PERFORMANCE OF SIX 4.5 m SSC DIPOLE MODEL MAGNETS

E. Willen, P. Dahl, J. Cottingham, M. Garber, A. Ghosh, C. Goodzeit,
A. Greene, J. Herrera, S. Kahn, E. Kelly, G. Morgan, A. Prodell,
W. Sampson, W. Schneider, R. Shutt, P. Thompson
and P. Wanderer
Brookhaven National Laboratory
Upton, N.Y. 11973

Abstract

Six 4.5 m long dipole models for the proposed Superconducting Super Collider have been successfully tested. The magnets are cold-iron (and cold bore) 1-in-1 dipoles, wound with current density-graded high homogeneity NbTi cable in a two-layer $\cos\theta$ coil of 40 mm inner diameter. The coil is prestressed by 15 mm wide stainless steel collars, and mounted in a circular, split iron yoke of 267 mm outer diameter, supported in a cylindrical yoke containment vessel. At 4.5 K the magnets reached a field of about 6.6 T with little training, or the short sample limit of the conductor, and in subcooled (2.6 - 2.4 K) liquid, 8 T was achieved. The allowed harmonics were close to the predicted values, and the unallowed harmonics small. The sextupole trim coil operated well above the required current with little training.

INTRODUCTION

This paper reports on test results from six 4.5 m long model dipoles for the proposed Superconducting Super Collider (SSC). The magnet is a collaborative effort between Brookhaven National Laboratory, Lawrence Berkeley Laboratory, and Fermi National Accelerator Laboratory. The magnet, also known as Reference Design D, consolidates the principal features of earlier Reference Designs A and B[1], and draws on the collective experience with magnets for the CBA Project[2] and the Tevatron[3]. The design is based on high field ($\geq 6T$) superconducting dipole magnets, allowing a relatively "modest" SSC ring circumference (90 km for a guide field of 6.6 T). The high field is achieved with newly developed high homogeneity NbTi conductor. Additional magnet features include a relatively small (40 mm) bore and long (16.6 m) effective length. Several full-length demonstration magnets have been constructed but not yet tested. A more detailed description of this magnet can be found in the Conceptual Design Report and its Appendix issued in the Spring of 1986[4].

MAGNET DESIGN

Figure 1 shows a cross section of the collared coil, and Figure 2 a section of the coil-in-yoke subassembly mounted in the yoke containment vessel. The overall diameter of the iron yoke is 266.7 mm. Omitted from Figure 2 is the outer vacuum vessel and magnet support system, not needed in the pool boiling tests discussed here.

On the outside of the stainless steel cold bore tube is mounted a distributed sextupole correction winding, required for compensating systematic errors including magnetization effects in collider operation. Between it and the main dipole coil are longitudinal insulator strips spaced to furnish annular helium cooling passages in forced-cooling operation. Both inner and outer dipole coils are wound from a partially keystoned, high homogeneity NbTi cable of the Rutherford type. The lack of full keystoning commensurate with the coil aperture is compensated by copper wedges in the coil cross section (Figure 1). The wedges also furnish additional degrees of freedom in the field-shaping optimization procedure. To ensure cost-effective superconductor utilization, the inner coil layer (16 turns/quadrant) is wound from a 23-strand cable of Cu:SC ratio 1.3:1 and the outer layer (20 turns) from a 30-strand cable of ratio 1.8:1. The current density of either cable is $\sim 2100 A/mm^2$ (at 5 T, 4.2 K), and the filament size is approximately 20μ. The layers are powered in series. Cable insulation consists of an overlapping layer of Kapton followed by a layer of fiberglass-epoxy. The present coils retain a strictly provisional feature from Reference Design A: their ends are flared out to increase the minimum bending radius, allowing the possibility of substituting prereacted Nb_3Sn. Ongoing experiments indicate that a flared end is not necessary for NbTi, and future models of this series will utilize straight ends.

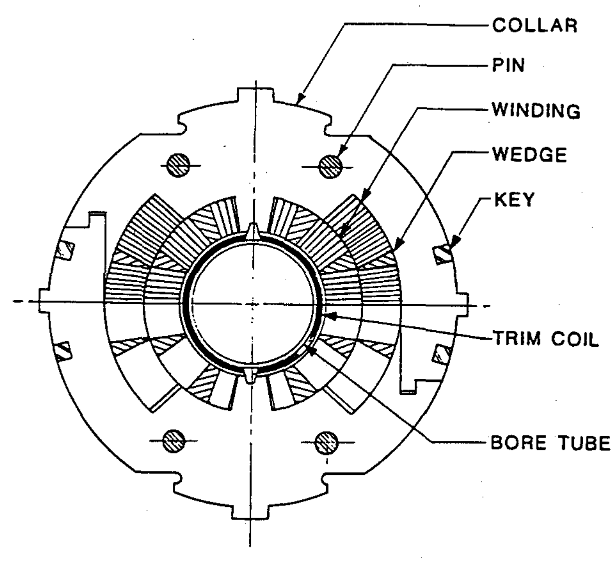

Figure 1. Cross section of collared coil assembly showing bore tube, main coils and stainless steel collar. The trim coil, mounted on the outer diameter of the bore tube, is not explicitly shown.

The coils are compressed with 15 mm wide collars of fully austenitic, nonmagnetic stainless steel, similar to those developed for the Tevatron except that no welding is involved; pins and keys are used instead. They provide the necessary restraint to maintain the coil under a compressive stress of about 6 kpsi. With the cold iron separated from the coils by the 15 mm width of the collars, the iron contributes $\sim 1.7T$ to the $6.6T$ central field, but saturation effects are quite small (the change in the sextupole harmonic is 2×10^{-4} of the dipole, at 1 cm).

The yoke laminations (Figure 2), punched from low-carbon steel, contain keyways for accurately locating the collared coil subassembly. The two large rectangular slots will carry the main and diode bypass electrical bus (top) and correction element leads in a magnet string. The four large holes are channels designed to bypass most (100 g/sec) of the 4 atmosphere supercritical helium mass flow; only about 1 g/sec is needed for transferring heat in the coil region. The yoke and helium containment vessel is fabricated from stainless steel half shells closed on the midplane by tensioned stainless steel bands.

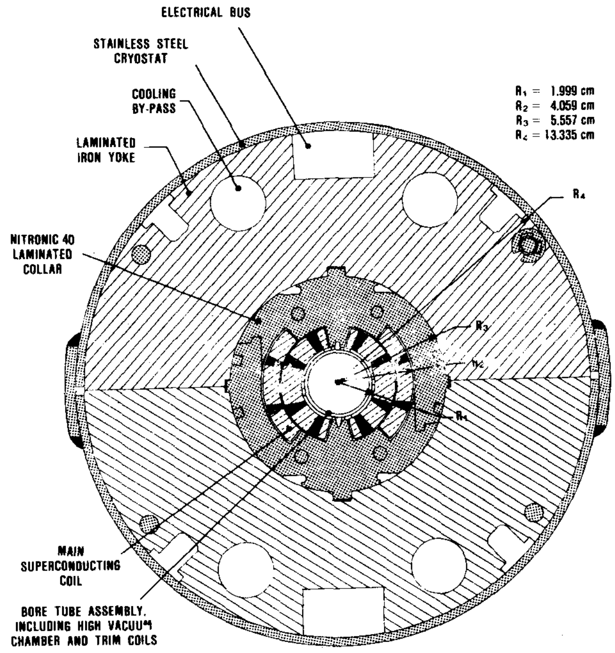

Figure 2. Overall cross section of magnet, showing collared coils mounted in split yoke support (and helium containment) vessel.

MAGNET CONSTRUCTION

The four coil sections of a dipole are wound separately on a laminated, convex mandrel with a semiautomatic winder. They are then epoxy-cured in a laminated, concave fixture at 130 C under pressures in the range 60-120 MPA. The epoxy in the fiberglass conductor wrap is controlled so that none comes into contact with the wires during the cure. The coil sections are assembled around a bore tube to which the trim coil has already been attached. During this assembly additional insulation is introduced: Kapton on the midplane and Kapton and a Teflon slip plane between coil layers. The collars, preassembled in packs, are assembled over the coil package already insulated on the o.d. with several layers of Kapton. They are compressed incrementally with a press and keys are inserted to keep them closed. The material specified for the collars is Nitronic 40 stainless steel, a product of Armco, selected because it meets the strength requirements and also exhibits excellent magnetic (low permeability) properties at cryogenic temperatures. Keys, unlike welds, facilitate repair of magnets. Finally, the collared coils are mounted in the iron yoke (Figure 3), previously assembled from module blocks, and the yoke containment shell is closed by stretched stainless steel bands with the top and bottom yoke subassemblies held in contact under pressure. In production, the containment shell would be closed by welding. Figure 4 shows a finished magnet, ready for tests.

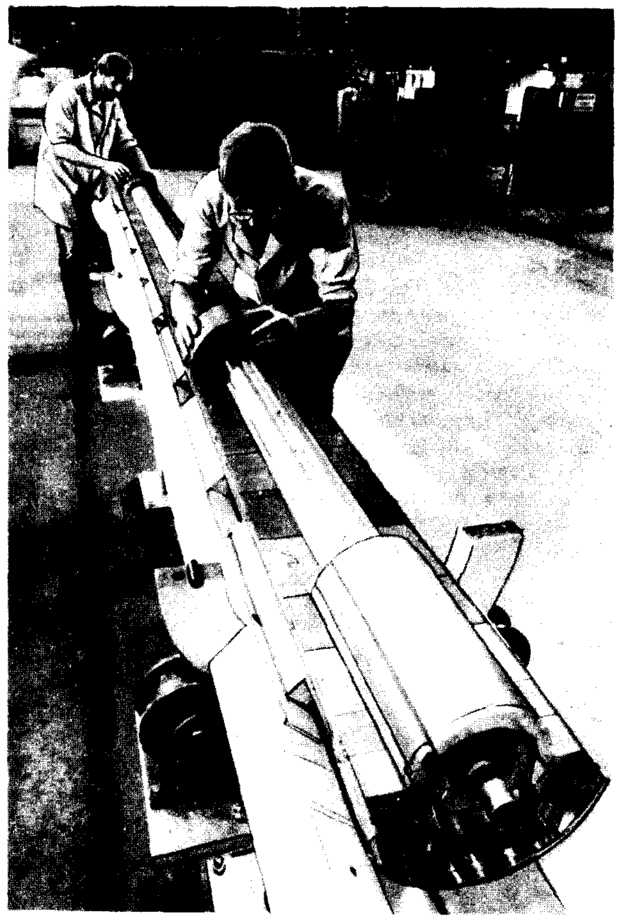

Figure 3. Collared coil installed in bottom yoke half, with top yoke modules being installed. Note larger diameter collars in magnet ends to accommodate flared coil ends.

MAGNET PERFORMANCE

Training History

The training performance of six dipoles in liquid helium at 4.5 K is shown in Figure 5. The magnets all reached a stable quench plateau of 6.6 T, in qualitative agreement with short sample expectations (about 2% lower) at this temperature, with relatively modest training. The subsequent maximum fields reached in subcooled liquid are also indicated in Figure 5. (The short sample prediction is about 8 T at 2.5 K.)

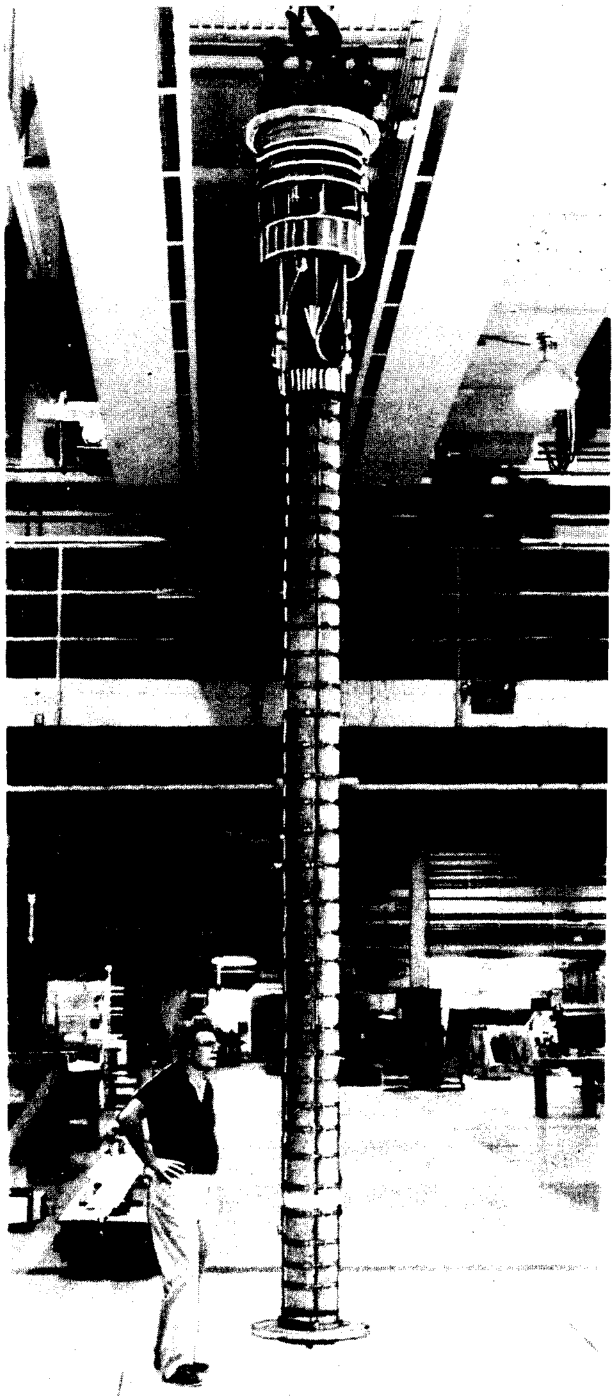

Figure 4. Assembled magnet being lifted for installation into test dewar.

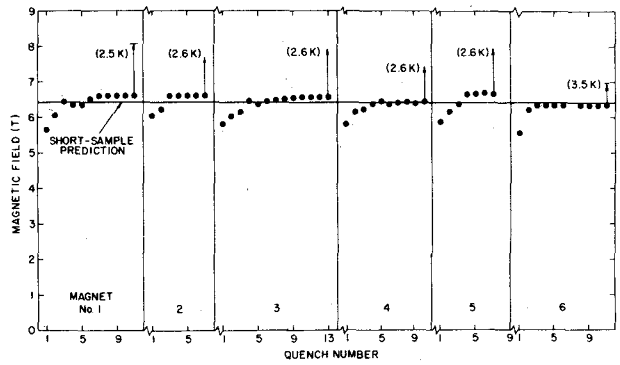

Figure 5. Dipole quench performance at 4.5 K, with performance in subcooled helium also indicated.

Field Quality

Table I summarizes the integral harmonics, designated by the usual notation (b_1 = normal quadrupole, etc.). Column 2 gives the means, and column 3 the standard deviations, of the measured values. Column 4 gives the expected standard deviations for the harmonics in these magnets, as extrapolated from CBA and Tevatron experience with magnets of this type[5]. It can be seen that in all cases, the measured σ is less than that expected, indicating that these early magnets are being constructed to the field quality requirements of the SSC. The mean value of the unallowed harmonic, a_1, is nonzero because of a possible unanticipated vertical interference fit between the collared coil and iron yoke assembly. The mean values of the allowed harmonics b_2 and b_4 are nonzero because of the flared ends and because of necessary shim adjustments to assemble the magnets; the means are, however, close to the calculated values for the shims actually used. It is anticipated that in future magnet series, the mean values for all the allowed harmonics will be reduced to near zero. The data presented in Table I results from a more careful analysis of the measurements and hence the numbers differ somewhat from the results of the preliminary analysis published earlier[4].

Table I
Measured Integral Harmonics ($10^{-4} B_o$) at 1 cm

Harmonic	Mean	σ, Measured	Specified Tolerances
b_1	0.29	0.78	0.7
b_2	8.74	1.51	2.0
b_3	-0.03	0.16	0.3
b_4	-0.70	0.28	0.7
b_5	0	0.03	0.1
b_6	0.01	0.05	0.2
b_7	0	0	0.2
b_8	0.81	0.01	0.1
a_1	-3.31	0.75	0.7
a_2	1.04	0.23	0.6
a_3	-0.34	0.46	0.7
a_4	-0.08	0.12	0.2
a_5	-0.07	0.11	0.2
a_6	0.02	0.03	0.03
a_7	0	0.01	0.2
a_8	0.02	0.01	0.05

Figure 6 shows the measured sextupole and decapole harmonics over the full excitation range in the six magnets, and Figure 7 the transfer function for one of the dipoles as a function of excitation. The effect of magnetization currents at low field is apparent in Figure 6, as well as the small saturation effect at high field.

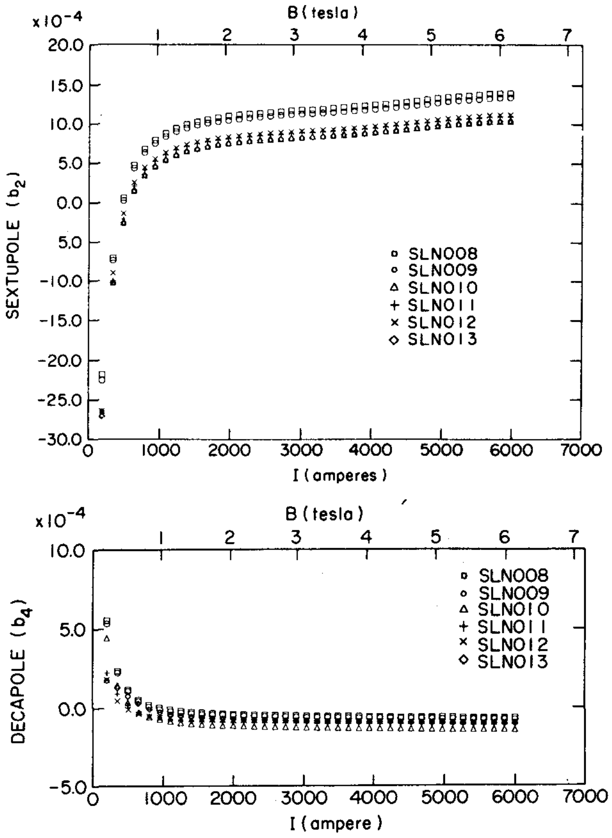

Figure 6. Variation of sextupole (top) and decapole (bottom) harmonics with excitation for the six dipoles.

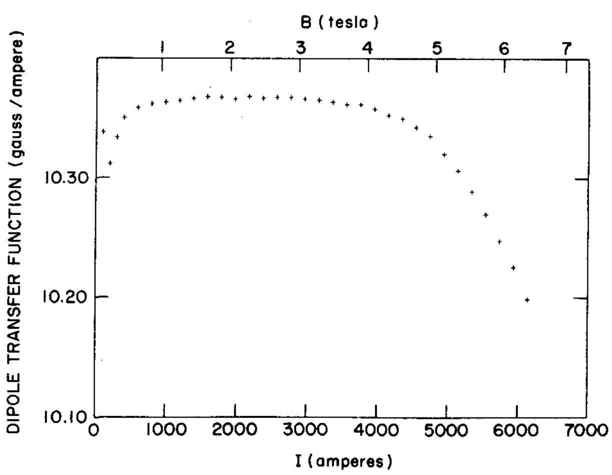

Figure 7. Transfer function, B_o/I, as a function of excitation for one of the dipoles.

Trim Coil Construction and Performance

These magnets utilized sextupole trim coils, manufactured in the case of the last four magnets by the Multiwire Corporation. These trims take advantage of an industrial proces which is an offshoot of printed circuit technology and allows wires to be placed in a layer of fiberglass and epoxy with greater accuracy ($\pm 25\mu m$) than can be achieved with conventional winding methods. The NbTi wires, 0.2 mm in diameter, are bonded to a flat rectangular sheet of substrate and secured to the bore tube with a Teflon adhesive and an overwrap of epoxy-impregnated Kevlar. Accurate positioning on the bore tube is achieved by aligning slots cut in the substrate onto guides attached to the bore tube. The bore tube is keyed to the dipole collars at the top and bottom. Spacers between the trim and the main coils limit flexure during operation.

The trim coil quench currents have been determined at three values of the dipole field; injection (0.03 T), midfield (2 T), and close to peak field (5.8 T). The results are shown in Table II. Quench current at 5.8 T is at the short sample limit. Several training quenches are required to reach this limit. As can be seen from the Table, the trim coil operates with a large safety margin at all dipole fields.

Table II
Quench Performance of the Multiwire Trim Coil in the Sixth 4.5 m Dipole

$B_o\,(T)$	Maximum Achieved	Required
0.3	66	0.3
2	66	2
5.8	16	4

The harmonics from the final Multiwire trim coil were measured and found to be acceptable. The normal 18-pole term, b_8, is the first allowed multipole. The amount of b_8 produced was small, about 0.005 units, at the maximum trim coil operating current over the whole range of dipole field. All other harmonics were also small compared to the random variation from the dipole itself.

References

1. Report of the Reference Designs Study Group on the Superconducting Super Collider, Draft II (May 8, 1984), unpublished.
2. E.J. Bleser, et al., "Superconducting Magnets for the CBA Project", Nucl. Instrum. & Methods, A235, 435-463.
3. R. Palmer and A.V. Tollestrup, "Superconducting Magnet Technology for Accelerators", Ann. Rev. Nucl. Part. Sci. 1984, 34 (1984), 247-248, and references therein.
4. Superconducting Super Collider Conceptual Design, Ed. J.D. Jackson, SSC-SR-2000, March 1986.
5. H.E. Fisk, et al., "Magnetic Errors in the SSC", SSC Central Design Group Internal Report No. SSC-7 (1985).