THE SUPERCONDUCTING SUPER COLLIDER

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The SSC (Superconducting Super Collider) is a 20 on 20 TeV proton-proton collider using two rings of superconducting magnets 87 km in circumference. Construction of the SSC is planned for completion prior to the end of this decade. In its initial configuration, the SSC will support four interaction regions (IRs). SSC design parameters listed in Table I are essentially unchanged since 1986.

The SSC Laboratory has now been in Texas for a year and a half. During this time, high priority has been given to determining the final collider lattice and geometry, evaluating and selecting the collider dipole aperture (5 cm), and developing an overall site-specific conceptual design, executive summary, and revised cost estimate.[1,2] Dipole magnet prototypes with 4-cm aperture continue to be built and tested. Quadropole test results are encouraging. A 5-cm dipole design has been initiated and the 5-cm R&D program has begun.

Layout

The exact collider ring geometry, location, and orientation has been specified so that "footprint" coordinates (land boundaries) needed for land acquisition could be made public and the land acquisition process initiated. An Injector layout has been established and the West Injector-Campus Area determined as well as a smaller East Campus area for the IRs on that side of the ring. First land acquisition by the State of Texas is expected this summer and the environmental impact record of decision later this year.

Figure 1 shows the siting of the SSC. The layout of the collider rings have twofold symmetry with a pair of IRs on the west and on the east (total of four IRs). Provision has been made to allow for four additional IRs through the implementation of inner bypass regions.

Adjacent to the IRs are utility straight sections. On the west, the utility straight is used for transferal of the beam from the HEB to the two counter rotating collider rings and, for beam abort systems, form these rings. On the east, use of the utility straight is as yet unspecified. The two utility IRs are connected to the north and south by long arc regions, each 35 km of repetitive half-cells with a total of 10 service/refrigerator areas and five 55-ft shafts for magnet installation.

The tunnel is located about 50 meters below the surface in a combination of chalk, marl, and shale, and is at a slight 0.17 degree dip to level.

The injector (Fig. 2 - Table II) has a linac followed by three circular accelerators or booster rings (low, medium, and high energy -- LEB, MEB, HEB). The HEB is tangent to the collider at the utility section and 17 meters above it. The MEB and LEB are closer to the surface. Initially, slow extraction beam will be provided from the MEB for test beam operations. Provision has been made to allow for implementation of extraction from the HEB as well.

Booster energies have been set by the requirements of collider injection aperture (to be discussed below). A conservative approach calls for 2-TeV HEB peak energy. The HEB is a superconducting ring. The present plan is to operate it with excitation reversal on every other beam pulse so that the two collider rings are loaded alternately. Every effort is being made to try to use collider style magnets in the HEB in order to minimize development. An R&D program is under way to see if 2-1/2 μ filaments could be used here in order to reduce hysteresis and persistent current effects for these magnets and thus reduce refrigeration requirements.

The MEB is a conventional magnet accelerator. Presently the intent is to use designs in development for the Fermi Main Injector for much of this accelerator. Beam passes through transition in the MEB, and we must assure ourselves that potential emittance dilution is not a problem. Long transfer lines connect the MEB to the bipolar HEB. The MEB will have a resonant extraction system to provide beam to the test beam areas.

The test beam areas will have three target and secondary beam calibration areas. Primary beams with intensities of 5×10^{11}/sec will be used to provide 100 Hz lepton rates of about 100 Gev and 10^7/sec hadron rates at about 50 Gev. The area design will be carried out so that at a later time the beamline, target areas, and secondary lines can be upgraded to 2 TeV with extraction from the HEB.

The LEB is a 10-Hz fast cycling accelerator operating to 12 GeV/c. It is desirable for it to be designed with no transition crossing and with as small a circumference as feasible so as to reduce injection space-charge tune shift. These are competing restraints and have driven the design to a very strongly focused lattice. The LEB has multi-turn H^- injection and semi-adiabatic capture. The LEB, MEB, HEB all operate at 60 MHz $f_{rf} = \infty$ (5 meter bucket spacing). At this time the LEB design is not optimized as will be discussed below.

The linac is a 600-MeV (K.E.) H^- drift tube and side-coupled structure. Transition between the DTL and CCL takes place at 70 MeV. Frequencies of the DTL and CCL are 428 MHz and 1284 MHz, respectively. Normalized emittance out of the linac is designed for 0.21π mm-mr (rms). The requirement is for less than $0.5\pi \times 10^{-6}$m.

Extreme care will need to be taken at all stages of the accelerator chain in order to assure emittance for collider operation of $1\pi \times 10^{-6}$ at intensities of $3/4 \times10^{10}$ per bunch. Not reaching this emittance goal would mean higher bunch intensities and more synchroton radiation, and thus refrigeration would be required to meet the design luminosity.

Design optimization for the injector will continue, especially in the areas of LEB and MEB. At present the LEB gamma T (14.5) is too close to the extraction gamma (12.8). Synchronization between LEB and MEB is awkward, and the synchronized frequency in the LEB drops below 60 Hz as peak excitation and transfer time is reached.

In the MEB, gamma T at 15.9 is also too close to injection gamma (12.8). This can be easily changed by raising the phase advance per cell from 60 to 90 degrees.

Along with increasing the rf voltage, LEB design options include changing the lattice for higher gamma T, transferring the beam at a lower energy, or finding a way to manipulate gamma T via an imaginary gamma T lattice or by programming gamma T as extraction time is needed. These approaches are all under evaluation. The basic coordinate layouts must be finalized for construction design by early in '91.

Colliding beam requirements that do not put heavy demands on the bunch intensity required from the injector though emittance requirements are state-of-the-art ($1\pi \times 10^{-6}$ mm-mr). Although calibration test beam requirements do not need appreciable intensity, it seems important in the design of the injectors that care is taken not to foreclose any probable future uses by building in performance bottlenecks that could be easily corrected in this design phase. To this end an arbitrary secondary requirement has been placed on the injectors that their design be consistent with the possibility of achieving intensities of 5×10^{10} per bunch at $4\pi \times 10^{-6}$ m normalized rms emittance It is principally this secondary requirement which makes transition crossing in the MEB and the aperture of the HEB important considerations.

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Luminosity

The potential of a future luminosity upgrade to the collider also dictates the prudence of injector design with performance margin. Luminosity of 1.7×10^{34} can be achieved in principle with bunch intensities of 3×10^{10}, emittance of $1.5\pi \times 10^{-6}$ m rms and no other changes except increased refrigeration. With improved beta optics, this luminosity is possible with less intensity increase.

Figure 3 indicates the region of ultimate luminosity that is in principal realizable with the limitations of long-range and head-on beam-beam tune shift on the one hand, and head-on beam-beam tune shift and synchroton radiation on the other hand. The amount of synchroton power chosen (0.4 watt/meter) is four times our present specification .

In order to have confidence that such luminosities are achievable, issues such as synchroton light intercepts, vacuum desorption problems, and gas scattering must be addressed as well as beam instability control. A thorough analysis of beam loss mechanisms and of energy deposition in the vicinity of the IRs, scrapers, and from gas scattering must be carried out to understand both heating, quench problems, and radiation damage to the magnets and local environs.

Collider Aperture and Simulations

The SSC collider aperture and related injection energy and collider cell length have undergone extensive study in order to assure a conservative dynamics design.[3] The goal here is to make the operation and installation of the accelerator as uncritical as possible and to try to assure a straight forward commissioning program insofar as foreseen difficulties can be addressed. The challenges of the SSC lie in its great size and needed engineering reliability and in the unforeseen with its twenty times scale increase over existing proton accelerators. Our knowledge of, and ability to predict, dynamical behavior in real accelerators is not sufficiently understood for us to put too fine a line on the choice of aperture that is sufficient. Simulation design tools are not the real world; adjustments that may seem easy in a computer when looking at single particles need not be so transparent during real commissioning. Correction and magnet sorting schemes are best if they can be kept as simple as possible or need not be done at all.

Cell length, injection energy, and aperture all enter into the aperture equation. For example, the chromaticity $\Delta\xi=\langle b_2\beta D\rangle$ was 3400 for the original conceptual design report (CDR). This implied a sextupole corrector setting accuracy of 0.15% to keep the chromiticity to 5 units. This would need to be done dynamically to compensate for the persistent current b_2 and its possibly different decay rates. By changing the half-cell length from 114 m to 90 m, the injection energy from 1 to 2 Tev, and the magnet aperture from 4 to 5 cm, we have decreased $\Delta\xi$ by a factor of 8 or $\Delta\xi \approx 425$, whereas the natural chromiticity is about ≈ 173. This comes about because β scales like L, and D, the dispersion, scales like L^2, yielding β D 1/2 of the previous value. The persistent current sextupole b_2 goes from -8.44 (units of 10^{-4} at 1 c.m.) to -3.29 in going from 1 to 2 Tev and to -2.11 in going to 5 cm at 2 Tev. Thus b_2 becomes 1/4 of the initial value.

With these changes we believe that effects due to persistent current and its time variations should be manageable. The expected persistent current value of b_2 is -2.1 units. By comparison, construction errors have an rms value of 1.1 units relative to construction errors. Expected variations in p.c.b_2 of 20% magnetization variation (0.42 units), 1°K temperature variation (0.42 units) and a factor of 2 variation in time drift (0.21 units), when added to the construction variations, increase the rms b_2 by only 14%. The average drift must still be tracked.

For some time it has been recognized that operating proton accelerators do have long term particle loss mechanisms[4] that are not consistent with a sharp well defined aperture boundary but rather with a boundary that is ill defined, which shrinks with time and is dependent on such variables as synchroton oscillations. This type of observation has been qualitatively born out by simulations performed on a model of the Fermi Main Ring.[5] The Main Ring was chosen for extensive study because of its history of sensitivity to small operational changes and adjustments. Particles launched very close together in phase space can survive for very different number of turns, and the aperture continues to slowly shrink as longer and longer tracking times are investigated. There is no sharp threshold edge within which very long-term survival is assured.

In simulations for the SSC collider, three types with input are required: the definition of the required aperture, the model of magnetic errors assumed, and the model of corrections, adjustments, magnet sorting, and particle off-momentum assumed. Those input assumptions are subjective at best and certainly open to controversy. However, progress over the years has indeed been made in that now the simulations can be carried out to time durations of real interest. Substantial effort has gone into developing computer codes that can with reasonable computer time obtain tracking results to a few $\times 10^6$ turns. The injection period in the SSC, the exitation region which has been extensively studied, can last for up to about 70 minutes or 1.5×10^7 turns.

Assumptions

The needed aperture criteria chosen was ~10σ of the beam size or 3.8 mm with a $\Delta p/p$ of 5×10^{-4}. Synchrotion oscillations were incorporated. There are many ways of looking at the 10σ number; but certainly if you knew for sure what beam size to expect, you would need a minimum of 3σ. Then based on how much confidence you give to a simulation model, you might give a factor of two safety margin. The SSC emittance of 1π (rms) is beyond present accelerator performance and certainly will not be available on day one; thus the choice of 10σ.

The magnetic fields chosen for the simulations of 4 and 5 cm are listed in Table III along with measured field from the Tevatron and HERA scaled to the SSC 4-cm coil size. (Some of the original simulations were carried out with slightly different assumptions.[3]

Correction, adjustment assumptions that have been used are as follows for three models.

1) Plausible model - unsplit tune
   a. Magnetic elements located to 1mm rms with respect to beam
   b. Chromaticity corrected to 5 units
   c. Persistent current decapole corrected to 25% of calculated value
   d. Tune set to X0.425, Y0.410
   e. Random sextupole reduced to 1/5 of value by magnet placement (sorting)
   f. Skew quad corrected to zero at four β locations (4 knobs)
2) Plausible model - split time X1.425 Y0.410
   a. 0th and 1st harmonic skew quad corrected (12 knobs)
   b. Other as above in 1
3) Operational model
   a. Same as 2 except
      1. Magnets not sorted
      2. Decapole not corrected
      3. 1 mm orbit drift after tuning

Results are shown in Fig. 4. During the simulation programs it was found that splitting the tune by one unit made a substantial improvement in the dynamic aperture, as long as the coupling corrections (12 knobs) can be set as expected. This margin can be used to further reduce requirements on higher-order correctors, sorting, and on tolerance to orbit changes after tune-up adjustments.

A key indication to long-term stability is the change in oscillation amplitude in one dimension as a function of time. Figure 5 shows this behavior for a 4-cm magnet and can be compared with the results in Fig. 4. Any variation in the X aptitude is a good indicator of a non-stable aperture region.

Magnet Program

The 4-cm dipole program

The 4-cm program will be winding down by the end of 1990 in preparation for the construction and test of the new 5-cm magnets. To date, about eight of the improved design 4-cm magnets have been successfully tested. Quench results of recent 4-cm prototype dipoles constructed at BNL are shown in Fig. 6. These magnets exhibit very little training and reach specified excitation.

The 5-cm program

Basic parameters of the new 5-cm magnet design are given in Table IV. This design is being carried out by a task force with members from BNL, FNAL, LBL , and SSCL, and led by Bob Palmer. This magnet is strongly based on the SSC 4-cm design and experience derived from that program. Changes that are being incorporated in the 5-cm design are directed toward obtaining a more conservative configuration that backs away, as much as possible, from potential problem areas, real or imagined.

The new design incorporates wider cable with more strands than the 4-cm magnet: 12.2 mm vs 9.3 mm width with 30 vs 23 strands of 0.808 mm strand and a 1.5/1 vs 1.3/1 cu/sc ratio for the inner coil; 11.7 mm vs 9.7 mm width with 36 vs 30 strands of 0.648 mm strand and 1.8/1 cu/sc ratio for the outer coil. Operating margin to cable short sample spec is 10%. The higher copper to super conductor ratios selected for the inner coil is based upon some evidence that the number of training quenches experienced is minimized in higher cu/sc cable. As the cu/sc ratio is varied, optimization must, of course, be made between the number of quenches and the ultimate short sample margin above the operating point.[6]

The base line design for the 5-cm dipole incorporates a) vertically split iron yoke, b) with horizontally ovalized coil collars that are forced to round when the yoke is closed and the magnet warm. The collars return to oval when the magnet is cooled and bear on the yoke in the horizontal plane, so there is minimal further collar distortion under power. c) The contour of the end design minimizes stresses in the cable end turns and has grouped windings with collet type end support and a splice external to the iron yoke. This design should simplify end construction complexity dramatically. d) The cable insulation is Kapon film with epoxi glass "barber pole". e) The cryostat, scaled up version of the 4-cm design, now has redesigned interconnect region with domed ends on the cold mass and small diameter independent bellows for helium and buss connection instead of a large single-phase bellows coaxial with the beam tube vacuum pipe. f) There now is sufficient space between the bore tube and the coil so that helium cross flow cooling flow schemes in the laminations that were contemplated for the 4-cm design are no longer necessary. Bore tube correctors have been removed and are located in the spool pieces. Fermilab is undertaking the construction of model and prototype magnets using the generic tooling they have had under development for the 4-cm magnet.

BNL will work on a backup 5-cm program that more closely follows the existing 4-cm magnet. This program will have horizontally split yoke, with vertically ovalized collars, ends with turn spacers, and a ramp splice contained in the coil assembly.

Additionally, a backup program is under way to evaluate different cable insulation schemes that do not use epoxi glass in order to have available alternatives, should incidence of turn-to-turn shorts become a major problem during routine manufacturing.

Quadrupole prototypes are being built and tested at LBL. A first model magnet has recently been successfully tested. A backup program will be initiated at SSCL as soon as industrial space is available.

Schedule

The Near Term

The highest priority of the project is directed to establishing a working 5-cm dipole design that can be efficiently and cost effectively manufactured in industry. To this end near-term milestones are being developed to lead to a string test at the end of '92. Ten dipoles, along with quadrupoles, spool pieces, and associated accelerator systems (prototype, power supplies, quench protection, controls, etc.) will be needed for this test of two half-cells.

The Project Schedule

The project schedule and more detailed information for each accelerator are given in Table V. This schedule is considered to be optimized from the technical point of view but does not reflect potential constraints such as funding profiles or tunnel construction start dates. The schedule is based on a model of eight tunnel contracts for the collider with five 60-person installation crews to install and leak check of up to 27 elements/crew-week and magnet production of 50 dipoles/week.

The plan calls for collider first half-sector installation in '94 and beam commissioning in '98. Tunnel and hall construction of the collider extends through '96. It is planned to cool down power and test each sector as it is installed.

The injector through the MEB will be built to provide test beams for detector calibration starting in mid '96. This means the linac should be ready for start of commissioning late in '94 to allow for sufficient time for the installation and commissioning of the LEB and MEB. Civil construction for these accelerators is planned for completion by early '94.

The HEB and connecting injection tunnels is given lower priority. Civil construction completion is planned for '96 with commissioning to start in late '97 in order to supply beams to the collider in the summer of '98.

Acknowledgment

The SSCL staff has put tremendous effort into the Site-Specific Conceptual Design Report. Special acknowledgment is due to all the people who worked on the simulations. Other laboratories (in particular BNL, FNAL, LBL, and LANL) have made and continue to make major contributions to the dipole development program and to the design. Without their efforts, work reported here would not have been possible.

References

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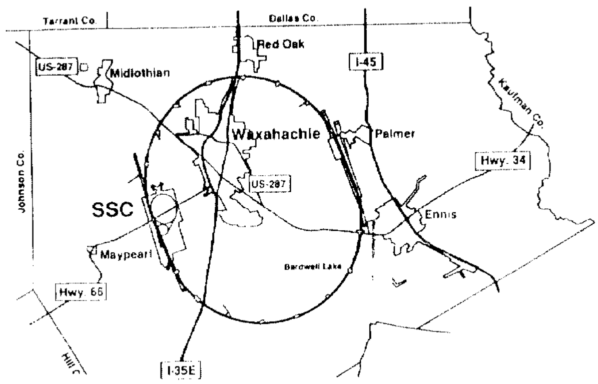

Fig. 1. Site of the SSC

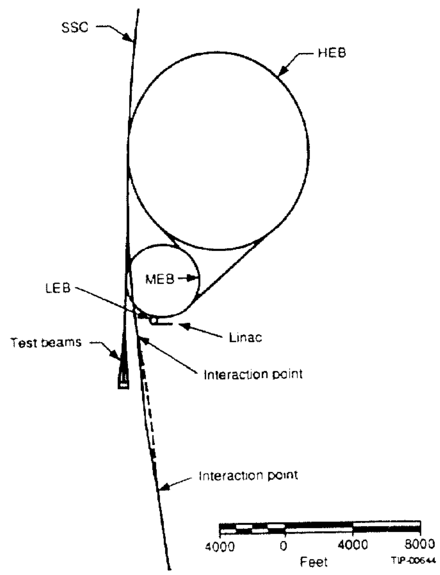

Fig. 2. Schematic layout of the injector complex.

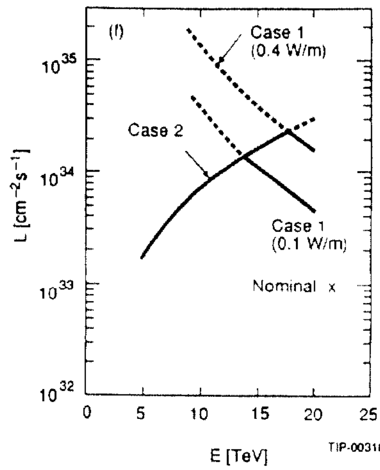

Fig. 3. Luminosity of the collider

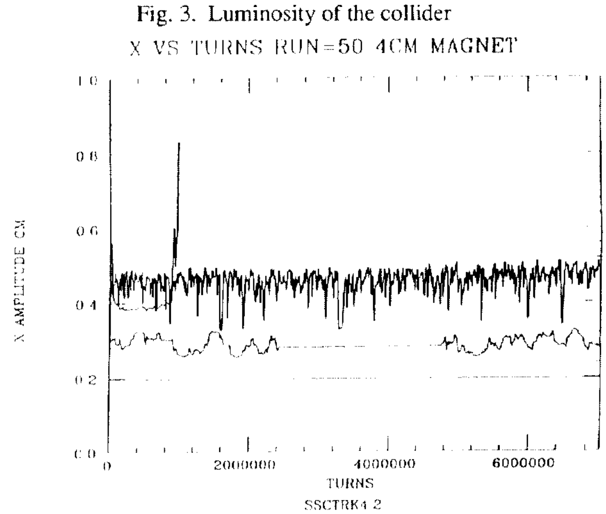

Fig. 5. Oscillation amplitude variations in one plane as a function of initial amplitude.

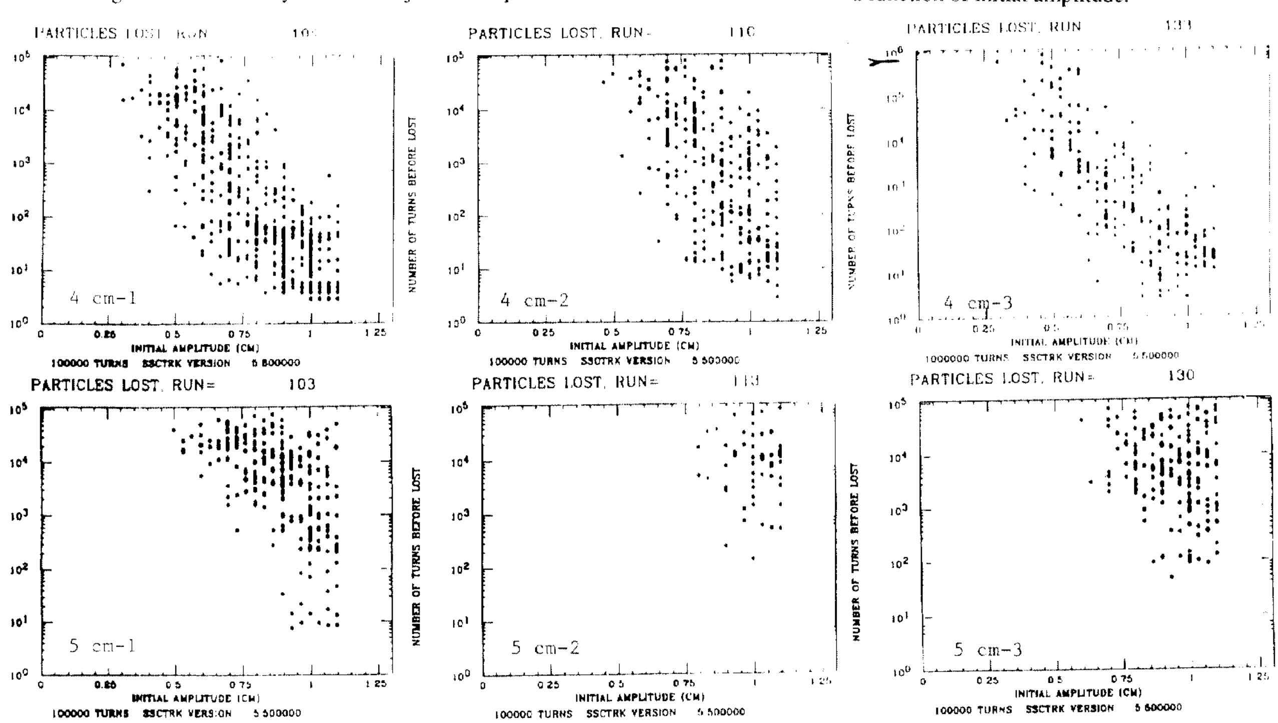

Fig. 4. Tracking results for 4- and 5-cm magnets from models 1, 2, and 3.

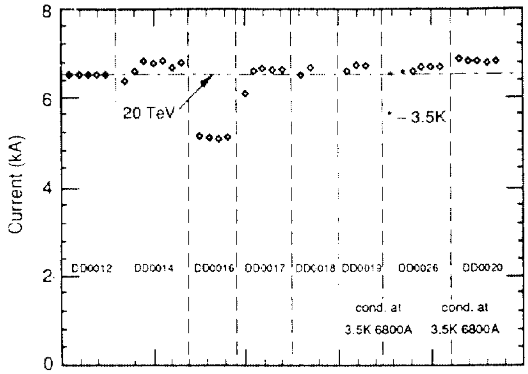

Fig. 6. 4-cm magnet quench sequence.

TABLE I
SSC Parameters

Energy	20 TeV
Particles/bunch (N)	0.75×10^{10}
Circumference	87,120 m
No. of bunches (B)	17,424
NB	1.3×10^{14}
$f_{\rm rot}$	3.4 kHz
$f_{\rm collisions}$	60 MHz
S_b	5.0 m
ε_N (σ)	1 π mm-mrad
β^*	1/2 m
σ^* (μm)	5
Luminosity ($\mathcal{L}$)	1×10^{33} cm^{-2} s^{-1}
$\mathcal{L}$/hit	1.6×10^{25} cm^{-2}
$\Delta\nu_{HO}$ (total)	0.003
$\Delta\nu_{\rm LR}$ (total)	0.004
Sync. rad. power at $NB = 1.3 \times 10^{14}$	8.75 kW/ring

TABLE II
General Parameters

	Collider	HEB	MEB	LEB
Kinetic energy	20 TeV	2 TeV	200 GeV	11.1 GeV
Momentum	20 TeV/c	2 TeV/c	200 GeV/c	12 GeV/c
Mono-bipolar	(2 rings)	bi	mono	mono
Superconducting/normal	SC	SC	normal	normal
Peak field (T)	6.55	6.40	1.7	1.2
Circumference (km)	87.12	10.89	3.96	0.54
Bunch spacing (m)	5	5	5	5
Harmonic number	$17{,}424 \times 6$ $(2^4 3^2 11^2)$ 6	2178 $(2\ 3^2\ 11^2)$	792 $(2^3\ 3^2\ 11)$	108 $(2^2\ 3^3)$
Emit for collider operation (π mm-mrad, rms, norm.)	1.0	0.8	0.7	0.6
N for collider operation	0.75×10^{10}	1×10^{10}	1×10^{10}	1×10^{10}
$N_{\rm tot}$ for collider operation	1.3×10^{14}	2×10^{13}	8×10^{12}	1×10^{12}
Cycle time for coll. oper.	–	2 min	3 s	0.1 s
Emit for test beam oper. (π mm-mrad, rms, norm.)	–	4	4	4
N for test beam operation	–	5×10^{10}	5×10^{10}	5×10^{10}
$N_{\rm tot}$ for test beam oper.	–	10^{14}	4×10^{13}	5×10^{12}
Cycle time for test beam	–	3 min	4 s	0.1 s

TABLE III
Multipoles Scaled from HERA and Tevatron and Multipoles Used for SSC Simulation of 2 TeV Injection

TeV-4 cm	HERA-4 cm		4 cm	5 cm
-0.007	-0.29	<A1>	0.37	0.30
0.80	1.74	σA1	1.75+	1.25+
0.044	-0.038	<B1>	0.37	0.30
0.57	0.68	σB1	0.70	0.50
0.06	-0.164	<A2>	0.15	0.10
0.96	0.35	σA2	0.62	0.35
-2.57	0.175*	<B2>	-3.29	-2.11
2.80	2.00*	σB2	2.01+	1.15+
-0.016	0.093	<A3>	0.06	0.031
0.92	0.52	σA3	0.69	0.32
-0.093	0.068	<B3>	0.06	0.031
0.49	0.16	σB3	0.34	0.16
-0.012	0.029	<A4>	0.024	0.01
0.23	0.11	σA4	0.14	0.05
0.036	0.274*	<B4>	0.23	0.09
0.58	0.36	σB4	0.59	0.22
na	-0.017	<A5>	0.01	0.004
na	0.07	σA5	0.16	0.047
na	-0.14	<B5>	0.01	0.004
na	0.04	σB5	0.059	0.017
na	-0.002	<A6>	0.004	0.0012
na	0.03	σA6	0.034	0.008
0.887	0.047+	<B6>	-0.060	-0.016
0.22	0.07	σB6	0.075	0.018

+Earlier simulations used slightly different values.
*HERA data measured at high field.

TABLE IV
Collider Dipole Parameters

No. of dipoles (long/short)	7956/504
Overall length	15.81/13.29 m
Field (Central/max)	6.60T/6.91T
Current	6503A
Temperature max.	4.35°K
Collar inner diameter	100 mm
Yoke inner diameter	135 mm
Cold mass diameter	340 mm
Cryostat diameter	660 mm
Coil diameter (inner/outer)	50mm/75.4mm
No. of turns per coil section	14/26
Cable mid thickness	1.58/1.17 mm
Jc (A/mm^2) at (7T - 4.2°K/5.6T - 4.2°K)	1730/2540
Filament diameter	6µ

TABLE V
Major Project Milestones

No.	Name	Date	
M1-1	A/E award	May	90
M1-2	Baseline validation complete	July	90
M1-3	Collider dipole magnet (CDM) contract award	Aug	90
M1-4	SEIS record of decision	Nov	90
M1-5	Start SSC civil construction	Jan	91
M1-6	Collider string test complete industry prototypes	Oct	92
M1-7	Start first sector CDM delivery	Oct	93
M1-8	Begin excavation of experimental halls	Mar	93
M1-9	First collider sector – start installation	Jan	94
M1-10	Linac – start commissioning	Oct	94
M1-11	First sector – start cooldown	May	95
M1-12	MEB – start commissioning	Oct	95
M1-13	Beneficial occupancy of large experimental halls	Oct	95
M1-14	HEB – start installation	Jan	96
M1-15	MEB – test beams available	Apr	96
M1-16	HEB – start commissioning	Oct	97
M1-17	Detectors – start commissioning	Mar	98
M1-18	Collider – start commissioning (beam)	July	98
M1-19	Collider – complete commissioning beams to expts	Oct	98