

CONF-840937-12

BNL-35252

TEST RESULTS FROM TWO 5m TWO-IN-ONE SUPERCONDUCTING MAGNETS FOR THE SSC*

CONF

J.G. Cottingham, P.F. Dahl, R.C. Farnow, M. Garber, A.K. Ghosh, C.L. Goodzeit, A.F. Greene, J.C. Herrera, S.A. Kahn, E.R. Kelly, G.R. Morgan, R.B. Palmer, A.G. Prodell, W.B. Sampson, W.J. Schneider, R.P. Shutt, P.A. Thompson, P.J. Wanderer, E.R. Willen

Brookhaven National Laboratory
Associated Universities, Inc.
Upton, New York 11973

BNL--35252

DE85 001227

Abstract

Two 5m long superconducting dipole magnets with specifications similar to the reference design for the proposed Superconducting Super Collider have been successfully tested. The "cos θ " coils of the magnets were made from two layers of "standard" CBA/Tevatron NbTi superconductor, keystoned to an angle of 2.8 degrees. The inner diameter of the inner layer was 3.2 cm. The ends of the coils were flared to increase the minimum bending radius so that future magnets can be wound from prereacted Nb₃Sn. The windings of the two-aperture magnets were clamped in a "two-in-one" iron yoke with a tensioned stainless steel shell. The fields of the two apertures were closely coupled, since the flux in one aperture returned through the other. The inner and outer layers of the coil were powered separately so that their short-sample limits would be reached simultaneously. With minimal training the magnets reached a central field of 6 T, the short sample limit of the conductor at the 4.5 K temperature of the liquid helium bath. At 2.6 K, a central field in excess of 7 T was reached, again with minimal training. The measured values of the allowed sextupole and decapole harmonics are within 10% of the calculated values and the non-allowed harmonics are all small or zero, as predicted.

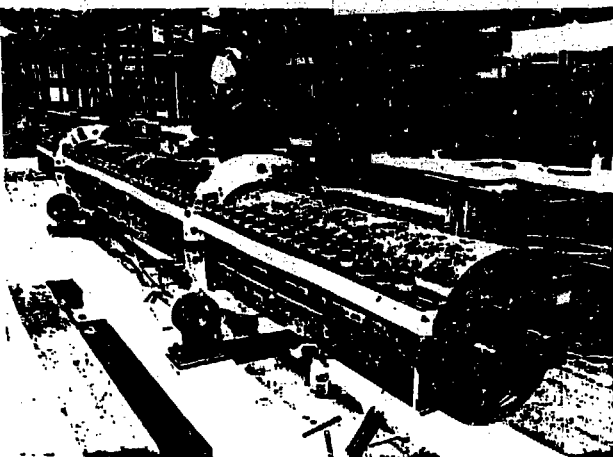


Figure 1. Overall view of one of the magnets.

Introduction

This paper reports the first results from a series of magnets being built to test concepts that will be used to minimize the cost of the proposed Superconducting Super Collider.¹ In the design of the magnets reported here, lower cost is achieved through the use of a high field, a small aperture, and a cold-iron 2-in-1 yoke. The high field is to be reached through the use of high homogeneity NbTi or prereacted Nb₃Sn, with the coil ends flared out and clamped in stainless steel so that, in the case of Nb₃Sn, the strain-induced reduction in critical current will not limit the performance of the magnet. The two magnets reported here were tested with standard CBA/Tevatron NbTi cable, keystoned to 2.8° because of the smaller bore size. (The present inner coil diameter is 3.2 cm, whereas SSC Reference Design A calls for a bore size of 4.0 cm, which should simplify construction.) Future magnets will be tested with either Nb₃Sn or high homogeneity NbTi. Figure 1 shows the first magnet in the final stage of assembly prior to testing.

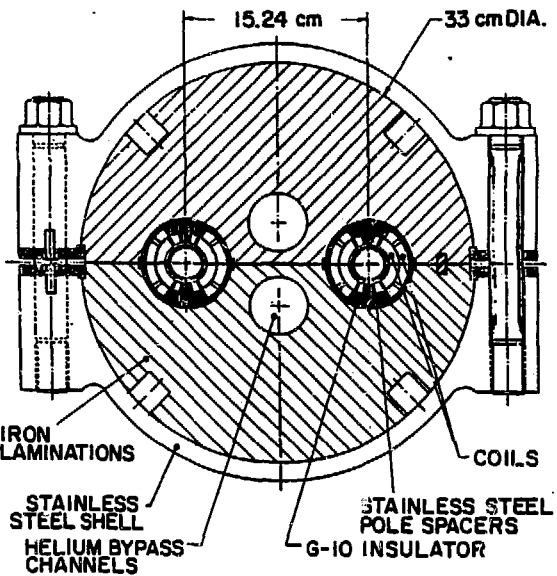


Figure 2. Cross section of 2-in-1 dipole.

Magnet Design

The 2-in-1 yoke is based on the concept, first discussed by Blawett,² of using each bore as the return path for the flux from the other bore. This reduces the amount of iron below that required in two standard yokes. Figure 2 shows a cross section of the dipole, including coils, yoke, and yoke support system.

Transfer function and field harmonic calculations were made with the program MDP, using saturated iron at high fields. As with the CBA magnets,³ the principal

allowed harmonics (sextupole, decapole, ...) were varied by adjusting the size of the pole spacers and inert wedges in a two-layer coil. The inner coil layer in this magnet has 16 turns extending to 76.3° above the midplane, with wedges after the 6th and the 11th turns. The outer layer has 17 turns extending to 54.5° above the midplane, with a wedge after the 12th turn. The short time scale for the construction of this model did not allow fine tuning of the coil design to meet the sextupole and decapole requirements for the SSC. The present results do, however, allow comparison of the calculated and measured fields to be made. Values of the allowed harmonics suitable for the SSC can be achieved by iterating this design.

*Work performed under the auspices of the U.S. Department of Energy.

Manuscript received September 10, 1984.

MASTER

Handwritten initials

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

In the absence of left-right symmetry, the quadrupole term is an allowed harmonic. In this design, the quadrupole is kept small by adjusting the helium bypass holes punched in the yoke laminations above and below the midplane, between the two bores.

For a SSC magnet, minimum cost is achieved through the use of "graded" conductor in both layers so that the two layers have the same margin in critical current. For the models tested here, which have the same conductor in both layers, operation with graded conductor was simulated by powering the layers separately. It was calculated that both layers would be at critical current simultaneously if the current in the outer layer were 35% greater than the current in the inner layer.

Calculations of the field in the region of the flared ends indicated that the reduction in the field is substantially greater than the loss in critical current expected in this region with Nb_3Sn , which is expected to be at most 10% due to strain-induced effects.

Magnet Construction

The 23-wire NbTi superconducting cable used in these magnets was the same as that used for CBA magnets except that it was keystoned to 2.8° instead of 1.1° . At a resistivity of 2×10^{-12} ohm-cm, the critical current of the cable was 5.58 kA for magnet SSC-1 and 5.36 kA for magnet SSC-2 in a 5.0 T perpendicular field at 4.22 K. The reduction in critical current due to cabling was about 12%, the same as for CBA in spite of the increased keystone angle. The anticipated limits in magnet performance, extrapolated from the short-sample test with a formalism developed for CBA, are shown in Figure 3. The cable insulation, two overlapping layers of 0.025 mm Kapton and a single layer of 0.075 mm fiberglass impregnated with B-stage epoxy, was the same as that used for CBA.

The eight individual coils were wound and cured on CBA 4.5 m fixtures adapted to the smaller SSC coil diameter. Coils were wound on a convex mandrel with a semi-

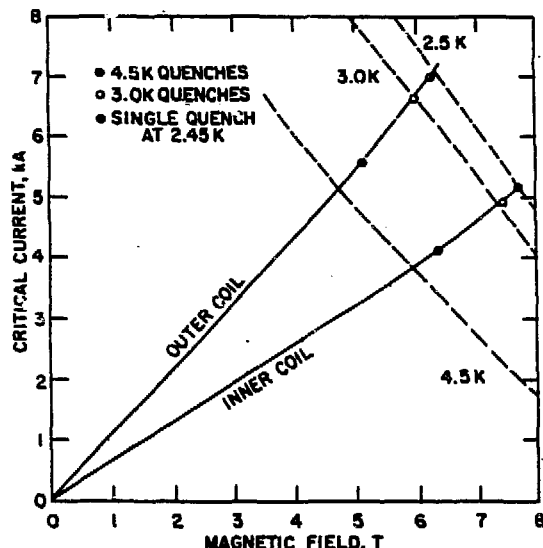


Figure 3. Critical current vs. magnet field at 4.5 K, 3.0 K, and 2.5 K for the 23-strand NbTi cable. Load lines for the two separately powered inner and outer coils are also shown, with the calculated peak fields corresponding to the quench plateaus attained by dipole SSC-1 at the three bath temperatures.

automatic winder. The mandrel and coil were then lowered into a concave fixture for curing of the epoxy at relatively high pressure and temperature. The amount of epoxy was controlled so that none came into contact with the wires during the cure. As was the case with early CBA magnets, the curing fixture available for these coils was unable to reach the pressure necessary to bring the coils to a uniform size and they are slightly larger than the design size. (High pressure curing fixtures are now in use.)

The basic unit of the yoke was a glued-together block of iron laminations, made using the methods developed for CBA. The outer diameter of the lamination was 33 cm, and the length of a yoke block was 14.7 cm. The two bores had inner diameters of 7.47 cm and their center-to-center separation was 15.2 cm. The helium bypass holes, which also helped reduce the quadrupole harmonic, were 5 cm in diameter, centered 3.5 cm above and below the midplane. Four rectangular notches for cabling were cut into the iron periphery, located symmetrically at 45° to the midplane. The lamination blocks, split at the midplane, were brought together during the assembly process. The magnet coil was isolated from the yoke by 4.8 mm thick G-10 insulators. The coil's azimuthal location was determined by stainless steel pole spacers which were keyed to the G-10 insulators. The insulators, in turn, were keyed to the yoke. A system of helium flow paths, unnecessary for the present test but necessary for the SSC, were also incorporated into the magnet. The general arrangement of the coils, pole spacers, and G-10 insulators was similar to that used in the CBA magnets.

The assembly of the two half yokes applied the necessary prestress to the coils and was accomplished by placing a semicircular stainless steel shell around the yoke blocks. (This technique was adopted in order to develop inexpensive assembly techniques for the SSC.) During assembly, the stainless steel shell was stretched by bringing together flanges that were cast integral to the midplane of the shell. The CBA assembly press was used to close the shell, and yoke bolts then held the shell closed for testing. To make the distribution of force more uniform along the periphery of the yoke, 0.025 mm-thick Teflon film was placed between the yoke and the shell. In a production design the shell would be welded at the midplane; in the present R&D program, bolted flanges allow reuse of the yoke. Both magnets reported here used the same yoke. For the magnets, the inner coils were assembled with room temperature prestress greater than 530 kg/cm^2 ; the outer coils were assembled with prestress greater than 980 kg/cm^2 . The prestress of each of the 8 coils was measured by strain gauges located in the stainless steel center posts. With the midplane of the yoke closed along its outer diameter, a gap between the bores of the order of 0.13 mm was present. No shorts were encountered in the assembly of either magnet.

Magnet Performance

When magnet SSC-1 was tested initially, quenches in the leads propagated to the magnet, obscuring the initial training behavior. Even so, the first quench was at a field of 5.6 T. More copper was added to the leads in order to increase their stability at high currents. In order to make this modification the magnet was thermally cycled twice but it was not otherwise affected by the lead modification, since the leads were external to the coils and yoke assembly. With stable leads, the magnet operated immediately at the 5.9 T short sample limit at 4.5 K (Figure 4). At 3.0 K and 2.5 K, the magnet went to the 6.9 T and 7.2 T short sample limits, respectively, after 2 to 3 training quenches. Magnet SSC-2 quenched twice at 96% of short sample at 4.5 K and then quenched at its short sample limit, which was about

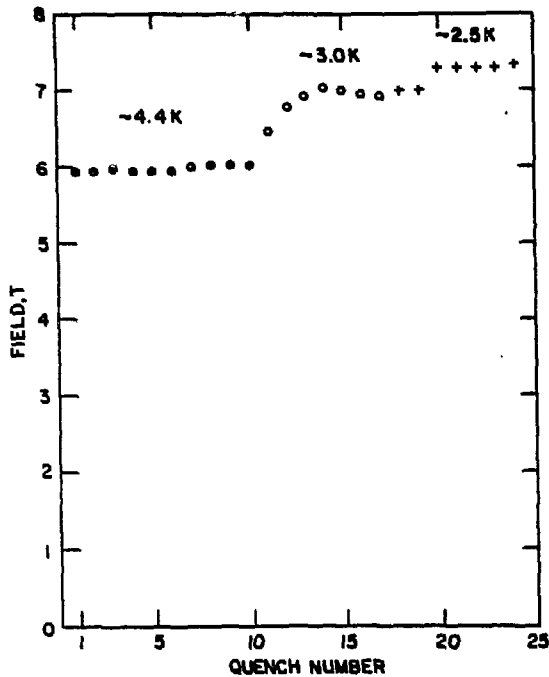


Figure 4. Quench performance of dipole SSC-1.

2% below the short sample limit of magnet SSC-1. At 2.6 K, SSC-2 reached its 6.9 T short sample limit after several training quenches. The results at 2.5 K demonstrate that the present method of magnet construction will be adequate to test Nb₃Sn coils to their full potential, 7.5 T at 4.5 K. Also, tests were made to verify that the ratio of currents in the inner and outer coils was correct. When the current in the inner coil was decreased 2%, quench origins switched from the outer layers to the inner layers, as expected.

The maximum field reached by magnet SSC-1 is compared with the predicted performance based on short sample measurements and CBA experience in Figure 3. It can be seen that the magnet exceeds the prediction by 6% along the load line. This is equivalent to 12% in the short sample current at fixed external field, an effect much greater than the uncertainty in the short sample measurement itself, estimated to be 2%. The uncertainty in the field strength of the magnet is ±1%, based on a measurement in a calibration magnet. At lower temperatures, there is closer agreement between the prediction and the magnet performance; however, the extrapolation from the 4.22 K temperature of the short sample measurement to the operating temperature of the magnet is much less certain in this instance. Comparison of the short sample prediction and the performance for SSC-2 leads to similar conclusions.

The next several figures show the first two allowed multipoles as measured in the central 75 cm of the first magnet. Figure 5a shows the variation of the sextupole multipole as a function of current for an up ramp (+) and for a down ramp (□). Figure 5b is a similar plot for the decapole multipole. The effect of superconductor magnetization is seen in the separation of the points at low current. The variation of the harmonics with current at high excitation is due to iron saturation.

Figure 6a and 6b compares the sextupole and decapole multipoles as measured in the adjacent bores of the first magnet. The near overlap of the two sets of

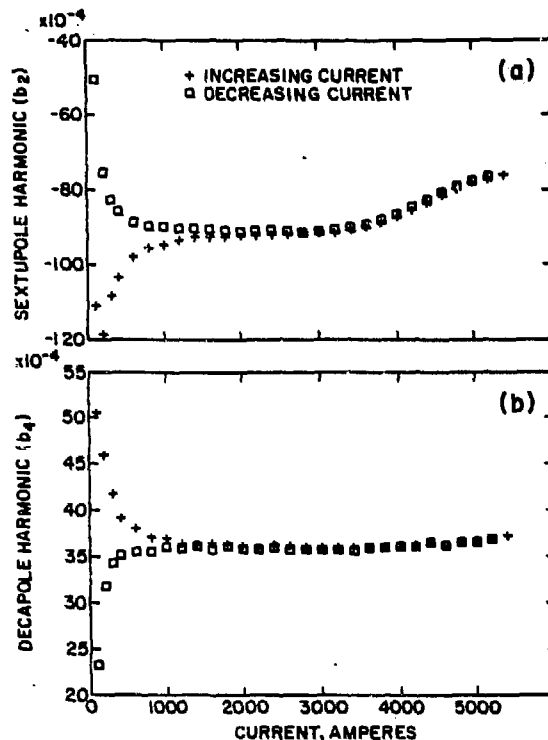


Figure 5. Measured sextupole and decapole multipoles as a function of magnet current in dipole SSC-1.

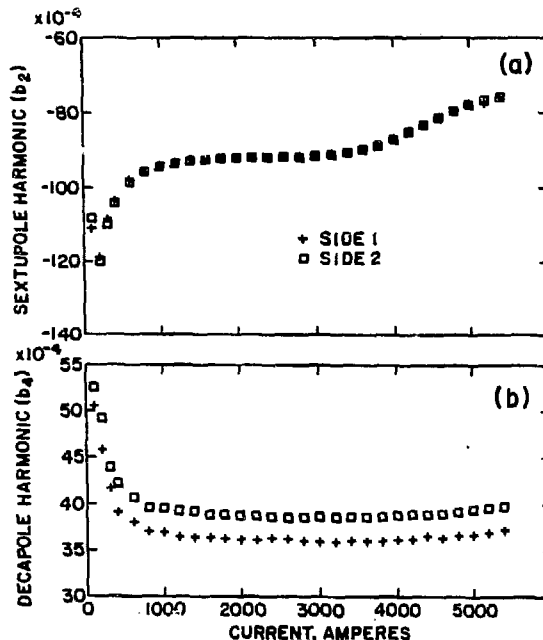


Figure 6. Comparison of sextupole and decapole multipoles measured in the two bores of dipole SSC-1.

points demonstrates that the coils have been manufactured to the required close tolerances for the SSC; the difference between the sets of points is consistent with the difference which would arise from the expected 0.05 mm random variation in the location of the current blocks in the coils.

The measured values of the allowed sextupole and decapole multipoles are within 10% of the calculated values, which is considered to be good agreement within the uncertainties of the calculation. Because of the large values of the sextupole and decapole multipoles built into the magnet, and because of possible offsets of the measuring coil from the magnetic center, it is difficult to establish the amount of built-in quadrupole and octupole components. The data indicate, however, that the non-allowed multipole components are either small or zero, as expected from the magnet symmetries.

References

1. SSC: Reference Design Study Group, Draft II (May 8, 1984), unpublished.
2. J.P. Blewett, Proc. 8th Int. Conf. on High Energy Accelerators: CERN, 1971, p. 501.
3. E.J. Bleser et al., "Superconducting Magnets for the CBA Project," submitted to Nuclear Instruments and Methods; also BNL Formal Report No. 34863.