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Performance of Trim Coils Made by a Novel Method*

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Abstract. **A precision, automated method of manufacturing trim coils based on printed circuit technology has been developed. Excellent quench performance and increased radiation resistance have been achieved in recently-tested models of sextupole trim coils developed for operation inside 40 mm-aperture SSC Main Collider dipoles.**

I. INTRODUCTION

In the Conceptual Design Report for the Superconducting Super Collider (SSC), certain corrections were to be made "locally" by superconducting trim coils located inside the main collider dipoles[1]. To achieve this goal, printed circuit technology for precisely placing wires was adapted to the manufacture of trim coils. An initial test of this method gave encouraging results[2]. Following this initial test, development continued in order to improve the quench performance and radiation hardness of the system. In this paper, test results from two short models and one full-length model are reported.

II. TRIM COIL CONSTRUCTION

Three trim coils were tested. Two were short test models 1.3 m long, tested in 1.8 m-long dipoles. One was a full-length model (10 m), tested in a full-length (17 m) dipole. All three trims were wound with 20 turns of multifilamentary wire. The wire used in the short trims was 0.35 mm in diameter; in the long trim the diameter was 0.325 mm.

The wire was located to an accuracy of about 25 μm by pushing it into a flat, pliable substrate. The substrate was epoxy-bonded to the 34.544 mm O.D. cold bore tube, which had previously been wrapped with Kapton[3] insulating tape and fitted with locating pins. A wet layup of epoxy-impregnated fiberglass tape was then placed over the substrate. The cured epoxy provided support against radially-outward and tangential wire motion. Details of the initial construction methods have been previously published[4]; the present method will be described elsewhere.

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III. QUENCH TEST RESULTS

The most severe test of the trim coil occurs when the central field of the dipole is maximum, 6.6 T. The required current in the trim at this dipole field is about 15-20 A. One trim coil did not train in either polarity, with plateau quench currents of 47 A independent of polarity. This was in agreement with the short-sample estimate of 45 A. The polarity was reversed several times, and no training was found.

The other trim coil quenched initially at 18 A and trained to over 40 A in 11 additional quenches. Due to test difficulties, additional quenching was at a slightly lower field (6.1 T), where it was found that the trim did not require added training when powered with the opposite polarity. Also, no further training was found when the polarity was reversed several times. For both trims, the plateau quench currents increased to 107 A at 2.5 T dipole field[5].

During the R&D program, the trim coil length was reduced from 17 m to 10 m with the same integral field requirement. The increased performance demand was met by increasing the number of turns from 17 to 20 and by increasing the wire size. Roughly speaking, the Lorentz force per turn was about 50% higher than originally. Nonetheless, the quench performance at 6.6 T (as judged by the margin over operational current) was significantly better than that achieved in the original trim coil program.

IV. MAGNETIC FIELD MEASUREMENTS

In discussing the multipole fields of the trim coil, we consider the results normalized to a background dipole field of 2 T. The notation for the multipole representation of the magnetic field is defined by the following equation:

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n)(x+iy)^n$$

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

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cm. In this notation the normal sextupole is b_2.

The trim coil correction to the dipole field is largest as a fraction of the dipole field at injection, where the b_2 correction is 3.5 units. (Actually, the 10 m trim produces six units of b_2 locally, to correct the magnetization of the 17 m trim.) In order to easily compare the trim coil fields to the SSC tolerances on magnetic field harmonics, the trim coils are treated as though they had the same length as the dipole in the following discussion. The SSC tolerances used here are scaled from the tolerances of the 50 mm-aperture dipoles.

There is some interaction between the magnetization currents in the dipole and trim coil. To establish repeatability, the following procedure was followed: First, the dipole was cycled to high field, very low field, and then up to the desired level (e.g., 2 T, 6.6 T). Next, the trim was cycled twice through its bipolar operating range. Measurements taken following this procedure were reproducible at the level of the measuring coil short-term repeatability (typically, a few hundredths of a unit in sextupole, for example).

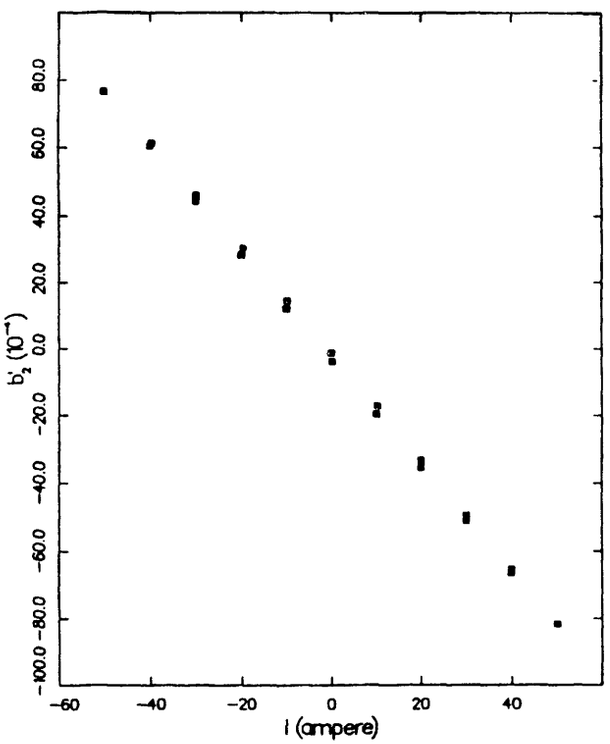

Figure 1. Measured sextupole field coefficient vs. trim coil current for two 1.3 m trim coils in 2 T background dipole fields.

The trim coils [illegible] a field of 3.4 x 10^{-4} T/A at a radius of 1 cm. The two-dimensional field strength of the three coils varied 3%. The linearity of the field strength with trim coil current can be seen in Figs. 1 and 2. In Fig. 1, in a background dipole field of 2.5 T, a small amount of magnetization can be seen as a difference in the sextupoles measured with increasing trim current and decreasing trim current. The data for the two 1.3 m trims are both plotted; differences between the two are too small to see in this plot. Fig. 2 shows the trim coil measurements made in a background field near the SSC operating field.

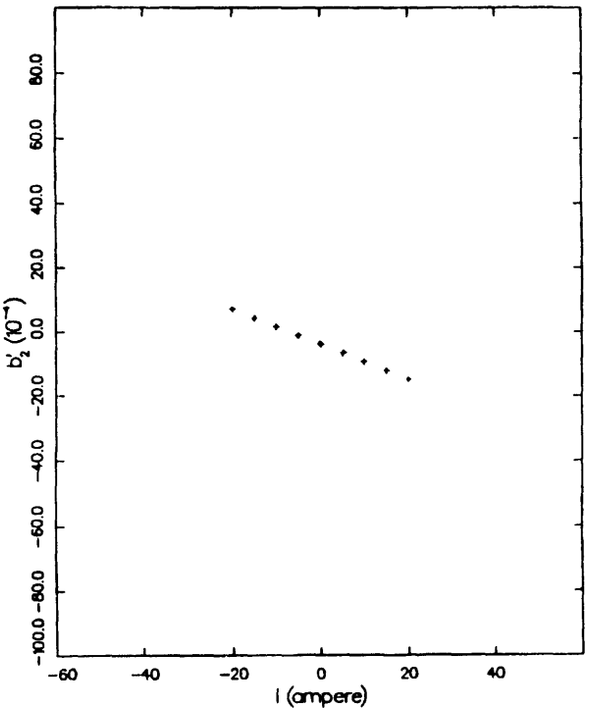

Figure 2. Measured sextupole field coefficient vs. trim coil current for a 1.3 m trim coil in a 6.1 T background dipole field.

For the 10 m trim coil, the angle between the dipole field and the trim coil field had an average value of 1.4 degrees, with an rms variation of 0.5 degrees. For the two 1.3 m trim coils, the values of this angle were -1.3 degrees and 0.3 degrees.

The angular misalignment produces a skew sextupole (a_2). For the 10 m trim, the average skew sextupole is about 10% of the normal sextupole, or about 0.3 units at injection. If this misalignment were random (the most likely case), it would be acceptable, since it is half the tolerance for the rms variation in a_2, 0.6 units, and would be added in quadrature to the errors in the dipole itself. If it were systematic, it would have to be reduced significantly to be a small fraction of the systematic tolerance, 0.05 units.

The relative transverse locations of the dipole and trim coil were determined by taking the difference between the off-centering of the two magnets with respect to the rotating coil. The 20-pole terms were used in the dipole off-centering calculation, and the quadrupole terms in the trim

coil analysis. The difference between the centers of the dipole and the trim was about 0.2 mm in both x and y. The consequence of this is that the beam in the center of the dipole sees an apparent quadrupole term. If the offset, 0.2 mm, is random (again, the most likely case), the resulting quadrupole terms, 0.14 units, would be much less than the tolerances for the rms variation (1.74 units for a_1, 0.70 units for b_1). A systematic offset of 0.2 mm would be unacceptably large, since the systematic tolerance for the quadrupole terms is 0.05 units.

The multipoles higher than the sextupole are small as a fraction of the trim coil field. The largest is the octupole (0.5% to 2.5%, at 1 cm radius), followed by the decapole (0.3% to 0.6%). The remaining terms are 0.2% or less. The first allowed term (b_8) is 0.04%.

Comparison of the octupole to the tolerances gives the following conclusions: the normal octupole b_3 (0.03 to 0.08 units) is acceptable if the error is random (tolerance 0.35 units) but marginal if it is systematic (tolerance 0.05 units). The skew octupole terms are half the normal octupole terms, and acceptable either as random or systematic errors. In the analysis of the previous series of trim coils, it was concluded that the most likely source of the octupole was a gap between the edges of the substrate wrapped around the cold bore tube. This would be the focus of effects if the octupole terms were systematically too large.

In the previous trims, made with monofilament conductor,it was found that the decapole term due to magnetization effects was significant. Multifilamentary conductor was used in the three trims reported here, and magnetization-induced decapole terms were negligible. In the first of the three trim coils of this set, the geometric decapole was too large, but it was negligible in the next two coils.

V. CONCLUSIONS

Quench test and field measurements from this set of three trim coils were substantially better than for the initial set of trim coils. Insofar as can be determined from three coils, the trims met the required specifications. The use of these coils was made unnecessary in the current SSC design (SSC Site-Specific Conceptual Design Report), and this note marks the conclusion of this effort.

However, trim coils made with this construction method will be used in the Relativistic Heavy Ion Collider (RHIC), now under construction at BNL. The four-layer corrector will contain dipole, quadrupole, octupole, and decapole windings[6]. In RHIC, the trim package occupies its own slot in the lattice, thus removing the requirement of operation in a large background dipole field. Tests of the initial RHIC trims have also been quite encouraging.

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