THE SUPERCONDUCTING SUPER COLLIDER MAGNET SYSTEM*

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Introduction

The Superconducting Super Collider (SSC) will have two 20-TeV proton beams traveling in opposite directions in separate storage rings in the same tunnel, 83 kilometers in circumference. Over 9600 superconducting magnets are required for bringing the beams into collision and for injection and abort. The magnet system is the single most costly technical system of the SSC. The use of superconductivity on a large scale is what makes the SSC practicable.

Magnet System

Requirements to meet the technical performance of the SSC magnet system must have the following characteristics: high field strength, field uniformity, reproducibility, and reliability over a long life time. These characteristics have to be met within reasonable cost boundaries. The individual magnets shall be designed to withstand, during 20 years of operational lifetime, 10^4 power cycles, 20 thermal cycles between ambient temperature and operating temperature, approximately 50 quenches, and a radiation dose of 10^6 Gys. The magnet assembly shall be capable of withstanding, in addition to operational loads, in-place seismic, transportation, and installation loads.

Magnet System Configuration

The magnets are arranged into two racetrack-shaped rings 70 cm apart (see Fig. 1). Over 9600 magnets are required, including 7860 dipoles, 1360 quadrupoles in regular cells,[1] and 648 special magnets for bringing the beam into collision in six places and for injection and abort as shown in Table I.

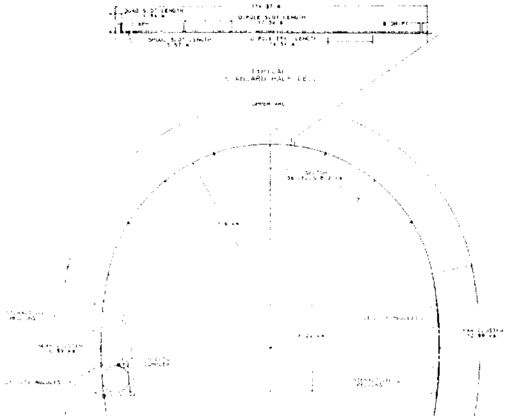

Fig. 1. Collider Ring.

Table I shows that dipole magnets play a dominant role in magnet system performance; consequently major effort in R&D is being devoted to dipole design. One has to achieve the maximum,within economic limits, to construct high-performance and intrinsically reliable magnets which are in a machine to stay, since they cannot be readily modified after installation. Development effort in optimization, characterization of material properties, analytical techniques, and subassemblies like the cryostat and others will be directly applicable to other magnet system elements.

TABLE I
Magnet System Elements

Magnet Type	Field		Magnet Length (m)
Standard Dipoles	7680	6.6 T	16.60
Standard Quadrupoles	1360	230 T/m	3.30
Spool Pieces	1656	Var.	3.35-4.98
Vertical Dipoles	232	5.2 T	8.00
I.R. Focusing Quad	4	231 T/m	14.50
I.R. Focusing Quad	8	230 T/m	11.79
I.R. Focusing Quad	4	227 T/m	13.04
I.R. Focusing Quad	16	212 T/m	8.17
I.R. Focusing Quad	8	164 T/m	13.60
I.R. Focusing Quad	8	203 T/m	6.80
I.R. Focusing Quad	4	210 T/m	9.20
I.R. Focusing Quad	8	202 T/m	7.50
I.R. Focusing Quad	4	210 T/m	7.00
I.R. Focusing Quad	16	212 T/m	7.50
I.R. Focusing Quad	8	111 T/m	7.50
I.R. Focusing Quad	8	137 T/m	7.50
Disp. Supp. Region Quads	32	212 T/m	4.88
Disp. Supp. Region Quads	32	212 T/m	4.80
Disp. Supp. Region Quads	32	212 T/m	4.58
Disp. Supp. Region Quads	32	212 T/m	4.05
Disp. Supp. Region Quads	32	212 T/m	3.48
Disp. Supp. Region Quads	96	212 T/m	7.54
Spec. Utility Region Quad	16	212 T/m	7.83
Spec. Utility Region Quad	16	212 T/m	8.46
Spec. Utility Region Quad	16	170 T/m	10.88
Spec. Utility Region Quad	16	170 T/m	11.11
TOTAL	9688		

Dipole Magnet Design

Early studies indicated that it would be possible to build dipole magnets for the SSC with several possible designs. The magnet R&D program developed a number of these proposed designs to the point where definitive cost estimates and an evaluation of their performance characteristics could be made. The choice that emerged is a high-field, cold iron, 1-in-1 magnet of 16.554 m magnetic length, utilizing a two-layer cosine theta coil of 4.0 cm inside diameter. This design is intended to achieve central field strength of 6.6 Tesla at 4.35 K operating temperature. The strength of the dipole field determines the ring size, and it is chosen as high as is practical, consistent with total accelerator cost.

Coil

The collared coil assembly is shown in Fig. 2. The high field strength produced by this coil is made possible by recent improvements in NbTi alloy,

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multiple heat treatments, and use of diffusion barriers. The critical current in excess of 2750 A/mm^2 at 5 T and 4.2 K in filament ranges of 5-10 microns were produced for SSC. Cable and strand optimization is continuing to achieve balance between critical current and magnetization (particularly at injection field of 0.33 T), and cable properties suitable for reliable coil production.

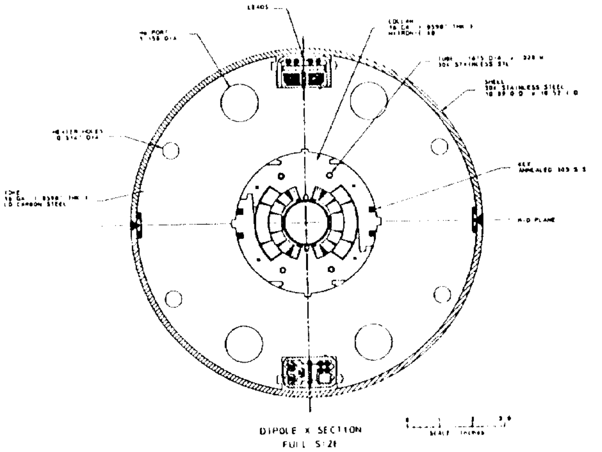

Fig. 2. Cold Mass Cross Section.

The inner cable has 23 strands of 0.0318 in. diam wire with a copper-to-superconductor ratio of 1.3; the outer cable has strands of 0.0255" diam wire with a copper-to-superconductor ratio of 1.8. The amount of copper in each layer is designed to provide adequate quench protection behavior and stability. The strands do not need to be insulated from one another because the rate of field increase during acceleration in the SSC is very low (approximately 15 minutes to accelerate from 1 to 20 TeV). The cable is compacted to an average of about 90% of its maximum density. One edge is thinner than the other to maximize the number of turns. Wedges inserted to achieve the required uniformity of the field and are also designed to provide for mechanical stability of the winding under the high circumferential compressive stress that is applied when the collars are squeezed into place. The winding is not supported on its inner diameter.

The interlocking collars shown in Fig. 2 provide coil structural support. Rectangular keys are used to lock the collars together. The collars provide precompression of the winding and complete support of the Lorentz forces. To prevent the coils from pulling away from the poles when energized, the collar must maintain a minimum prestress of 3600 psi for the inner coil and 2900 psi for the outer coil.[2-4] To minimize the radial collar thickness, a high-strength stainless steel, 21-6-9 was selected which allows a 15 mm thickness.

The beam tube separates the helium cooled magnet structure from the beam high vacuum chamber. The inside surface of the beam tube is copper plated to minimize the electrical resistance of the wall to the image currents. On the outside of the tubes are mounted superconducting distributed correction coils (see Fig. 3.). The beam tube is designed to withstand Lorentz forces generated by the eddy currents in the copper plating during quench. The beam tube is also subject to the increased helium pressure in the annulus as a result of rapid rise of the coil temperature during quench.

The magnet yoke stacked iron laminations split on the mid-plane mounted in the helium containment shell. They are the arc accurately die-punched from 1.5 mm thick sheets of low carbon steel. The four large holes are the channel for helium flow.

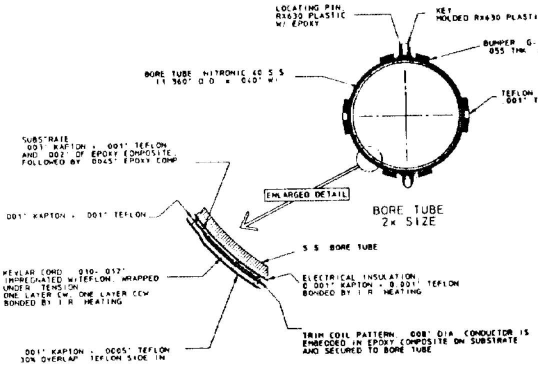

Fig. 3. Beam Tube.

Recent tests of short R&D magnets have shown that the design field of 6.6 T at 4.35 K is routinely exceeded. Short sample limits from 6.8 to 7.0 T have been attained.

Cryostat

To maintain adequate magnetic field quality, the coils must be maintained at a uniform low temperature. The cryostat design achieves this reliably and efficiently. The cold mass 17.34 m long is mounted in a cryostat using a low heat leak folded post support system.[5]

Supercritical helium at 4.15 K and 4 atm is passed through the cold mass assembly to remove heat and to maintain coil temperature at or below 4.35 K. The static heat load from conduction and radiation is estimated to be 0.02 W/m and that due to synchrotron radiation is 0.12 W/m. The synchrotron radiation load is absorbed by the helium flowing in annular space between the beam tube and the inner coil. This gap is small; however, the heat load is transferred radially to the main helium flow principally by conduction and the 1 g/s flow in the gap serves to distribute the heat over the inner bore. Approximately 100 g/s of total axial flow is required to limit the temperature increase to less than 0.2 K between recoolers. This larger flow passes through four holes in the yoke. The cold mass subassembly is surrounded by concentric aluminum heat shields maintained at 20 K and 80 K, by helium gas and liquid nitrogen, respectively, with intervening thermal insulation consisting of layers of aluminized Mylar. Cryogenic supply and return pipes are located as shown in Fig. 4. Table II shows the heat leak design requirements. Tests of a cryostat model indicate that the heat leak budget will be met with minor design improvements.

Table II
Dipole Heat Loads

	4 K (watts)	20 K (watts)	80 K (watts)
Infrared	0.05	2.16	17.7
Supports	0.12	0.82	7.2
Connects & Instrumentation	0.15	0.32	2.1
Synchrotron Radiation	2.21		
Total	2.53	3.30	27.0

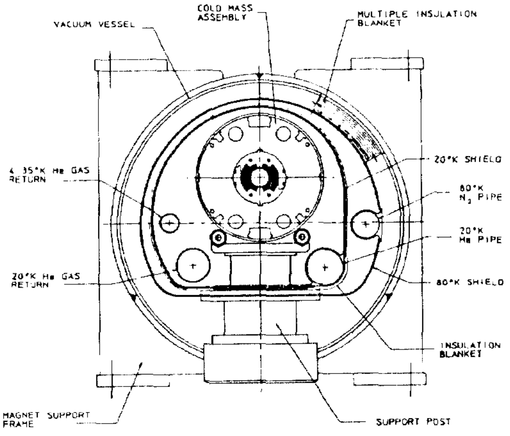

Fig. 4. Magnet Assembly Cross Section.

Field Uniformity

Field uniformity is the important prerequisite for a good beam lifetime.

The field of each dipole magnet must be uniform within [ΔB/B] of about 10^{-4} at one centimeter radius. There is some random variation of the dipole from magnet to magnet, and there are also small built in field distortions (systematic multipole). Uniformity requirements at 1 cm radius are shown in Table II. To minimize field distortion caused by magnetization currents at injection, the superconductor has 5 μm - 8 μm filaments. The systematic variations must be correctable using a combination of distributed and lumped shim magnets to about $[\Delta B/B] < 10^{-5}$. Understanding the trade-offs in economy and reliability between manufacturing control of the main magnet and the various correction windings schemes is an important objective of the R&D program. Test data indicate that these requirements can be met.

Table III
Specified Tolerances
($\times 10^4$)

Multipole	Random	Systematic	Measured* Multipole Coefficients
a_1	0.7	0.2	-0.04
a_2	0.6	0.1	-0.08
a_3	0.7	0.2	0.06
a_4	0.2	.02	-0.15
a_5	0.2	--	-0.05
a_6	0.1	--	-0.06
a_7	0.2	--	-0.03
a_8	0.1	--	0.02
b_1	0.7	0.2	0.53
b_2	2.0	1.0	-3.88
b_3	0.3	0.1	-0.30
b_4	0.7	0.2	-0.32
b_5	0.1	0.02	0.04
b_6	0.2	0.04	-0.07
b_7	0.2	0.06	-0.01
b_8	0.1	0.1	-0.02

$\Delta(BL)/BL$, RMS $\pm\ 3 \times 10^{-4}$
*Measurements from recent short magnet test.

Reproducibility

Test data from short and long magnets indicate that the selected design can meet field uniformity requirements with appropriate correction windings. The important question is reproducibility, in other words, the random errors of deviations found in a set of actual magnets. On the basis of the details of the magnet fabrication process and its various tolerances, a number of models were developed to permit estimation of random errors.[6] Model parameters were adjusted to fit the measured random errors of the Tevatron and CBA magnets and then to make predictions for SSC magnets. These predictions are considered conservative and provided the basis of initial aperture selection. The measurements on SSC models indicate even smaller random errors will be achieved and one concludes that the manufacturing techniques are capable of producing magnets of acceptable field quality. Currently employed fabrication techniques assure reproducibility and are readily transferable to industry.

Reliability

One of the design goals of the SSC is to aim for high operational availability of the machine for physics experiments. The SSC magnet system containing over 9600 magnet represent a critical element in determining operational availability of the collider. The operation of the Tevatron and other HEP facilities provides a large data base for SSC magnets. Furthermore, engineering techniques are now available that can be used to identify critical items and increase the reliability of magnet systems.

Reliability is determined largely by the quality of design and is intimately linked with quality assurance. Quality assurance begins with the detailed engineering designs and prototype testing.

At the present time, extrapolation of available data, evaluation of current design, and experience with laboratory models indicate that the availability goal of 96% for the magnet system is achievable. The above availability is based on mean time to restore (MTTR) of five days and requires 120 days between failures (MTBF) for the system. The corresponding MTBF for individual magnets is over 1×10^6 days. Bayesian statistical analysis and use of influence diagrams will form the basis for system reliability modeling. Coupled with accelerated life tests, and other prototype tests, this analysis will provide the necessary data to arrive at reliable long life design.

Conclusion

Progress in research and development to date has achieved many SSC technical goals. The short model magnets reached high field performance of 7.0 T at 4.35 K and ~9.0 T at 1.8 K characterized by very little training.

It was demonstrated that the required field uniformity is achievable. The two full length models reached ~96% of the desired field but erratic training behavior (~500 A drop) is the problem. Several causes have been postulated: insuffcient cooling areas, instability at high field of the conductor with Cu/Sc ratio of 1.3, mechanical motion in "dog-bone" end configuration. The FY87 program is structured to address all of these issues.

Results from short R&D models demonstrated that training can be eliminated by preconditioning magnets at reduced temperature. We have almost two more years to arrive at an optimum, reliable, and cost effective magnet design.

The R&D program has achieved considerable success, and no technical breakthroughs are necessary. Solid technological foundations were laid for the FY88 construction start.

Acknowledgment

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References

1. Central Design Group, SSC Conceptual Design Report, SSC-SR-2020, March 1986.
2. R.J. LeRoy, Collar for the Design "D" SSC Dipole: A Design Review, SSC Tech. Note No.45, BNL, March 1, 1986.
3. C. Peters, Springback, Creep, and Cooldown Prestress Losses in Nineteen Collared 1-M Dipole Models Constructed at LBL, SSC-N-296, February 1987.
4. V.N. Karpenko, M. Zaslawsky, Response to Operations Conditions of the SSC Magnet Using Non-Linear Finite Analysis, SSC Central Design Group, SSC-112, March 1987.
5. R.C. Nieman, J.A. Carson, N.H. Engler, J.D. Conzy, T.H. Nicol, SSC Dipole, Long Model Cryostat Design, FNAL.
6. R.B. Meuser, Effect of Manufacturing Errors on Field Quality of Dipole Magnets for the SSC, April 1985.