Test of Eight Superconducting Arc Quadrupoles for RHIC

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Abstract—Test results from a group of eight superconducting quadrupoles made at Brookhaven National Laboratory are presented. The magnets have been designed for use in the arc regions of the Relativistic Heavy Ion Collider now under construction at Brookhaven. Novel features of the design include a single-layer coil, the use of injection-molded phenolic for the pole spacers, and a yoke that also serves as a collar. This R&D series has been used to verify the magnet quench performance and field quality prior to the start of the production run in industry.

I. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) will be a colliding beam facility with design energy of 100 X 100 GeV/u for ions as heavy as Au. The arcs will contain 276 quadrupoles of 80 mm aperture, 1.11 m magnetic length, and a design gradient of 71 T/m at the design current of 5 kA. In addition, the insertion regions contain 144 additional 80 mm quadrupoles with lengths ranging from 0.93 to 1.81 m.

Before beginning quadrupole production at Grumman Aerospace Corporation, it was decided to verify the design with a set of eight magnets made at BNL. This note summarizes the quench performance of the eight magnets and compares the field quality at room temperature ($I=10A$) and 4.35 K ($I=3$ kA). A report on a subset of these magnets, including details of the design, ends, and saturation, has recently been presented [1].

II. MAGNET CONSTRUCTION

A cross section of the magnet is shown in Fig. 1. The single-layer magnet coil has 16 turns and a symmetric copper wedge. For reasons of economy, the design uses many features of the dipole design, including the 30-strand cable with all-Kapton [2] insulation [3], an injection-molded phenolic spacer between the coil and yoke, and a two-piece yoke with a tapered midplane and horizontal split. The yoke laminations are 6.35 mm thick, with an inner diameter of 109.2 mm and an outer diameter of 266.7 mm. Steel keys are used in the yoke.

An internally pressurized mandrel was used to seat the coils and insulators during assembly. Axial preload was applied to the magnets with set screws, which pressed against the 19 mm-thick stainless steel end plates.

Figure 1. Cross section of QRB quadrupole cold mass.

The coils for these magnets were all made from the same spool of cable and were sorted after curing to minimize the variation in azimuthal size for a given magnet. Within a single magnet, the azimuthal size variation (largest - smallest) was 40 μ m at most, averaging 16 μ m. Averaging over each magnet, the difference between the smallest and largest mean azimuthal size was 80 μ m [4]. Assembly shims, placed between the poles and coils, were the same thickness in all the magnets.

III. QUENCH PERFORMANCE

A plot summarizing the quench testing of the eight magnets is shown in Fig. 2. The magnets trained in two to six quenches to the conductor limit. No magnet quenched below 6 kA, 20% over the operating current. At the conductor limit the quench current was about 10% greater than the value calculated from short-sample measurements (I_m).

IV. FIELD QUALITY

For these magnets, the horizontal and vertical field components, B_x and B_y , throughout the magnet aperture are given in polar coordinates (r, θ) by

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$$B_y + i B_x = 10^{-4} B(R) \sum_{n=0}^{\infty} (b'_n + i a'_n) (\cos n\theta + i \sin n\theta) \left[\frac{r}{R} \right]^n$$

where i is the imaginary unit and $B(R)$ is the magnitude of the field due to the *fundamental* at the reference radius. In a normal quadrupole, $b'_1 = 10^4$ and $B(R) = GR$ where G is the gradient $\partial B_y / \partial x$ at the magnet center. It is conventional to refer to the coefficients evaluated at a radius of 25 mm and scaled by $10^4 / GR$ as (dimensionless) "units." The data reported here are integrals over the magnet length at 10 A (at room temperature) and 3 kA (at 4.35 K). The measurements have been corrected for feeddown effects by assuming that the magnet has zero dipole term along its axis. The uncertainty in the magnitude of the harmonics is estimated to be 5%. The uncertainty in the integral of the quadrupole field is estimated to be at the 1% level.

Figure 2. Quench performance of QRB quadrupoles at 4.35 K ramped at 83 A/sec.

Measurements of the lowest order terms are reported in Fig. 3 and in Table I. The figure shows the correlation of the room temperature and 4.35 K measurements. The correlation is of particular interest because it is planned that only a small fraction of the magnets will be cold-tested, to reduce the cost of testing. The figure is scaled so that the horizontal and vertical axes have the same scale. Harmonics that have the same value: warm and cold, with no measurement error, would lie on the solid 45° line. Values for many of the harmonics ($n = 2, 3$) fit this model. Warm and cold values for the lowest-order allowed term, $n = 5$, are well-correlated but do not lie on the solid line because there is a small change of shape during the cooldown of the magnet.

The same measuring coil was used for warm and cold measurements. Its radius, sized for cold measurements inside a "warm finger", reduced the strength of signals from the highest order terms, making the warm-cold correlations

worse. Nonetheless, warm and cold measurements of the second allowed term ($n = 9$) are still correlated at the level of 0.05 units [5].

At 3 kA, the effective length was measured to be $1.0973 \pm .0002$ m; the design value is 1.020 m. The harmonics at 3 kA are given in Table I. There is generally good agreement with the calculated values, which include not only the allowed terms b_2 and b_4 but also b_3 , b_7 , and a_5 . The b_3 and b_7 terms are present due to small distortions in the yoke, which has dipole (but not quadrupole) symmetry. The a_5 term is due to the magnet leads which exit at the pole and run parallel to the magnet length for several cm. In magnets of this length, minimizing the harmonics due to the coil ends and leads is an essential part of optimizing the field quality.

Table I. Average Quadrupole Integral Harmonics Calculated and Measured for QRB007-012 at 3 kA up ramp.

n	b_n Calc	b_n meas	σb_n	units
2	0	-1.35	1.42	b'_2
3	9.3	7.08	0.66	b'_3
4	0	0.62	0.54	b'_4
5	-0.23	2.54	0.69	b'_5
6	0	-0.07	0.07	b_6
7	0.05	0.18	0.05	b'_7
8	0	-0.14	0.06	b'_8
9	-1.02	-1.15	0.04	b'_9
n	a_n Calc	a_n meas	σa_n	units
2	0	-1.64	2.21	a'_2
3	0	0.08	0.65	a'_3
4	0	2.83	0.48	a'_4
5	-1.6	-3.65	0.21	a'_5
6	0	0.15	0.14	a_6
7	0	-0.02	0.11	a'_7
8	0	0.06	0.08	a'_8
9	0.02	0.35	0.03	a'_9

On the basis of calculations and warm measurements, a method has been identified to reduce b_3 in production magnets. As initially built, the midplane half gaps between the coils were 0.1 mm thick due to the presence of the coil-to-coil insulation. One magnet (QRB012) was rebuilt with the midplane half gaps doubled, to 0.2 mm, on the horizontal midplane only. This reduced b_3 from 6.5 units to -0.9 units.

The increased thickness of the half gap generated two other harmonics of interest. The normal dodecapole b_{12}

Figure 3. Correlation of the warm (10 A) and cold (3 kA) harmonics. The data would lie on the solid line if the two measurements were identical.

increased 3.0 units. To obtain a value for b_3 in the production magnets at an acceptable level, the size of the wedge was changed. Also, the magnitude of b_3 increased from 0.05 to -0.71 units. This value is acceptable.

The need for confirming calculations with magnet tests was indicated by the results of a previous shimming experiment which involved the assembly shims. Normally, the eight shims all have the same thickness. As a test, the four shims on the sides of the poles facing the horizontal midplane of the magnet were made thicker than the four shims on the sides of the poles facing the vertical axis. A calculation which assumed that the phenolic pole was rigid indicated that this should have reduced b_3 by about 7 units and b_5 by 1.7 units. However, when tried in a magnet (QRB009), b_3 decreased only 0.4 units, although b_5 did change as expected. The fact that b_3 did not change indicates that the modulus of the collar is comparable to that of the coil.

The harmonics of these magnets are being used as those expected for the production run of magnets, except for the anticipated reduction in b_3 and b_5 noted above. These "expected" values are now used in the computer beam-tracking models of RHIC. Also, it is interesting to note that the r.m.s. variation of these harmonics is essentially the same as for the production run of the two-layer quadrupoles for HERA.

REFERENCES AND FOOTNOTES

- [1] P. Thompson et al., "B Series RHIC Arc Quadrupoles," 1993 Particle Accelerator Conference, May 17 - 20, 1993 (to be published).
- [2] Kapton is a registered trademark of the Dupont Corporation.
- [3] M. Anerella, A. K. Ghosh, J. Schmalzle, E. Willen, "Improved Cable Insulation for Superconducting Magnets," 1993 Particle Accelerator Conference, Washington D.C., May 17-20, 1993 (to be published).
- [4] J. Schmalzle, "RHIC 8 cm Quadrupole Magnets QRB005-12 Summary of Construction Details," BNL RHIC Magnet Division Note 489-7 (RHIC-MD-193), March, 1993 (unpublished).
- [5] A measuring coil with better sensitivity will be available in production.

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