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TEST RESULTS FROM 1.8-M SSC MODEL DIPOLES

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Abstract

We report results from the first four in a series of 1.8 m-long dipoles built as part of the Superconducting Super Collider (SSC) R&D program. Except for length, these models have the features of the SSC design, which is based on a two-layer cosθ coil with 4 cm aperture. As compared to 17 m, the SSC design length, these 1.8 m magnets are a faster and more economical way of testing changes in field shape, the ratio of copper to superconductor, cable support at the coil center and ends, and similar variables. The two most recent magnets in this series have the design field shape and improved quench performance.

Introduction

The training and field shape of the eight 4.5 m dipoles made during the initial SSC R&D effort were generally satisfactory [1]. However, the achieved prestress levels were lower than desired and accelerator physics studies led to a significant reduction in the maximum allowed value of the 18-pole term. Further, the training of the first full-length 17 m magnets is too slow [2]. To quickly test ideas for solving these problems with magnets made on the same tooling as the 17 m prototypes, a new program of short magnet construction has been underway at BNL. Existing tooling sets the length at 1.8 m. The magnets are operated in liquid helium in a vertical dewar.

To study training, the most important features of the magnets tested were the ratio of copper to NbTi superconductor in the inner coil conductor, the strength of the stainless steel collars (by spot welding pairs of collars), and the strength of the coil ends. For field shape, a new cross section (which uses the turn thickness as determined from experience with the 4.5 m magnets) was designed to reduce the 18-pole term. Also, the yoke design was altered to reduce saturation effects.

Magnet Design

This discussion of magnet design focuses on improvements identified in the 4.5m magnets which have been incorporated in the 1.8 m models. A cross section of the collared coil is shown in Fig. 1. The coil aperture is 4 cm and the coil outer diameter is 8 cm. In a cold mass assembly, the collared coil is mounted by the four collar tabs in an iron yoke split at the midplane. A stainless steel helium vessel clamps the yoke blocks in place [3]. The yoke inner diameter is 11.1 cm; its outer diameter is 26.7 cm. The magnet is designed to operate at 6.6T in 4.35 K helium with a current of 6.5 kA [4].

Coil Cross Section

In the SSC Conceptual Design Report (CDR), the following notation for multipoles is defined:

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

where B_0 is the design bending field, x and y are the horizontal and vertical coordinates measured from the magnet center [5]. It is convenient to define a multipole "unit" as 10^{-4} of the dipole field, with the multipole evaluated at a radius of 1 cm.

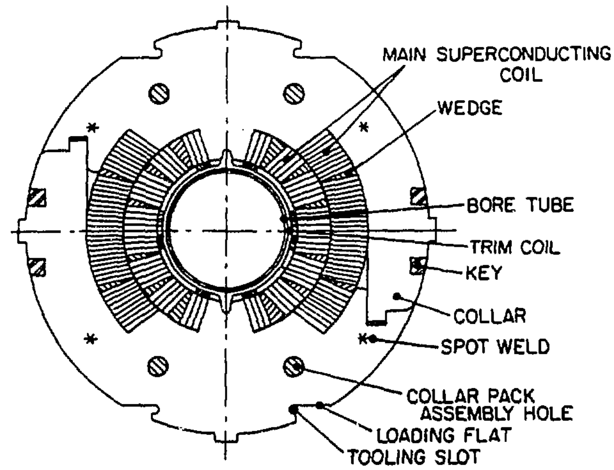

Fig. 1 Collared coil with C358A cross section.

The goal of coil design is to achieve a satisfactorily pure dipole field while maximizing the transfer function (B/I). In the cross section developed for the 1.8 m magnets (called C358A [6]), the most important variables are the size and position of the wedges (three in the inner coil, one in the outer coil), the pole angles of the two layers, and the freedom to vary the angle of all coil blocks (except those on the midplane) away from the radial direction. (Changes to the sizes of the cable would have taken much longer to implement.)

Satisfactory values of the high-order multipoles were achieved in a four wedge, non-radial block design developed for the CDR [7]. The C358A design uses these same variables, but with turn thicknesses determined from the assembly of the 4.5 m magnets. Design multipoles and the SSC requirements are given in Table II.

The design multipoles given in Table II are for unsaturated iron. Computer studies made since the CDR indicated that the vertical notches in the iron yoke which position the collared coil made the dominant contribution to the saturation sextupole [8]. Reducing this notch area in the 1.8 m yokes a factor of four decreased the saturation sextupole from 2 units to a maximum of 0.4 units.

Insulated cable

The ratio of copper to superconductor has been found to be an important variable in determining the number of quenches required to "train" a piece of cable prior to a short-sample measurement [9]. To study this effect in the inner coil layer of SSC magnets, cables with two different ratios (1.3, the value given in the CDR, and 1.6) have been used in the 1.8 m magnets (Table I).

Also, for most of the magnets in this series, it was decided to fix the overlap between successive spirals of the 25 μm kapton insulation at 45% to mimimize the buildup of the turn-to-turn insulation. (A 55% overlap produces a three-high stack over a small portion of the cable, adding about 0.25 mm to the coil size and increasing prestress loss via creep.)

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Table I – Magnet Parameters

Magnet	Cu:Sc Ratio (inner coil)	Kapton overlap	G-11 Coil end supports	Coil End strengthening
DSS1	1.3	55%	no	unfilled
DSS2	1.3	55%	no	unfilled
DSS2 retest	1.3	55%	no	filled
DSS4	1.6	45%	yes	filled
DSS5	1.6	45%	yes	filled
DSS7	1.3	45%	no	unfilled

Common features: 1.8 m length; 5 μm NbTi filaments; C358A coil cross-section; stainless steel, spot-welded collars; rectangular keys; "straight" ends; 1.8:1 Cu:Sc ratio in outer coil.

Coil Production

NMR measurements of the first full-length SSC dipole revealed a 152 cm periodicity in field strength [10]. Although this variation is acceptable for the SSC, all the tooling used in the production of the cold mass was closely examined so that the cause could be identified and removed. As part of this study, the sizes of 17 m coils were measured in 5 cm steps at a fixed pressure close to that desired in the assembled coils. The periodicity was traced to the coil molding procedure. The procedures were modified and the 1.8 m coils were molded as a test of the modification. The peak-to-peak size variation in a given coil was reduced from 10 to 5 mils and the revised procedures are now used in manufacturing full length coils. Additionally, the uniformity of the tooling has been improved.

The coils are molded to a fixed size; hence, the maximum pressure applied during molding varies due to within-tolerance variation of the size of the materials (cable, wedges, kapton, epoxy-impregnated fiberglass) used in the coil. The range of pressure allowed during coil molding was lower for the 1.8 m magnets than for the 4.5 m magnets. This was done to reduce the risk of damage to the turn-to-turn insulation during molding. The 1.8 m coils were molded in the pressure range 5-9 kpsi, whereas maximum cure pressures of the 4.5 m coils exceeded 15 kpsi.

The magnet design calls for the ends to be restrained from moving under the 17 kpsi axial Lorentz force present at 6.6T. To do this, a support is glued to the rounded ends of the winding during molding so that the coil will have a uniform length which can be supported externally. In the later 1.8 m magnets, this support was machined from a G-11 fiberglass-epoxy cylinder, replacing the silica-loaded epoxy ("green putty") used in the initial 1.8 m magnets and in the 4.5 m magnets.

Further, the support of individual turns in the coil end was improved by coating the end of the molded coil with a viscous mixture of epoxy and alumina powder and then holding the coil end in a small section of molding tooling under presure while the epoxy cured. In a test of this "filling" procedure, it was verified that the epoxy-alumina mixture did not come in contact with the superconductor, which could result in degradation of stability. (As a test of the need for the end support, the ends of one of the 1.8 m magnets were modified after the initial test so that axial motion of the coil could occur.)

In the coil end region, the iron yoke is spaced away from the coil by 2 cm on the radius so that the peak field will be reduced in the end, where the prestress may be lower. For the 1.8 m magnets, this end region configuration of iron was extended 5 cm into the inner coil straight section to further reduce any field enhancement at the end.

Collared Coil Assembly

Before the stainless steel collars for the 1.8 m magnets were clamped around the coils, pairs were spot welded together as indicated in the drawing (Fig. 1). (The collars behind those shown in the drawing are left-right reversed.) The welds transmit the shear forces between adjacent collars, rather than the pins as in the 4.5 m magnets. Further, the position of the keys was altered to reduce the stress concentrations and yielding found in collars used on the 4.5 m magnets. A stiffer collar has come from these changes. As a result, the difference between maximum pressure which must be applied during assembly (when the keys are inserted) and the pressure after collaring has decreased from about 9 kpsi to about 5 kpsi. This allows coils to be collared at the design prestress (7-9 kpsi) without damage to the turn-to-turn insulation which has been found to occur at collaring pressures above 18 kpsi.

The initial 1.8 m dipoles were used to obtain the correct coil size for assembly with spot-welded collars. Magnets DSS4 and DSS5 were assembled with the coil compressed to the design size with 6 kpsi initial prestress in DSS4 and 10 kpsi in DSS5. These two magnets are then the reference points for comparing the measured dipole field with the calculated values.

Test Results

B/I, field uniformity

As is noted above, magnets DSS4 and DSS5 were assembled with the coil compressed to the C358A design size. Measurements of the allowed multipoles for these magnets are given in Table II. The design values are less than 0.1 unit. The significance of differences between the design and measured values is evaluated by comparing the differences to the estimated magnet-to-magnet construction variation [11] and to the maximum mean value allowed for magnets, estimated from accelerator physics considerations [12]. These two reference numbers are also given in Table II.

Table II – Multipoles

Coefficient	Measured DSS4	Measured DSS5	Estimated rms Variation	Maximum Value of Mean
b_2	2.5	2.0	2.0	1.0
b_4	0.54	0.40	0.7	0.2
b_6	−0.07	−0.09	0.2	0.04
b_8	0.06	0.07	0.1	0.1
b_{10}	0.07	0.08	–	–
b_{12}	−0.02	−0.02	–	–

Entries have units of 10^{-4} B_0 and are evaluated at 1 cm radius. Measurements are of the central 76 cm, averaged from 2 kA through 3 kA and over the up-ramp and down-ramp.

In making this comparison for the sextupole, for example, the difference between the two magnets, 0.5 units, is seen to be much less than the estimated rms variation, 2.5 units. This is an encouraging result, but it does not mean that the estimates for construction variation were too conservative since DSS4 and DSS5 were wound with cable from the same spools. Both magnets have sextupoles about twice as large as the 1.0×10^{-4} upper limit to the mean. A third magnet in this series will be tested soon. On the basis of these three magnets, it will be decided whether to make changes to the C358A design to reduce the sextupole. Such changes would be small.

The same discussion and conclusions also apply to the next two allowed multipoles, b_4 and b_6. Terms above b_6 are within the limits. Values for the unallowed multipoles are not presented here since the effects of feeddown can be important. However, the measurements do not show large values for these terms.

For both magnets B/I was measured with an NMR probe to be 1.0429 T/kA. When the calculation [6] is corrected for the thermal contraction of the iron, there is agreement with measurement within about 0.1%. Also, measurement confirms the calculated reduction in saturation sextupole.

Operating field

Two aspects of quench performance are important in determining the maximum useful field of the magnet: the number of quenches required to reach the short-sample limit and the quench-to-quench variation σ in current after training. Data on the magnetic field at quench for four 1.8 m magnets are given in Fig. 2 and in Table III. All four magnets were assembled with spot-welded collars [13]. The last two magnets tested, DSS4 and DSS5 [14], also have the other two major improvements (higher ratio of copper to superconductor in the inner coil cable, "filled" ends). The retest of DSS2 (discussed below) has also provided quench performance data.

Table III – Quench Performance

Magnets	Mean I_Q(A)	$\sigma[I_Q(A)]$	Notes
DSS2	6379	85	
DSS7	6620	108	4
DSS2 (retest)	6578	12	1
DSS4	6435	9	
DSS4 (retest)	6450	13	3
DSS5	6401	21	2

Notes:

1. A correction has been made for variation of the helium temperature. For the uncorrected data, the mean I_Q = 6655, σ = 24A.
2. Only quenches in the lower inner coil have been included.
3. For this retest, axial motion of the coil was not restrained.
4. The two low quenches following training are in separate coils. If they are excluded from the average, the mean I_Q = 6682A, σ = 26A.

As with the 17 m magnets, quenches in the 1.8 m magnets are all in the inner layer [15]. Comparing results of DSS2 and DSS7 with results from DSS4, DSS5, and the retest of DSS2, a marginal reduction in the number of training quenches and a significant improvement in the variation of quench currents after training can be seen.

To isolate the effect of filled ends, DSS2 was completely disassembled after its initial test so that the epoxy-alumina mixture could be applied to the coil ends. (The quench data of a reassembled magnet are usually quite similar to the initial data.) In Table III, it can be seen that the average quench current and the quench-to-quench variation are better in the DSS2 retest than in the initial test. Other quench performance data were also better in the retest of the magnet: Retraining after a thermal cycle was reduced (0.3T vs. 0.9T) and a higher maximum field at reduced temperature (7.4T at 3.0K vs. 7.0T at 2.6K). Conclusions based on the test of a single magnet are necessarily limited, but the "filled" ends do appear to have improved the quench performance of the magnet.

A test of the sensitivity to coil axial motion was made by removing about 1 cm of material from the ends of the coils of DSS4 so that the coils could expand along the magnet axis. Initially, the magnet quench current at 4.5K was unchanged, but the quench current became erratic in subsequent testing at lower temperatures.

Conclusions

The first two magnets made with the C358A design have achieved multipole values close to the design and close to SSC requirements. Further iterations in the cross section, if any, will be small. The use of spot-welded collars has reduced the prestress loss in collaring and increased the range of coil sizes which can be assembled with satisfactory prestress. The combination of an increased copper-to-superconductor ratio and strengthened ends has improved the quench performance of the 1.8 m magnets.

References

1. P. Wanderer, "Summary of quench performance and field quality data from 3.5 m and 4.5 m R&D magnets," in "SSC Conceptual Design Magnet Design Details," SSC-SR-2020B, SSC Central Design Group, Lawrence Berkeley Laboratory, One Cyclotron Rd., Berkeley, CA 94720 (1986).

2. J. Strait et al., "Tests of Prototype SSC Magnets," presented at this conference, Tenth International Conference on Magnet Technology, Boston, MA, Sept. 21-25, 1987.

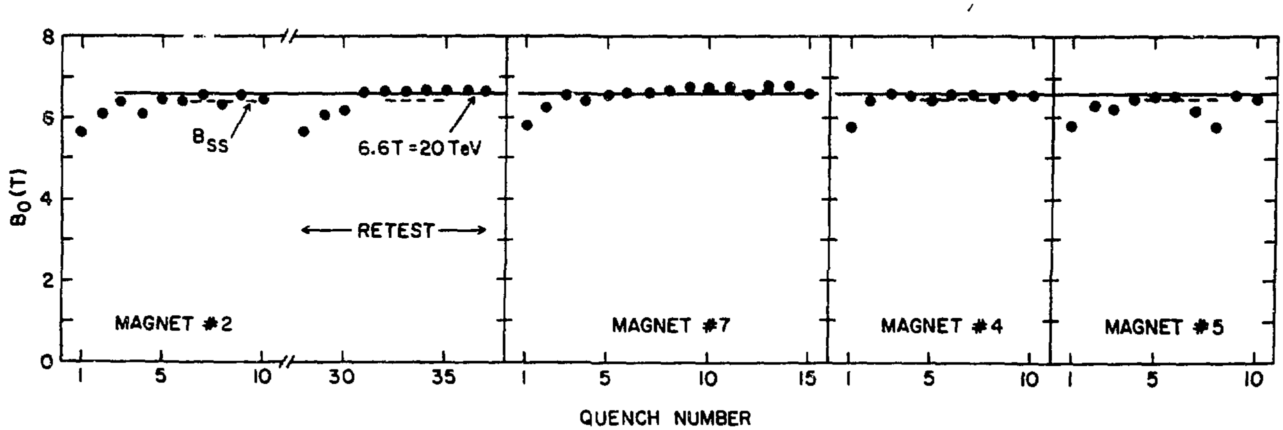

Fig. 2. Central dipole field at quench for four 1.8 m SSC dipoles ramped at 8A/sec in 4.46K liquid helium. The dashed lines denoted B_{SS} are the quench fields estimated from measurements of short samples of the cables used in the magnets. The estimates include self-field effects in the short-sample measurement. The solid line indicates the SSC operating field. The seventh and eighth quenches in magnet no. 5 are believed to be the result of a faulty coil and have been excluded from the analysis.

3. The half-shells are welded at the magnet midplane to form the helium vessel of the 17 m dipoles. For the 1.8 m dipoles, the half-shells are clamped together for ease of assembly and disassembly.

4. C. Taylor and P. Dahl, "Dipole Magnets: A Brief Description," see ref. 1.

5. "Conceptual Design of the Superconducting Super Collider," SSC-SR-2020, SSC Central Design Group, Lawrence Berkeley Laboratory, One Cyclotron Rd., Berkeley CA 94720, p. 124 (1986).

6. G. Morgan, "C358A – A New SSC Dipole Coil and End Design," Technical Note AD/SSC/Tech. No. 62, Brookhaven National Laboratory, Upton, N.Y. 11973 (1987), unpublished.

7. S. Caspi, M. Helm, L. J. Laslett, and C. Taylor, "NC515 – A New Dipole Cross Section for SSC," see ref. 1.

8. R. C. Gupta, G. H. Morgan, and P. Wanderer, "A Comparison of Calculations and Measurements of the Magnetic Characteristics of the SSC Design D Dipole," 1987 Particle Accelerator Conference, Washington, D. C., March 16-19, 1987.

9. W. Sampson, private communication.

10. J. Strait et al., "Tests of Prototype SSC Magnets," 1987 Particle Accelerator Conference, Washington, D.C., March 16-19, 1987.

11. See ref. 5, p. 127.

12. A. Chao and M. Tigner, "Requirements for Dipole Field Uniformity and Beam Tube Correction Windings," SSC-N-183 (unpublished), May 1986.

13. Data from the first 1.8 m magnet, DSS1, are not included because of a fault in the assembly.

14. The seventh and eighth quenches in magnet DSS5 are believed to be the result of a faulty coil and have been excluded from the analysis.

15. The axial location of quenches in the 1.8 m magnets is not known.

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