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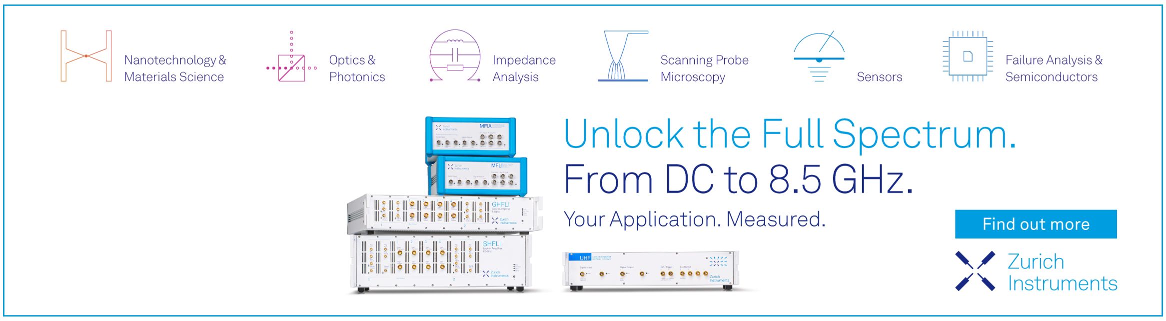

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FUTURE HADRON COLLIDER: THE SSC

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Abstract

The design of the SSC is briefly reviewed, including its key machine parameters. The scientific objectives are twofold: a) investigation of high-mass, low-rate, rare phenomena beyond the standard model; and b) investigation of processes within the domain of the standard model. Machine luminosity, a key parameter, is a function of beam brightness and current, and it must be preserved through the injector chain. Features of the various injectors are discussed. The superconducting magnet system is reviewed in terms of model magnet performance, including the highly successful ASST. Various magnet design modifications are noted, reflecting minor changes in the collider arcs and improved installation procedures. The paper concludes with construction scenarios and priority issues for ensuring the earliest collider commissioning.

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The SSC is now under construction just south of this campus in Ellis County, Texas. As you know, it is a proton-proton collider enclosed in a race-track-shaped underground tunnel (see Figure 1). The machine consists basically of two arcs housing the two proton rings. The rings are built one above the other in two arcs of bending magnets and focusing magnets. The straight section on the west side of the ring provides the various devices needed to inject the beams and, when required, to dump them. Most important are the interaction regions where the beams will be collided and the experiments mounted. Because the rings are mounted one on top of the other, the beams cross vertically such that there are two collision points on each side of the machine. In addition, on the east side there is an extra utility straight section, where it may be possible someday to extract a beam from the main collider rings, or do other kinds of specialized experiments with internal gas jets and the like. The main campus area, which encloses the buildings for the staff, the injector accelerators, and other operations, is in a large parcel of land on the west side of the machine. On the east side is a smaller campus where, for geological reasons, we will site the very large detectors, which are essentially under construction now. Aside from small service areas around the arcs, where there are refrigerators and power supplies and other facilities, the tunnel of the machine goes underground without disturbing existing farms and countryside. The basic design of the SSC is described in a supplementary design report.

Table 1 lists some of the key parameters of the SSC. The high energy of 20 TeV

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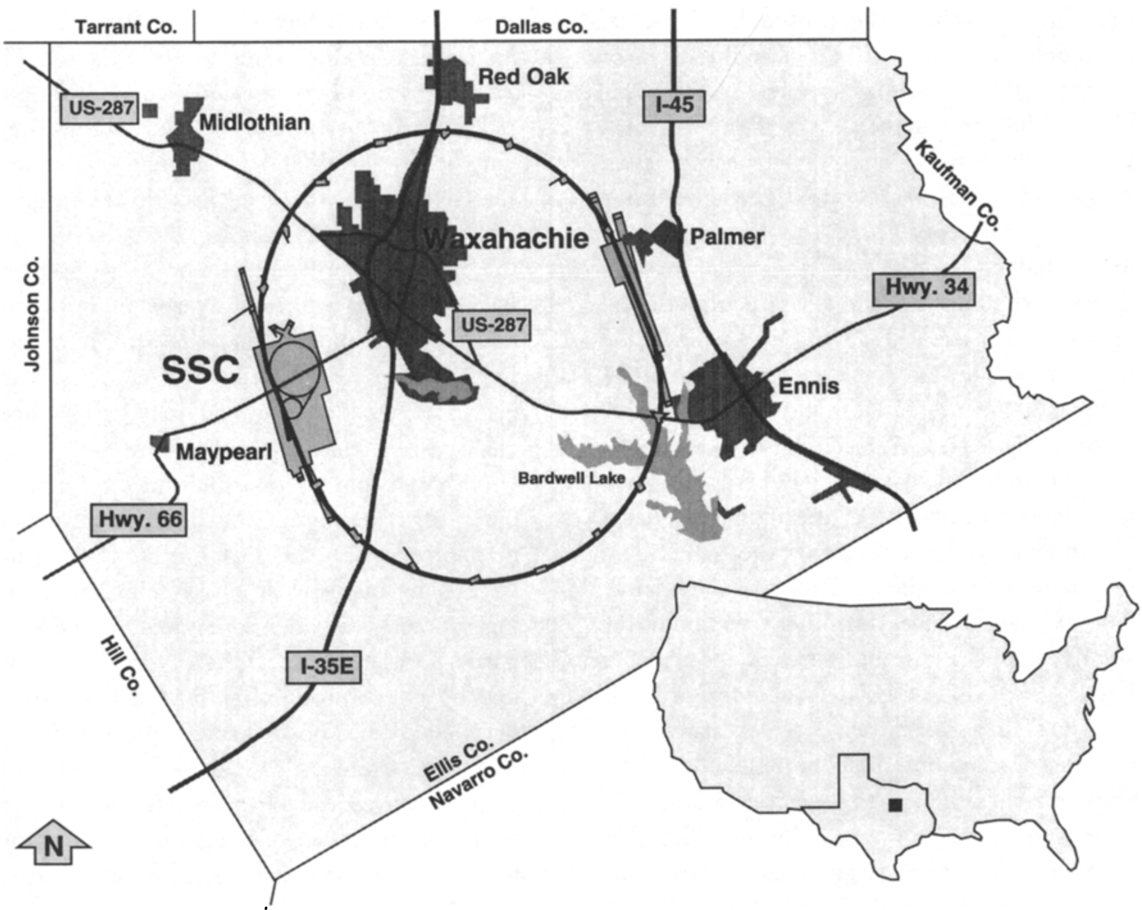

Figure 1. The SSC locale.

Table 1. SSC parameters.

Proton Energy	20 TeV
Circumference of rings	87 km
Protons per r.f. bunch	0.75×10^{10}
Bunch spacing	5 meters
Number of bunches/ring	17,424
Total particle energy/ring	418 megajoules
Emittance (RMS)	1π millimeter-milliradian
Interaction region focal spot size RMS radius, ($\beta^* - 0.5$ m)	5 micrometers
Proton-proton collision rate	60 MHz
Luminosity	1×10^{33} cm^{-2}sec^{-1}
Synchrotron radiation power	8.75 kilowatts/ring

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per ring in each of the proton machines is, of course, unique. The beam intensity of roughly 10^{10} protons per bunch is comparable to that in current state-of-the-art proton accelerators.[1] The bunch spacing is an important experimental quality because it has a great impact on how the detectors and associated electronics are designed. In this machine the bunch spacing is 16 nanoseconds, or about 5 meters in distance. An awesome number is the stored energy in the beam of each ring, nearly half a gigajoule. A major engineering aspect of designing such an accelerator is to handle that stored energy properly and safely to prevent it from damaging parts of the ring or the detectors. Another important parameter is the emittance of the beams. The SSC design relies on emittances somewhat smaller than the current figures at accelerators like the Tevatron or HERA. The design luminosity of 10^{33} was chosen after extensive discussions throughout the community on a balance of issues related to expected production rates for physics processes of interest, detector construction, ease of triggering, backgrounds, radiation damage, and other factors to determine a prudent value for the luminosity for launching a major facility like the SSC. The talk of Takahiko Kondo[2] covers many of the issues. Synchrotron radiation begins to be a serious issue in a machine like the SSC. In particular, we are designing for a nominal load of slightly less than 10 kilowatts per ring, which must be absorbed by the cryosystem of the accelerator.

The scientific targets of the SSC have been discussed extensively for years, and I need only touch briefly on them here. The principal motivation for building the SSC is to discover phenomena that will give insight into physics beyond the standard model. The strategy chosen for doing that is to elucidate the nature of electroweak symmetry breaking, which is really an attempt to understand the detailed structure and behavior of the Higgs mechanism as it pertains to the standard model. The goal is not simply the discovery of another particle, because we already know that the Higgs must exist: the W and Z exist and are made of the Higgs field, whatever it is. So the target is really the more difficult one of understanding the full structure of the symmetry-breaking mechanism. In addition, everyone hopes, and many people expect, that there must be new physics beyond the standard model. Various ideas, while not yet convincing, have been discussed at length over the years.

In addition to the high-mass, generally low-rate, rare physics that we can anticipate in exploring for the Higgs, important studies can be made with super colliders involving processes within the context of the standard model. There will be very high rates for top quark production that should permit detailed studies once the top quark is found. Similarly, the exciting questions surrounding B-quark physics need more attention at high energy colliders because, again, of the copious production cross-section for B-quarks. If we give the same kind of attention to the detectors for these facilities that we have given those in our proposed electron-positron factories, we should also be able to contribute substantially to a better understanding of standard model processes. It has been pointed out recently[3] that there will probably be interesting and perhaps exciting low-Q^2 physics involving the Pomeron and the structure of the vacuum.

With the SSC we are trying to design a balanced and diverse experimental program that can address all these topics. But highest priority will go to understanding the nature of symmetry breaking and to learning new physics beyond the standard model. These questions have been studied and Monte Carloed to death by any number of detector proposals: the crucial parameter of the SSC is its high beam energy chosen so that we can find a definitive

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answer to the question of symmetry breaking within a reasonable period of time. As was discussed throughout this conference, possible masses for the Higgs and relatives of the Higgs will probably span a range from current limits up to the 1 TeV scale (see Figure 2). It is important to note that we now have a solid basis for belief that this full range of possibilities will be addressed by the SSC and fairly soon, too.

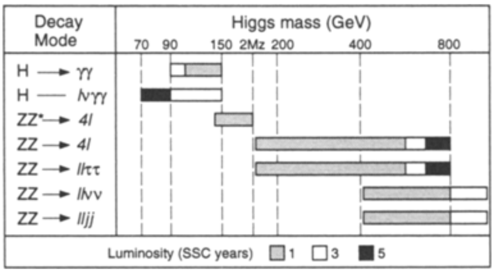

Figure 2. Typical detection limits for the Higgs.

We started our Laboratory about three years ago, taking up residence and rental office space on the southern edge of Dallas (see Figure 3). About two years ago, the first parcel of land was acquired by the state of Texas and turned over to the federal government. This is the land now designated as the N-15 site. About a year ago, we took over a major new building that we call the Central Facility, where now roughly half of the staff resides, in particular most of the people working on the technical design of the accelerators and related systems. Currently, we have a staff of about 2000 distributed among the various facilities.

How well have our engineering designs and technical developments achieved the goals set out for the SSC? The nominal design has a luminosity of 10^{33} $cm^{-2}s^{-1}$ at a beam energy of 20 TeV. As pointed out by Bob Siemann,[4] the expected luminosity can be described as the product of two important parameters. One is the beam brightness, which is the number of particles per bunch, per unit invariant transverse phase space of the bunch; the other is the total current in the ring. Ultimately, the luminosity will be limited by each of these parameters: the brightness and the total current. The nominal luminosity is, we believe, well within the limits that are possible in these accelerators; higher luminosities are ultimately limited by various effects (see Figure 4). In particular, we feel that the brightness figure will actually be limited by the chain of injectors that provide beams to the collider rings. Therefore beam emittance or brightness is something that we have to reflect throughout our designs. The total current for a fixed brightness will be limited at high energies by synchrotron radiation and at low energies by beam-beam phenomena. The latter is essentially the problem of one particle seeing the long line of charge of the other beam as it crosses the interaction region. We believe that it is reasonable to expect substantial increases above the nominal luminosity in the future.

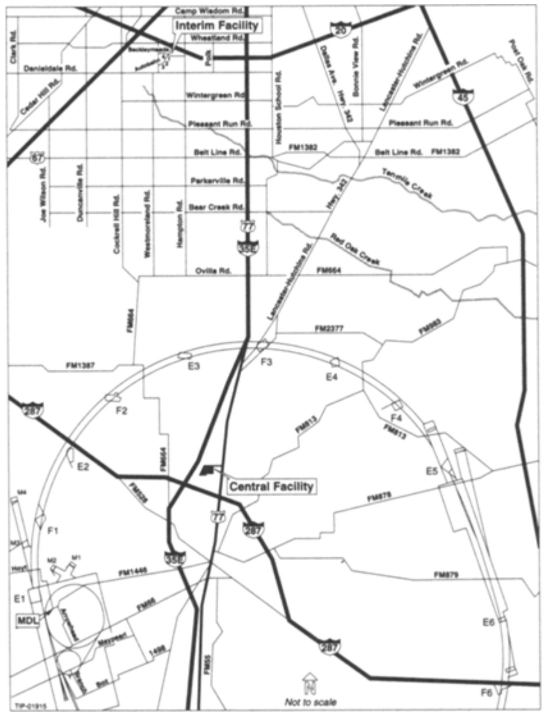

Figure 3. SSC sites.

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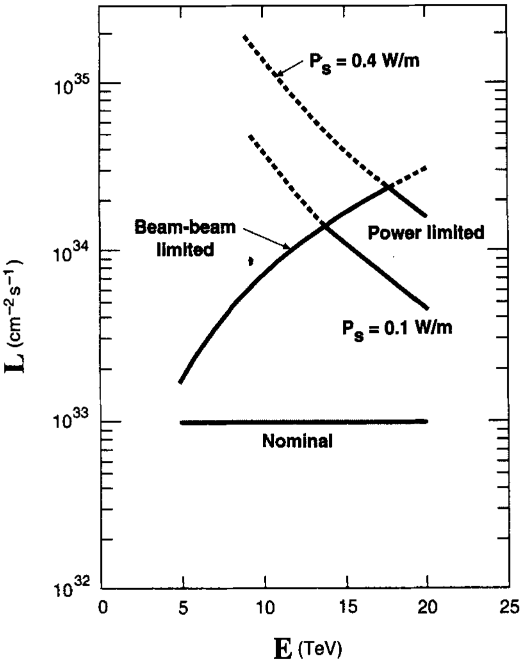

$L \sim B \cdot I$

B = Brightness (N_B/ε_N)

I = Total current

Figure 4. SSC luminosity potential.

Let me now discuss the brightness issue as it relates to the SSC's hierarchy of injectors (see Figure 5). We start with a linear accelerator; then we feed a low-energy booster, a medium-energy booster, and a high-energy booster. The brightness must be maintained from the beginning. The Linac itself, and its related instruments, are now under construction (see Figure 6). A small forest can be seen just off the right edge of the photo where the campus buildings will eventually be located. The Linac is actually a series of different accelerators (see Figure 7). It starts with an ion source, which has been under operation for well over a year. The ion source has achieved the emittance goals necessary for the full design luminosity. The next stage is an RFQ, which is essentially complete and is undergoing initial performance tests. We have ordered the drift-tube linac, and we are working with our colleagues at the electron-positron facility at the high energy physics laboratory in Beijing, who are building with us the coupled-cavity Linac. The most critical bottleneck in the ultimate brightness of the SSC occurs at the next stage in the transfer from the Linac to the low-energy booster. We have chosen the Linac energy to be 600 MeV. However, the tunnel will be long enough to allow us to increase that energy to 1 GeV if we need to. A change from 600 MeV to 1 GeV has the potential of raising the brightness of the beam by as much as a factor of 3.

The low-energy booster is a demanding machine technically (see Figure 8). It is a 10 Hertz, rapid cycling, proton synchrotron, with a large swing of proton velocity and, hence, frequency. This booster is being built in collaboration with the Budker Institute at Novosibirsk where there is outstanding expertise in this class of machines. The Russians

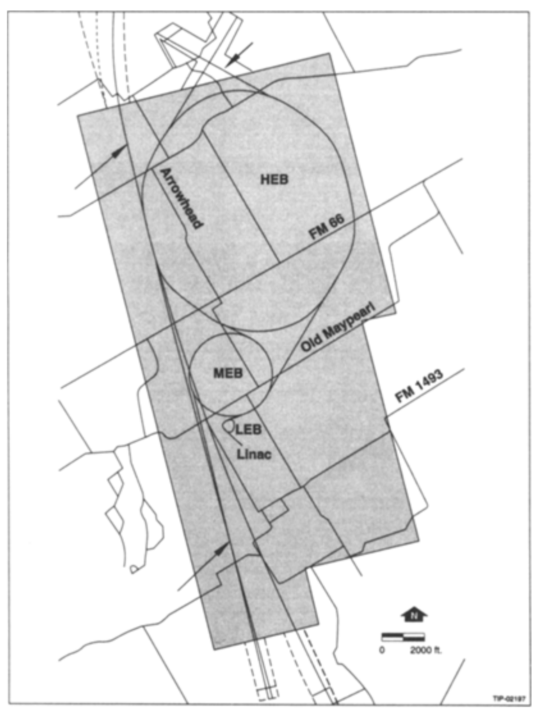

Figure 5. The SSC injectors.

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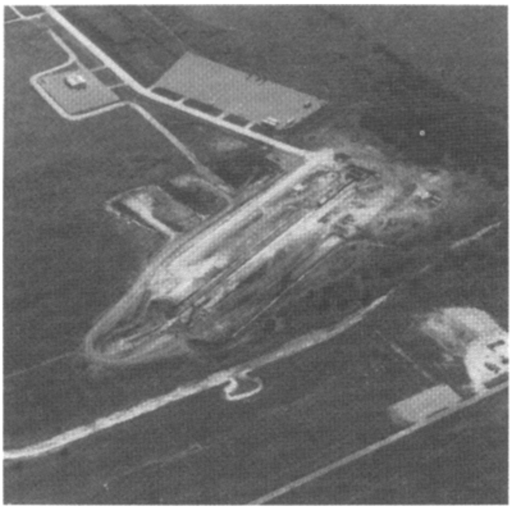


Figure 6. The Linac construction site.

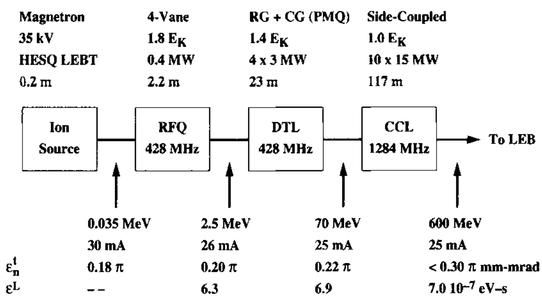
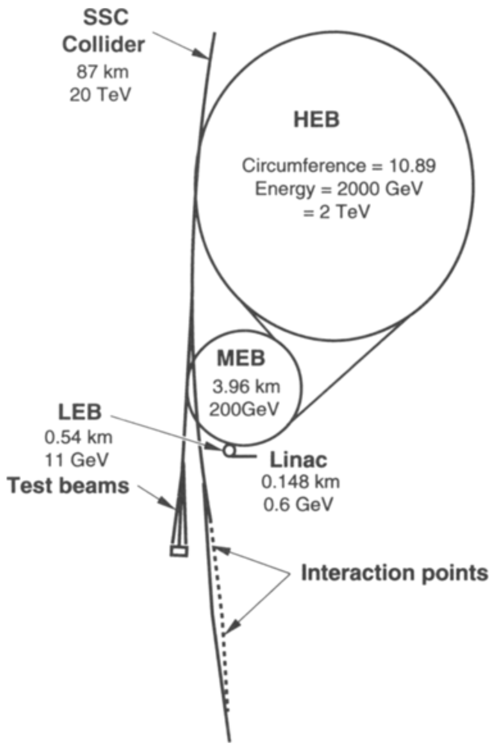


Figure 7. Linac design.

are providing critical help. The next machine in the series is a relatively conventional proton synchrotron accelerator, much like the Fermilab main-ring injector or, indeed, the main ring itself or the SPS at CERN. We are currently collaborating with Fermilab on the design of the magnets for the medium-energy booster.

The high-energy booster is a rapid cycling, bi-polar 2 TeV synchrotron. It will become the second highest energy accelerator in the world. One of the key challenges of this machine is its bi-polar nature, which is required to inject protons into the two proton collider rings in opposite directions. From the outset we will design a bi-polar cycle in that machine



5 Stages of Acceleration

Linac	0 – 0.6 GeV
LEB	0.6 – 11 GeV
MEB	11 – 200 GeV
HEB	200 – 2000 GeV
Collider	2 TeV – 20 TeV

Figure 8. Injector stages.

so that it never has a preferred direction. It will inject into one ring and into the other ring, and keep cycling in this way. A critical aspect of maintaining the emittance and beam brightness is in the various transfer lines indicated in Figure 8. In these efforts we are being assisted with key optical components by physicists from India and China and elsewhere.

The rapid cycling nature of the high-energy booster as shown in Figure 9 also puts demands on the superconducting mag-

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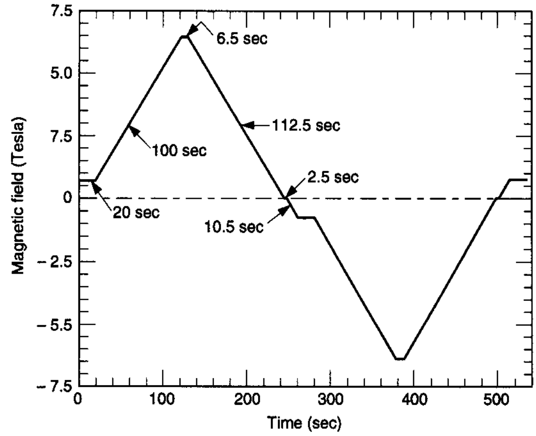

Figure 9. HEB acceleration cycle.

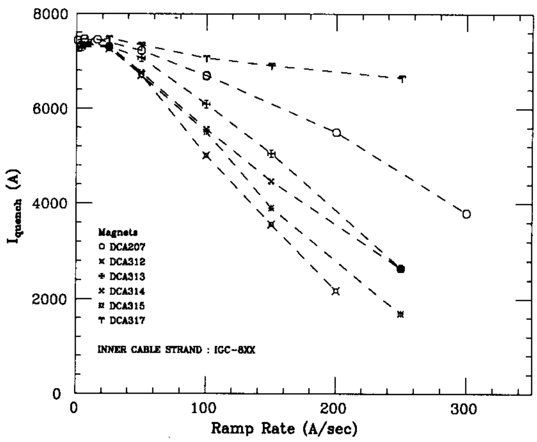

Figure 10. Quench current vs. ramp rate.

nets, which are quite similar in concept to the collider magnets. Some recent results are important and interesting. Figure 10 shows tests of the quench current capabilities of our dipole magnets as a function of ramp rate. The nominal ramp rate for the high-energy booster is 70 amps/second, and there is a wide spread in the currents at which these magnets quench. Some of them quench at relatively low currents at a high ramp rate, and we are actively investigating to understand why. The collider itself ramps at a very low rate, so the ramp rate dependence is really not an issue for the main collider. The quench properties are believed to arise from eddy current heating in the magnet cable during the ramp. In addition to quench properties, there are also effects on the quality of the field associated with the high ramp rate. We have developed over the past few months a detailed model of this phenomenon (see Figure 11). The model describes eddy-current effects by the linkage of flux through connected turns of different wires in a cable; different strands in the cable form a loop around which an EMF can be generated and hence currents can flow. The circulating currents will both heat up the copper matrix of the wire slightly and disturb the quality of the magnetic field. The model has been run on the computer, and it explains rather satisfactorily the phenomena we are observing in terms of the interstrand resistance of the wires as they are pushed into one another during the fabrication of the cable. Figures 12 and 13 show some of the multipoles of the magnets, the non-uniform field components that we observe as a function of current. The important thing to notice is that, in addition to the intrinsic, persistent current phenomena that one sees in the superconducting magnets having to do with the filaments inside the wires, one sees this eddy current effect in the cable. We are now trying to understand this as it relates to the quality control and manufacturability of the cables. A class of magnets exists with resistances high enough that this is not a problem, and we are trying now to control the production of the cable so that it always provides satisfactory magnets. We expect there to be a straightforward engineering solution to the ramp-rate issue.

We have made some minor changes in the final design of the main collider arcs. The lattice was modified by removal of 124 dipoles to produce space in the arcs for utility feeds that match the location of surface facilities, and the magnet interconnect space was increased from 65 to 82.5 cm. The consequences of these changes are shown in Table 2. The peak magnetic field has actually been raised

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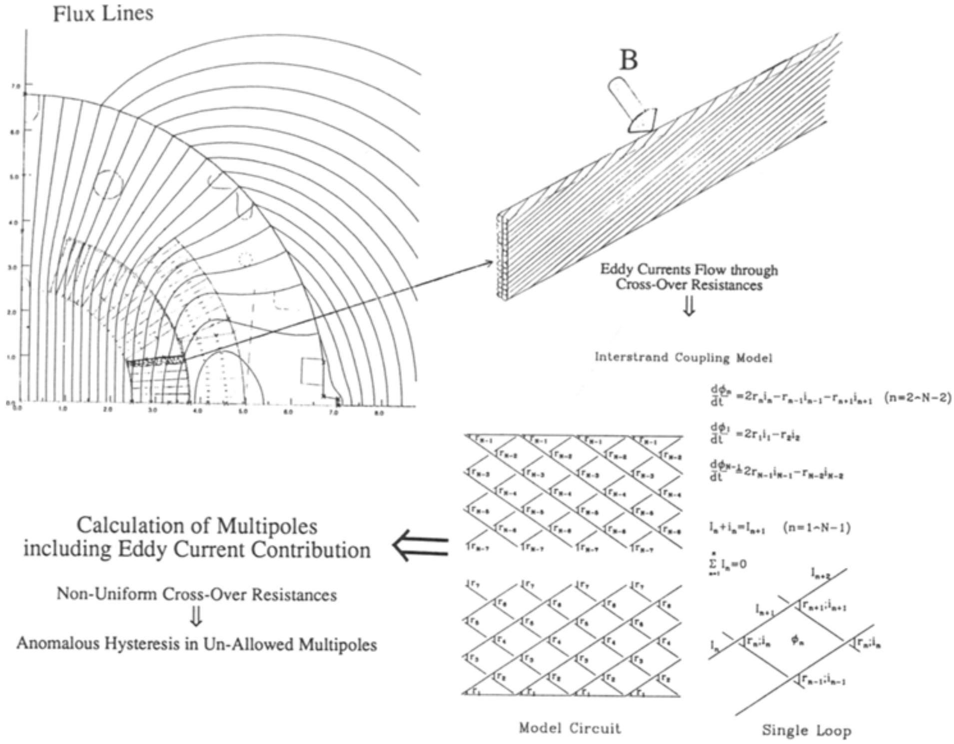

Figure 11. Model of eddy-current effects.

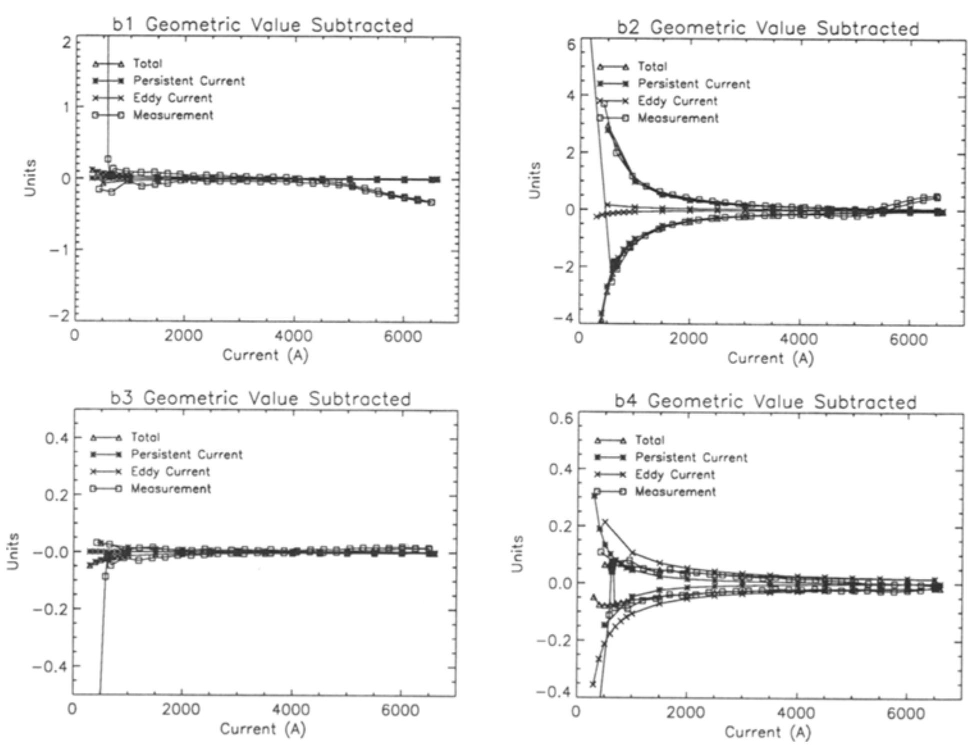

Figure 12. Dipole magnet multipoles (start).

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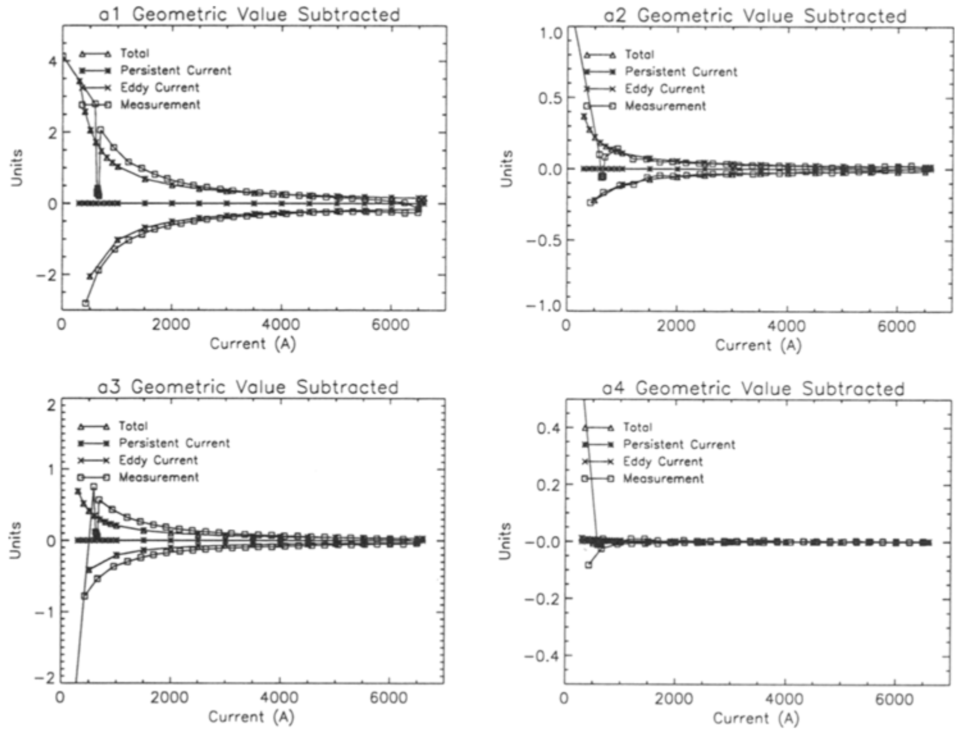

Figure 13. Dipole magnet multipoles (end).

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Table 2. Collider arc lattice.

Quantity	SCDR Lattice	Current Lattice
15 m CDM field integral @ 20 TeV	100.008 T-m	101.363 T-m
13 m CDM field integral @ 20 TeV	83.424 T-m	84.469 T-m
15 m CDM magnetic length	15.165 m	14.99 m
CDM field @ 20 TeV	6.6 T	6.762 T*
CDM margin	> 10%	> 10%
Quadrupole integrated gradient @ 20 TeV	1069 T	1069 T
CQM magnetic length	5.2 m	5.025 m
Quadrupole gradient @ 20 TeV	205 T/m	212.7 T/m
Collider operating temperature	4.35°K	4.25°K
Collider operating current @ 20 TeV	6500 A	6668 A

* Increased CDM saturation requires an increase in the quadrupole corrector strength for tracking during acceleration.

slightly to provide more room in the lattice for other components. We have lowered the temperature slightly to keep the operating margin for the magnets; the operating current will then be somewhat over 6600 amps. The precise geometry of the collider and injectors is fixed so that construction of the tunnel can proceed. Figure 14 gives an overview of the tunnel design. In addition to the main tunnel, which is about 14 feet in diameter, there are a number of shafts from the surface down to the tunnel that are used to provide access for utilities or personnel; the oval shafts are used for magnet installation. At present we have completed a triplet of shafts, and we have under contract the four sections of tunnel indicated by the shadings in Figure 14. The contracts cover essentially half of the collider tunnel, and we will be getting under way with tunnel boring machines in September of this year.

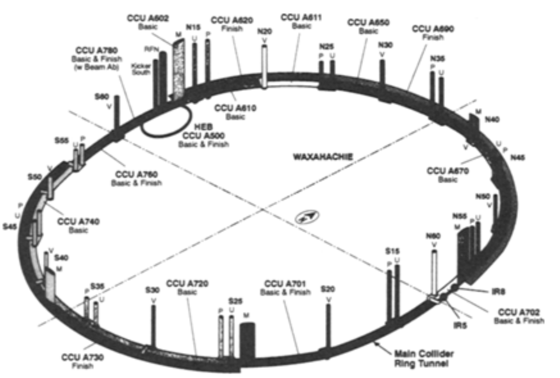

Figure 14. Tunnel design overview.

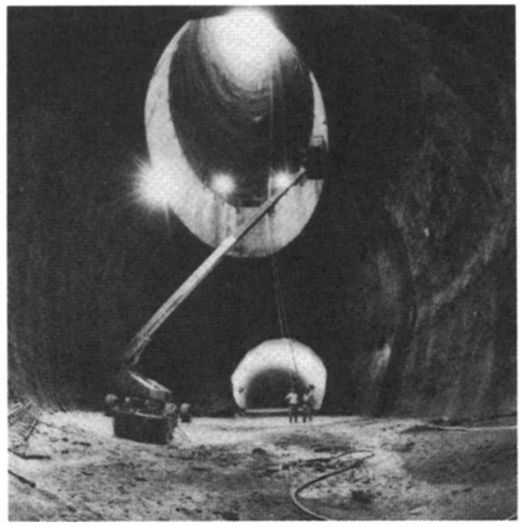

Figure 15. Inside magnet delivery shaft.

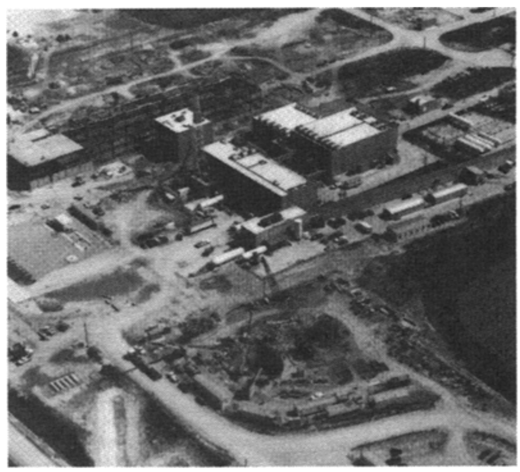

Figure 16. N-15 construction site.

Figure 15 is a photograph taken down inside the large magnet delivery shaft where they are preparing the way for the large tunnel boring machine. Figure 16 shows the surface area of the magnet delivery shaft. Under construction here is the utility tunnel where the cryogens and power supplies, which will be housed in the buildings shown, will feed this region of the ring. The N-15 service area shown in Figure 16 is typical of those that will be located at intervals around the ring. Twelve of them will be built for the full complex of the high-energy booster and the collider.

The most critical technical components in the collider are the 50-mm dipole magnets. We have been working with Fermilab, Brookhaven National Laboratory, Lawrence Berkeley Laboratory, Saclay, and KEK on the development of the magnets needed for this facility. Elegant engineering is being focused on the ends of the

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magnets to improve our ability to install them and service them in place. These magnets exhibit excellent mechanical integrity. Figure 17 displays quench curves for several magnets, indicating a healthy operating margin between typical quench currents and the current required for 20 TeV operation with a virtual absence of training quenches. We have just about completed the preliminary development cycle for the collider dipoles. Eighteen of the 50 mm magnets have been built, 12 of them by industry working at Fermilab and Brookhaven. Three more dipoles will be produced in this preliminary phase; two of them will be built at our Magnet Development Laboratory (see Figure 18). We built the MDL on our campus site, and it is already an active laboratory. Soon, magnets will be tested in the Magnet Test Laboratory and constructed at the N-15 site. The MDL also has the capability for mass producing dipoles (see Figure 19). We will probably focus, however, on constructing various special magnets that are needed in relatively small quantities; most of the magnets of standard design will be built by industry.

We are now in the midst of a very critical undertaking called the Accelerator System String Test, which is a full system test of one half-cell of the machine. The test consists of

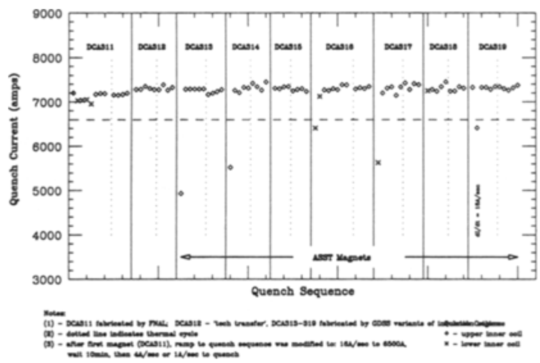

Figure 17. 4.35K quench performance.

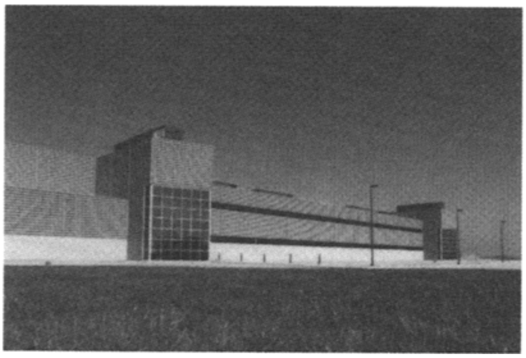

Figure 18. The magnet development laboratory.

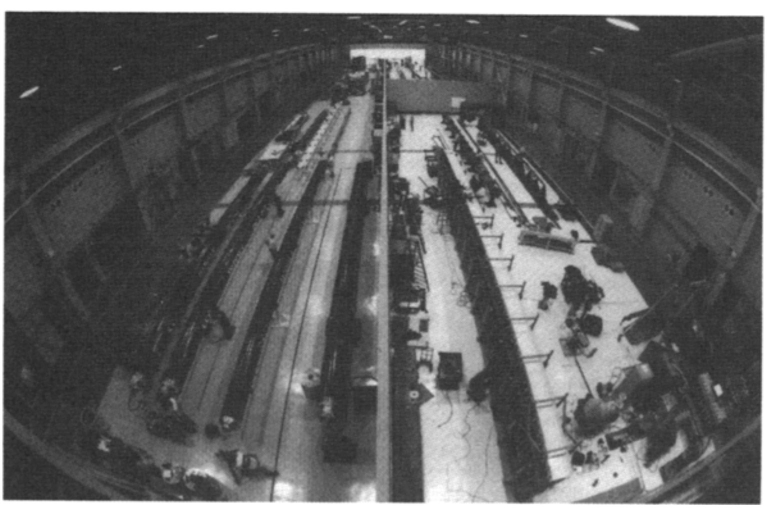

Figure 19. MDL interior.

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five dipole magnets, a quadrupole magnet, and a "spool piece" where all the plumbing and correction coils are found. Also installed at the N-15 site, the test has been cooled down and is now being operated (see Figure 20). It has a full control room where we can begin to test some of the concepts of our control system (see Figure 21). We began to cool down the string at the end of June; the waves of reduced temperature propagating through the string of magnets can be seen in Figure 22.

Figure 20. The ASST.

Figure 21. ASST control room.

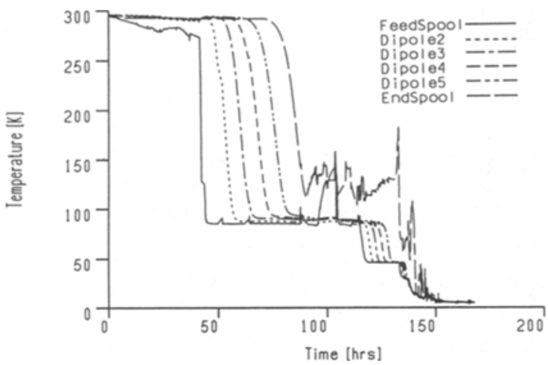

Figure 22. ASST cool down.

Just two years ago, literally to the day, before this string of magnets became superconducting, the land for the N-15 site was purchased by the State of Texas. It was poor, unimproved land, but today there are 100 meters of superconducting magnets there and a lot of related instrumentation. Typical voltages, pressures, and currents during quenches are shown in Figures 23, 24, and 25. In early August we began increasing the current, and we achieved operation at 4000 amps, roughly two thirds of that required for the full 20 TeV operations. (Author s note: The magnet string was successfully ramped to 6.6 T, the nominal SSC operating field, on August 14, and held at that level for some minutes before being lowered to zero.)

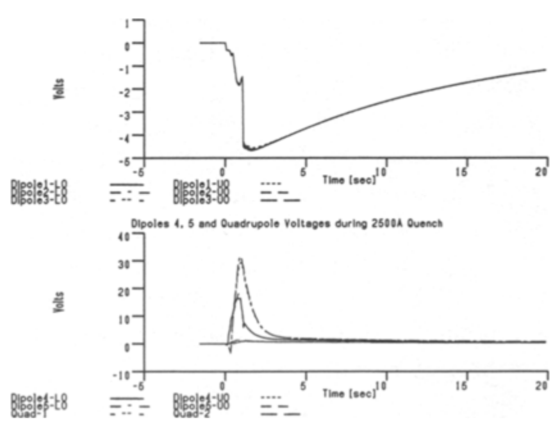

Figure 23. ASST quench characteristics (start).

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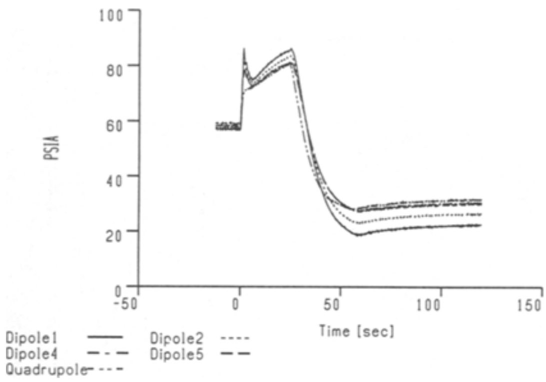

Figure 24. ASST quench characteristics (cont'd).

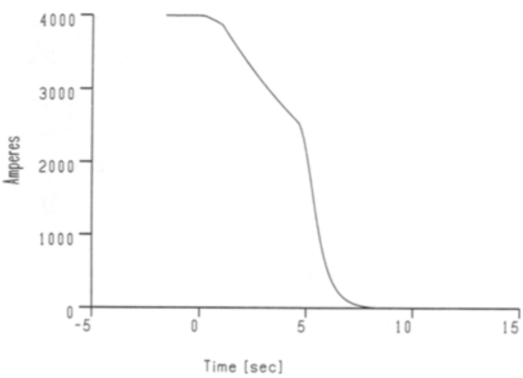

Figure 25. ASST quench characteristics (end).

A significant problem presented by the very high luminosity performance of machines such as the SSC will be the vacuum in the beam tube because of the desorption of gas molecules by synchrotron radiation from the beams. To deal with this vacuum issue, an extensive R&D program is already under way. It is a collaborative, world-wide effort to study problems of photo-desorption of gas off the cold surfaces inside the superconducting magnets. An important decision facing us within the next few months will be whether to put a special liner in the beam tube to intercept the synchrotron radiation.

Regarding schedule, we are already beginning to build the Linac. Depending largely on the total funding that is voted by Congress, we are placing the highest priority on maintaining the collider schedule. Other desirable systems, such as our test beam facility, will have to be delayed, however. We feel it will still be possible, but *difficult*, to complete the machine in the spring of 1999 and to begin commissioning during the summer of that year so that the physics could begin in the fall (see Figure 26). Depending on funding in subsequent years, this schedule may be delayed.

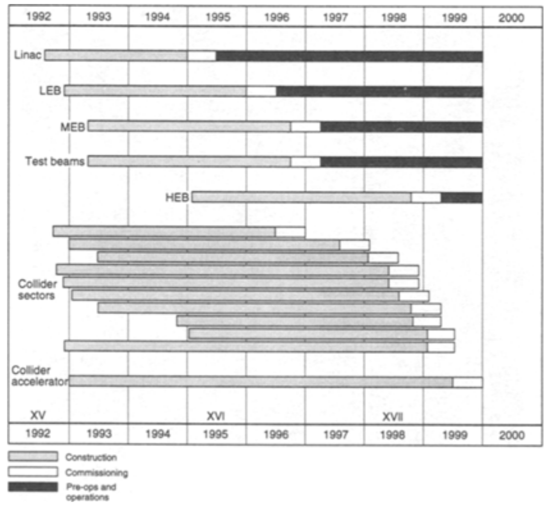

Figure 26. SSC schedule to FY2000.

The SSC's initial scientific program was covered well in the presentation by Takahiko Kondo.[5] We began the process of defining the SSC's initial scientific program with the receipt of Expressions of Interest in June of 1990. To date we have received 21 Expressions of Interest and they run the full gamut from huge detector collaborations down to one-person, one-page proposals. We are now in the process of formal reviews that will move forward to the selection for construction of two large detectors. These are huge international efforts representing roughly half of the U.S. experimental high energy physics community and a comparable, maybe even larger, number of foreign participants. We and our advisory committees

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feel that it is important to reserve some capital funds for the support of smaller experiments that can address other aspects of SSC physics. We are now in the process of hosting workshops and will be calling for new proposals for smaller experiments sometime within the next two years. The worldwide effort in detector R&D over the last three to five years has been outstanding, giving us confidence that the very large and smaller experiments can be designed to operate at the 10^{33} level of luminosity and perhaps higher.

In conclusion, the scientific opportunity at the SSC will be unparalleled. The machine represents a 20-fold increase in energy beyond what is available today, and it will be able to explore physics beyond the standard model. We are making every effort at our Laboratory to preserve the possibility of a diversity of experimental areas. As of today, much of the Laboratory staff has been assembled, and they are a smoothly working team of the highest caliber. Substantial construction is under way; the string test is in progress (see the author's note above), and two large detector collaborations are moving ahead. We look forward to the view beyond the standard model that the SSC will give us beginning at the turn of the century.

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DISCUSSION

Gil Gilchriese, Lawrence Berkeley Laboratory, USA

While the SSC is not out of danger yet, what would you as the director of the SSC suggest to us, the future users of the machine, to tell our Congressmen to convince them that this is a necessary machine?

Schwitters

I think the best way to get the message to Congressmen is to convince the people who vote for them how important the SSC is. I believe we owe it to society to do our best in explaining the values of high energy physics to our fellow citizens, since they are paying the bill. You should go out and talk to the local Lions club, Cub Scouts, and similar groups. Such an educational effort is a huge task, but it is important and needs doing without delay.

C. Rubbia, CERN

You have shown a table indicating that by the end of the century the machine will be finished as a construction project. Do you have a funding profile associated with it? If you want to spend 8 billion dollars in eight years, it takes at least 1 billion dollars every single year.

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Schwitters

The plan for the upcoming fiscal year called for $650 million in federal funding. As you know, the Senate voted for $550 million. We are, of course, analyzing the impact of such a reduction on the schedule. Priority is going to the collider in order to maintain that schedule. It may make it more difficult for us to provide test beams, say, as early as we desire. The shortfall in funds will also lead to inefficiency and increased costs through inflation that will increase the overall construction cost. We are not yet projecting a delay in the completion date for the collider, but continued shortfalls in funding will certainly delay things. The biggest danger we face, in my view, is chronic funding reductions leading to major slippage in schedule. We are doing everything we can to maintain the schedule.

Georgio Belletini, Sezione Infn di Pisa

Recently, a study was made by the accelerator group of the SSC indicating that if you take the start of the machine for physics to be when the luminosity is 10^{30}, it would take 3 calendar years to reach 10^{33} with a factor of ten increase per year. How technically sound is this study, and what are the real limitations?

Schwitters

You are referring to a preliminary "what if" study. What if the luminosity goes up in steps like this? That study represents a set of judgments by physicists and accelerator experts, an attempt to plan a rational early program for the SSC. I would describe it as the initial response, and now we must review the plan with all the various parties involved—detectors and accelerators—and refine it accordingly.

K. Cahill, University of New Mexico, USA

It may be possible to improve injection into the low-energy booster by having an H^- physics facility there, and it might only cost a half million dollars. It would also blunt criticism from the atomic physics community. Is there any movement in that direction?

Schwitters

We received a proposal to do just that. The idea is to study the H^- system as an example of a three-body quantum-mechanical system. There are some interesting resonances and questions that one can study with relativistic H^- beams where the Doppler shift can help. We also plan to have a special channel to divert protons or H^- ions from the Linac to be used in a proton therapy facility. Here one can use laser-stripping to make a fail-safe mechanism to bring the protons out in a safe manner.

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