THE SSC PROJECT

Presented for the SSC Central Design Group*

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Abstract: The SSC Project

The SSC is a 20-TeV, proton-proton collider proposed for construction by the U.S. Department of Energy (DOE). Completion is planned for the mid-1990s. A technical description of the accelerator is given along with a report on the status of the project.[1]

Introduction

It was a pleasure to have Professor Zichichi precede me in this series of presentations, since it allows me to describe the SSC as a modest accelerator. Professor Zichichi's remarks should give all of us hope for the future beyond LHC and SSC. I hope that the SSC is not the end of the line for hadron colliders; it would be wonderful if the Eloisatron were built.

It is fitting that I remind this audience that a more ambitious proposal was made by Enrico Fermi more than thirty years ago. As a graduate student I had heard of his proposal for an earth-circling accelerator as part of the folklore that is passed on from teacher to student. While preparing this talk, I decided to track down just what the proposal was. Thanks to the memory of one of my colleagues, who heard Professor Fermi speak, and to the diligence of the History of Accelerators Project at Fermilab and the J. Regenstein Library, I was fortunate enough to receive a copy of Professor Fermi's typewritten notes for the farewell address that he gave to the American Physical Society on 29 January 1954. Tradition required that the outgoing president of the American Physical Society address the Society at the New York meeting when the new president was inaugurated. Professor Fermi chose as the title of his talk, "What Can We Learn with High Energy Accelerators?" He reminded the audience of what had been learned about elementary particles in the last few decades. He noted that there were too many so-called elementary particles. In spite of the stupendous number of names there was a tantalizing vista. Fermi asked rhetorically "What to do?" His answer was to clamor for higher and higher energy. He extrapolated to 1994; for that date he proposed a machine with a radius of 8000 km, a field of 20000 gauss, and an energy of 5×10^{15} eV (5×10^{3} TeV in our contemporary units). He even had a cost estimate: $170 billion.

Although Professor Fermi's machine was a fixed-target machine, I am sure that he would have added another ring if the practicality of colliding beams were then known. Two such rings would give 10^4 TeV in the center of mass. (There is still a goal to shoot for beyond the Eloisatron.) Clearly, the Fermitron would be an international laboratory, since its magnets would circle the earth 1600 km above the surface. As a fixed-target machine, the center-of-mass energy proposed by Professor Fermi was 3 TeV. We are not quite on his ambitious schedule, although the Tevatron has already reached 1.8 TeV in the center of mass. The LHC and SSC will exceed that energy, although a bit later than 1994.

Essential Parameters of the SSC

The Superconducting Super Collider, the SSC, is a proposed high-energy, high-luminosity, *pp* collider.[1] The basic parameters, which are by now familiar to many people, are given in Table 1.

Table 1. SSC Parameters — Collider Rings

Circumference of each ring	83.631 km
Interaction Region (IR)	6 (4 initially configured)
Beam Energy	20 TeV
Peak luminosity (at $t = 0$), $\mathcal{L}_p$	10^{33} cm^{-2}sec^{-1}
Bunch Intensity at $\mathcal{L}_p$	8×10^9
Number of bunches at $\mathcal{L}_p$	15,456
β^* at low-β IR	0.5 m
Normalized betatron emittance	1 mm-mr
Nominal beam storage time	24 hr

The 40-TeV center-of-mass energy will be more than adequate to produce experimentally observable collisions of quarks and gluons, the point-like constituents of the protons, at center-of-mass energies in excess of 3 TeV. This should bring us to the threshold of understanding some, if not all, of the many parameters in the standard model.

I will talk about a few aspects of the R&D program today. Let me begin with the Conceptual Design, then move to the magnet systems, and finally review the status of the site selection.

Conceptual Design of the Injector

The Conceptual Design Report[1] (CDR) for the SSC was published in March 1986. It provided a very detailed description of the SSC. No matter how detailed such a description is, however, it is not static; time allows the development of small improvements. While the basic elements of the SSC have remained unchanged since the CDR was completed, a number of refinements have been made and will continue to be made to the design. I will take note of some of them today.[2] Let me begin with the injector. Some of its basic parameters are given in Table 2.

Table 2. SSC Injector Parameters

	Linac	LEB	MEB	HEB
Injected particle	H^-	H^-	H^+	H^+
Injection momentum (GeV/c)	0	1.22	8.45	100
Extraction momentum (GeV/c)	1.22	8.45	100	1000
Circumference/length (m)	125.0	342.8	1751.5	5336
f_{rf} at extraction (Mhz)	1263.2	62.0	63.0	63.0
Average current (mA)	3.9	100	95.0	95.0
Normalized rms transverse emittance (mm-mr)	0.45	0.75	0.83	0.91
Longitudinal rms emittance/ bunch (eV-sec)	0.012×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	35.0×10^{-3}
Cycle time (sec)	0.1	0.1	4.0	60.0

* Operated by Universities Research Association for the U.S. Department of Energy.

The Linac accelerates H^- ions to a momentum of 1.22 GeV/c. These ions are injected into a rapid-cycling, 10-Hz synchrotron, the low-energy booster (LEB), where they are stripped and accelerated to 8.45 GeV/c. The 8.45 GeV/c protons are transferred to the medium-energy booster (MEB), a second synchrotron built with conventional magnets. Five LEB cycles are needed to fill the MEB. After the MEB is filled, the protons are accelerated to 100 GeV and are then transferred to the high-energy booster (HEB), a synchrotron made with superconducting magnets. After three MEB cycles, when the HEB is filled, the protons are accelerated to 100 GeV/c and then transferred to one of the collider rings. Sixteen HEB cycles, which take a total of 16 minutes, are needed to fill each collider ring. After one is filled, the polarity of the HEB is reversed and the second ring is filled. The total filling time for both rings is expected to be less than one hour.

During the past two-and-a-half years, the lattices of the LEB, the MEB, and the HEB have each undergone some change as the designers have sought to make them easier to tune and operate, to reduce the dispersion, and to reduce the sensitivity to the alignment errors. Parameters, such as the tunes, will undoubtedly continue to change slightly as the design is refined further. It is intended to complete the refinement of the lattice design of each of these accelerators next year, following selection of a site. Prototype development of the injector components could begin soon thereafter. Since each of these injector accelerators has a close counterpart in operation today, the need to build prototype components is not nearly as urgent as it is for the collider rings.

Conceptual Design of the Collider Rings

The collider rings consist of two arcs, each containing 144 cells 228.5-m long. Each half-cell contains six 16.54-m 6.6-T dipoles, one 230-T/M quadrupole, and a correction element package. The correction element packages are used to control global properties of the ring such as tune and chromaticity, as well as local beam orbit distortions. In addition, each dipole is intended to have its own small correction package, the bore-tube corrector, which can be thought of as compensation for the unwanted multipoles of the host dipole. The arcs are joined by two clusters of four modules, designated "near" and "far"; within each module there is a straight section.

Two of the IRs in the near cluster are intended to be high-luminosity intersections for large, general-purpose detectors. There will be a 340-m free space centered around the collision point, and β^* will be equal to 0.5 m. The luminosity in these locations is intended to be in excess of 10^{33} cm^{-2}sec^{-1}. The two remaining straight sections in the near cluster will be used for injection, abort, rf, and other accelerator systems requiring space in the straight sections. Two of the IRs in the far cluster are intended to be medium-β IRs with a free space of 234 m centered around the collision point. The luminosity of these interaction regions is expected to be 5×10^{31} cm^{-2}sec^{-1}. The remaining two straight sections in the far cluster have been set aside for future interaction regions.

Because the cost of the SSC is dominated by the cost of the collider rings, they have received the most attention. The largest single cost of each collider ring is the cost of its superconducting magnets. Since their cost is roughly proportional to the diameter of the coils, and since the unwanted multipoles of order n are inversely proportional to the diameter to the $(n+1/2)$ power, there is a strong tension between cost and useful aperture. After an extensive analysis of particle orbits, the inner diameter of the inner coil was chosen to be 40 mm.[3] Subsequent work, as will be noted later, indicates that this diameter provides an adequate dynamic aperture for the beam. Since the CDR was completed, the phase advance/cell of the collider lattice has been increased from 60° to 90°, in order to improve the aperture-versus-cost optimization and to improve the off-momentum beam behavior.[2] The designs of the dispersion suppressor and of the straight sections have also been changed.[3] The current values of the collider ring parameters are summarized in Table 3.

Table 3. Collider Ring Parameters

Circumference	83.631 km
Arc cell length	228.5 m
Half-cell composition	6 dipoles, 1 quadrupole 1 corrector package
Number of cells/arc	144
Phase advance/cell	90°
Horizontal and vertical betatron tune	95.285, 95.265
Dipole field (length*)	6.613 T (16.54 m)
Quadrupole gradient (length*)	228.7 T/m (3.64 m)
Bore tube inner diameter	32.23 mm
Linear aperture (radius)	~ 10.7 ± 2.0 mm
Dynamic aperture (radius)	15.0 ± 0.6 mm

*magnetic length

The available good field aperture has been defined in terms of the linear aperture, defined to be the aperture for which the rms variation with time of the Courant-Snyder invariant amplitude, W, is less than 6.4 percent. W is given by

$$W = \left(\frac{x^2 + (\alpha x + \beta x')^2}{\beta}\right)^{1/2}$$

It approaches zero as the betatron amplitude of a particle approaches zero. The dynamic aperture is defined as the largest betatron amplitude that remains bounded after an arbitrarily large number of turns. For machines built in the past, the dynamic aperture has usually been larger than the physical aperture of the vacuum chamber and, in those cases, has been only of academic interest. This is not the case for the SSC, since the unwanted multipole fields of the dipole fields limit the dynamic aperture to a value that is less than the bore-tube diameter. The required linear aperture (radius) is estimated to be about 5 mm.

Because the operational performance of the SSC will depend on whether the linear aperture can be achieved with the proposed magnet design, a great deal of effort has gone into theoretical modeling of the particle orbits through tracking programs and analytical calculations. The various methods of calculation give the same results for the size of the linear and dynamic aperture. It is worth noting that these calculations showed that if nothing further were done to reduce the effect of these multipoles, the linear aperture would only be 5 mm for the multipole specifications that have been subsequently adopted for the 16.54-m collider dipoles. In addition, the results of tracking programs have been checked against beam behavior in the Tevatron in experiment E778. In this experiment, the sextupole strength of a number of sextupoles was increased while the tune and chromaticity were kept fixed, in order to simulate the conditions that a beam would encounter in the SSC. The preliminary results reported at this conference are very encouraging, since it appears that the theoretical prediction of the size of the linear aperture agrees with the observed linear aperture.[4] The understanding is not complete, since the predicted dynamic aperture is 20–30 percent larger than the observed dynamic aperture. One possible reason for the discrepancy is that the simulation was obtained in a tracking for a relatively small number of revolutions (500). This work will continue.

As noted earlier, if the systematic multipole fields of the dipoles were corrected only once per half-cell and the random multipole fields were left uncompensated for, then the linear aperture would be considerably smaller than 10 mm. The multipole field of the greatest significance is the sextupole, which has particularly large systematic and random contributions that must be compensated for more often than once per half-cell. Two schemes to neutralize these unwanted multipoles are under consideration. Both have been developed since the CDR was completed. In the first scheme, each dipole has a corrector mounted on the bore tube; each bore tube; each corrector has a sextupole and decapole winding.[5] Since these windings can be individually powered, each can be assigned to a bin according to the sign and magnitude of the random part of a particular multipole of the host dipole. By having up to seven bins for each multipole, and by connecting all of the bore tube corrector windings in each bin in series and then exciting each circuit separately, the random multipole contribution per dipole can be decreased by a factor of five. Thus the unwanted random multipole fields of the dipole can be compensated for locally.[6] The unwanted systematic multipole fields of the dipoles can be compensated for by incrementing the currents in all windings of a given multipole by the same current. This magnet-by-magnet compensation can be achieved either by placing a short magnet on the bore tube at one end of each magnet or by placing thin windings on the outer surface of the bore tube. The latter approach is favored at the moment, and the design is based on it.

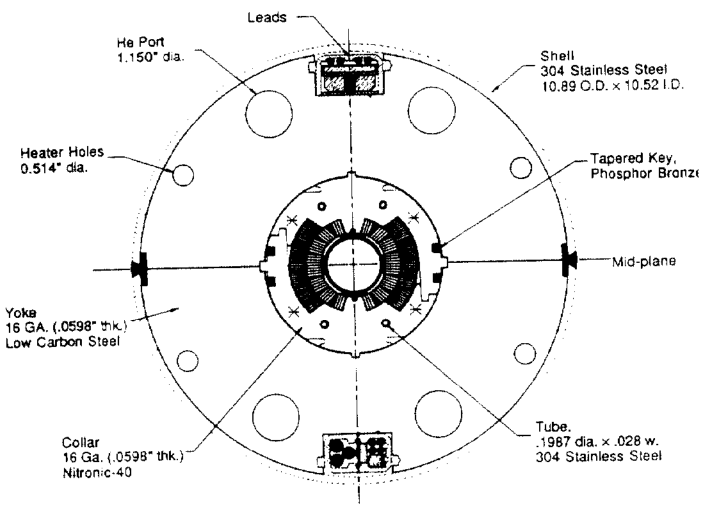

Figure 1. SSC dipole cross section, with BNL C358A coil.

The second scheme, due to Neuffer, uses a single additional set of correctors located in the middle of each half-cell.[7] The standard correctors located next to the quadrupoles in each half-cell, together with an additional correction element placed in the middle of each cell, are binned in accordance with the multipole content of the six dipoles in each half-cell. Studies have shown that this second scheme can provide sufficient linear aperture, provided that the sextupole error is below a reasonable level. Beyond this level, it was suggested that octupoles could be added to correct the non-linearities introduced by the strong sextupole correction elements. It appears that both schemes can do the job. The results of the calculations and experiments to date give one confidence that the relatively strong multipoles of the SSC dipoles can be accommodated.

Magnet Development Status

An R&D program to develop a suitable dipole for the collider was initiated by the SSC Central Design Group (CDG) four years ago. Since that time, the CDG has directed an active program of building model magnets at Brookhaven National Laboratory, Fermilab, and Lawrence Berkeley Laboratory. In 1985, the CDG adopted the basic magnet design of a two-layer coil with an approximate cos θ current distribution, a non-magnetic collar to limit mechanical motion of the coil perpendicular to the beam direction, and an iron yoke within the cryostat. As can be seen in Figure 1, a cross section of the collared coil, there are four inert copper wedges per quadrant interspersed with the coil windings. The locations of these wedges make it possible to reduce all of the unwanted multipoles, except for the sextupole, b_2, to the specified values. At low fields b_2 is determined by persistent currents in the conductor, and at high fields it is determined by the saturation of the iron yoke. The specification for the random variation of the multipole fields was determined by scaling from the Tevatron and CBA dipoles. To date, the random variations have been less than those tolerances.

Because it is intended that the iron yoke provide 2.2 T of the 6.6-T field, the radial separation between the outer surface of the outer coil and the inner surface of the yoke is only 15 mm. Although this leads to a magnet with a stronger field for a given number of ampere turns, the collar alone does not have sufficient rigidity to limit the mechanical motion of the coil perpendicular to the beam to 50 μ when the coil is excited to 6500 A. Its expansion must be constrained by the iron yoke if the coil is to reach its design current without quenching. Initially, it was intended that the collared coil be unconstrained by the yoke, but we now recognize that the yoke plays a critical role in limiting the coil motion. In order to clamp the coil in this way the temperature of the yoke must be held at 4.35 K. While there are some operational disadvantages with this choice—the iron yoke is the dominant contribution to the mass that must be cooled down—it makes it possible to design a very efficient cryostat and support system. Some of the systems requirements for the collider dipole are summarized in Table 4.

Table 4. Dipole Systems Requirements

Magnetic properties		
Peak magnet field at 4.35 K	6.613 T	
Transfer function at 1 TeV	1.0309 T/kA	
Transfer function at 20 TeV	1.0147 T/kA	
Magnet length	16.54 m	
Random variations of magnetic multipoles (rms)		
b_2 (a_2)	2.0	(0.6)
b_4 (a_4)	0.7	(0.2)
b_6 (a_6)	0.2	(0.1)
b_8 (a_8)	0.1	(0.1)
Heat leak budget/dipole		
at 80 K	27.0 W	
at 20 K	3.3 W	
at 4.35 K	0.32 W	
Synchrotron radiation power deposited in the bore tube dipole	2.34 W	
Critical mechanical dimensions		
Slot length	17.34 m	
Bore tube inner diameter	32.26 mm	
Vacuum vessel outer diameter	60.96 cm	

As noted earlier, magnet development is being carried out at three national laboratories under the direction of the CDG. Brookhaven has been responsible for the initial design and subsequent fabrication of all cold masses for the 16.5-m prototypes. Fermilab has been responsible for the design of the cryostat and has installed the 16.5-m cold masses in cryostats. LBL, together with industry, has been responsible for the development of the superconducting wire and cable. To date, all cold masses for 16.5-m full-scale prototypes have been built at BNL and then shipped to Fermilab for installation in a cryostat. Tests of the 16.5-m magnets have been done at Fermilab. In addition to the fabrication and testing of prototype 16.5-m dipoles, BNL and LBL have fabricated and tested short models at their laboratories. During the past year, all of the laboratories have helped to identify and solve problems associated with the 16.5-m prototypes by building and testing short magnets.

The cable performance, the cryostat performance, and nearly all aspects of the cold mass performance meet the requirements of the collider rings. One critical aspect of the first five full-length prototypes that was unsatisfactory was the large number of training quenches required to achieve the 6.6-T design field. Three of the first five magnets did not reach the design field of 6.6 T after twenty or more training quenches; two did after about twelve quenches. The sixth magnet, the most recent magnet to be built, reached a plateau above 6500 A at 4.35 K—which is consistent with predictions based on the short sample limit of the cable—without any training quenches.[8] The magnet reached 7675 A, well in excess of the design current, when operated at 3.2 K. The cable used in this magnet was purchased more than two years ago when cable of SSC quality was not being produced regularly, and its short sample current falls somewhat below SSC specifications. Since the cable now being produced meets the SSC specification, magnets made with the new cable should exceed the 6504-A design field at 4.35 K by several hundred amperes. A plot of the quench current versus quench number for magnet DD0012, the most recent magnet to be tested, is shown in Figure 2.

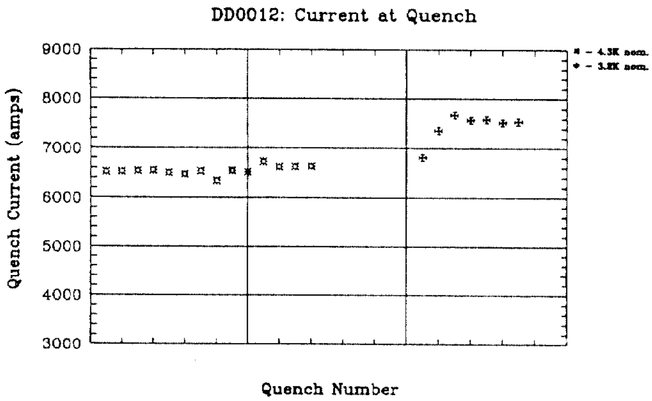

Figure 2. Plot of quench current vs. quench number for DD0012.

The improved performance is a result of significantly improved mechanical clamping of the coil, azimuthally and radially. During the past year we have carefully reviewed the possible causes of conductor motions. Two stood out: motion of conductors within the body of the magnet perpendicular to the beam direction, and motion of the conductors in the ends. The former caused quenches in the body of the magnet, and the latter caused quenches in the ends of the magnet. With the instrumentation that has been in place since the fifth long magnet, it has been possible to determine the half-turn of the coil in which the quench started. The longitudinal position within the half-turn can be located to within a few tens of centimeters. This instrumentation has allowed us to pinpoint defects in the magnet construction. A year ago, it was established that the curing fixtures expanded under pressure during the curing process. This caused a larger than allowable variation in the coil size at certain points along the 16.5-m length of the coil. It is believed that the improved coil-clamping scheme introduced in the sixth magnet made it possible to achieve the desired preload in spite of the coil size variation.

Further analysis of both magnet performance and finite-element models of the magnets should remove any remaining uncertainties. In the meantime, the curing fixtures are being rebuilt. It is anticipated that the new fixtures will reduce the coil size variation by a factor of three, within the acceptable range. These fixtures will be available to wind coils early in 1989.

One might wonder whether magnet DD0012 was the result of a favorable fluctuation in dimensions. An examination of the performance of the 1.8-m magnets built and tested at BNL during the past year shows that this is not the case. Table 5 shows the performance of 1.8-m magnets built at BNL during the past year.

Table 5. Performance of recent 1.8-m model dipoles*

1.8-m Model	I on first quench	No. of quenches to reach I_Q at **	I_Q (T)
DSS6	6215 A	3	6460 A (4.49 K)
DSS6R	6491 A	0	6470 A (4.50 K)
DSS9*	6130 A	1	6800 A (4.46 K)
DSS10	5416 A	4	6510 A (4.48 K)
DSS11	6372 A	1	6690 A (4.36 K)

* DSS9 has an NC-9 cross section with aluminum collars; all other models have a C358A cross section with stainless-steel collars.

** I_Q is typically observed to be 2–3 percent higher than the measured short sample current of the cable.

The yoke blocks of DSS6R, DSS10, and DSS11 press against the collars of the collared coil and thus limit the expansion of the collared coil in the horizontal direction. Since this was achieved by placing shims between the collared coil and the yoke, there is a nominal 0.15-mm gap between the yoke blocks. As the magnet is excited, the two yoke halves are attracted toward one another, thus creating a vertical force along the collared coil proportional to I^2. This force increases the mechanical clamping of the coil. While in principle the yoke blocks do not bear against the collars in DSS6, this could not be established because the clearance between the yoke blocks and collars was not well defined. The clamping scheme used in DSS6R, DSS10, and DSS11 was also used for DD0012. Magnet DSS9 has an aluminum collar. Since there is an interference at the midplane between the collared coil and the yoke blocks at assembly, the expansion of the collared coil in the horizontal direction (along the midplane) is limited by the yokes. In this respect the collared coil constraint of DSS9 is similar to DSS6R.

It is worth noting that all of these magnets exceeded 7 T when tested at 4 K. The difference in the plateau quench current I_Q is due to the widely differing copper-to-superconductor ratio of the superconducting cable. Magnet DSS9 reached a field of 7.8 T at 3.3 K.

Work was begun several years ago at LBL on a 1-m dipole with aluminum rather than stainless-steel collars. The intention of this second design is to exploit the favorable difference in thermal contraction between the aluminum collars and the Cu/NbTi coils. The aluminum collars are expected to shrink more than the coils when cooled from 300 K to 4 K. The large decrease in the coil preload at the collar pole, inherent in magnets made with stainless-steel collars, should thus be reduced. During cooldown the loss in preload of the stainless-steel collared coil amounts to 2000 psi.

In addition to the single 1.8-m magnet of this design built at BNL, a large number of 1-m models of this design have been built and tested at LBL. As a rule, they have reached the design field of 6.6 T at 4.4 K with three or fewer training quenches. In addition, when cooled to 1.8 K these magnets have reached a field of nearly 9 T with very few training quenches. In a joint effort, LBL and BNL built two full-scale 16.5-m prototypes of this design at BNL during the past nine months. They will be tested sometime this summer at Fermilab after being installed in cryostats.

Relative motion of the conductors in the ends of the inner coil has also contributed to excessive training. The ends of the inner coil are difficult to fabricate because of their very small diameter. Small voids between the conductors that collapse during excitation have been difficult to eliminate. The ends of the much larger outer coil, comparable to the inner coil of a Tevatron dipole or a HERA dipole, have not been a problem. Improvements, each a matter of small details, have been steadily made to the fabrication technique. As of this writing, training quenches are no longer occurring in the ends. Nevertheless, we expect to introduce an internal support to the ends this fall, thereby further increasing their strength.

During the past year, a great deal of effort has been spent trying to understand why the long magnets did not perform as well as the short magnets. After all, a long magnet has the same ends and the same two-dimensional cross section. We have found that the small differences in construction of the short and long magnets have led to important differences in the control of the coil dimensions. While our understanding is not complete, we expect to be able to build magnets meeting all of the basic systems requirements once we have completed the evaluation of the six magnets under construction and the upgrade of the tooling and fixtures. This work should be complete early in 1989.

Site Selection and Conventional Facilities

In September 1987 the Department of Energy (DOE) received 36 proposals that were responsive to its site criteria: the site had to be within the United States and the group submitting the proposal had to be able to convey title to the land needed for the SSC. At the request of DOE, these proposals were reviewed by a panel appointed by the National Academies of Sciences and Engineering. The panel recommended eight sites as "best qualified" to the DOE in December of 1987. After completing its own review, the DOE accepted these recommendations and announced the list of eight best qualified sites in January of 1988. Subsequently, the site in New York State was withdrawn from further consideration by the Governor of New York. The remaining seven sites are in Arizona, Colorado, Illinois, Michigan, North Carolina, Tennessee, and Texas. The location of these sites is shown in Figure 3.

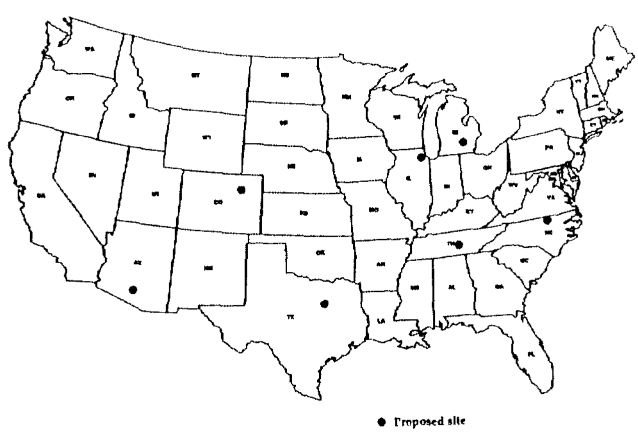

Figure 3. SSC sites proposed and recommended as best qualified.

Since the best qualified sites were announced, site visits have been made by the DOE in order to obtain further information. A major part of that effort is included in an environmental analysis of each site. An announcement of the final site is expected by early 1989.

A Possible Timetable for the SSC

For the SSC, the past is certain and the future is dreams. The following schedule represents the aspirations of SSC/CDG and the DOE:

Preferred Site Designated	November 1988
Final Site Choice	January 1989
Construction Complete	1996
Commissioning Commences	1996

While 1996 is two years later than the date that Professor Fermi proposed 34 years ago as he retired as President of the American Physical Society, we should hardly be embarrassed. The reality of exceeding 20 TeV in the center of mass is nowhere near as speculative as it was in 1954, for it is now within the realm of the possible.

References

[1] *Conceptual Design of the Superconducting Super Collider*, SSC-SR-1020, edited by J. D. Jackson (March 1986).

[2] A. A. Garren and D. E. Johnson, "Status of the SSC Lattice Design," in these proceedings; D. Neuffer, "Lumped Correction of the Multipole Content of the SSC," in these proceedings; J. M. Peterson and E. Forest, "Correction of Random Multipole Errors in the SSC," in these proceedings.

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[4] N. Merminga, "An Experimental Study of the SSC Magnet Aperture Criterion," in these proceedings; J. M. Peterson, "Dynamic Aperture Measurements at the Tevatron," in these proceedings.

[5] *CDR*, "Correction Coils," Sec. 5.2.7, p. 290.

[6] R. Talman, Private Communication (October 1987).

[7] D. Neuffer, "Lumped Correction of the Multipole Content of the SSC," in these proceedings.

[8] It is actually about 100 A higher than predicted; this is well within the accuracy of the short sample measurement combined with the extrapolation procedure.