STATUS OF THE SSC DESIGN

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ABSTRACT

The SSC is proposed as a high luminosity (10^{33} cm^{-2} sec^{-1} scale) 20 TeV per beam proton-proton synchrotron collider. A Conceptual Design Report for this facility has just been completed and is under review. The design is based on 6.6 T superconducting magnets; the circumference of the collider is 83 km. Prototype magnet fabrication is in progress, and initial systems tests are scheduled to begin this Summer.

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1. Introduction

This paper presents a brief account of the current status of the proposed Superconducting Super Collider (SSC). In July 1983, the High Energy Advisory Panel of the U. S. Department of Energy recommended "the immediate initiation of a multi-TeV, high luminosity, proton-proton collider with the goal of physics experiments at this facility at the earliest possible date." In turn, the Department of Energy authorized an R&D program pointed toward a conceptual design for a 20 TeV on 20 TeV proton-proton collider with a luminosity of 10^{33} cm^{-2} sec^{-1}. That conceptual design has now been completed. In the coming months, it will be reviewed by the DOE and discussed by the HEP community.

In the Moriond talk, I showed many transparencies taken from a draft copy of the design report. But when this written version appears, the Conceptual Design Report will be generally available, and so there is little point in reproducing those figures here. Here, I will confine myself to some remarks about high luminosity superconducting colliders in general, a few highlights of the SSC conceptual design, and a concluding comment on the SSC schedule.

2. Some Orders of Magnitude

The combination of a luminosity at the 10^{33} cm^{-2} sec^{-1} level and a total effective cross section of 100 mb or so implies an event rate of about 100 MHz on the average. This last figure is ominous enough in itself; to make it conceivably tolerable at all means that the SSC be designed as a "many bunch" collider. The mean number of events per bunch-bunch collision is

$$\langle n \rangle = L\sigma \; (S_B/c) \simeq S_B(\text{in meters})/3 \qquad (1)$$

where L is the luminosity, σ the effective total cross section, and c the speed of light. The collision time of a pair of bunches is less than one nanosecond, so $\langle n \rangle$ should be limited to "a few." For instance, if the bunch spacing is 6 m, the average number of interactions per bunch-bunch hit would be ~2. The circumference of each ring in the conceptual design is 83 km, hence there will be over ten thousand bunches in each beam.

The number of particles in each bunch will be relatively small in comparison to present practice. The luminosity can be written in the form

$$L = \left(\frac{c}{S_B}\right) \; \frac{1}{\beta^*} \; \frac{\gamma}{4\pi\epsilon_N} \; N_B^2 \qquad (2)$$

where N_B is the number of protons per bunch. The three groups of factors in front represent, in turn, the bunch-bunch collision frequency, the influence of the collider ring beam optics through the amplitude function at the interaction point, and the characteristics of the proton beam itself. In the last group, γ is the Lorentz factor of the protons, and ϵ_N the normalized emittance. This emittance is a measure of the area in a one degree-of-freedom phase space for one of the transverse coordinates of the beam, and is the factor in the equation that conveys some sense of beam quality. If we take $\beta^* = 1$ m, $\epsilon_N = 1$ mm mrad, and the other quantities as in the preceding example then $N_B \simeq 1.1 \cdot 10^{10}$.

This value of N_B is about an order of magnitude less than the corresponding number for either existing lepton or hadron colliders; in fact, it is similar to the number of protons per bunch typical of a fixed target synchrotron. Without even bothering to calculate the head on beam-beam tune shift, we therefore would expect to hear less about this famous effect for the SSC than for present colliders, even though the normalized emittance selected for the conceptual design is a factor of four smaller than that of the SpS. But with the small bunch spacing, the beams must cross at an angle to avoid having a multiplicity of interaction points in the neighborhood of a detector, and so there will be a number of close passages of bunches on either side of the nominal collision point. As a result, we will hear more about the so-called long range beam-beam effect, which, though less intrinsically nonlinear than the head on case, must be taken into account.

The total number of particles in each ring is large, in the 10^{14} range. At 20 TeV, the kinetic energy of each beam for the conceptual design parameters is 400 MJ. The main impact of these numbers on the SSC design lies in the synchrotron radiation and in the potential for energy deposition in the superconducting magnets.

For the SSC, synchrotron radiation emerges as an important design consideration for a proton ring. The energy radiated per turn by a proton following an orbit with radius of curvature ρ is

$$W = 78 \left(\frac{E_{TeV}}{10}\right)^4 \frac{1}{\rho_{km}} \quad \frac{keV}{turn} . \qquad (3)$$

The bending magnets in the SSC design have a field of 6.6 T at 20 TeV. The radius of curvature is 10 km, and so the radiation per particle per turn is 125 keV. By electron synchrotron standards this is trivial, as is the synchrotron radiation power of ~10 kW. But in the superconducting environment, this power must be removed at liquid helium temperature and represents about one-half of the 4 K load. Even if the refrigerators operate as high as 20% of ideal Carnot efficiency, a power input of 5 MW per ring is required.

The characteristic time for synchrotron radiation processes is the ratio of the particle energy to the rate of energy loss, i.e., the time in which the energy must be replaced by the radiofrequency acceleration system. For the SSC parameters, this time is 13 hours and is the time constant for damping of synchrotron oscillations; the betatron oscillation time constants are twice as long. Though much longer than the few millisecond time constants of electron rings, these periods are not long compared with a storage cycle of a day or so and have implications for the luminosity lifetime as noted in the next section.

A troublesome accelerator physics problem in the design of the fixed target Energy Doubler was the protection of the superconducting magnets from particles scattered by the primary extraction septum. The counterpart of this problem in the SSC is the energy flux departing an interaction point as a result of the collision of the two beams. About 300 watts leaves the beam in each direction, most of which must be intercepted before entry into the superconducting magnets. I don't mean to imply that there is any fundamental design problem here; rather, it is interesting that in each case it is the end use process that leads to a large energy flux (large on the scale that the magnets can tolerate) headed toward the magnet coils.

3. Sketch of the SSC Design

Viewed from above, the SSC resembles a racetrack. At the "North" and "South" ends, semi-circular arcs composed mainly of bending magnets return the beams to the clusters of straight sections on the "East" and "West" sides. Each of the arcs is 32 km in length. There are four straight sections on either side of the layout: four interaction regions to the East, and two interaction regions and two utility sections at the West. The straight section centers are 2.4 km apart and about 100 mrad of bending is interposed between them to reduce the effects of interactions in one on detectors in another.

Two varieties of interaction region are included in the present design. On the East side, there are two high luminosity IR's with $\beta^* = 0.5$ m and a separation between quadrupoles near the interaction point of ± 20 m. The two IR's on the West side have $\beta^* = 10$ m to yield an intermediate luminosity in the $0.5 \cdot 10^{31}$ range; these have an open space of ± 100 m at the interaction point. The other two straight sections to the West are utility regions for injection, beam abort, and other accelerator functions. The remaining two straight sections on the East side are reserved for future development.

The proton rings of the SSC are located one above the other in their underground enclosure. The over-under arrangement was selected primarily for convenience of installation, operation, and maintenance. These same considerations led to the choice of separate cryostats for the two rings.

A few of the parameters of the design are shown in Table I. Some of these have already been given above; most of the others are included simply to convey a sense of scale.

Table I

Selected parameters of the SSC design.

Bunch separation	4.8 m
Circumference	82.9 km
Bunches per ring (incl gaps)	~$1.6 \cdot 10^4$
β^*	0.5 m & 10 m
Normalized emittance ($\gamma\sigma^2/\beta$)	1 mm mrad
Protons per bunch /per ring	$7.3 \cdot 10^9$/~$1.2 \cdot 10^{14}$
Bend field	6.6 T
Radius of curvature ρ	10.1 km
Gradient, arc quadrupole	215 T/m
Excitation current	6500 A
Number of dipoles (2 rings)	7680
Number of arc quads (2 rings)	1356
Arc cell	192 m, 60° phase advance
Bend length per cell	$10 \cdot 16.6$ m
Quad length per cell	$2 \cdot 3.45$ m
Acceleration period	1000 s
Energy gain per turn	5.25 MeV
Bunch length - rms	7 cm
Accel system frequency	375 MHz (0.8 m)

Considerable effort has been devoted to the vexing magnet aperture and field quality issue. Many years ago, this reduced to a question of whether or not the magnet was good enough. Now, large synchrotrons do not work without a host of auxiliary magnets that make corrections and adjustments. So a discussion of main magnet aperture and field quality requirements requires a variety of inputs, including:

- scaling of field imperfections with magnet size and type,
- design of correction magnet system,
- magnetic measurement plan,
- installation procedures,
- performance specification.

For the SSC, the performance specification is based on the operational need for near-linear, rational beam dynamics with the region of the aperture typically explored by the particles. This requirement in conjunction with the other inputs above was used to specify physical apertures for the candidate magnet types.

The bending magnet chosen for the conceptual design is a 6.6 T shell coil dipole. The procedure outlined in the preceding paragraph was used to conclude that an inner coil diameter of 4 cm would be adequate to satisfy field quality needs. The NbTi superconductor represents a large fraction (about 30%) of the cost of the magnet system; the parameter of primary importance in specifying the superconducting material is the critical current density at the appropriate operating temperature and field. When construction of Energy Doubler magnets got underway, the critical current was specified as 1800 A/mm^2 at 4.2 K and 5 T. Improvement in the NbTi alloy in just a few years makes it possible to use a figure of 2750 A/mm^2 at the same temperature and field today. Also, reductions have been made in the filament size that can be achieved in production quantities. The filament size for the current SSC material is 5 μm. Conductor has been made commercially at a filament diameter of 2.5 μm; use of filaments at this scale would greatly ameliorate the persistent current correction problem.

Finally, let me comment on the luminosity lifetime. When the beams are brought into collision, particle loss will occur due primarily to the interactions at the crossing points. But at the same time, the transverse emittance will shrink as a result of the damping of betatron oscillations by synchrotron radiation. The second effect has the larger impact on the luminosity, and the luminosity rises for about a day, reaching a peak of twice its initial value after some 24 hours. Eventually the emittance reduction slows as intrabeam scattering becomes more of a factor at small emittance, and the luminosity drops, returning to its initial value 50 hours after the beginning of the run. The integrated luminosity at a high luminosity IR for this period would be 280 pb^{-1}.

4. Remarks on the Schedule

The completion of the Conceptual Design Report in March of this year is timed with respect to the Federal budget cycle so that the SSC can be considered for a start-of-construction date of October 1987. The construction phase is estimated to require about 6.5 years; that is, if construction approval is effective in October 1987, then the construction completion date is April 1994.

A particularly important near-term milestone is the initiation of real systems tests. By the end of this coming Summer, four full scale dipole magnets will have been completed. These will be installed in a tunnel-like enclosure (but at ground level), and hooked up to appropriate refrigeration and power supplies. This arrangement will permit early operation of a multiple magnet system, in order to study peak field performance, quench behavior, cryogenic properties, and various operational simulations.