	0.37
b) $E_T > 80$ GeV jet requirement	20	250	0.32
Third Trigger Level: Charged particle $p_T > 10$ GeV pointing to electron calorimeter cell	220	1.1	0.32

Note that the 1.1 nb cross section corresponds to a 1 Hz data rate at maximum luminosity. For an integral luminosity of 10^{40}cm^{-2} the number of events surviving all final analysis cuts is as follows:

m_H(GeV)	Higgs Signal	Background
300	1400	1800
800	340	560

These results suggest that the Higgs can be detected if its mass is between about 200 and 1000 GeV. However, at the highest mass it is very broad and appears as no more than a shoulder in the W pair mass distribution so that the background will require detailed understanding. Furthermore, the study is only now beginning to address realistic detectors with their proper resolution, plausible segmentations, cracks, and pileup problems. On the other hand, the only sure way to identify the Higgs may be through its ZZ decay where each Z decays into a lepton pair.[31] The Higgs example provides an interesting challenge for the development of SSC detector facilities and for SSC physics analysis. It should provide plenty of food for thought and discussion at the upcoming Snowmass 1986 workshop in June.

A second physics example that has received considerable attention is one of new physics rather than of the Standard Model, that is, the SUSY process of gluino pair production. When the gluinos decay each into a quark pair and a photino which escapes detection, the event is characterized by large missing transverse energy and several jets.[29] Background comes primarily from hard gluon scattering in which one gluon goes to a b-quark pair with one b quark decaying leptonically with large transverse missing energy going into a neutrino. These processes have been modelled in detail and trigger strategies have been found[30] to give 1 Hz rates at signal to background ratios of 1 to 0.03 for gluino masses between 100 and 1000 GeV. The analysis requires excellent QCD jet reconstruction, which is a further challenge to SSC detector design. Gluino pair production provides yet another stimulating topic for Snowmass 1986.

The third SSC physics example is the horizontal gauge boson which is postulated to connect quark and lepton families. Its production and decay leads to very massive and unmistakable lepton pairs such as $e\mu$ or $\mu\tau$. Triggering on high p_T leptons gives an acceptable data rate with little loss of signal. The dominant background comes from W^+W^- pairs,[32] but there is good separation of the signal from background (Figure 10). If the mass were 5 TeV, hundreds of clean events would be collected per year, justifying in itself the construction of the SSC. New physics processes of this type do not suffer from pileup and so provide motivation[33] for preserving in the the design of the SSC and its experimental facilities the possiblity of running at luminosities greater than 10^{33} $cm^{-2}sec^{-1}$.

As the SSC proceeds towards construction, the issues of detector R&D and of the design of the experimental facilities are now beginning to receive greater attention. An effort commensurate with the design of the machine itself is urgently needed to provide the best possible exploitation of its physics potential. The upcoming Snowmass workshop on the Physics of the SSC (June 23–July 11) will provide a lively and useful forum to help focus the energies of the high energy community in this direction.

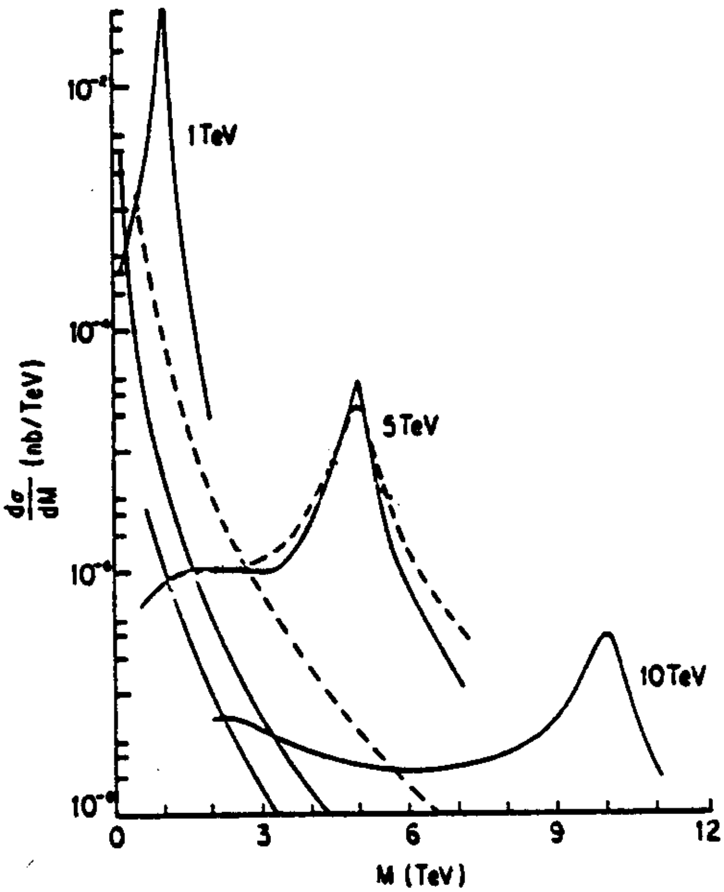

Figure 10. Cross section for production and decay of the horizontal gauge boson into $e\mu$ lepton pairs for masses of 1, 5, and 10 TeV. Reconstruction smearing is illustrated at 5 TeV by the dashed curve. Background from WW decay to $e\mu$ is shown as the solid curves with and without 200 GeV p_T cuts and from Drell-Yan production $l\bar{l}$ as the dashed curve.

V. Conclusion.

We have said little of the physics motivation for SSC. Chris Quigg's talk at this conference gives a sharply defined prospectus of the exciting physics expectations. The Snowmass proceedings[1,11] and both the Reference Design Study[7] and the Conceptual Design Report[13] contain excellent summaries of the physics potential. A number of recent articles address the subject for a broader audience.[34]

In briefest summary, there is an increasing belief that the basic questions posed by the extraordinary success of the Standard Model will be answered by new physics in the 1 TeV mass region which is accessible only to the SSC in the foreseeable future.

The broad consensus that the SSC is of highest priority continues in the U.S. high energy community and is persuasive for strong federal support. The cooperation of the national laboratories and universities has been an outstanding achievement of the program. While sharp technical debate over choices such as the magnet type has occurred, the choices are accepted and a strong collaborative effort continues. The Conceptual Design Report is receiving high marks in its reviews and the DOE has said that the information needed for the SSC decision is in hand.

The broad debate over the high cost of the SSC has continued with concern among the other sciences that funding will detract from their programs. Furthermore, in a Gramm-Rudman-Hollings year the argument for SSC must be made with special clarity. The debate[35] has highlighted, however, the gradual deterioration of support for basic science during a time when the R&D program for national defense is rapidly growing. A dramatic turn around of this imbalance is called for and it is increasingly clear that every effort must be made to increase greatly the support for basic science in general. While the SSC funding rate will not greatly exceed, in proportion to national income, the rate during the construction of Fermilab and other parallel high energy projects, it is proposed in a different fiscal climate and attitude toward basic science.

Nevertheless, the time for the SSC has come. We hope that the favorable decision to proceed will soon be made.

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