PERFORMANCE OF FOUR 4.5 m TWO-IN-ONE SUPERCONDUCTING R & D DIPOLES FOR THE SSC*

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Abstract

Four 4.5 m long superconducting dipoles built to specifications similar to those for SSC Reference Design A have been successfully tested. They were wound with NbTi cable in two-layer cosθ coils of 3.2 cm inner diameter. The coil ends were flared to increase the minimum bending radius, anticipating coils wound from prereacted Nb_3Sn. The coils were mounted in a reusable "two-in-one" iron yoke prestressed by means of a bolted stainless steel shell. The first two magnets as well as the fourth one, a special magnet designed to study cross-talk between the bores, used CBA/Tevatron cable. The third utilized cable with improved ("high homogeneity") NbTi conductor. All four reached central fields corresponding to their short sample limits at 4.5K without training, nearly 6.0T for the first two magnets, 6.5T for the third, and 5.4T for the fourth. At 2.5K modest training was required to reach short sample limits of 7.2T, 7.1T, 7.8T, and 6.6T respectively. The measured values of the allowed harmonics were within several x 10^{-4} of the calculated ones.

Introduction

This paper reports on tests with a series of model magnets constructed to evaluate several design concepts for minimizing the cost of the proposed Superconducting Super Collider: A high operating field, a small magnet aperture and a cold-iron 2-in-1 yoke. The high operating field is to be achieved by exploiting newly developed high homogeneity NbTi conductor, or alternatively prereacted Nb_3Sn--a longer range goal. The magnet design allows for the latter possibility by incorporating coils whose ends are flared out and clamped in stainless steel so that the strain-induced reduction in critical current does not limit the magnet performance. The first two magnets tested,[1] as well as the fourth, utilized standard CBA/Tevatron NbTi cable, keystoned to 2.8° because of the smaller bore size; the third magnet was wound from an early sample of high homogeneity NbTi cable with the same keystone. The present coil aperture (I.D. of inner coil) is 3.2 cm, whereas SSC Reference Design A[2] (and its subsequently modified version D) calls for 4.0 cm; the larger aperture would simplify construction. The 2-in-1 concept, a cost-cutting option for PP colliders, is based on two adjacent coils in a common iron yoke. The fields of the coils in such an arrangement are coupled, since the flux generated in one bore returns in the adjacent bore. Figure 1 shows one of the magnets in its first stage of assembly.

Magnet Design

Figure 2 shows a cross section of a dipole, including coils, iron yoke, and yoke support system. The two yoke apertures had a diameter of 7.47 cm, with center-to-center separation of 15.2 cm; the outer diameter of the yoke was 33 cm. The magnet design calculations, performed with an infinite-μ program, involved varying the size of the coil pole spacers and wedges until a set of acceptably small allowed field harmonics was obtained. A second pro-

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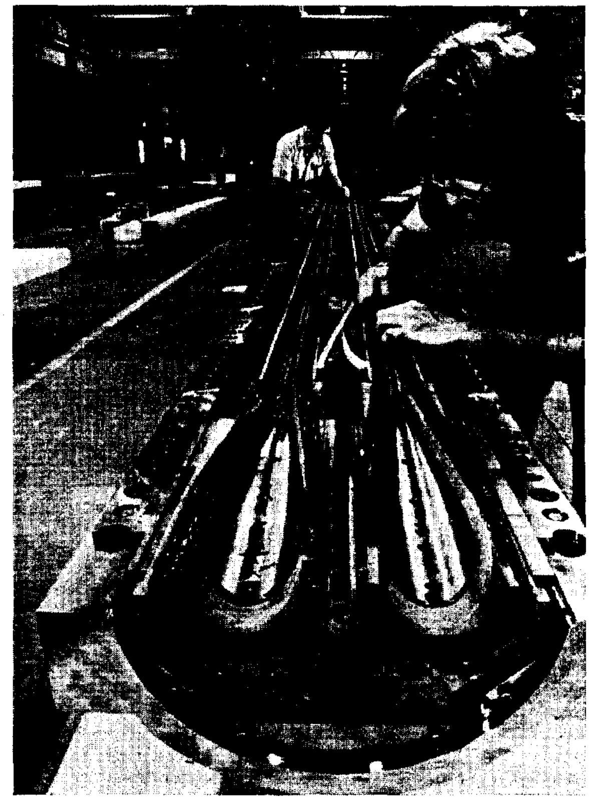

Figure 1. First stage in dipole assembly. Two side-by-side "bottom" coil subassemblies have been positioned in a previously constructed lower yoke assembly. Note the flared coil ends.

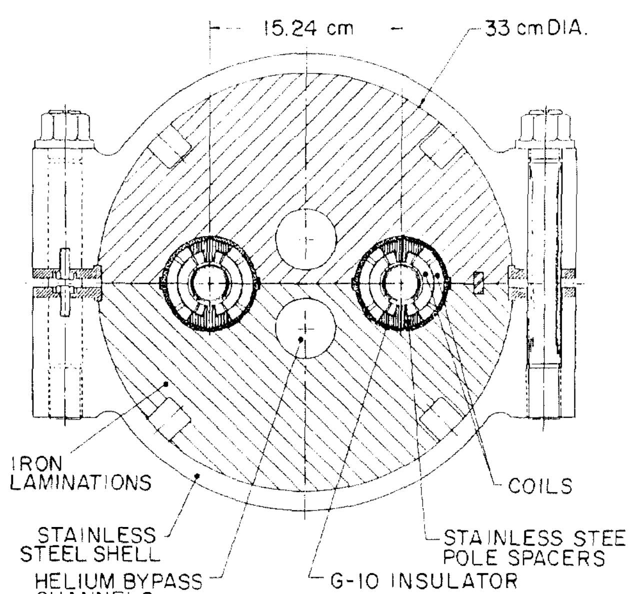

Figure 2. Cross section of 2-in-1 dipole.

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gram with variable-μ capability was used for fine tuning by varying the size and location of the helium bypass holes, particularly thereby adjusting the quadrupole term which, in a 2-in-1 design, is an allowed term in the absence of left-right symmetry. The press of time prevented iterating the design for the first three magnets to the point of strictly satisfying the allowed harmonics required for the SSC. (The design of the fourth magnet incorporated a small modification to reduce the allowed harmonics; this special magnet, and its performance, is discussed in the last section.) The inner coil layer had 16 turns per quadrant with two interspersed wedges, and the outer layer 17 turns and a single wedge. In order to ensure that both coil layers had approximately the same operating margin relative to the critical current of the conductor, the two layers were separately powered with the current in the outer layer 35% higher than the current in the inner layer. (In SSC Reference Design A optimum use of superconductor is achieved by grading the superconductor current density in the two layers). The calculated infinite-μ transfer function (B_o/I) for the first design was 10.9 gauss/ampere, where I is the outer coil current. Saturation reduced B_o/I by approximately 4% at B_o = 6.0T. The peak field enhancement, about 7%, occurred in the straight section of the coil, not in the coil ends (which protruded beyond the end of the iron portion of the yoke).

Conductor

The geometry and insulation of the 23-strand cable were similar to that used for the CBA magnets,[3] except for the larger keystone angle: two overlapping layers of Kapton followed by a single layer of fiberglass-epoxy. As noted, the first two magnets (and the fourth) used cable produced from available CBA/Tevatron cable. The critical current (at 4.2K, 5.0T, and a resistivity of 2×10^{-12} ohm-cm) of the two first batches of cable was 5.58 kA and 5.36 kA, respectively. (The reduction in critical current due to cabling is typically 12%, somewhat insensitive to the amount of keystoning.) The high homogeneity conductor of the third magnet had a critical current of 7.30 kA--the improvement being due in part to better current density in the superconductor (1950 A/mm^2 vs. 1750 A/mm^2 for CBA) and to a lower Cu:SC ratio (1.3:1 vs. 1.7:1).

Magnet Construction

Magnet assembly relied on procedures developed for the CBA project, and magnet construction utilized modified CBA tooling for speed and economy. The eight individual coils of a dipole were wound separately on a convex mandrel with a semi-automatic winder. The mandrel and coil were then lowered into a concave fixture for curing the epoxy used to impregnate the fiberglass conductor wrap; the amount of epoxy was controlled so that none came into contact with the wires during the cure. The coils were cured at 130°C and at pressures ranging from 60 MPa to 120 MPa.

Upper and lower halves of the iron yoke were assembled from 14.7 cm long blocks of glued laminations. The magnet coils were isolated from the yoke by thick G-10 insulators (Fig. 2). The azimuthal coil positioning was determined by laminated stainless steel pole spacers keyed to the G-10 insulators. The insulators, in turn, were keyed to the yoke. The assembly of the two half yokes applied the necessary azimuthal prestress to the preassembled coil package, accomplished with the aid of a tensioned stainless steel shell around the periphery of the yoke. The modified CBA assembly press was used to stretch and close the semicircular shell halves, and bolts through flanges at the midplane of the shell held it closed for subsequent magnet testing. To minimize friction at the interface between the yoke and the support shell a thin sheet of Teflon was introduced between the two surfaces, acting as a slip plane. Note that in a production design the yoke support shell would be closed by welding along the midplane; in the present R&D program a bolted design allowed repeated use of the same yoke (and facilitated coil repair in case of shorts uncovered in routine electrical inspections following magnet assembly). The magnets reported here were assembled with a room temperature prestress on the inner coils of approximately 70 MPa and approximately 110 MPa on the outer coils. The prestress was controlled by inserting shims of predetermined size between the coils and pole spacer. The prestress achieved in each of the eight individual coils was measured by strain gauges located in the pole spacers.

Magnet Performance

The training performance of all four magnets in a vertical liquid dewar is shown in Fig. 3. At a bath temperature of 4.5K the first two magnets reached a stable quench plateau of about 5.9T and 5.8T respectively, essentially without training, in qualitative agreement with the short sample currents of the conductors. (In fact, calculated peak fields for the inner and outer coils, corresponding to the quench plateaus, both exceeded the short sample predictions by about 6% along the respective load lines.) The third magnet reached a plateau of about 6.5T with minimal training. At a bath temperature of 2.5K, the first two magnets reached quench plateaus of 7.2T and 7.1T with varying amounts of training, or probably the short sample limit at this temperature. The third magnet reached a maximum field of 7.8T without having clearly reached its short sample limit as evidenced by a stable plateau. The considerable training encountered at this temperature probably indicates that the prestress limit had been exceeded.

The first three dipoles were not constructed with "field quality" as an explicit objective. Because we were unable to achieve the 4° keystone assumed in the initial magnet design, an alternative design using 2.8° keystone cable was used. This design had large built-in allowed harmonics ($b_2 = -75 \times 10^{-4}$, $b_4 = 31 \times 10^{-4}$). Moreover, there were variations in assembly shims and curing pressures, as noted. Nevertheless, for all six bores the measured values of the allowed harmonics were within several x 10^{-4} of the design values. Magnet-to-magnet reproducibility was studied by correcting for the different shims used in the first three dipoles (six bores). The r.m.s. variations were: $\sigma(b_2)$ = 2.8 units, $\sigma(b_4)$ = 2.1 units, $\sigma(b_6)$ = 0.5 units, and $\sigma(b_8)$ = 0.2 units. These data, while limited, provide a reference point for estimates of construction errors being made for current SSC cosθ designs.[4] Due to the large built-in allowed harmonics, it was difficult to distinguish built-in unallowed harmonics from those generated from possible offsets of the measuring coil with respect to the magnetic axis.

In order to study the effect of cross talk in the two-in-one yoke, a simple design modification (removing two turns per quadrant from the inner coil layer) was found to provide small harmonics for equal inner and outer currents, albeit with a loss in transfer function of about 4.6%. The performance of this fourth magnet is shown in Fig. 3; the level quench plateaus indicate that short sample performance was readily attained at both bath temperatures. More significantly, the measured sextupole and decapole harmonics (Fig. 4) were about 2% and 3% of the previous built-in harmonics ($b_2 = -1.6 \times 10^{-4}$, $b_4 = -1.1 \times 10^{-4}$). A detailed comparison of field measurement

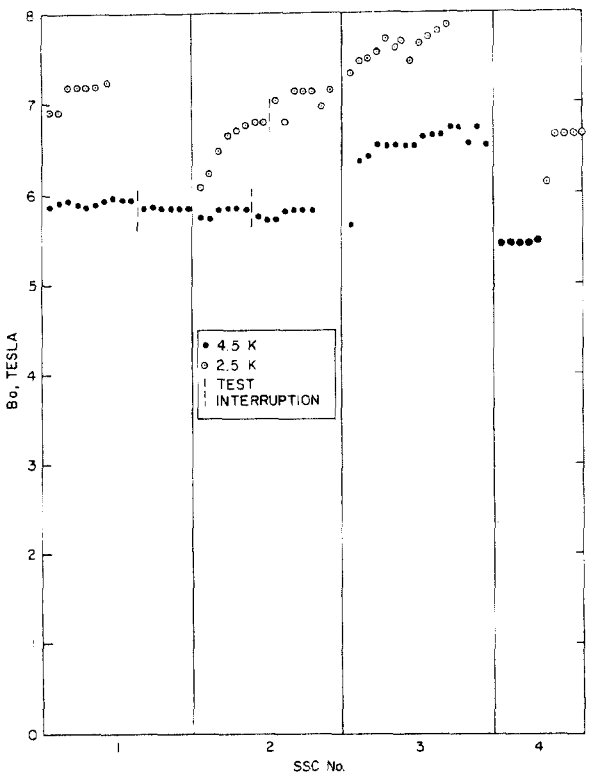

Figure 3. Dipole quench performance for two different bath temperatures. Field values corresponding to the level quench "plateus" at 4.5K are in reasonable agreement with quench predictions based on short sample properties of the various conductors. Note that, by design, B_o/I for dipole no. 4 was lower than that for the previous magnets. At 2.6K magnet no. 3, possessing the highest critical currents, was still training when the test ended.

data with calculated field harmonics as a function of current for asymmetric operation of the two sides of the magnet is still in progress.[5]

The first two dipoles utilized NbTi conductor with filaments of 9 μm diameter, whereas the filament diameter for the high homogeneity conductor was 21 μm. Magnetization measurements were made by taking multipole measurements, subsequent to cycling the magnet through a complete magnetization cycle, at regular current intervals from low to high field, and back down to low field. The magnetization-induced multipole of harmonic number n at a given current or field is defined as b_n (up ramp) - b_n (down ramp) at that excitation. Both the sextupole and decapole magnetization harmonics thus determined for the high homogeneity magnet at a field corresponding to the nominal SSC injection field for Reference Design A, were twice those measured for the magnets wound from CBA conductor. This result is in good agreement with predictions made on the basis of low-field measurements of magnetization.[6]

Quench protection studies with the third dipole, based on quench velocity and temperature measurements, are reported elsewhere in these proceedings.[7]

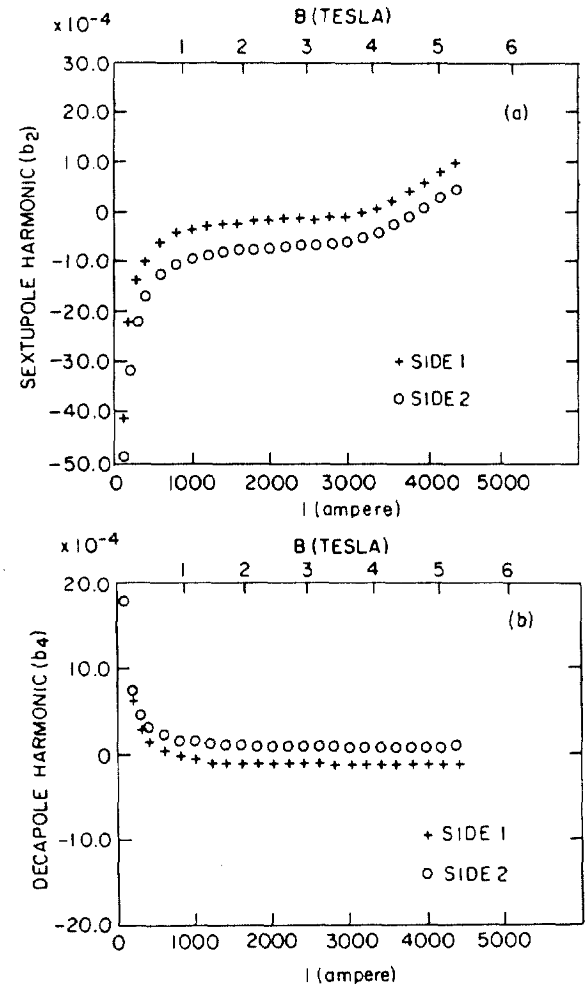

Figure 4. Comparison of sextupole and decapole multipoles measured in the two bores of dipole no. 4. (About half of the difference between the sides arises from differences in the shims.)

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