SSCL-Preprint-135

# Superconducting Super Collider Laboratory

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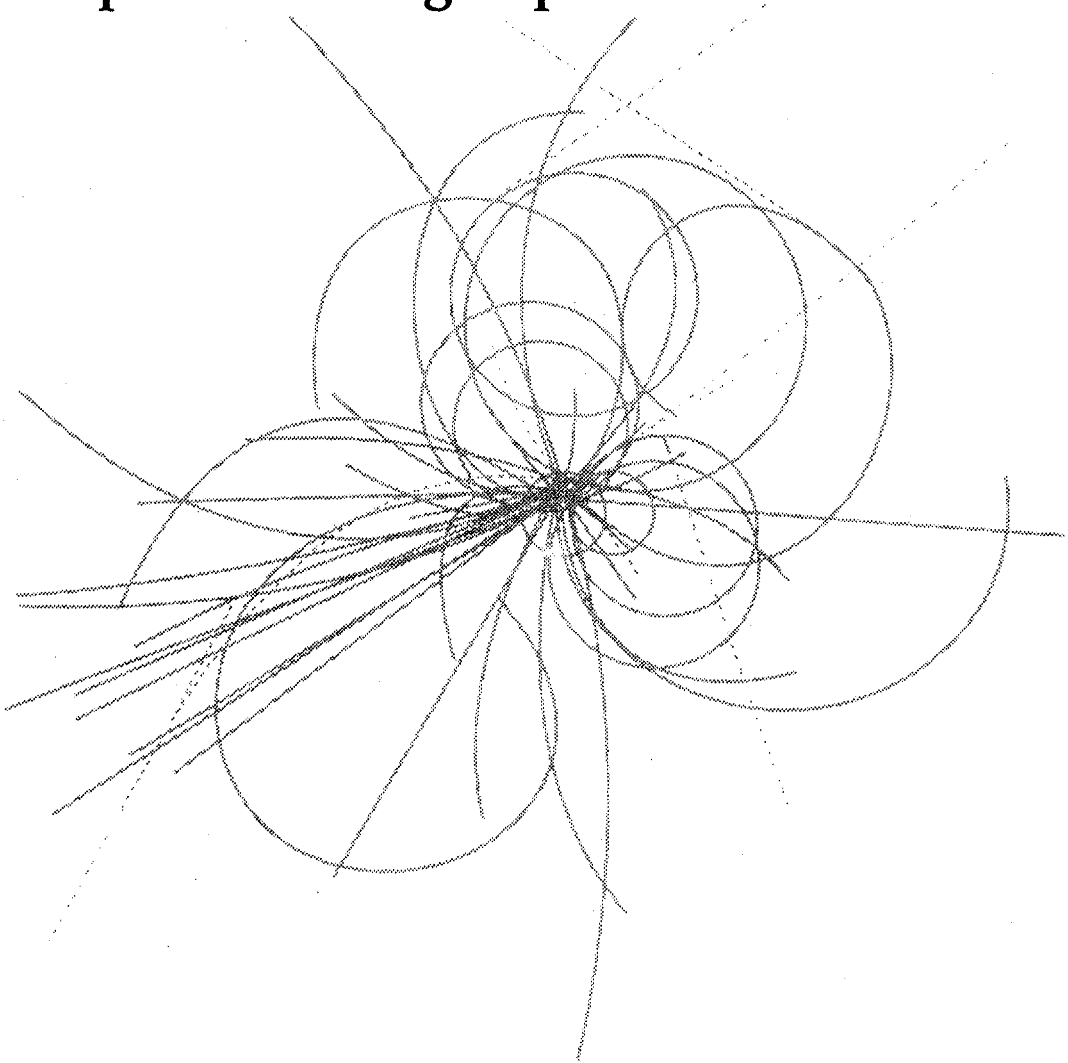

# Status of the SSC

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G. Dugan

Superconducting Super Collider Laboratory†
2550 Beckleymeade Avenue
Dallas, Texas 75237

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# STATUS OF THE SSC

G. Dugan

Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, Texas 75237, USA

## ABSTRACT

The Superconducting Super Collider (SSC) is a proton-proton colliding beam accelerator which, when completed, will provide collision energies of 40 TeV in the center-of-mass, at a luminosity of $10^{33}$/cm$^2$/sec. This paper will describe the current status of the design and construction of the project.

## 1 INTRODUCTION

The accelerator complex will include 4 injector accelerators which will provide 2 TeV proton beams. These beams will be injected into two superconducting synchrotrons which will accelerate them to an energy of 20 TeV. The proton beams will collide at four locations around the rings. The complex, when completed, will be the world's largest scientific instrument and will provide a unique tool of unparalleled scope for the study of high energy physics. The Superconducting Super Collider Laboratory (SSCL) is located in the state of Texas, about 30 miles south of Dallas.

The principal design parameters of the SSC are shown in table 1. One of the major challenges is the relatively small value of the design beam transverse emittance. Achievement of this emittance will require great care in the development and preservation of the brightness of the beam throughout the injector complex, and during the injection and acceleration cycles in the main SSC rings. Additional challenges in this machine are related to the substantial amount of stored energy in the beam (100 times greater than in existing superconducting high energy accelerators) and the need to cope with significant amounts of synchrotron radiation from the proton beam incident on the cold bore tube.

| Parameter | Design Goal | Units |
|---|---|---|
| Initial luminosity | $10^{33}$ | cm$^{-2}$sec$^{-1}$ |
| Center-of-mass energy | 40 | TeV |
| Bunch spacing | 5 | m |
| Circumference | 87120 | m |
| Particles/bunch | 0.75 | $10^{10}$ |
| Number of bunches | 17424 | |
| Total number of particles | 1.3 | $10^{14}$ |
| Rotation frequency | 3.441 | kHz |
| Collision frequency | 60 | MHz |
| Cycle time | 24 | hours |
| RMS normalized transverse emittance | 1 | π mm-mrad |
| Beta at IP | 0.5 | m |
| Beam rms transverse size at IP | 5 | μm |
| Beam-beam tune shift (total) | .007 | |
| Synchrotron. Radiation Power/ring | 8.75 | kW |
| Availability | 80% | Scheduled time |
| Beam Stored Energy/ring | 400 | MJoule |

*Table 1:SSC Parameters*

## 2 ACCELERATOR SYSTEMS AND COMPONENTS

The injector complex includes a 600 MeV Linac, a 12 GeV/c rapid-cycling Low-Energy Booster, a 200 GeV/c Medium Energy Booster, and a 2 TeV superconducting High Energy Booster.

### 2.1 Linac

Beam (in the form of H$^-$ ions) will be delivered to the first element of the Linac (a 2.5 MeV, 428 MHz RFQ) from a 35 keV magnetron ion source. Beam will be accelerated in the RFQ and injected into a 428 MHz drift-tube structure (DTL) which will accelerate the beam to 70 MeV. Both the RFQ and the DTL will be powered by 4 MW klystrons. The DTL will contain 14 quadrupoles for transverse focusing.

Beam from the DTL will be matched into a side-coupled linac (SCL) operating at 1284 MHz. The side-coupled linac will accelerate the beam to 600 MeV. It will be

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powered by 10 20 MW klystrons, and it will contain 61 quadrupoles for transverse focusing. Subsequent to exit from the SCL, the beam will be transported to and injected into the Low Energy Booster (LEB). The total length of the Linac will be 146 m. It will cycle at 10 Hz.

The principal technical challenge for the Linac is the preservation of the tight transverse emittance specification. The output rms normalized transverse emittance is required to be < 0.3 $\pi$ mm-mrad, at a peak current of 25 ma. This has required care in the design of the matching sections between the ion source and the RFQ, the RFQ and the DTL, and the DTL and the SCL. The details of the SCL lattice design are also important.

A prototype magnetron ion source has been assembled and tested at SSCL. The rms normalized transverse emittance obtained from the source has been measured to be .12 $\pi$ mm-mrad at 30 ma.

It is currently planned that the SCL rf cavities will be fabricated in China.

## 2.2 Low Energy Booster (LEB)

$H^-$ ions from the Linac will be charge-exchange injected into the LEB at 600 MeV. The LEB will be a rapid-cycling (10 Hz) synchrotron with superperiodicity 3 and a circumference of 570 m. The lattice of the machine will be configured to place the transition gamma (22.15) well above the operating range of the machine. The design betatron tunes are 11.65(H) and 11.60(V). The rf system is required to tune over a substantial frequency range (47.5-59.8 MHz); this is planned to be achieved through the use of perpendicularly biased ferrites. The synchrotron's main magnetic fields will be provided by conventional resistive magnets: 48 4-m dipoles and 90 0.6–0.7-m quadrupoles.

The principal technical design challenge in the LEB is the preservation of the beam transverse emittance during the low energy end of the machine's accelerating cycle. This will be challenging because of the substantial space-charge tune spread. The output rms normalized transverse emittance is required to be < 0.6 $\pi$ mm-mrad, at an intensity of $10^{10}$ protons/bunch. If the baseline design fails to meet the emittance growth budget, the principal remedy is the provision for increasing the injection energy: the civil construction of the Linac tunnel will allow a future upgrade to a 1 GeV Linac. Another option under consideration is the use of a higher harmonic rf system to reduce the peak bunch current.

Other technical challenges include preservation of the emittance during acceleration (facilitated by the lattice design, which avoids transition); compensation for eddy current sextupole fields during ramping; and the control of transverse and longitudinal multibunch instabilities.

The LEB main magnets are currently planned to be fabricated at BINP in Novosibirsk, Russia.

## 2.3 Medium Energy Booster (MEB)

The MEB will be a large, slow-cycling synchrotron which will accept 11.1 GeV beam from the LEB and will accelerate it to 200 GeV/c. The circumference of the MEB will be 3.96 km; it will cycle with a period of about 8 sec, and will have betatron tunes near 25.4. Transition crossing in this machine will occur at an energy near 25 GeV. The machine will contain a conventional 60 MHz rf system with a peak voltage of 2.1 MV. The accelerator's main magnetic fields will be provided by 340 6.5-m dipoles and 206 2.4-m quadrupoles; all these magnets will be resistive. Substantial power systems for the magnets will be required: the dipoles, for example, require 16 5200-A, 16-kV power supplies.

The MEB will deliver fast-extracted 200 GeV/c-beam to the High Energy Booster (HEB). In addition, it will deliver slow-extracted 200 GeV/c beam to experimental areas for use in producing test beams for SSC detector calibration.

As in the case of the LEB, one of the technical challenges in the MEB is transverse emittance preservation during the lowest energy part of the operating cycle. The output rms normalized transverse emittance is required to be < 0.7 $\pi$ mm-mrad, at an intensity of $10^{10}$ protons/bunch. The issue in this case is principally the quality of the machine's magnetic field. This implies care in the design of the magnets to limit the influence of remnant fields at minimum magnet excitation. An additional technical challenge involves transition crossing, which must be performed with a minimum of transverse emittance growth.

Prototypes for the MEB dipoles and quadrupoles are currently planned to be constructed at Fermilab.

## 2.4 High Energy Booster (HEB)

The HEB will be the last accelerator in the injector chain. It will receive 200 GeV/c beam from the MEB and will accelerate it to 2 TeV for injection into the Collider. Because of its high operating energy, it is most economically realized as a superconducting accelerator.

This machine will be a slow-cycling synchrotron, with a circumference of 10.8 km, located in a tunnel whose average depth is 46 m. The machine will operate with a bipolar cycle of duration 515 sec. The basic lattice structure will be 90° F0D0 cells, with two dipoles, a quadrupole and a spool per half-cell. The design betatron tunes are 39.4(H) and 38.4(V). There will be six straight sections, with dispersion suppressors at each end. The straight sections will be used for both clockwise and counterclockwise injection, extraction and abort systems. The principal superconducting magnet systems will include 512 12.3-m dipoles (peak field 6.7 T) and 318 1.6-m quadrupoles (peak gradient 184 T/m). Both dipoles and quadrupoles will have 50-mm apertures. This is required both to provide sufficient dynamic aperture at injection and to maintain the option (not implemented in the baseline design) for slow-extracted 2 TeV beam to the test beam areas. The superconducting systems will be cooled to cryogenic operating temperatures using 2 LHe plants, each providing about 6 kW of cooling at 4°K and 7 kW of cooling at 20°K. The machine will have a conventional 60 MHz rf system.

As in the other machines in the injector chain, one of the principal technical challenges in the HEB is the preservation of the beam's transverse emittance during the operating cycle. The output rms normalized transverse emittance is required to be < 0.8 $\pi$ mm-mrad, at an intensity of $10^{10}$ protons/bunch. As noted above, this challenge is addressed by providing a sufficient coil diameter (50 mm) for the superconducting magnets.

A further technical challenge is the bipolar cycle for the machine. Such a cycle is unprecedented for a machine of this type.

The HEB dipoles are currently planned to be fabricated by Westinghouse Electric Corporation. Model magnets are scheduled for mid-1993, and prototypes for mid-1995. Delivery of production magnets is scheduled to start in mid-1996. Design of the HEB quadrupole cold mass is underway at Saclay. This cold mass design will be combined with a cryostat design to be implemented by SSCL, leading to a build-to-print contract for the HEB quadrupoles to be awarded in 1994. Delivery of production quadrupoles is scheduled to start in mid-1996.

One of the major recent issues in the design of the HEB superconducting magnets is related to the relatively large ramp-rate dependence of the quench current seen in recent Collider model dipole magnets[(2),(3)]. This problem must be solved before HEB magnets can be produced in quantity. A program of attack on this problem is currently underway as a joint effort between SSCL and the HEB dipole and quadrupole magnet subcontractors.

### 2.5 Collider (SSC)

The Collider will be a pair of superconducting synchrotrons which will also function as storage rings at their top energy. The two rings will share a common circumference of about 87 km and will be located one 90 cm above the other. Injection from the HEB will occur at 2 TeV. Many of the machine's basic parameters are listed in table 1.

The Collider tunnel will be located at a depth which varies from 15 to 60 m, in a mixture of Austin chalk, Eagle Ford shale and Taylor marl. The ring plane will be tilted by an angle of 0.19° with respect to a normal to the average direction of gravity. The elevation and tilt of the ring have been chosen to optimize the geotechnical features of the tunnel.

The basic geometry of the Collider is that of two arcs (north and south), separated by two long straight sections (east and west). Each straight section is divided into a utility region and a pair of intersection regions. In order to provide the most stable geotechnical environment for the foundations of the major detector halls, they will be located at the east interaction regions.

2.5.1 <u>Collider arcs</u> The basic lattice in the arcs is a 90° F0D0 cell structure; each half-cell will contain 5 dipoles, one quadrupole and one spool piece. The design betatron tunes of the machine are 124.28(H), and 123.28(V). There will be 7634 15-m dipoles (peak field 6.7 T), 104 13-m dipoles, and 1564 5.2-m quadrupoles (peak gradient 204 T/m) in the arcs. The required cryogens for the Collider systems are provided by 10 LHe plants, each providing about 6.5 kW of cooling at 4°K and 14.4 kW of cooling at 20°K. The associated power systems for the magnets consist of both ramping and holding supplies capable of 7 kA. The cryogenic plants, main power supplies, and auxiliary services will be located at 10 service areas distributed around the ring. Extensive quench protection and energy dump systems, required to protect the superconducting magnets, will be located in niches below ground at the tunnel depth.

Dynamic aperture requirements at the injection energy can be satisfied with dipoles whose inner coil diameter is 50 mm, and quadrupoles whose inner coil diameter is 40 mm, together with a straightforward correction system in the spool pieces. The spool piece correctors will consist of correction dipoles, quadrupoles, sextupoles, octupoles, and decapoles. The sextupole system will be used to compensate for the persistent current sextupole in the superconducting dipoles. The need for additional decapole and octupole correctors at mid-half-cell locations is under review. Coupling control will be provided by a system of skew quadrupoles located both in the arcs and in the straight sections. There will be 104 empty cryostats in the arcs which can be used for the placement of additional devices whose need is yet to be specified (e.g., devices for the preservation of beam polarization).

Plans for the construction of the arc dipole and quadrupole magnets are well underway. The first prototype 50 mm bore full-length dipole magnets have been fabricated at Fermilab and Brookhaven in collaboration with magnet subcontractors (General Dynamics and Westinghouse): these magnets have been quite successful[(1),(2)] except for the ramp-rate dependence problem[(2),(3)] noted above under the discussion of the HEB.

The multipole content of the magnets[(3),(4)] is well within the requirements for the machine. Additionally, the variation of the sextupole and decapole with current is as expected from a model of the persistent current magnetization for most of the magnets. However, several of the magnets with the largest dependence of quench current on ramp rate also showed evidence of anomalous behavior in several of the multipoles, which may be attributable to cable eddy currents[(5)]. Work is underway to provide a better understanding of this phenomenon.

The final design of the Collider arc dipole production magnets will be completed with the existing leader-follower contract with General Dynamics and Westinghouse, respectively, ending in 1994. The full production contract will be let subsequently to one of these vendors.

Full-length prototypes of the 40 mm bore arc quadrupole cold mass have been fabricated and tested at LBL, installed in cryostats at SSCL, and re-tested at BNL. These magnets have shown a poorer training performance than the dipoles. The arc quadrupole development contract has been awarded to Babcock and Wilcox. The Collider spool piece development contract, based primarily on a performance specification, has recently gone out for bid. Installation of the Collider components and associated systems is planned to be done by an industrial firm; several vendors are currently involved in planning for this. Other major procurements anticipated in the near future include the cryogenic plants and the main power supply systems.

2.5.2. Collider interaction regions The interaction regions of the Collider will be located in pairs, two on the east and two on the west.

Those on the east will be provided with optical systems capable of reaching a $\beta^*$ of 0.5 m at the crossing point. The beams will cross at at angle of roughly 75 μrad. The final focus will be accomplished using a quadrupole triplet located roughly 20 m from the interaction point. The triplet quadrupoles will be roughly 15 m long, have a 5 cm bore, develop a gradient of 190 T/m, operate at the standard Collider operating temperature (4°K) and use cross-flow cooling to cope with the substantial (roughly 50 watts) of power deposited by secondary reaction products from the interaction point. The dynamic aperture of the Collider during colliding-beam operation at full energy is expected to be dominated by the the peak β (9 km) region of the triplet. Transition from the injection optics ($\beta^* = 8$ m) to collision optics will be possible independently for each ring.

The west interaction regions, at which smaller, low-luminosity experiments are envisaged, have not received detail design attention to date.

It is currently planned to fabricate many of the special magnets required for the interaction regions at the SSCL. Some of the magnets may be subcontracted to one or more of the arc magnet vendors.

2.5.3 Collider utility regions The west utility region will be used for injection into both the top and bottom rings, abort from both the top and bottom rings, for the Collider 360 MHZ rf system, and for beam scraper and collimator systems. The utility region lattice will contain primarily 5 cm bore quadrupoles. A prototype 5 cm bore short quadrupole magnet has been designed, fabricated and tested at SSCL. It has shown good quench current performance.

The detailed design of the west utility has nearly been completed; the current design has a number of improved features over the baseline design. One of the improvements has been in the flexibility and reliability of the abort system. The configuration of the abort kickers, Lambertsons, and related shielding has been altered to make the system much more fault-tolerant, particularly to abort kicker prefires. The rf system design has been re-examined, based on the use of single-cell cavities rather than the baseline 5-cell cavity design. The injection systems, and the transfer lines from the HEB to the Collider, have also been reoptimized.

In the present design, the east utility region does not contain any special accelerator systems.

2.5.4 Collider vacuum The SSC will be the first proton accelerator for which the energy is high enough that the phenomenon of synchrotron radiation becomes an important design issue. The cryogenic systems have been designed to handle the synchrotron radiation power which is incident on the cold bore tube. However, photodesorption of hydrogen from the cold bore tube by the synchrotron radiation, and the consequences for the bore tube vacuum, are also important considerations.

Although some measurements have been made at cryogenic temperatures, and much information is available at room temperature from experience at electron synchrotrons, a full understanding of the photodesorption process in the SSC environment is not yet at hand. A program of measurements aimed at an understanding of the situation from a fundamental point of view, together with experiments using electron synchrotron radiation in an environment similar to that of the SSC, is being carried out by SSCL in collaboration with the University of Texas at Arlington and BINP in Novosibirsk.

Since there is a significant probability that the problem can only be solved by the use of a synchrotron radiation intercept inside the bore tube (a liner), R&D on the design of a liner for the Collider is also being pursued in parallel.

## 3 CIVIL CONSTRUCTION

The first major civil construction for the SSC project has begun at the site of one of the collider service areas, called N15. At this site, the laboratory has completed several buildings during the past two years. The largest building is the Magnet Development Laboratory (MDL), an 82,000 ft$^2$ building which will be used for the fabrication of superconducting magnets. Adjacent to the MDL, the buildings which house the cryogenic facilities for the N15 sector of the collider, and the Accelerator Systems String Test, have also been completed. Nearby, the Magnet Test Laboratory is now under construction; when completed and outfitted near the end of this year, it will be the site at which cold tests of vendor and SSCL produced superconducting magnets will be carried out.

Adjacent to the N15 cryogenic buildings, an oval-shaped (60 ft by 30 ft) vertical shaft has been excavated down to the level of the collider tunnel (about 200 ft depth at this location). This is the first of the 5 magnet delivery shafts, which will be spaced around the collider ring and used to lower completed Collider components into the tunnel for installation. Basic shaft excavation will be completed in September of this year; at that point, the tunnel boring machine to be used for the first horizontal tunnel drive (from N15 to N20) will be lowered into the shaft to begin construction of the tunnel.

Two other vertical shafts, one for utility access to the tunnel, and one for personnel access and ventilation, are also under construction at N15. As of this writing, contracts have been awarded, or bids have been received, for the entire north arc of the Collider. Contracts have also been awarded for the Linac tunnel and service buildings.

Design is in progress for all of the south arc of the Collider, most of the Collider service buildings, and the Low Energy Booster tunnel and service buildings. It is expected that by the end of 1992, all of the north arc of the Collider will be under construction.

## 4 ACCELERATOR SYSTEMS STRING TEST

The Accelerator Systems String Test [6] (ASST) will be a full system test of a prototype Collider half-cell.

The test will utilize a 600 W refrigerator, a prototype Collider power supply, and a full complement of Collider-prototypical quench protection and sensor data acquisition systems. The dipole magnets in the string are full length, 50 mm bore prototype Collider dipoles which have been industrially fabricated. The quadrupole is one of the full length protoptypes described above under the Collider. The spool pieces, which provide power and cryogenic feed and turnaround, have been fabricated in industry.

The goal of the first phase of the test is to achieve an operational current level (6500 A) in the string to demonstrate the basic feasibility of the system. All components of the string were completed, delivered to SSCL, and installed in the ASST enclosure at the N15 site, by the end of May of this year. During June, all interconnects were completed, and all system insulating vacuum, cryogenic, and high power connections, were completed. Vacuum and pressure testing was successfully carried out, and in late June cryogens were introduced into the string. The string cold mass reached operating (superconducting) temperature in early July. As of this writing, the final checkout of the electrical and quench protection systems is well underway. Low power tests are expected to begin in late July, with achievement of the goal of the first phase expected in August, well ahead of the October 1 scheduled date for completion.

Subsequent phases of string operation will involve heat leak measurements, quench propagation measurements, power supply regulation studies, and magnet vibration studies. Modifications and additions to the string are planned to expand it to a full pair of cells which will allow additional tests.

## 5 CONCLUSION

The present long-range schedule for the SSC project can be logically divided into two general activities which both culminate six months before the end of the project. These two activities are the fabrication, installation and commissioning of the injectors; and the fabrication, installation, and commissioning of all cryogenic and electrical systems of the Collider, without beam.

The first activity includes completion and commissioning of the Linac (1995), followed by the Low Energy Booster (1996) and the Medium Energy Booster (1997). The resistive accelerator complex will then be operated during the period from 1997 to near the end of 1998 to provide test beams at 200 GeV/c to calibrate various detector subsystems for the Collider detectors. Meanwhile, the High Energy Booster will be completed, and commissioned in early 1999.

The second activity will proceed in parallel. As the various sectors of the Collider tunnel are completed, arriving components from the several subcontractor vendors will be installed in the tunnel sectors. This will be a carefully choreographed exercise in which tunnel construction, component completion, and installation, must be properly phased together. When a complete sector has been installed, the magnet strings will be cooled down using the cryogenic plants on the surface, and energized. This will allow many of the technical systems to be thoroughly exercised well in advance of when they will be required for beam. This process will culminate in early 1999, at the same time as completion of the beam commissioning of the High Energy Booster.

During the last six months of the project, the Collider, which will have had all of its cryogenic and electrical systems exercised without beam, will be commissioned using beam from the High Energy Booster. This commissioning activity will end when the Collider is able to provide proton-proton collisions with sufficient energy and luminosity at the interaction points that the experimental detectors can begin a useful physics program. Evolution of the machine performance from this point forward toward the design goals of the SSC will be done in collaboration with the experiments in order to maximize the physics output of the program.

## 6 ACKNOWLEDGEMENTS

The accomplishments described in this paper are the result of the collaborative efforts of the staff of the SSC Laboratory, several other national laboratories (Fermilab, BNL and LBL), and SSCL subcontractor industrial firms (principally General Dynamics and Westinghouse).

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