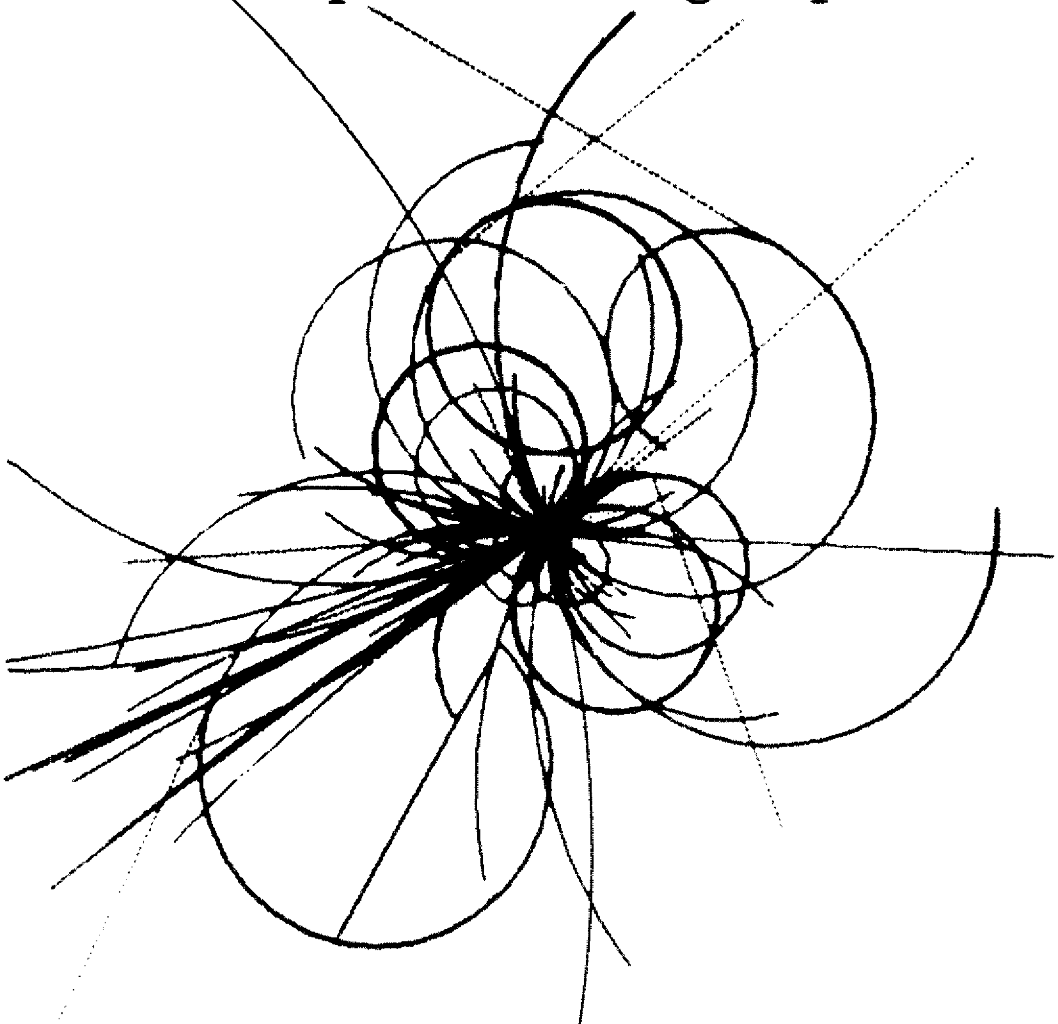
SSC-117

The Superconducting Super Collider



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THE SSC STATUS AND OUTLOOK*

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The SSC: Summary

The proposed Superconducting Super Collider is a high luminosity proton-proton collider designed to provide collisional energies at least an order of magnitude greater that those presently available at existing high energy physics facilities, or a maximum center-of-mass energy of 40 TeV. It will, thereby, be able to probe the 1-2 TeV scale -- a frontier energy region believed to be replete with new physics. The technical feasibility of this ambitious undertaking is largely the result of recent advances in superconducting magnet technology. These advances, moreover, are the fruit of a nation-wide R&D program, now in its fourth year, being coordinated by the SSC Central Design Group. The project is now well into the conceptual design stage. Development of technical sub-systems has begun. President Reagan has recently announced his support of the project, and congressional hearings on the matter have started. The basic SSC parameters are listed in Table 1.

Table 1
Basic SSC Parameters

Machine type	pp collider
Energy	20 TeV per beam
Luminosity	$10^{33} cm^{-2} s^{-1}$
Event rate per bunch crossing	1-2 (assuming 100 mb inelastic pp cross section)
Number of IRs	6 (4 initially)

Physics Issues

The driving force behind the SSC is the expectation of fundamentally new phenomena in the roughly 1 TeV mass region, perhaps signaling the onset of the unification of the electroweak and strong interactions and possibly supersymmetry between fermions and bosons, or indications of the compositeness of quarks and leptons and yet undiscovered particles in the TeV mass range[1]. More generally, a quantum-mechanical principle holds that new physical phenomena, deeply related to the origin of mass, should begin to emerge at about this energy. Finally, A. Salam has wisely admonished the scientific community on being open minded[2]:

> Do not ask theorists at which energy to aim for the next generation of high energy accelerators. Aim at the highest possible. One may recall the cautionary story of Lord Kelvin who (reviewing what his generation had accomplished in the nineteenth century) remarked in his address to the British Association for the Advancement of Sciences: "There is nothing new to be discovered in physics now; all that remains is more and more precise measurement". This happened to be the same year when (subsequent to Lord Kelvin's speech) J.J. Thomson announced the discovery of the electron!

History of the SSC

The need for an economically realistic machine able to probe the TeV mass domain has been recognized by the world community of high energy physicists for over a decade. The ICFA workshops of 1978 and 1979 addressed physics and accelerator aspects of the novel energy domain. The exciting possibilities were scrutinized in greater depth at the 1982 workshop of the Division of Particles and Fields of the American Physical Society; here attention focused for the first time on specific alternative superconducting magnet options for a 20 TeV x 20 TeV proton collider. Additional workshops were held in 1983 at Cornell University and the University of Michigan, where the technical feasibility was established and cost and accelerator issues explored in greater detail. In the summer of 1983, on the basis of the DPF and other studies, the High Energy Physics Advisory Panel recommended the SSC to the DOE as the unanimously preferred route into the new domain to confront forefront challenges into the next century. With congressional approval, funds were reallocated to support research and development, paving the way for the new facility.

The following year, a Reference Designs Study was commissioned by DOE to compare three superconducting magnet approaches and their cost estimates: relatively low (3 T), medium (~ 5 T), and high field (>6 T) superconducting magnets and the correspondingly implied machine circumferences. Based on the conclusions of that study[3] and its subsequent review, the DOE contracted with Universities Research Association a management structure to coordinate the necessary R&D to narrow the technical choices leading to a conceptual design proposal, and, subsequently, a construction plan. The result was the Central Design Group, created by a Board of Overseers under delegation by URA, with the Lawrence Berkeley Laboratory acting as host. The group was installed on LBL premises by the fall of 1984.

The R&D since then has been mainly performed by Brookhaven, Fermilab, LBL, and the Texas Accelerator Center, with contributions from various universities, and, by subcontract, from industry. The first major milestone was passed in the fall of 1985, with the selection of a particular magnet design -- the high field option -- after a thorough review process. The next milestone was the Conceptual Design Report, issued in the spring of 1986. The CDR, a document of 700 pages with several thousand pages of attachments, was favorably reviewed by DOE in April and June of 1986. It was also the subject of an in-depth critique by the high energy community at a DPF workshop during June-July, 1986; no essential faults were uncovered.

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Conceptual Design

The Conceptual Design Report (CDR) encompassed all the systems, sans detectors, necessary for a facility meeting the basic specifications of Table 1. The report[4] demonstrated the technical feasibility of the collider, provided a secure foundation for the subsequent design optimization, and allowed a cost estimate sufficiently detailed to be a basis for an executive decision on whether to proceed with the SSC. It built on experience with ISR, SppS, Tevatron, and earlier accelerator facilities, and relied heavily on recent advances in superconducting magnet technology -- advances engendered by the SSC R&D effort itself.

The general layout of the SSC is shown in Fig. 1. The oval racetrack measures 85.7 km in circumference. The clustered layout has the advantage of convenient access to the experimental areas which, with the utility regions, separate the two long arc sections. A clustered layout has, in fact, certain advantages from the point of view of beam optics, compared to a symmetrical placement of interaction and utility regions. The Near Cluster (Fig. 2) includes the injector complex, RF and abort systems, as well as the main laboratory facilities. Each regular arc is approximately 32 km long, divided into 139.5 cells containing 10 bending magnets and two focusing magnets each. The inclusion of bending between collision points prevents particles produced in one region from interfering with the study of collisions in the adjacent region.

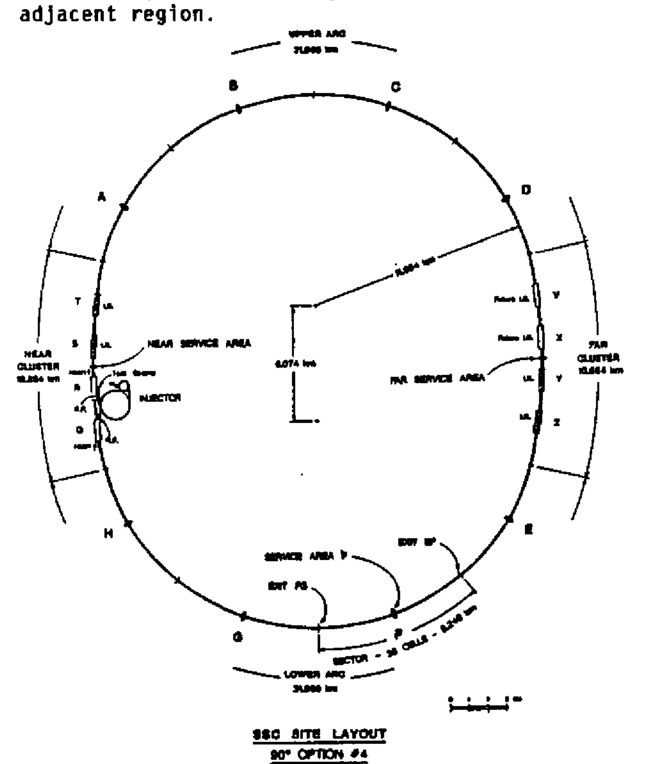

Fig. 1. Layout of the SSC (90° Option)

From the point of view of the experimental physicists, the essential feature of the SSC is a machine which will provide proton-proton events at a rate of about 10^8 per second. This is achieved through a significant (i.e. inelastic) collision rate of about 1.4 per bunch-bunch encounter, the bunches themselves being separated by 4.8 m. Each bunch, as it passes through an interaction region, is 15 cm long and 10μ wide, and contains 7×10^9 protons. In the IR, there is 20 m of free space between the high gradient quadrupoles on either side of the collision point. The present Conceptual Design includes two high luminosity IRs with the foregoing parameters, but also has two lower luminosity IRs, with $\mathscr{L} = 5.7\times10^{31} cm^{-2}s^{-1}$, which will have a larger free space of ±100 m. The remaining pair of IRs may initially be left vacant, to be allocated for later use.

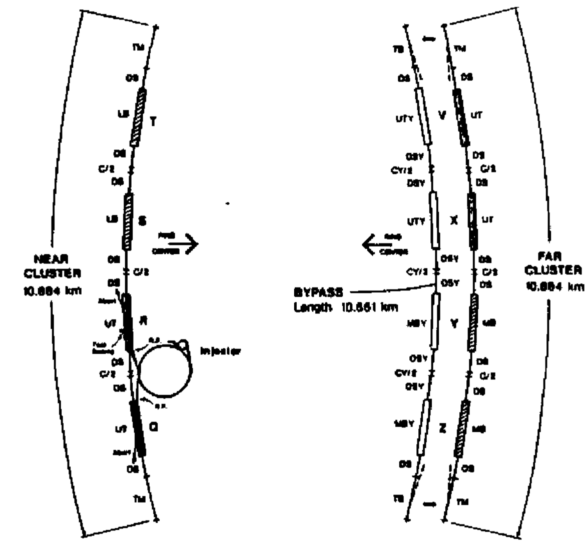

Fig. 2. Details of Near and Far Clusters

The details of beam behavior and properties will not be described here, but a few particulars are worth pointing out. The beam-beam tune spread, at $\Delta\nu = 0.0008$ per interaction region, is an important but not dominant factor in beam evolution. In general, the dynamics of the beam are dominated by single particle interactions: the operating beam current of 73 mA is much smaller than the threshold for significant collective effects. Each beam radiates a synchrotron power of 9 kW, giving a damping time of about 12 hours. The major determining factor of beam lifetime is proton loss through inelastic collisions at the interaction regions. Figure 3 shows the evolution of luminosity, number of particles per bunch, and emittance, in a period of two days following beam injection. The initial rise in luminosity is due to synchrotron damping of the betatron oscillations.

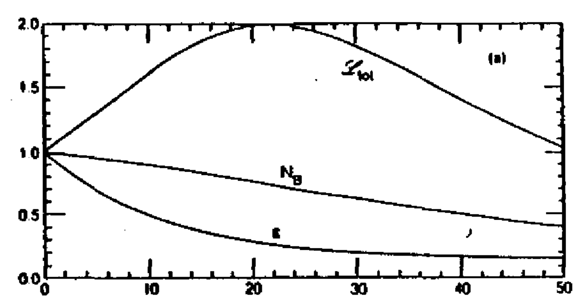

Fig. 3. Evolution of beam luminosity and emittance, and number of particles per bunch, in a two-day period following injection

Determination of the appropriate magnet aperture for the SSC was an issue which occupied much discussion early on in the R&D program. Because the true dynamical aperture of a magnet lattice cannot be computed in any reliable and systematic way, the more conservative approach employed for the SSC was *based on the idea of a linear aperture.* This is defined to be the size of the physical region in the magnetic field within which particle motion about a closed orbit is essentially linear. The linear aperture will be smaller than the true aperture, which is determined by the nonlinear forces. It is further discussed in the accompanying paper by D.V. Neuffer and J.M. Peterson.

The aperture required of the lattice depends on numerous interlinked factors, including beam size, injection errors and alignment errors. Consideration of these and other questions led to the choice of 5 mm as the needed linear aperture, with a momentum spread $\Delta p/p = \pm 10^{-3}$. Conversion of this number into a design figure for the inner diameter of the magnet was done by using data from previously built magnets and from lattice analysis which agrees with previous tracking studies. The most important feature of these calculations is the variation of multipole coefficients from one magnet to another. The upshot of this work was the decision to design magnets with an inner coil diameter of 4 cm; correction coils and the beam tube itself fit inside the coils, so the actual space for the beam is smaller.

The general conclusion of the work leading to the Conceptual Design is that the SSC can be built with engineering parameters close to current practice. We can therefore be confident that the design is feasible, and that the required beam parameters can be achieved in a practical way.

Cost Estimate

The project cost summary, as given in the CDR, is listed in Table 2, which does not include the cost of detectors, computers, and R&D. (The latter items are estimated to total $1,000 M.) The largest uncertainty in the cost estimate pertains to the conventional systems as no site has yet been selected.

Table 2
Cost Summary (FY 1986)

Conventional Facilities		576.265
Site and Infrastructure	85.433	
Campus Area	42.860	
Injector Facilities	39.758	
Collider Facilities	346.803	
Experimental Facilities	61.412	
Technical Components		1424.161
Injector Systems	189.252	
Collider Ring Systems	1234.909	
System Engineering and Design		287.607
Management Support		192.334
	Subtotal	2480.367
	Contingency	529.951
	Total	3010.318

Technical Status

Research and development for the SSC has concentrated on the superconducting magnet system, the costliest machine component. It is discussed in considerable detail in the accompanying paper by V.N. Karpenko. The most critical magnets, due to their demanding operating specifications and sheer number (nearly 8,000), are the regular arc dipoles. The dipole field strength determines the circumference of the collider rings, and, thus, the cost of the tunnel. The minimum required coil aperture and available superconductor current density dictate the overall magnet size and, hence, its cost. (The superconductor alone accounts for approximately 30 percent of the cost.) The R&D has been carried out chiefly at Brookhaven, Fermilab, LBL, and the Texas Accelerator Center, coordinated by the SSC Central Design Group.

The dipoles must, aside from attaining the required field strength with minimal "training", satisfy a number of requirements. The uniformity of the field must be high to ensure long lifetime of the stored beams; technically, this means multipole components within tolerable bounds and with minimal variation from magnet to magnet. The operating life of the collider and fractional "on" time for physics experiments depends on magnet reliability and a conservative design. (For a projected machine lifetime of twenty years, a magnet must tolerate 10^4 acceleration cycles, more than twenty thermal cycles to and from cryogenic temperatures, repeated quenches to the normal state, and an estimated radiation exposure of 3×10^4 Gy per year.)

The multipole coefficients a_n and b_n are defined in terms of the usual expansion:

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n)(x+iy)^n$$

where B_0 is the dipole strength, the even a_n are the normal multipole coefficients with dipole symmetry and the a_n are the skew coefficients. The multipole order follows from the index n as 2(n+1); thus, b_2 is the normal sextupole component, etc. For dipoles meeting the SSC specifications the order of magnitude of the lower order coefficients is 10^{-4} cm^{-n} which, by convention, is known as 1 "unit." The multipole tolerances, both random and systematic, are listed in Table 3. These figures represent a compromise between what is practical from the magnet manufacturing standpoint and correction coil requirements -- a matter under continuing review with the aim a solution which guarantees reliability with greatest cost effectiveness.

Table 3
Multipole Tolerances

Skew	Random	Systematic	Normal	Random	Systematic
a_1	0.7	0.2	b_1	0.7	0.2
a_2	0.6	0.2	b_2	2.0	1.0
a_3	0.7	0.2	b_3	0.3	0.1
a_4	0.2	0.2	b_4	0.7	0.2
a_5	0.2	--	b_5	0.1	--
a_6	--	--	b_6	0.2	--
a_7	0.2	--	b_7	0.2	--
a_8	--	--	b_8	0.1	0.1

Recent work on improving the quality of commercially available superconducting wire has been highly successful. The NbTi wire used in the Tevatron magnets had a current carrying capacity of between 1800 and 2000 A/mm^2 at 5 T and 4.2 K. Now, less than four years later, industrial vendors have produced filaments which will handle nearly 3700 A/mm^2. The SSC continues to update its specifications as further improvement is made. The

Reference Designs Study of 1984 took 2400 A/mm^2 as a specification for the current density, and by the time of the CDR this figure had risen to 2750 A/mm^2. It appears practical to achieve the needed correct density with filament diameters of about 6 micrometer. Such small sites are advantageous in reducing persistent correct effects at low temperatures.

A cross section of the dipole magnet and cryostat assembly is shown in Fig. 4. The magnet design is basically a cosine-theta dipole of 16.6 m magnetic length and, as noted, 4 cm coil aperture. Its operating field is 6.6 T. The conductor is a flat, twisted and keystoned cable of typically 30 multifilamentary wires containing CA. 10,000 twisted NbTi filaments in a copper matrix. The two-layer coil is supported by stainless steel collars in a split iron yoke. The yoke, in turn, is held within a split and welded stainless steel support tube which is also the outer wall of the helium containment vessel. This "cold mass" assembly is supported by cylindrical, reinforced plastic posts inside the cryostat. The cryostat contains, in addition, two aluminum heat shields, layers of superinsulation, and cryogenic headers, all housed in a vacuum vessel 60 cm in diameter. The over/under magnet arrangement in the SSC tunnel is shown in Fig. 5. The beam separation is 70 cm.

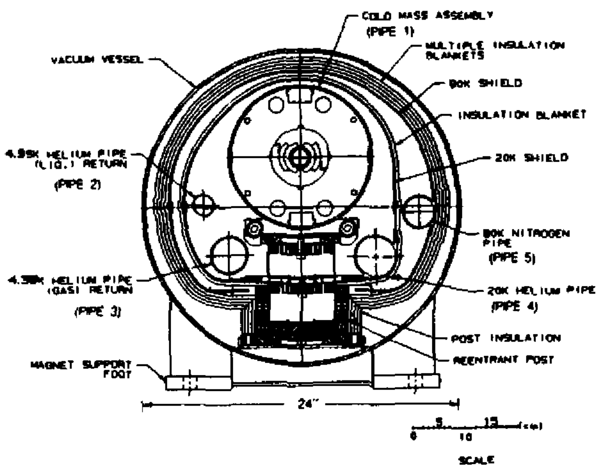

Fig. 4. Cross section of the magnet and cryostat assembly

To date, approximately 25 model magnets of the current design have been tested; these include 18 1m long models, two 3.5 m models, six 4.5 m models, and, most recently, two full-length (17 m) models. The short and medium-length models reached peak fields of 6.3 - 6.4 T in boiling liquid helium with very little training, and fields in excess of 7.5 T in subcooled liquid, in spite of being wound from relatively "old" superconducting cable. Multipole coefficients were uniformly within specifications. The few short models tested thus far with newer superconductor exhibited even higher fields: B ~ 7 T at 4.5 K and almost 9 T in superfluid helium (1.8 K). With only two tested[5], performance statistics for the full-length models are lacking. Peak field performance was not as good. Although the first long magnet model achieved 85% of the nominal operating field and the second exceeded 6.9 T at 3.5 K, the maximum quench current was erratic. The source of this behavior is believed to be a loose coil portion at the end. Field quality results were very encouraging. Equally important, quench behavior was excellent, with relatively modest energy dumped in the coils during quenching.

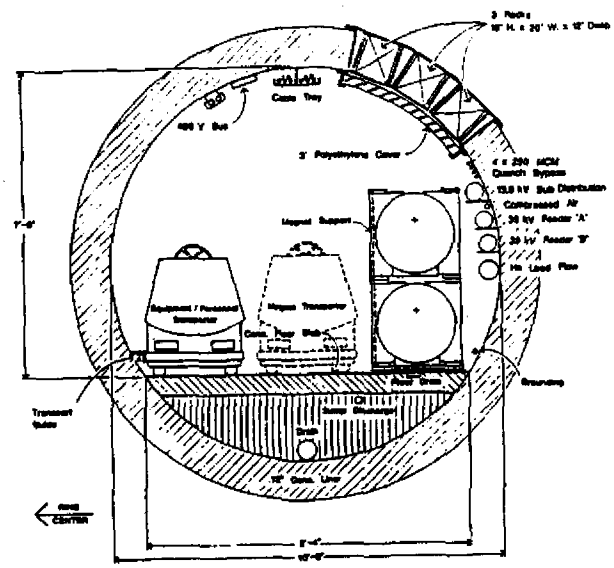

Fig. 5. Cross section of the main ring tunnel.

Further models for FY 1987, both short and long (two of the latter), will focus on several issues, among these training and magnet stability vis-a-vis cooling mode (gas vs. liquid) and conductor stabilization (amount of copper), coil ends, and prestress. Design features verified in these magnets will be incorporated in model dipoles for FY 1988.

Administrative Status

An important milestone was reached on January 30 of this year, with the announcement that President Reagan supports construction of the SSC. On February 10, DOE announced the following site-selection process:

1. April 1987 - DOE issues invitation for site proposals.
2. August 1987 - DOE to receive and screen proposals.
3. September 1987 - DOE to refer qualified proposals to NAS/NAE for evaluation.
4. December 1987 - NAS/NAE recommends best qualified sites.
5. July 1988 - DOE to designate preferred site.
6. January 1989 - Safety and environmental review process complete.
7. January 1989 - Final site selection.

The FY88 SSC budget request calls for $35 M: $25 M to continue R&D with emphasis on magnets, and $10 M for initial construction activities (procurement of long lead-time materials, e.g., superconducting wire). Congressional hearings on the SSC are imminent. The presently envisioned project funding profile (in FY 1988 dollars) is shown in Fig. 6. The profile covers a total of $4,375 M and includes an initial complement of detectors and computers as well as the collider facility and supporting R&D and pre-operational costs. Start-up is scheduled for mid-1996.

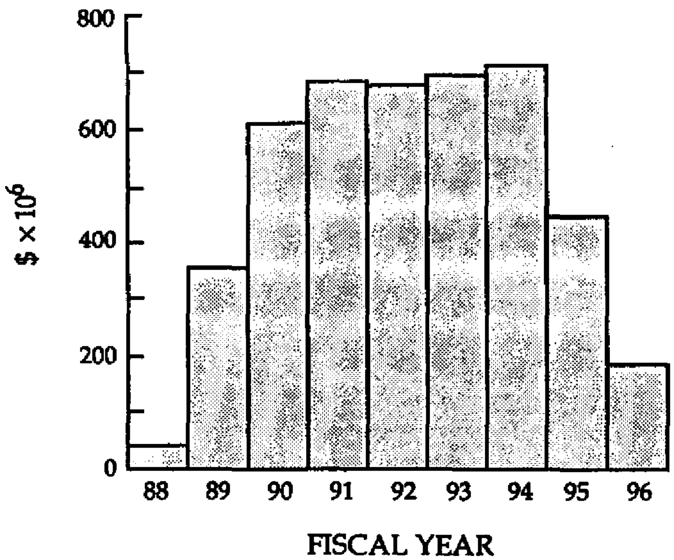

Fig. 6 SSC Funding Profile

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3. Report of the Reference Designs Study Group on the Superconducting Super Collider, Draft II (May 8, 1984), unpublished.

4. Conceptual Design of the Superconducting Super Collider, J.D. Jackson, editor, SSC-SR-2020, March 1986.

5. J. Strait, et al., "Full Length Prototype SSC Dipole Test Results," Proc. 1986 Applied Superconductivity Conference, to be published.