PERFORMANCE OF R&D SEXTUPOLE TRIM COILS FOR SSC DIPOLES*

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Abstract

For the proposed Superconducting Super Collider (SSC), trim coils placed inside the main coils of the dipoles are needed to correct for field nonuniformities due to superconducting magnetization, iron saturation, and systematic construction errors. Four 4.5 m superconducting sextupole trim coils have been made using methods adapted from printed circuit technology and suitable for mass production.[1] This paper presents measurements of the multipoles and quench currents and compares them with SSC requirements. Based on these results, this type of trim coil ("Multiwire") looks quite promising for use in the SSC.

Introduction

SSC requirements call for the systematic sextupole to be zero within about one part in 10^6 of the field in the main dipole magnets. It is planned that this level of accuracy will be achieved by building the dipoles so that the sextupole is zero within a few parts in 10^4 and then adjusting sextupole trim coils during accelerator operation. To be most effective, the trim coils need to be placed inside the dipole so that the distortion and the correction occur at approximately the same place along the proton orbits.

Four 4.5 m trim coils made using a process which can be adapted to mass production[1] have been tested in SSC R&D dipoles. For each coil, the quench current and the multipoles have been determined at three dipole fields: 0.3T (injection), 2 T (midfield), and 5.8 T (near the maximum field). This paper summarizes these results and compares them with SSC requirements. Where appropriate, the limited data available from the first 17 m trim (made with the same method) will be referenced. Also, the decapole due to magnetization currents in the trim coil has been measured.

The principal features of the trim coil are six poles, 17 mm radius, 17 turns per pole, 0.20 mm diameter wire with a single 120 μm filament. (The first trim coil, however, used 0.15 mm diameter wire with a single 90 μm filament.) Two changes made during the R&D work had significant effects on the multipoles. First, the alignment of the windings on the bore tube was substantially improved in the fourth 4.5 m trim and for the 17 m trim. Second, the adhesive used to bond the coil to the bore tube was reduced in thickness beginning with the 17 m trim. This latter change slightly reduced the coil radius and eliminated a gap of about 4 degrees between two poles of the coil. Details are given in Ref. 1.

In the SSC Conceptual Design Report (CDR), the following notation for multipoles is defined:[2]

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

where B_0 is the design bending field, x and y are the horizontal and vertical coordinates measured from the magnet center. It is convenient to define a multipole "unit" as 10^{-4} of the dipole, with the multipole evaluated at a radius of 1 cm. Since the trim coils are to be operated inside the dipole field, the harmonic content is stated in units scaled to the dipole field.

Training

The required field for the trim coils is set by the magnetization, saturation, and coil geometry of the dipole. The most severe demand occurs when the dipole is operated at its maximum central field of 6.6 T. At this field, iron saturation produces .4 units of sextupole. The calculated and measured values of iron saturation agree well,[4] leaving little uncertainty in this term. SSC requirements[3] include a safety margin for coil construction errors and call for 4 units of sextupole correction at this field, generated by 4A in the trim coil. At SSC injection (0.3 T), where magnetization effects are largest, dipoles which use wire having 5 μm NbTi filaments (the SSC design) will generate -5 units of sextupole. SSC requirements call for 10 units of correction capacity. Since the dipole field at injection is only 5% of the maximum, this requirement is easily met.

The maximum operating current of the trim coil is affected by the heat leak from the cryostat of the room temperature measuring coil which is normally inserted into the cold bore tube of the magnet. Two of the 4.5 m trim coils have been tested without this heat leak and their performance has been quite similar. These coils were tested in a 5.8 T field and exceeded 5 A before their first quench. The coils reached the conductor short-sample limit of 14 A for both polarities of trim coil current after about 15 quenches. One of the trim coils has been thermally cycled seven times and retested twice. After thermal cycles, the trim coil required training beyond 6 A. Thus, the trim coils tested so far meet the SSC quench current requirements. Efforts are underway to increase the margin.

Multipoles

The multipole data from the trim coil are given in Tables I and II in dipole units, for the case of a 2 T dipole field and 2 A of trim coil current. The trim coil then generates about 5 units of sextupole, the maximum correction from midfield to high field and the expected correction at injection. Trim coil tolerances have not been given for most multipoles, but comparison can be made to the dipole tolerances,[3] with the idea that the trim coils should not use a large fraction of them. For the quadrupole terms, it has been estimated that a tolerance of 0.4 units for the trim coil will be satisfactory.[5] The data from the 4.5 m coils in the tables are from measurements of the integral field, except for the sextupole itself which is from measurement of a 30" section in the center of the magnet to avoid problems due to the strong built-in sextupole of the dipole ends. At present, only data from a 60 cm section of the 17 m trim are available.

The discussion of multipoles is divided into three parts: the allowed terms (including the sextupole field itself); the unallowed terms which can be generated by errors in the positioning of the trim coil in the dipole; and the remaining unallowed terms. The allowed multipoles are the sextupole (b_2) and the 18-pole (b_8). For the sextupole field it is important that the variation among the trims be small when compared with the rms sextupole width due to dipole construction errors. It can be seen from the 4.5 m data in Table II that this is the case. (The increase in the sextupole field from the 4.5 m trims to the 17 m trim is consistent with the decrease in radius discussed above.) The transfer constant of the 17 m trim is 5.7 G/A (at 1 cm). Both the systematic and random values of the next allowed term, b_8, are much smaller than the dipole tolerances.

The low-order multipoles produced by mispositioning of the trim coil include the normal and skew quadrupole terms b_1 and a_1 (due to horizontal and vertical errors, respectively) and the skew sextupole (due to rotation errors).[6] For these three multipoles, Table I includes only data from the fourth 4.5 m trim coil because of the improvement in the positioning of the winding on the bore tube, mentioned above.[7] With data from just this 4.5 m trim and a

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60 cm section of the 17 m trim available, it is unclear whether the multipoles are systematic or random. From either viewpoint, both quadrupole terms are much less than the dipole magnet tolerances and the 0.4 unit tolerances. If the skew sextupole is a systematic term, it will need to be reduced.

The octupole and higher-order multipoles are given in Table II. For the four 4.5 m trims, both octupole terms a_3 and b_3 and the normal 12-pole b_5 are larger than the allowed systematic tolerance. However, these same multipoles in the 17 m trim are much reduced, as are b_4 and a_5. The sharp difference between the 4.5 m data and the bit of 17 m data suggest that the gap in the 4.5 m trims may be the culprit. The calculated effects[8] of an eight degree gap are quite similar to those seen in the 4.5 m data, indicating that the 17 m data, though scanty, are more likely to be representative of future trim coils than the 4.5 m models.

Thus far, it has not been possible to obtain good measurements of the dipole component of the trim coil because of the large background field from the dipole itself. For the 4.5 m trims, an upper limit of 1 unit has been established. Much of the interest in this multipole stems from quench protection considerations: will a dipole quench induce a large voltage on the trim coil? To address this question, the trim coil voltage was measured as a function of dipole ramp rate from 50 A/sec to 200 A/sec. It was found that the voltage increased linearly with ramp rate, as expected, reaching 9.1 mV at 200 A/sec. The maximum rate of current change during a dipole quench is estimated to be 70 kA/sec, which would generate a trim coil voltage of only 3.2 V.

Magnetization Effects

As an example of the multipoles produced by magnetization currents in the trim coil the decapole has been determined at 0.3 T and 0.7 T central field. This has been done by comparing magnets with trim coils to a magnet without a trim. Differences in coil geometry have been removed by subtracting the ramp-down data from the ramp-up data. The differences have been divided by two to obtain the effect of magnetization during the ramp-up. The result is an increase in decapole of 0.7 ± 0.03 units at a central field of 0.7 T. At 0.3 T the increase in decapole is 1.3 ± 0.2 units. The uncertainty is the rms variation of the three trim coils with 0.2 mm diameter wire. The magnetization decapole from the trim coil with 0.15 mm diameter wire is smaller, falling approximately with the cube of the filament diameter as expected. Also, the decapole increases about a factor of two from 0.7 T to 0.3 T, about as expected.

Acknowledgements

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References

[1] J. Skaritka et al., "Development of the SSC Trim Coil Beam Tube Assembly," submitted to this conference.

[2] SSC Central Design Group, "Conceptual Design of the Superconducting Super Collider," SSC-SR-2020, March 1986 (unpublished) p. 124.

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

[4] R.C. Gupta, G.H. Morgan, P. Wanderer, "A Comparison of Calculations and Measurements of the Magnetic Characteristics of the SSC Design D Dipole," submitted to this conference.

[5] SSC Central Design Group, op. cit., p. 149.

[6] An error of 0.1 mm in centering or in rotation (at the 17 mm radius of the trim coil) generates about 0.2 units of the appropriate multipole.

[7] The feeddown multipoles of the first three 4.5 m trims were at the level of several tenths of a unit.

[8] P. Thompson, "Field Quality for SSC Internal Trim Coils," SSC-N-226 (unpublished) August, 1986, and private communication.

TABLE I.

Multipole (units)	a_1	a_2	b_1
Dipole Tolerance (systematic ± random)	.2±.7	.1±.6	.2±.7
fourth 4.5m trim	.03	-.14	.01
First 17m (60cm section)	.09	-.39	-.06

TABLE II.

Multipole (units)	b_2	b_3	b_4	b_5	b_6	b_7	b_8
Dipole tolerance (systematic ± random)	±2.0	.1±.3	.2±.7	.02±.1	.04±.2	.06±.2	.1±.1
Four 4.5m trims (mean ± σ)	5.38± .08	.20± .04	.02± .02	.045± .03	.02± .01	.01± .01	.008± .002
First 17m (60cm section)	5.61	.035	-.02	-.008	.008	0	.009

Multipole (units)	a_3	a_4	a_5	a_6	a_7	a_8
Dipole tolerance (systematic ± random)	.2±.7	.2±.2	±.2	±.1	±.2	±.1
Four 4.5m trims (mean ± σ)	.26± .06	.10± .02	.02± .01	.02± .01	.02± .01	<.01
First 17m (60cm section)	.076	-.01	-.005	-.005	0	-.002

Table Captions

Table I. Low order multipoles from sextupole trim coils, scaled to a 2 A trim coil current in a 2 T dipole field. Multipoles are evaluated at 1 cm, in units of 10^{-4} of the dipole field.

Table II. Sextupole field and higher order multipoles from sextupole trim coils, scaled to a 2 A trim coil current in a 2 T field. Multipoles are evaluated at 1 cm, in units of 10^{-4} of the dipole field.