The Super-Collider - Progress, Options and Physics

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The Superconducting Super Collider (SSC) has been given high priority by the high energy physics community. Various aspects of the project - physics motivation, accelerator design, siting considerations - are discussed here. The project is moving rapidly and parts of this discussion have been updated to reflect the vast amount of work that has gone into the SSC since the Conference.

Development of the SSC Concept

The possibility of a 20 on 20 TeV proton-proton collider as an American facility was first seriously raised at the 1982 DPF summer study at Snowmass. While the work at Snowmass drew on earlier ICFA studies of such a machine, much additional design work and excitement were generated at the summer study. During the following year, workshops were held on detectors (Berkeley, 3/83), and on further design aspects of the accelerator itself (Cornell, 4/84). The results of these workshops, together with the success of the world's first superconducting accelerator, the Tevatron at Fermilab, lead to the unanimous recommendation of the 1983 Woods Hole Subpanel (chaired

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by S. Wojcicki) of "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."^5

At the time of the Conference (12/83), the Reference Designs Study (RDS) was being organized under the leadership of M. Tigner. After several months of concentrated effort by physicists and engineers from across the country, a detailed report was issued in May, 1984.\textsuperscript{6} Meanwhile, several additional workshops were held on various aspects of the SSC, ranging from accelerator physics to theoretical particle physics, and including options such as $\bar{p}p$\textsuperscript{7} and fixed target.\textsuperscript{8} The workshops culminated in the second DPF summer study at Snowmass (7/84), this one on the design and utilization of the SSC.

**Energy and Luminosity**

Over the years, the beam energy available to physicists has grown exponentially since the 1930's, with a doubling time of about two years.\textsuperscript{9} This has been achieved with a series of technologies, each hitting some practical limit and being overtaken by some other new method. As the energies became highly relativistic, the usual method of studying collisions, with the beam striking a "fixed target" (often a proton in a liquid hydrogen target), became increasingly inefficient, most of the energy of the incoming beam being needed just to conserve forward momentum. The useful (center of mass) energy in this case increases as $E_{\text{cm}} = \sqrt{2 \cdot E_{\text{beam}} \cdot M_{\text{target}}}$. The most recent technique for increasing $E_{\text{cm}}$ is to use colliding beams; in this case there is no net momentum and all the energy is available to make heavy particles, cause new types of interactions, etc.: $E_{\text{cm}} = 2 \cdot E_{\text{beam}}$. While the SSC will indeed be an enormous machine, to achieve the same $E_{\text{cm}} = 40$ TeV a fixed target machine would need an energy of $\sim 10^{18}$ eV, beyond the region of most cosmic ray studies. Even with strong (80 kG) superconducting magnets, $10^{18}$ eV would require a machine with a radius of 400,000 km, the distance from the earth to the moon!
While protons are much easier to accelerate than electrons to high energies, their energy is distributed amongst three valence quarks, gluons, and sea quarks. Each of these constituents carries only a fraction, $x_i$, of the parent proton's momentum, and the effective center of mass energy for collisions between a constituent of the first beam with one in the second is $E = \sqrt{x_1 x_2} E_{\text{cm}}$.

The event rate for colliders is given by

$$R = \mathcal{L}_\sigma,$$

where $\mathcal{L}$ is the luminosity of the machine and $\sigma$ the cross section of interest. Since the cross section for producing a heavy particle of mass $M$ scales as $1/M^2$, and since the distributions of the constituents in the proton are peaked toward low $x$, a high luminosity must be achieved for observable rates of massive objects.

Although the "standard model" presently explains many diverse phenomena, it is known to be incomplete. Related theories have been devised to explain additional aspects of the presently observed families of particles and their interactions, including the well-known puzzle of symmetry breaking. Two popular classes of these theories, "supersymmetry" and "technicolor," involve families of particles with masses in the TeV region. In any case, general arguments indicate that some new phenomena must exist in this region.

The sensitivity to heavy particles depends on both the center-of-mass energy and the luminosity. The trade-off between these two quantities was studied in detail at the 1982 Snowmass meeting and more recently by the definitive work of EHLQ. Examples of the 1982 Snowmass calculations are shown in Fig. 1, and some limits derived from the EHLQ study are shown in Table 1. While varying with the process under study, a very crude rule of thumb is that a factor of ten in luminosity is roughly equivalent to a factor of two in energy. These limits should be treated with a degree of skepticism, however, since they depend not only on rates but also on backgrounds and
Fig. 1. Trade-offs between luminosity and energy, suggested by contours of mass (or $2p_T$) giving 100 events in 10$^7$ seconds for (a) QCD jets; (b) technieta's; and (c) Drell-Yan muon pairs (from Ref. 10).
detector capabilities.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Process</th>
<th>Signature</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\mathcal{L}$ (cm$^{-2}$sec$^{-1}$)</th>
<th>$\int \mathcal{L} dt$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_T = E_T/\sqrt{s}$</td>
<td>pp + jet jet</td>
<td>2 jets</td>
<td>40$^{33}$</td>
<td>10$^{33}$</td>
<td>10$^{40}$</td>
</tr>
<tr>
<td>$M_Q$</td>
<td>pp + Q\bar{Q}X</td>
<td>{6 jets, 4 jets+$E_T^{\text{mis}}$}</td>
<td>2.7</td>
<td>3.8</td>
<td>4.8</td>
</tr>
<tr>
<td>$M_L$</td>
<td>pp + L$^+$L$^-X$</td>
<td>4 jets ($W^+W^-$)$+E_T^{\text{mis}}$</td>
<td>0.56</td>
<td>1.1</td>
<td>0.77</td>
</tr>
<tr>
<td>$M_W$</td>
<td>pp + W$^\pm X$</td>
<td>$Z + E_T^{\text{mis}}$</td>
<td>6.5</td>
<td>9.3</td>
<td>11</td>
</tr>
<tr>
<td>$M_Z$</td>
<td>pp + ggX</td>
<td>4 jets + $E_T^{\text{mis}}$</td>
<td>1.6</td>
<td>2.3</td>
<td>2.6</td>
</tr>
<tr>
<td>$M_{\tilde{Z}}$</td>
<td>pp + $\tilde{g}\tilde{g}X$</td>
<td>$Z^+$Z$^- + E_T^{\text{mis}}$</td>
<td>0.4</td>
<td>0.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Rate Limitations**

When discussing rate effects, it is useful to define $< n >$, the average number of inelastic interactions seen at one time by the detector. Taking $\Delta t$ to be the larger of a) the limiting memory or resolution time of the detector; or b) the time between bunch collisions, we have

$$< n > = \sigma \mathcal{L} \Delta t$$

For the reference design, the bunches were assumed spaced by 10 m (33 nsec); a luminosity of $10^{33}$ cm$^{-2}$ sec$^{-1}$ and an inelastic cross section of 100 mb then gives $< n > = 3.3$. This rate is somewhat high for good track-finding efficiency or for the careful study of the properties of minimum bias.
events. While some of these problems may be alleviated by going to a closer bunch spacing (a few meters seems possible) and very fast detector elements, some physics, such as the study of fast-lived particles with silicon-strip vertex detectors close to the beam pipe, will have to be done at $\lesssim 10^{32}$ cm$^{-2}$ sec$^{-1}$. Other physics, such as high-$p_T$ jets or the production of very heavy W's can be done with energy flow techniques at $\gtrsim 10^{34}$ cm$^{-2}$ sec$^{-1}$.

The DPF Workshop on Collider Detectors (Berkeley 3/83) concluded that general-purpose detectors (including tracking) could operate at $10^{33}$ cm$^{-2}$ sec$^{-1}$ with high segmentation. This means a large number of electronics channels, and an estimate of $\$146$ M (half fo. electronics) was made for such a "4π" detector, based on CDF costs. At the 1984 Snowmass study, it was suggested that two 4π detectors should be built, each costing about $\$230$ M.

Interaction Regions

Some of the parameters for the Reference Designs Study (RDS) are shown in Table 2. The small-angle crossing scheme used in the RDS for the interaction regions grew out of considerations of the PSSC study and is sketched in Fig. 2. This scheme allows the bunches to be more closely spaced than in the previous schemes considered. Further, special septum magnets are not required and one can run with differing amounts of free space in the various IR's.

Both the RDS bunch spacing ($D_B$) and angle ($\alpha$) between the beams at the collision points can be adjusted. While a close bunch spacing helps with the detector rate problems, the total number of protons required in each beam scales as $1/\sqrt{D_B}$ for the RDS regime in which the beam emittance (rather than the beam-beam tune shift) is the limiting factor. Since the sensitivity of the magnets to quenches by losses of a small fraction of the beam would increase at larger beam current, the RDS took $D_B = 10$ m as a reasonable compromise. As experience is gained with the machine, the current can presumably be increased and $D_B$ reduced.
Table 2. Comparison of RDS (v. 5 T) parameters with possible mode for eventual operation at high luminosity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RDS-A</th>
<th>High Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (GeV)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Luminosity ($\mathcal{L} (\text{cm}^{-2} \text{sec}^{-1})$)</td>
<td>10$^{33}$</td>
<td>10$^{34}$</td>
</tr>
<tr>
<td>Bunch spacing (m)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Inel. events/crossing ($\langle n \rangle$)</td>
<td>3.3</td>
<td>17</td>
</tr>
<tr>
<td>Machine param. at IP ($\beta^*$ (m))</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Inv. emittance (rms) ($\epsilon_n (10^{-6} \text{ m})$)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Beam-beam tune shift ($\Delta \nu (10^{-3}/\text{IR})$)</td>
<td>1.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Protons/bunch ($N (10^{10}/\text{bunch})$)</td>
<td>1.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Protons/90-km ring ($N_{\text{ring}} (10^{14})$)</td>
<td>1.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Stored beam energy ($U (\text{MJ/ring})$)</td>
<td>400</td>
<td>1300</td>
</tr>
<tr>
<td>Syn. rad. power ($P_{\text{sr}} (\text{kw/ring})$)</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>Length of lum. region ($\sigma_{\text{diamond}} (\text{cm})$)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Luminosity lifetime (tau hours)</td>
<td>64</td>
<td>23</td>
</tr>
</tbody>
</table>

Fig. 2. Sketch of the small-angle interaction region (from Ref. 16).
The beam-crossing angle is also a compromise between several factors. It must be large enough to avoid instabilities from the long-range beam-beam forces. Luminosity is gradually lost as the angle becomes large and the overlap of the two beams diminishes, however; further, synchro-betatron instabilities may be excited at largish crossing angles. The RDS took \( \alpha = 75 \) μrad, but this can be easily varied to find the optimal value.

**Synchrotron Radiation**

The SSC will be the first proton machine to have significant effects from synchrotron radiation. The emittance damping time from this effect is about 14 hours at 20 TeV and 6.5 Tesla (the damping time scales as \( 1/EB^2 \)). This should more than offset the slower diffusion of the beam due to effects such as intrabeam scattering and beam-beam interactions at the IR's. It does mean that energy must be continually pumped into the beam with the rf system if 20 TeV is to be maintained, however, and that an additional load of 8 kW per beam is placed on the 4.5°K cryogenic system for the 6.5 Tesla design (~ 30% of the expected 4.5°K refrigeration load).

The critical energy for the synchrotron radiation is 280 eV (at 20 TeV and 6.5 Tesla). The PSSC\(^{16} \) worried about the radiation emitted as the protons experience the sudden change of field at the magnet ends; this effect gives photons with roughly 20 times the usual energy (it was used at CERN to enable accelerator physicists to see visible light emitted by the 400-GeV SPS proton beam). With the low amount of power going into this harder spectrum, it should still be easy to avoid backgrounds in the detectors due to this effect.

**Beam Losses**

The primary loss of protons from the beam is expected to be due to collisions at the IR's. If we take an effective cross section of 150 mb (small-angle elastic scattering protons are not lost) and assume that the sum of the luminosities around the ring is \( 3 \times 10^{33} \) (for example, two IR's might be running flat out, with the remainder together adding to \( 10^{33} \)), then from IR
collisions alone $N/\dot{N} = 80$ hours for the 6.5-Tesla reference design. If the emittance is controlled to maintain a constant beam-beam tune shift, the luminosity lifetime is then 64 hours (including other expected beam losses). For such a lifetime, the rings would only need refilling once every day or two; for example, after 23 hours the luminosity would drop to 70% of its initial value.

The power lost per IR operating at $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ at 20 TeV is about 1 kW (for $\sigma = 150 \text{ mb}$). Most of this power will be deposited downstream from the IR on collimators interspersed with the insertion magnets. This collimator-scrapper system will need a careful design, not only to shield the superconducting magnets, but to insure that the induced radioactivity does not cause problems.

**High Luminosity Possibilities**

After some experience running the machine, it should be possible to push toward $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$. A possible set of parameters giving this luminosity is compared in Table 2 to the RDS parameters. It was assumed that $\beta^*$ will eventually be adjustable down to 0.5 m, that the bunch spacing can be reduced to 5 m, and that a factor of 3.2 increase in beam intensity will be tolerable. Although the limiting factor on the luminosity is hard to predict, many accelerator physicists suspect that it may be the number of protons that can be stored without some small loss of beam occasionally causing a quench. Again, this points out the need for a careful design of the collimator-scrapper system to pick off errant protons before they cause trouble.

**Magnet Designs**

Several magnet designs are being vigorously pursued in an effort to pin down the engineering details so important for reliability, costs, etc. Starting from low field and working up, superferric magnets of 2 to 3 Tesla are being prototyped at the Texas Accelerator Center, with the 3-Tesla design
being used for RDS-C. These magnets should be easy to build and require a minimal amount of superconducting cable. The field quality is mainly determined by the iron laminations (instead of conductor placement) and the field should thus be more easily reproducible. While there are known methods for maintaining good field quality as the iron saturates, these techniques must be checked with prototypes. One must also understand all the issues associated with the manufacture and installation of the very long magnets (140 m) called for in this design. Beginning with a low field for the SSC has the advantage that eventual upgrades with higher-field magnets could significantly increase the energy. It does mean, however, that the costs of the long tunnel will have to be well understood.

The advantage of medium field, say 4 to 6 Tesla, is that this is the range in which we have extensive experience with accelerator magnets for both the Tevatron and ISABELLE. Fermilab is working on a 5-Tesla design based on experience with the Tevatron, and this magnet was used as the basis for RDS-B.

At high fields the magnets must be tightly clamped as forces become large; further, one needs a considerable amount of superconducting material and the magnets become more expensive. The resulting small circumference has many advantages, however: it is easier to travel to experiments (or broken equipment) on the far side of the ring; fewer protons need be stored; certain instabilities are less bothersome; synchrotron radiation damping is stronger (though at the cost of added load to the cryogenic system); and one can pick from a greater selection of sites. Brookhaven and LBL are collaborating on the 6.5-Tesla design used for RDS-A, as well as looking at designs in the 8-Tesla region.

The RDS cost analysis indicated that the total cost of the facility appears to be similar for all three options, the higher cost of high-field magnets offsetting the higher tunnel cost at low field. A similar conclusion had been reached earlier at the SSC accelerator workshop held at Cornell (4/83). So much depends on the magnetic field that the design must be chosen early. The present schedule calls for this decision to be made October 1985, and magnet R&D has high priority in order to facilitate this decision.
SSC Sites and Terrain Following

Meanwhile, as part of R&D Phase 1A, site criteria will be developed with a preliminary site invitation scheduled for April 1985, and the final site invitation by DOE taking place following the magnet decision in October 1985. The size of the required site is closely coupled to the magnetic field, the RDS circumference being 90/113/164 km for designs A/B/C; this corresponds to average ring diameters of 18/22/32 miles.

Depending on the ring size and the nature of the site, the IR's might be clustered into two sets of three on opposite sides of the ring, or spaced out uniformly as in the RDS. Discussions and calculations done for the PSSC study and at Snowmass-84 indicate that backgrounds of muons and other particles from one IR impinging on the next can be kept to a reasonable level by inserting a 2° or 3° bend between IR's to effectively sweep out the background particles. Tracking studies are still needed to determine the effect of IR clustering on the dynamic aperture of the machine.

Potential sites for the SSC have been considered in several states. The Site Atlas contains a compendium of many of these sites, including the Quijotoa Site 70 miles west of Tucson, which many of the participants in this conference were able to view from the air. Figure 3 shows the general location of this site and Fig. 4 the variation of elevation around the ring.

Although the elevation of this site ranges from about 1800 to 2200 feet above sea level, the variation of the depth of the ring can be reduced to typically ±50 feet by using a tilted plane with a slope of about 0.25%. The variation could be further reduced by "terrain following" of the machine. This can be done in a simple and straightforward way by slightly rotating the bending magnets to introduce a horizontal field to give a slow vertical bend. For example, a roll of 40 mrad would give a vertical bend radius of 300 km (for RDS-A), sufficient to follow the gross fluctuations of elevation around the ring and to maintain most of the ring within a 10-foot range of depth below the present surface. This would allow highway-construction equipment to cheaply bulldoze a "road" such that the SSC could be installed at
Fig. 3. Map of southern Arizona showing the location of the Quijotoa site (from Ref. 18).
Fig. 4. Elevation above sea level of the Quijotoa Site as a function of angle around the ring.

A constant depth with cut and fill techniques. The slight loss in horizontal bending power (0.08%, 0.9 Tesla meter per cell) could be easily made up with the horizontal trim magnets, part of the correction-magnet package. The small amount of vertical dispersion (0.4% of the usual horizontal dispersion in the arcs) would be isolated by "dispersion killers" at each end of the vertical-bend sections. These dispersion killers would be identical in concept to the "missing-magnet" scheme used to kill the horizontal dispersion at the IR's. The size of the magnet rolls in the two cells (~ 400 m) on either side of the vertical-bend section would be set to values which depend on the phase advance per cell. An arbitrary number of half-cells of rolled bend magnets could then be inserted between each pair of dispersion killers.
Options

Several SSC options have been studied at various workshops and at Snowmass-84. The $\bar{p}p$ option was most carefully looked at by a workshop at the University of Chicago (2/84).\(^7\) By using 3 or 4 rings for $\bar{p}$ collection and cooling it appears that a source of $5 \times 10^8 \bar{p}$/sec should be feasible. This could give a luminosity in excess of $10^{32}$ cm\(^{-2}\) sec\(^{-1}\). Although the scheme for $\bar{p}p$ collisions discussed at that workshop suffers a loss of a factor of three in duty cycle compared to bunched $pp$ collisions, a method with helical separation of the protons and antiprotons may avoid this problem.\(^{21}\) The $\bar{p}p$ workshop concluded that the physics of both $\bar{p}p$ and $pp$ look very exciting; while results from the two types of collisions are expected to be much the same, it would be of interest to verify this prejudice. The capability to do both reactions would have to be designed into the machine from the beginning, however.

The fixed target option was considered at a Woodlands workshop (1/84),\(^8\) the PSSC study,\(^22\) and Snowmass-84.\(^23\) While slow extraction seems possible, it does have considerable impact on the design of the machine.\(^24\) External test beams of particles of several TeV seem readily available from interactions at the colliding beam IR's\(^25\) and may well be useful for some fixed target physics.

The ep option was studied by the PSSC\(^26\) and Snowmass-84.\(^27\) Several possibilities were explored for the electron ring, but no clear consensus emerged. The SSC itself may well have already made many discoveries by the time an ep option comes into being; additional information about these discoveries might then be obtained from ep collisions.

Ongoing Work

The FY-85 SSC R&D, aimed primarily at engineering and prototyping of the superconducting magnets, was approved in August 1984 as Phase IA. M. Tigner will be the Director of this effort, with the Central Design Group at LBL. This effort will be under the auspices of the Universities Research Association which has set up an SSC Board of Overseers with B. McDaniel as
Chairman.

To conclude, there has been considerable progress on the SSC over the past year. DOE has given its approval for the initial R&D phase and the project is moving ahead. As evidenced by the enthusiasm at many workshops and conferences, including this one, physics from this machine is eagerly awaited.
References


14. B. C. Barish et al., Ref. 3, p. 64.


17. R. Diebold and D. Johnson et al., Snowmass-84.


20. For example, for 80° phase advance per cell, as in the RDS, the amount of roll in the first and last cells ("outer" cells) of a terrain following section would be 60.5% of the roll of the central cells of the section, while the adjacent cells ("inner" cells) would be at 39.5%; see Ref. 19 for other examples.


25. L. Lederman; G. Dugan; T. Murphy, *Proc. Snowmass-84*.
