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MAGNETIC DESIGN AND FIELD QUALITY MEASUREMENTS FOR FULL LENGTH 50 mm APERTURE SSC MODEL DIPOLES BUILT AT BNL

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ABSTRACT

Field quality measurements of five 15 m-long, 50-mm aperture SSC R&D collider dipoles made at BNL are reported. Data include the multipole coefficients and dipole angle over the full operating range of the SSC. The variation of quench current with ramp rate is also presented.

1. MAGNET CONSTRUCTION

A general description of the construction of these magnets is given in a companion paper to this conference[1]. Here, we note several additional features. The thickness of the pole shims was essentially identical in the four magnets made with fiberglass and Kapton[2] cable insulation but different in the magnet made with all-Kapton cable insulation (DCA212). The diameter of the NbTi filaments used in these magnets was approximately 6 μm. The number of cold welds in the superconducting wires varied (zero for DCA207, one for DCA212, ten or more for the remaining magnets).

2. GEOMETRIC MULTIPOLE COEFFICIENTS

2.1 Definitions

A useful expression for the magnetic field is:

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

where x and y are the horizontal and vertical coordinates and B_0 is the dipole field strength. It is conventional to refer to the coefficients evaluated at a radius of 10 mm and scaled by $10^4/B_0$ as (dimensionless) "units." The skew terms are denoted by the a_n, the normal terms by b_n. The quadrupole coefficients have n = 1. The data reported here are integrals summed over the magnet's straight section measured in 1 m increments with a system which includes a rotating coil and a gravity sensor[3]. The measurements have been corrected for feeddown effects.

2.2 Measurements at 2.1 T (2 kA), 4.35 K

Normal coefficients with n even are allowed by dipole symmetry. The average values of the allowed multipole coefficients for the four magnets made with fiberglass and Kapton insulation are presented in Table I, along with the calculated values, which agree closely. (The quoted values include small corrections for magnetization effects.) The calculated values exceed the systematic tolerances because of small differences between the design[4] and actual sizes of some magnet components. With the effect of these differences now established, the present coil cross section design could be iterated to achieve satisfactory values for the allowed terms. The r.m.s. magnet-to-magnet variation is a factor of three or more better than the r.m.s. tolerances.

Table I. Allowed Multipoles (units) at 2.1 T

Multipole	Calc.	Measured	High Field Tolerances
b_2	3.97	4.65 ±0.43	0.80 ±1.15
b_4	-0.12	0.07 ±0.02	0.08 ±0.22
b_6	0.028	0.020±0.006	0.013±0.018
b_8	0.033	0.034±0.002	0.010±0.008
b_{10}	0.016	0.016±0.002	0.020±0.008

The mean values of the remaining ("unallowed") coefficients for all five magnets are given in Table II. They are all consistent with zero. However, the means of the three lowest-order terms (b_1, a_1, a_2) are not well determined from this small number of magnets. As with the allowed multipole coefficients, the r.m.s. magnet-to-magnet variation is a factor of three or more better than the tolerances.

2.3 Warm-cold-collared coil correlations

During the mass production phase, it is planned that all magnets will be tested at room temperature but only a fraction at 4.35 K. The r.m.s. tolerances are a useful benchmark for judging the required degree of correlation between warm and cold measurements. For these magnets, this correlation

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is sufficiently good that the r.m.s. width of the multipole distribution is not significantly increased if the warm measurements are used to predict the cold measurements. The correlation between warm measurements of the collared coil and cold measurements of the magnet is not as good. However, collared coil data will be useful as an assembly check.

Table II. Unallowed Multipoles (units)

Multipole	Measured	Tolerance
b_1	0.081±0.148	0.04 ±0.50
b_3	−0.005±0.014	0.026±0.160
b_5	0.000±0.000	0.005±0.017
b_7	0.000±0.001	0.005±0.010
a_1	0.228±0.230	0.040±1.250
a_2	0.024±0.054	0.032±0.350
a_3	−0.011±0.044	0.026±0.320
a_4	−0.008±0.008	0.010±0.050
a_5	0.000±0.004	0.005±0.050
a_6	−0.002±0.001	0.005±0.008
a_7	0.000±0.001	0.005±0.010
a_8	−0.001±0.000	0.005±0.008

2.4 Partial lifetime test

For three magnets, measurements made at 2.1 T during two different cooldowns have been compared. No differences common to the three magnets were found except for the normal sextupole, where the average b_2 increased 0.06 units, with an r.m.s. variation of 0.012 units.

3. MULTIPOLES DURING ACCELERATION CYCLE

3.1. Injection and initial acceleration

The magnets were quenched and then taken through an excitation history that approximately corresponded to the anticipated SSC operating cycle. The excitation sequence also included features chosen to minimize the time variation during injection. Multipole coefficients were then measured at a constant current of 635 A for an hour, the length of time for filling both rings. The variation of the normal sextupole during this time is shown in Fig. 1. (Previous measurements of this have been made on Tevatron[5] and HERA-p[6] magnets.) The cause of the differences among the magnets is not known.[7] The b_2 time variation is less than or equal to the tolerance, 0.3 units. The time variations of b_4 and b_5 are less than their respective tolerances.

An (unexpected) time variation in the skew quadrupole a_1 has also been observed. It is consistent with zero in the one magnet with no cold welds. Increases and decreases of 0.25 units have been observed in the others. The time dependence has been measured at two axial locations in each magnet. No differences have been found. The time variation of b_2 (but not that of a_1) increased when a magnet was held for a longer time at 6.6 kA.

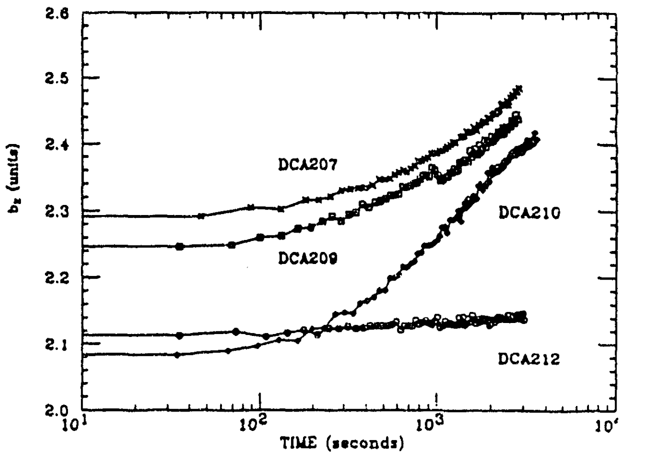

Figure 1. Time variation of the normal sextupole with I = 635 A for magnets DCA207 (O), DCA208 ([]), DCA209 (⊙), DCA212 (◊). For plotting purposes, constants have been added to the measured values of several of the magnets.

3.2. Measurements during ramp to midfield

Magnetization is the primary cause of current-dependence in the multipole coefficients. While the current is ramped at 4 A/sec, measurements are made on the upramp starting at 656 A and then on the downramp to provide the most complete information about magnetization. Normal sextupole data from a typical magnet are shown in Fig. 2 together with a calculation based on critical-current measurements[8]. Good agreement between the b_2 calculation and measurement is also found for the other magnets, and for the decapole up-ramp. The magnetization calculation does not take into account eddy current effects; thus, the good agreement indicates that these effects are small[9].

The skew quadrupole in the magnet with one cold weld, DCA212, showed no variation up to 4 kA. Changes in the other three magnets measured are at most 0.1 unit, with no trend emerging.

3.3. Measurement during ramp, midfield tc 6.7 T

At high field, the current-dependence of the allowed multipoles is due to the saturation of the yoke and small motions of the collared coil. In this region the measured variation of b_2 (Fig. 2) and b_4 are as small as desired.

The placement of the cold mass above the axis of the iron vacuum vessel produces a saturation skew quadrupole. This has been measured in two magnets by taking the difference between axial scans at 2 kA and 6.6 kA. The average decreases in a_1 were 0.22 units and 0.24 units. In both magnets, the r.m.s. axial variation of a_1 was 0.07 units.

4. DIPOLE ANGLE

The dipole angles of three magnets have been measured with an accuracy of approximately 0.3 mrad. The SSC tolerance on the r.m.s. variation is 1 mrad. Measurements on two magnets show no warm-cold differences. For one magnet, warm measurements before cooldown and cold measurements during the fourth cooldown show a change in the vicinity of 0.5–0.6 mrad. The axial variations of the dipole angle differ from magnet to magnet. Except at the lead end, the variation is less than the tolerance, ±2.5 mrad. A good correspondence was established between the dipole angle measured with the rotating coil system and the dipole angle determined from fiducial cutouts in the yoke's outer edge.

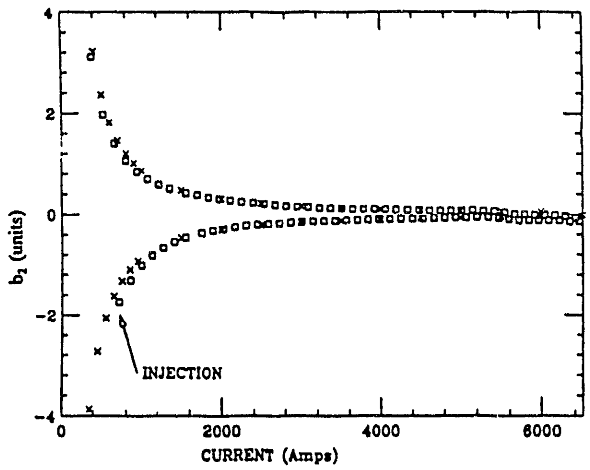

Figure 2. Variation of the normal sextupole with current in magnet DCA212 (▯). The magnetization calculation is also shown (×).

5. RAMP-RATE DEPENDENCE OF QUENCH CURRENT

The measured dependence of quench current on ramp rate (Fig. 3) is attributed to eddy currents in the cable. Although the number of magnets is small, the data suggest a grouping by wire manufacturer. The magnet made with all Kapton cable insulation (DCA212) had a different cure cycle than the others. No obvious effect of this difference can be seen in the data.

6. CONCLUSION

Good progress has been made towards meeting the SSC collider dipole field quality specifications. The measured values of the allowed multipoles are close to the design values. The unallowed multipoles are consistent with zero and the magnet-to-magnet reproducibility is excellent. The variation of the multipoles with current is in agreement with calculation and within tolerance. The time variation of b_2, b_4, and b_5 at injection is within tolerance. For the magnet with no cold welds, the time variation of a_1 is consistent with zero. Changes in the dipole angle due to cooldown, quenching, etc. are small.

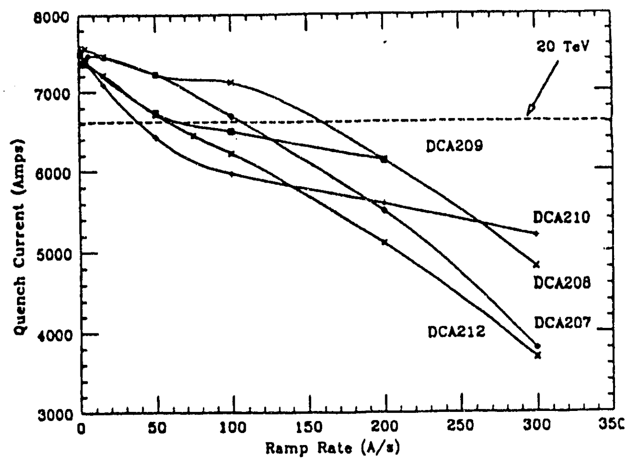

Figure 3. Variation of quench current with ramp rate for DCA207 (◊), DCA208 (×), DCA209 (▯), DCA210 (+) and DCA212 (⊗). Vendors for the wire used in the inner coil were IGC (DCA207, 208), Oxford (DCA209, 210), and Supercon (DCA212).

FOOTNOTES

[1] C. Goodzeit et al., "*Cold Mass Mechanical Design, Quench, and Mechanical Test Results for Full Length 50 mm Aperture SSC Model Dipoles Built at BNL*", paper submitted to XVth International Conference on High Energy Accelerators (this Conference).

[2] Kapton is a trademark of Dupont Corp.

[3] G. Ganetis et al., "*Field Measuring Probe for SSC Magnets*", Proc. 1987 IEEE Particle Accelerator Conf., p.1393.

[4] R.C. Gupta et al., "*SSC 50 mm Dipole Coil Cross Section*", Supercollider 3, p.587, Plenum Press, NY 1991.

[5] R.W. Hanft et al., "*Studies of Time Dependence of Fields in Tevatron Superconducting Dipole Magnets.*" IEEE Trans. on Magnetics 25, 1647 (1989).

[6] H. Brueck et al., "*Time Dependence of Persistent-Current Field Distortions in the Superconducting HERA Magnets*", DESY HERA 90-11, June 1990.

[7] See also A.K. Ghosh et al., "*Time Dependent Magnetization Effects in Superconducting Accelerator Magnets*", in this Conference.

[8] Y. Zhao, "*Effect of Persistent Magnetization Currents in SSC Dipole Magnets*", SSC Magnet Systems Division Note MD-TA-218, April 24, 1992 (unpublished).

[9] See also T. Ogitsu et al., "*Influence of Cable Eddy Currents on Magnetic Field Harmonics*", ICFA Workshop on AC Effects, KEK, June 1992.

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