THE SSC REFERENCE DESIGNS STUDY

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Introduction

In July 1983, the High Energy Physics Advisory Panel (HEPAP) transmitted to the Office of Energy Research of the U.S. Department of Energy (DOE) a unanimous recommendation for the "immediate initiation of a multi-TeV high-luminosity proton-proton collider project with the goal of physics experiments at this facility at the earliest possible date." This proposed facility was designated the Superconducting Super Collider (SSC). As a consequence the directors of the U.S. high energy accelerator laboratories chartered the National SSC Reference Designs Study to review in detail the technical and economic feasibility of a range of technical options for creating the SSC facility. The study, which was centered at the Lawrence Berkeley Laboratory from February through May 1984, involved some 150 scientists and engineers from several national laboratories and universities. The References Design Study is described in a report available from the DOE.1)

The primary objective of the study was to help the Department of Energy, the high energy physics community and the scientific community as a whole to decide how best to proceed with SSC research and development (directed toward improving the cost effectiveness of current accelerator technology). In particular, in commissioning the study, the laboratory directors were mindful of the upcoming Summer Study sponsored by the Division of Particles and Fields of the American Physical Society to be held at Snowmass, Colorado, June 23 to July 13, 1984, and the need of the Department of Energy to plan resources for SSC pre-proposal research and development.

The Reference Designs Study addressed three key areas:

- Technical feasibility: the technical (physics) designs of 20 TeV (per beam) proton-proton colliders were explored using three of several possible superconducting magnet styles as study models.
  Economic feasibility: the likely cost range was estimated using

pre-conceptual engineering designs for the three magnet styles and the other hardware and conventional facilities required to construct and operate technically feasible colliders.

- Required R&D: the R&D needed to verify design calculations and technical assumptions was identified.

It was not intended, however, that the Reference Designs Study report be either a design proposal or a site preference study.

A major purpose of the Reference Designs Study was to extend previous technical and economic feasibility studies. Primary emphasis was on estimating the cost range within which SSC construction can confidently be expected to fall. In doing this, the focus was on the cost of creating the accelerator itself. No consideration was given to the cost of the high energy physics research equipment, nor were preconstruction R&D funding needs or possible site acquisition costs treated.

In chartering this study, the laboratory directors suggested a set of primary design objectives to serve as a basis for the technical and cost analyses (see Table I). These parameters are consistent with the HEPAP recommendations. The directors additionally suggested that a range of magnet options be considered: a 6.5 tesla cold-iron design; a 5 tesla iron-free design; and a 3 tesla iron-dominated design. All assume a slightly improved version of the niobium-titanium superconductor used in the Fermilab Tevatron, the world's first high energy accelerator based on superconducting magnets. These three options correspond to designs being studied by various research teams around the country. Together with the primary SSC design objectives, these conceptual magnet designs form the basic technical input of the Reference Designs Study.

SSC Reference Facility Description

The three dipole magnet designs were chosen to embody a variety of design concepts and to span a range of field strengths from 3.0 to 6.5 T. All use superconducting cable of niobium-titanium cooled to 4.5 K. The high-field design has a 6.5 T central field and encloses both beam tubes in a common iron yoke and single cryostat; the medium-field design is a 5 T magnet, with each beam tube and coil in its own cryostat; the low-field iron-dominated, 3 T magnet, a so-called superferric design, consists of separate beam tubes and yokes in a common cryostat. The required main ring circumferences for the three designs, 90, 113, and 164 km, respectively, are in approximately inverse proportion to their field strengths. Even the smallest circumference is more than three times that of the LEP project at CERN, the world's largest funded accelerator project.

The SSC facility described in the report comprises a 20 TeV on 20 TeV proton-proton collider, and injector complex, and a campus-like arrangement of office and laboratory buildings. In the model layout used for the study, space is provided for six possible interaction regions for independent physics experiments. Four regions are assumed developed, leaving the other two for future development to respond to special physics needs as they arise.

Auxiliary systems for the three designs are similar. The injector complex includes a linear accelerator to accelerate the beam from rest to 1 GeV, a 70-GeV conventional-magnet synchrotron, and a 1-TeV superconducting synchrotron (comparable to the Fermilab Tevatron). A "median site" was established for the Reference Designs Study by combining representative geological, topological and meteorological conditions from around the U.S.

Technical Feasibility

In the course of this SSC Reference Designs Study, deeper and more extensive consideration has been given to matters of technical feasibility and cost than has been possible in previous studies. It has been shown that the basic accelerator system design principles successfully employed in existing accelerator facilities can be used directly for the SSC design. For producing the superconducting magnets--the primary components of the SSC--it has been shown that there are several viable technical approaches. Each requires substantial but well-defined engineering development based on existing superconducting materials and accelerator magnet technology. Thus, technical success of the SSC does not hinge on the success of a single design requiring extensive development of new technology, but rather on the selection (during the R&D phase) of the most suitable of a variety of designs. This selection will be based on comparisons of achieved magnetic field quality, refined cost studies, and demonstrated manufacturability and reliability, thereby ensuring the successful construction of the SSC.

Accelerator Physics

Several workshops dealing at least in part with accelerator physics issues relevant to proton accelerators of the scale of the SSC have been carried out, beginning with the ICFA Workshops of 1978 and 1979 and continuing through the DPF Snowmass Workshop of 1982, and 20 TeV Collider Workshop of March 1983, and most recently the DPF Workshop at Ann Arbor (devoted exclusively to accelerator physics topics at the SSC rather than to specific designs). The work of those studies has been applied, and in some cases extended, in this Reference Designs Study. Physics principles derived from these studies have been used to work out, from the specified end-use parameters, the myriad secondary parameters for the SSC. It is these latter parameters that describe the beam properties and subsystem performance specifications needed to achieve the desired energy and luminosity with good beam lifetime and sufficient operational flexibility. Results of this effort were then examined to ensure that they fell within the range of validity of the calculational procedures used. Principal areas of investigation were luminosity, required aperture, collective effects, lattice and beam optics design, beam lifetime, RF system requirements, synchrotron radiation effects, energy deposition by beam particles lost in the superconducting magnets, and injector system requirements. In every case the results represent a reasonable extrapolation from current practice.

Energy and Luminosity

The steady increase in accelerator energies of a factor of 10^7 over the past five decades makes us confident that achievement of a 20 TeV beam energy by extension of current methods is practical. Our luminosity goal of 10^{33} $cm^{-2}sec^{-1}$ is only a factor of ten higher than that achieved in the CERN ISR almost a decade ago. Substantial improvements in accelerator technology has occurred in the meantime. Parameters that directly affect the luminosity are beam current, beam emittance, focusing strength at the interaction point and the sustainable tune spread due to the non-linear beam-beam interaction. The SSC beam current required to achieve the specified luminosity, about 70 mA, is relatively modest. The design value of the tune spread (due to the beam-beam interaction) resulting from the chosen emittance and beam current is conservatively held to about one-half the value already achieved in $\bar{p}p$ collisions at the S$\bar{p}$pS. The normalized emittance corresponding to this tune spread, however, is about one-half to one-third of that commonly achieved in existing large proton rings.

Although existing proton linacs produce beams with smaller emittance than that required for the SSC, it has usually been the case that emittance dilution occurs in the early stages of acceleration in the booster synchrotron. Calculations indicate that this observed dilution is entirely attributable to space-charge-induced tune shifts and, in some cases, to collective instabilities driven by the relatively high impedance of the vacuum systems on these older accelerators. These problems will be eliminated in the SSC design by utilizing a relatively high energy (1 GeV) linac to reduce the space-charge tune shift, and by taking advantage of modern techniques for greatly reducing vacuum chamber impedances. Because the requisite design calculations are based on well-understood principles, achieving the specified SSC emittance should be straightforward.

Aperture

Next to the design energy itself, the physical aperture of the magnets is the single most important collider parameter in determining cost, since this determines the amount of material needed to construct the magnets. Because the magnetic field will not be perfectly uniform throughout the physical aperture, the useful magnetic aperture will be some fraction of the physical aperture, depending in a complex manner on the individual magnet design and fabrication tolerances as well as on the optics design of the lattice.

The useful aperture must be large enough to accommodate the beam size and provide additional space needed for beam-tuning procedures, such as finding an initial closed orbit, centering that orbit, measuring lattice parameters, or optimizing injection conditions. The full beam width, largest at lowest energy, is about 3.2 mm (95%) at the focusing magnets in the arcs. Adding to this the space needed for the above-mentioned procedures, a useful full aperture of 1 cm or more for particles having a fractional momentum deviation of $\pm 5\times10^{-4}$ about the design momentum appears desirable.

Determination of the actual useful aperture for each type of magnet must await measurements of field quality. In the case of the conductor-dominated magnets Designs A and B, calculations can serve as a reasonable guide prior to such measurements; these indicate that for Design A, with its 4 cm inside coil diameter, the 1 cm magnetic aperture requirement can be met. For Design B, with its 5 cm inside coil diameter, controlling conductor placement to achieve the required good field aperture would be correspondingly easier. For both Designs A and B, persistent currents in the superconductor distort the magnetic field significantly at injection energies; these distortions will be locally compensated by additional correction windings (provided for in the magnet designs). In the case of the iron-dominated Design C magnet, field quality calculations are more difficult, as they include the complex properties of magnetized iron; actual measurements on prototype magnets will be particularly important here. Approximate calculations done to date suggest that good field aperture could be improved by decreasing the cell length for Design C.

Collective Effects

Owing to the high energy and the tight focusing that can be achieved at the collision regions, rather modest beam currents are needed. The projected 70 mA average current (5 A peak current) is about one-third of that achieved routinely today in proton accelerators. Thresholds for instabilities that cannot be easily controlled by feedback are all comfortably above the design operating current of the SSC. Thus, it is believed that use of good, modern practice for design of the potentially high-impedance components of the vacuum envelope should suffice to render these instabilities harmless. It is noteworthy that the cold beam tube, which comprises the major part of the vacuum envelope, has a low impedance in the important frequency range so that the need to control impedance concerns only a few items.

Lattice Design

Linear lattice design methods currently used for accelerators and colliders can easily accommodate an accelerator of SSC class. At least two different schemes for correcting chromatic aberrations introduced by the strong focusing in the dispersion-free interaction regions have been found, each permitting adequate dynamic aperture. Future work will concern itself with optimization for economy and operational flexibility.

Luminosity Lifetime

After the beams are brought into collision the luminosity will tend to decrease with time due to loss of particles and due to emittance change. These factors result in a computed luminosity lifetime of about 30 hours if a total proton-proton cross section of 200 mb is assumed; this leads to a need to refill the collider about every 24 hours--an acceptable cycle time.

Acceleration System

Protons of 1 TeV injected into the SSC are already ultra-relativistic, permitting the use of a high-Q RF acceleration system. In addition, the acceleration voltages are modest by comparison with those needed in existing electron machines, where high-Q systems are routine. Control of noise engendered longitudinal diffusion will need further study owing to the closeness of the synchrotron frequency side-bands to the carrier. Detailed calculations are needed to produce final specifications for the frequency control system. Considerable recent work on this subject with regard to beam-cooling systems means that the needed calculational tools are already available.

Synchrotron Radiation

At 20 TeV, protons forced to follow curved orbits emit significant synchrotron radiation. For example, in Design A (6.5 T) at a luminosity of 10^{33} $cm^{-2}sec^{-1}$, each beam will radiate about 8.5 kW, primarily in the soft x-ray regime. The major impact of this radiation will be to increase the refrigerator load.

In the 6.5 T design, longitudinal and transverse emittance damping times (due to synchrotron radiation) of 7 and 14 hours, respectively, are computed; this damping will be useful in maintaining good luminosity lifetime. Previous experience with synchrotron radiation effects in electron machines (where they are very strong by contrast to the SSC) gives us confidence that calculations with regard to its effect on SSC beam parameters are well founded.

Beam Energy Deposition in the Superconductor

A central feature of the reference design lattice is the provision of special means to avoid beam loss into superconducting magnets during injection and beam abort. It appears entirely feasible to provide short lengths of normal magnets close to the places where beam might be lost during these operations.

At a luminosity of 10^{33} $cm^{-2}sec^{-1}$, about 760 W is continuously carried away from each interaction point by lost beam particles and reaction products. The energy flows in rather narrow cones directed along the two beam directions, representing a total of 4.5 kW for six interaction regions. Detailed calculations indicate that no more than 20% of this energy need be absorbed in the cryogenic system. More importantly, the calculation of energy flux density at the inner face of the superconducting quadrupoles nearest the collision point yields a local temperature rise of 0.01 K or less. Thus, the existence of superconducting quadrupoles in the interaction regions is not a concern.

Injector Design

The design of the injector is based almost entirely on existing accelerators and is straightforward. The ultimate design, carried out by well-established procedures during the R&D phase, will focus on optimization of economic and operation factors.

Summary

In general, the basic accelerator physics knowledge needed to produce a feasible and cost-effective design for an SSC is in hand. Needed are improvements to calculational procedures to make them more efficient as engineering optimization aids.

Accelerator Engineering

Conclusions regarding engineering feasibility concern the principal SSC technical systems of magnets, cryogenics, other accelerator systems, injector, and conventional systems. Previous studies have been extended and carried to a greater level of detail in an effort to evaluate the engineering feasibility of various approaches to the primary components and systems. A number of approaches appear viable at present; selection of the most cost effective of them must await evaluations of magnet prototypes.

Magnets

The primary motivation for studying superconducting magnet designs different from those now developed (or in use) is economic. Several major cost-saving possibilities are foreseen that can make the SSC magnet system considerably less expensive than would be systems built from existing magnet designs. In its own way, each of the three reference magnet designs makes use of several of the following cost-saving possibilities:

- the relatively small aperture needed for SSC magnets, resulting in reduced materials requirements per unit length;
- the expected increase in current carrying capacity of commercially available superconductor, already achieved in pilot runs of commercial quantities;
- the improved productivity of automated and simplified manufacturing and assembly methods;
- the use of longer magnet units to reduce assembly and handling labor;
- the use of improved and more energy-efficient designs to reduce cryogenic requirements.

Comparisons with existing designs show the expected cost savings.

All of the mechanical structures proposed represent reasonable assumptions about materials properties; each, of course, will have its own mechanical peculiarities requiring technical solutions for maintaining needed coil prestress and component alignment during assembly and cooldown.

All three designs are based on the assumption that Nb-Ti superconductor capable of supporting 2400 A/mm^2 at 5 T, 4.2 K will be available commercially. The comparable number for conductor used for constructing the majority of the Tevatron magnets is 1800 A/mm^2. Steady improvement of the critical current density has since been achieved. In laboratory quantity, critical current densities of 3800 A/mm^2 have been observed. Recent pilot runs in commercial quantity have yielded critical current densities of about 2700 A/mm^2, justifying the expectation of achieving 2400 A/mm^2 in production quantities.

Cryogenics

Cryogenic systems needed for the three designs are quite similar and follow current engineering practice closely. Any one of the systems could be adopted to any of the magnets, allowing a final decision to be made on the basis of further optimization studies. All magnet designs are estimated to have comparable heat leaks per unit length, each about a factor of five improvement over Tevatron magnets. This improvement is a result of magnet designs in which more space is available for thermal isolation, allowing longer supports and more favorable temperature gradation. Prototype measurements will be required, of course, to test the validity of the heat-leak calculations. Because the capital cost of the refrigeration is relatively small, the overall cost of the SSC facility is not particularly sensitive to the magnitude of the heat leak, although the operating costs would be. Long cryogenic transfer lines of complexity comparable to the magnet cryostats have already been fabricated that have even lower heat leaks than anticipated here. Integration of the multiple refrigerator units requires careful study and the development of realistic computer simulation models to optimize system behavio under transient conditions. This work will be a direct extension of work already done with regard to the Tevatron and CBA refrigeration systems.

Other Systems

Of the other accelerator systems, vacuum, power supplies, RF, injection, abort, beam instrumentation, controls and personnel safety, only the vacuum system represents something new in engineering practice for proton accelerators. Cryogenic pumping of the beam tube has been shown to result in extremely good vacuum in the Tevatron and in cold beam tube experiments in the ISR. Existing measurements of photodesorption in the relevant wavelength range lead to the estimate that the presence of the synchrotron radiation in the SSC should not result in an excessive pressure rise. Experiments on photodesorption of gas molecules carried out under anticipated SSC conditions are needed, however, to verify this conclusion.

For the other systems, SSC operating parameters are well within the range of current engineering practice and will pose no outstanding technical challenge. The same can be said of the injection system, as we already possess a 1 TeV synchrotron complex (the Tevatron) capable of producing the required beams.

Conventional Facilities

The standard construction practices and structure types used in the past appear to be entirely adequate for the SSC. Shielding needs of the collider ıre more modest than for the high intensity rapid cycling synchrotron now in existence at Fermilab. The interior environment of the SSC tunnel can be more austere than has been common practice in the past, because the magnet system is tightly sealed. As with other strong-focusing accelerators, foundation stability tolerances are not severe. As long as differential settlement occurs on a length scale having a typical dimension of circumference divided by tune, i.e., about 1 km, and on a time scale of many months or years, experience has shown that a combination of resurvey and orbit-correction settings easily accommodate observed changes. Consequently, none of the latest generation of large high energy physics accelerators has needed to employ pilings in its tunnel foundation and we do not anticipate the need here.

Cost

The Reference Designs Study was purposely constrained to use as large a group of common elements as possible to reduce the effort involved in creating multiple reference designs and estimating their costs. This approach is believed adequate to produce a cost estimate range, but cost differentials between the estimates for different reference designs will be less reliable than would come from three independent, fully optimized designs.

Costs for conventional facilities were estimated by the architect-engineering firm of Parsons Brinckerhoff Quade and Douglas, Inc., using standard industry practice. To estimate tunnel costs without a specified site, a "median site" was established for the Reference Designs Study by combining representative geological, topological and meteorological conditions from around the United States.

A complete accelerator design concept based on the Design A magnet was generated for the purposes of estimating technical facility costs. The estimate for Design A was based, where possible, on unit costs for materials, components, and subsystems taken from recent invoices and catalogs. Magnets and cryogenic systems received the most detailed attention. To produce estimates of complete accelerator systems based on Design B and C magnets, the other systems from the Design A concept were scaled and then costed. The results of these estimates are summarized in Table II.

These cost estimates are based on overall technical designs of the SSC that are firmly tied to existing accelerators. The variety and number of different subsystems envisioned for the SSC closely parallel those of existing facilities. Major component designs used in our estimate represent well-defined, albeit substantial, engineering developments based on existing hardware. For these reasons, it is certain that all needed systems are taken into account and that the quantities of materials needed for construction are well estimated. Labor estimates are based on schematic manufacturing plans. These plans, in the case of Designs A and B, are intended to be improved versions of plans developed for Tevatron and CBA magnets, respectively. For Design C, a plan was worked out directly from the design concept. All of the labor estimates represent an improvement over current practice. Where possible, comparisons with current practice were made. The labor estimates appear reasonable, given the assumption of improved tooling. Prototyping experience will show how to further refine these estimates, but at this pre-prototype stage, some costs are uncertain. Such cost uncertainty is accounted for in a detailed way in our contingency analysis, which is summarized below. A balanced view also requires discussion of possible cost savings; these are also briefly discussed below.

Contingency

Contingency on conventional construction is particularly difficult to estimate in the absence of a specific site. As mentioned, the cost estimate for conventional construction made here was based on the use of the median site, which has a mix of geological and topographical features representative to actual regions in the United States. The contingency was then estimated according to standard practice by assuming that the median site is an actual site.

Contingency on technical components was estimated by assessing the cost impact of partial failure of key assumptions or estimates. Items considered were: critical current density in the superconductor; ratio of physical aperture to magnetic aperture; head leak estimates; assembly labor estimates; unanticipated technical means needed to reach design performance; inadvertent neglect (at this stage) of a number of small items; unanticipated wastage of materials; and loss of assembly productivity due to material supply, quality or tooling problems and the like. Table II shows the cumulative result of these contingency estimates. The narrow range of cost estimates obtained leads us to conclude that the SSC can be developed from the most suitable of a variety of approaches rather than from a single approach.

Possible Cost Savings

In addition to treating possible cost increases due to the factors mentioned above, a balanced picture must consider the possibility that some of the assumptions made are overly conservative and that diligent optimization of the design during the R&D phase will result in lower costs. In terms of conventional construction, lower costs might result from the choice of a site more amenable to inexpensive tunneling techniques than the median site, the use of terrain following to reduce tunneling costs, or other optimization of conventional structures. Likewise, through steady improvement of the critical current density of commercially available superconductor (plus economies of production scale coupled with competitive pricing), through experience in magnet manufacture, and through optimization of accelerator system and component designs, savings on technical components are expected.

Research and Development

From the above discussion, it is clear that SSC performance objectives can be achieved. The Reference Designs Study has established cost estimates for the SSC that are valid under the assumption of a substantial R&D effort preceding actual construction. Given that the SSC is fundamentally feasible and that no radical departures in concept or technology are called for, this R&D effort will largely be an engineering task, aimed at optimized component and overall facility design and the experimental verification of projected performance of key systems, most importantly the superconducting magnets. The central R&D goals then are readily stated:

- Detailed engineering of candidate magnet types and key cryogenic system components, and verification of their performance projections.
- Establishment of optimized overall designs based on these magnets.
- Establishment of engineering solutions for other critical performance-related systems.

- Selection of a magnet type, followed by a detailed cost and performance demonstration including optimization of production and installation procedures.

The Reference Designs Study and the work preceding it, most importantly superconducting magnet R&D efforts at a modest level, have led to a clear perception of the critical issues and have allowed research teams responsible for particular design approaches to formulate initial concepts on which further efforts will build. Central to the pursuit of cost-effective designs are:

- development of small-aperture, low-heat-leak magnets of optimized length;
- reduction of materials, cryogenic-system, and labor costs;
- assurance of beam stability; and
- survey of available technologies and components for ensuring the reliability of a large and complex system.

In the envisioned approach to solving these problems and achieving the stated goals, the major fraction of the R&D will be directed towards superconducting magnet development; however, other parallel efforts are vitally important. In particular, a substantial fraction of the accelerator physics effort will directly support magnet R&D by providing guidelines and criteria to assess adequate field quality. Such accelerator physics R&D is discussed briefly below, after a short discussion of superconducting magnet R&D.

Magnet Technology Developments

The development of superconducting magnet technology for the SSC will involve both the development of alternative magnet designs and--during the initial stage--parallel generic superconductor R&D applicable to all magnet designs. Many smaller, hardware-oriented R&D tasks will also be carried out in parallel with the main ring magnet and superconductor R&D. For example, a number of special components must be developed, such as magnets in the experimental and utility insertions. Also, many operational aspects of large cryogenic systems can be studied at the Tevatron, and some components, such as cold valves, must be evalated and tested. Most critical in the area of vacuum design will be the study of gas desorption from cold surfaces induced by synchrotron radiation.

uperconductor Development

Superconductor development will be carried out in parallel with the initial stage of magnet development to minimize the amount of superconductor required to achieve the design field for a given aperture, and to arrive, at an early stage, at the optimum cable design. The relevant figures of merit are the critical current density at the design field and the copper-to-superconductor ratio. Critical current density will be increased by extending to large scale the successful small-scale production of highly homogeneous Nb-Ti and by improvements in the mechanical cabling process. Studies of quench propagation and the performance of quench protection systems in model magnets will allow the determination of a minimum safe copper-to-superconductor ratio and, it is anticipated, allow the use of passive quench protection. Because the magnitude of persistent current effects depends on filament size, the optimum approach for the correction of field errors due to these persistent currents will also be established during this superconductor R&D phase.

In addition to studies aimed at improving Nb-Ti, the potential of Nb_3Sn, now in pilot production, deserves vigorous pursuit. Nb_3Sn offers the possibility of operation at higher magnetic fields, up to perhaps 8 T, without significant increase in magnet cost per unit length. Consequently, for those magnet designs in which the field is conductor dominated, the ring circumference could be reduced for a given field level, yielding significant savings on tunneling costs. Use of Nb_3Sn for the interaction region quadrupoles and beam separation magnets would be beneficial either for reducing their size or for producing even tighter focusing at the crossing point.

Magnet Development

Initial magnet design efforts will concentrate on model magnets, beginning with the design and construction of short models and leading to the production of full-length models. Major emphasis will be on efficient use of superconductor and demonstration of the required field quality. Subsequently, low-heat-leak designs will be developed. As the magnet designs approach the final configuration and small numbers of full-length model magnets become available, careful measurements of heat loads will lead to refined specifications for the cryogenics system.

After demonstration of the basic performance objectives, final engineering designs will focus on optimum production methods and the development of the required tooling. At this stage, relevant R&D includes the use of larger billets of bulk superconductor, implementation of labor-saving procedures (automation, elimination of some intermediate tests, etc.), and development of efficient alignment methods and rapid, precision field measurement techniques in full-length magnets.

When enough prototype magnets of the selected type become available, quench protection will be investigated and repeated thermal cycling tests will be carried out to ensure that field-quality degradation does not occur. With a long string, about 1.5 km of prototype magnets, firm cost projections will be possible, and refined tests of system performance will be carried out. In particular, realistic operational tests of cryogenic and vacuum system performance, as well as quench protection tests will be possible.

Accelerator Physics Studies

The central tasks of SSC accelerator physics studies are to pursue self-consistent optimized designs, to assure beam stability, and to give proper considerations to relevant aspects of machine operation.

Design optimization begins with specifying and then verifying the feasibility of beam parameters that ensure achieving design luminosity with a minimum of stored beam (thus minimizing both synchrotron radiation power to the cryogenic system and stored beam energy). Information on achievable emittance, tolerable beam-beam interaction strength, beam lifetime, and the effect on particle motion of very strong focusing at the interaction points must be assessed and integrated.

Because duty factor is of prime importance to the user, alternative beam configurations, e.g., "quasi-coasting" beams, or closer bunch spacing must be explored. Ideally, the largest possible fraction of the circumference ought to be occupied by bending (dipole) magnets, but trade-off studies are required with respect to magnet aperture, field quality, and strength and number of correction elements.

The single most important accelerator physics task is the establishment of minimum required field quality by analytical methods, computer tracking studies, and experiments on existing machines. This may well determine the extent to which aperture reduction as a means of cost savings can be pursued. Without such guidelines, measurements of field quality of prototype magnets have no context.

Calculations of machine impedances and assurance of collective stability must proceed continually through the design phase. Most crucial are the investigation of techniques for maintaining small emittance, the establishment of the effects of RF noise, and the determination of the growth time of various coupled-bunch instabilities. The engineering design of feedback systems will be directly affected and guided by these considerations.

Most of the required methods and procedures are in hand, at least in principle. Urgently needed are more effective organization and coordination of relevant computer codes to actually perform the many consecutive calculations--involving a huge number of interrelated parameters--that are required in the process of optimization.

Progress beyond today's state of the art is expected in the area of nonlinear dynamics, required to deal with the beam-beam interaction and the effects of imperfect magnetic fields. A three-pronged approach is envisioned: improved algorithms; the use of dedicated processors; and experiments on existing machines, such as the Tevatron or the S$\bar{p}$pS.

Possible Plan for Realization of the SSC

Steps leading to realization of the SSC may be grouped into phases. The model we have used includes three phases: Studies of feasibility, a survey of available technical options, and palnning of R&D--referred to as Phase 0; an R&D and design phase leading to a specific proposal for a facility--referred to as Phase I; and a construction phase--referred to as Phase II. The actual phasing of the project should be such that the SSC can serve the scientific need for access to the TeV mass domain with minimum delay.

Phase 0

In this, the current phase of activity, concentrated efforts are being made to detail the technical and economic feasibility of the SSC project and to survey the technical options. Included in these efforts are preliminary studies of various possible superconducting magnet designs, preliminary technical component and system design activities, and the Reference Designs Study, whose work is described in this document. As part of this study, an attempt has been made to expand and codify the preliminary technical systems studies, to estimate the probable cost of the project in a systematic way, and to enumerate the R&D goals that must be met prior to the start of SSC construction. An R&D and management plan detailing the means to achieve these goals is also a part of this preliminary phase, and is being formulated by the R&D manager. It is expected to be available in June 1984.

An SSC working group was also established at DOE headquarters under the direction of L. E. Temple, Jr., to assist the Division of High Energy Physics in managing SSC activities.

Phase I

We expect that primary activities in Phase I will involve carrying out the R&D plan and producing a construction proposal. This construction proposal will contain a complete and optimized technical design, a detailed cost estimate (based on the R&D results and a complete study of the civil construction requirements), and a time-ordered plan for carrying out the construction and assembly of the SSC. Demonstration of proposed mass-production techniques and verification of cost predictions for major technical components would be important parts of Phase I.

Formation of an interim management organization to guide the R&D effort is now under way, and a contractor for the anticipated R&D has already been selected. This phase of the project is envisioned to have a 3-year duration; it could thus be completed in time for consideration of the SSC in the FY 1988 Federal budget.

Phase II

Phase II would include the construction of the SSC. In this study, we have assumed a six-year construction period, which would lead to completion in early 1994 if construction were to begin in FY 1988. The optimum duration of the construction period should itself be an object of study in Phase I. It will depend on many factors, such as the detailed scope of the facility that is ultimately proposed, the technical means devised for its construction, and the spending pattern needed. Finding ways for minimizing the delay between start of construction and first use for physics research must be given great emphasis.

Based on the assumptions above, initial operation of the SSC could begin in FY 1994. This timetable is compatible with the target date in the mid 1990s for an operational SSC and will thus ensure continued scientific progress of the U.S. high energy physics program.

Summary

In the Reference Designs Study we have shown that the basic principles of design used successfully for existing accelerators can be conservatively extended to a proton-proton collider having the SSC primary specifications of energy and luminosity. Furthermore, each of the three reference magnet styles studied could serve as the foundation for an SSC facility meeting these specifications. A vigorous R&D program of approximately three years duration will be required to refine the cost estimates for the magnets, to determine their actual performance, to determine their manufacturability and reliability, and to develop cost-effective methods for their assembly and quality assurance. It is anticipated that the magnet options can be narrowed to a single design during an early phase of the R&D program. An important R&D goal will be to produce, using mass-production methods, a significant number of magnets of the chosen style. These magnets would then be thoroughly tested under conditions simulating actual collider operations.

Taking into account the range of computed costs for facilities based on the three magnet styles, the current state of knowledge about the various important cost factors, and the normal contingencies associated with similar technical systems, it is concluded that the SSC facility described herein would cost between $2.70 billion and $3.05 billion (FY 1984 dollars); with intense R&D efforts, even lower costs should result.

Reference

1) U.S. Dept. of Energy, Division of High Energy Physics, Washington, D.C. 20545. Attn: J. Lewis.

Maximum beam energy [TeV]	20
Injection energy [TeV]	1
Maximum luminosity [$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	10^{33}
Maximum number of interactions per bunch crossing (at max. luminosity)	10
Number of interaction regions	6 (4 initially developed)

Table I Primary SSC reference design objectives

	Design A (90 km)	Design B (113 km)	Design C (164 km)	Common Systems
Conventional Facilities				
Central Lab. Facilities				86.0
Injector Facilities				39.6
Experimental Facilities				87.4
Collider Facilities	398.7	496.1	733.5	
Technical Facilities				
Injector - Linac/LEB/HEB				147.2
Collider Magnets	783.0	955.3	357.5	
Collider Cryogenics	123.9	115.9	158.2	
Collider, Other				96.8
AE/CM + EDI	255.5	287.0	271.7	
Project Management and Equipment				154.5
Common Systems	611.5	611.5	611.5	611.5
Subtotal	2,172.6	2,465.8	2,132.4	
Contingency	552.3	589.0	567.2	
Total	2,724.9	3,054.8	2,699.6	

Table II Estimated costs, including contingencies, for reference designs A, B and C (in FY 1984 M$)