

# FIELD QUALITY EVALUATION OF THE SUPERCONDUCTING MAGNETS OF THE RELATIVISTIC HEAVY ION COLLIDER\*

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Abstract

In this paper, we first present the procedure established to evaluate the field quality, quench performance,<sup>1</sup> and alignment of the superconducting magnets manufactured for the Relativistic Heavy Ion Collider (RHIC),<sup>2</sup> and then discuss the strategies used to improve the field quality<sup>3</sup> and to minimize undesirable effects by sorting the magnets. The field quality of the various RHIC magnets is briefly summarized.

## I. INTRODUCTION

The RHIC magnet system<sup>2</sup> consists primarily of the superconducting dipole, quadrupole, sextupole and corrector magnets for guiding, focusing, and correcting the counter-circulating ion beams into the design orbits in the regular arcs of the machine lattice. A large complement of special magnets is also required for steering the beams into collisions at the six interaction regions where the ion beams interact.

Besides reaching fields with substantial margins above the required range, all of the RHIC magnets must meet stringent requirements on field quality, reproducibility, and long-term reliability. In order to fulfill this goal, a committee of magnet division and RHIC accelerator physics personnel jointly review the field quality, quench test performance, survey and other engineering aspects of the magnets. Subsequently, the magnets are sorted to minimize undesirable effects resulting from unexpected changes in the manufacturing process.

Currently, the arc dipoles (DRG) and quadrupoles (QRG) are built by the Northrop-Grumman Corporation, the arc sextupoles (SRE) and trim quadrupoles (QRT) are built by the Everson Electric Corporation, and other special magnets (corrector magnets (CR), etc.) are built by the BNL magnet division. Table I shows the status of the manufactured magnets. The first 30 dipoles

Table I  
Status of the RHIC magnets (April 1995).

No.	DRG	QRG	SRE	QRT	CR
built	127	150	300	55	215
quench tested	42	60	60	12	110
cold measured	42	60	53	12	48
needed	288	372	288	72	420
installed	112	14	14	0	14
spare needed	10	8	12	6	10
spared	2	1	0	0	0

and 20 quadrupoles were fully tested at both room temperature

(warm) and superconducting temperature (cold) at various currents including those corresponding to injection (660 A), transition (1450 A), and storage (5000 A) operation. Thereafter, while all the magnets are still warm tested, 10% of them are cold tested to ensure the established warm-cold correlations.

After the magnets are measured and tested, the magnetic field quality data, including transfer function, field angle, multipole harmonics, magnetic center offsets, etc. at all the test currents, is recorded along with the warm mechanical survey measurements of the fiducial positions, sagitta, mechanical length and field angle. The data are transferred from the magnet division into the RHIC database (MAGBASE), formatted into a self-describing standard (SDS) dataset, and then analysed by studying trends, comparing with the expected values, and evaluating the deviation from the mean using the computer program MAGSTAT.<sup>4</sup>

## II. REVIEW OF INDIVIDUAL MAGNETS

### A. Arc dipole (DRG)

The RHIC arc dipoles are designed to operate at nominal current of 5 kA at top energy for ion beams with magnetic rigidity 840 T·m. Fig. 1 shows that the minimum quench currents during

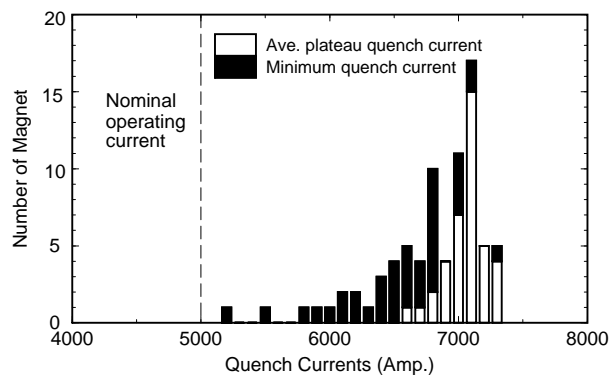


Figure 1. RHIC dipole magnet quench performance.

the entire testing process for all the tested magnets are above the operating current, while the average quench current after the plateau is reached easily exceeds a 30% margin.

The high quality of the RHIC dipoles is demonstrated by magnetic field profiles at the horizontal ( $y = 0$ ) and vertical ( $x = 0$ ) midplanes (Figs 2a and b), respectively, measured at the top operating current. The overall performance of the magnetic multipole harmonics exceeds nominal operation requirements, as indicated by the expected range shown by the dashed lines for normal (Fig. 2a) and skew (Fig. 2b) multipoles.

The dominant multipoles of the dipole magnets are  $b_2$  (normal sextupole) and  $b_4$  (normal decapole) resulting from the dipole symmetry of the magnets, and  $a_1$  (skew quadrupole) resulting

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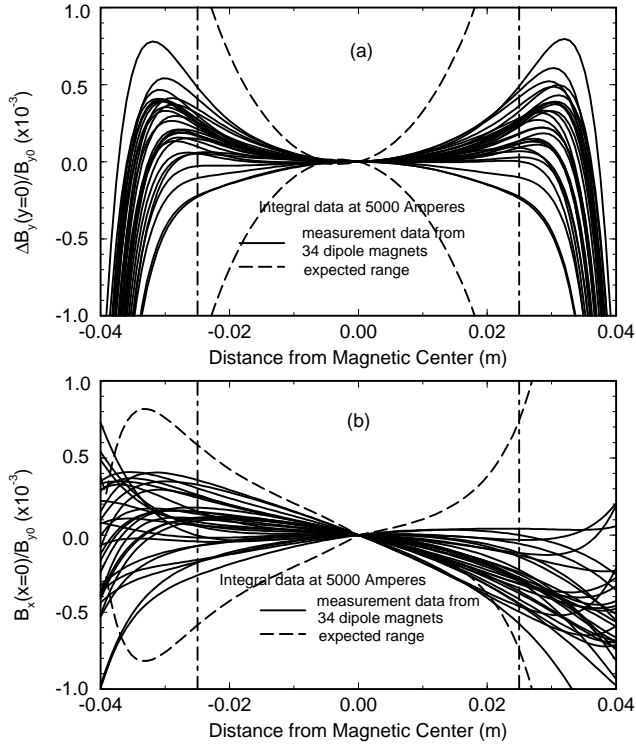


Figure 2. RHIC dipole magnet a) vertical field profile at horizontal midplane and b) horizontal field profile at vertical midplane.

from the asymmetric vertical placement of the magnet cold mass in the cryostat, as shown in Table II. From a beam dynamics point of view, a large  $b_2$  would require a stronger chromaticity correction, especially at top beam energy when the low  $\beta^*$  lattice is used. Large  $a_1$  and  $b_4$  would require linear decoupling and tune-spread minimization at the injection energy when the beam size is the largest in the arc. Fortunately, due to the relatively high injection energy and the small diameter of the coil filaments, the persistent current is small. Magnet design has minimized  $b_2$  and  $b_4$  (Table II) for both injection and storage currents by optimizing the cross-sections of the coil and the yoke taking into account the persistent current and saturation effects.<sup>3</sup> The minimization of  $a_1$  is achieved by making the lower half yoke heavier than the upper half during the assembly process.

During March 1995, a drop in dipole integral transfer function of about 0.1% was noticed and traced to the narrower width of the phenolic insulator used between the coil and the iron. Although the problem has been corrected, these 20 magnets affected are

Table II

Some integral multipole harmonics of the RHIC dipoles measured at various test currents (mean $\pm$ standard deviation in prime units<sup>6</sup> at the reference radius of 2.5 cm).

	$a_1$	$b_2$	$a_2$	$b_4$
30 A (warm)	$0.1\pm 1.5$	$4.8\pm 1.4$	$-1.0\pm 0.2$	$0.0\pm 0.4$
660 A (cold)	$0.7\pm 1.3$	$1.0\pm 1.4$	$-1.0\pm 0.2$	$-0.6\pm 0.5$
1450 A (cold)	$0.6\pm 1.2$	$2.9\pm 1.4$	$-1.0\pm 0.2$	$-0.4\pm 0.5$
5000 A (cold)	$-1.3\pm 1.4$	$1.4\pm 1.5$	$-1.1\pm 0.2$	$-0.1\pm 0.5$

being sorted,<sup>5</sup> along with all subsequent dipole magnets. The sorting procedure is based on the strength minimization of the horizontal dipole correctors required to compensate for the variation in the integral transfer function. With sorting, the maximum current required for such compensation is decreased from 12 A to about 3 A. Table III presents other field quality issues of the

Table III

Warm measured means and standard deviations (SD) of the integral and body transfer function, integral field angle, body field angle standard deviation, and center offsets of the RHIC arc magnets.

	DRG	QRG	SRE
Integ. trans. func. (relative SD)	$3.0\times 10^{-4}$	$4.8\times 10^{-4}$	$1.8\times 10^{-3}$
Body trans. func. (relative SD)	$3.1\times 10^{-4}$	—	—
Integ. field angle (Mean $\pm$ SD) (mr)	$-0.5\pm 0.8$	$-1.8\pm 0.4$	$0.0\pm 0.3$
Body field angle SD (Mean) (mr)	0.8	—	—
Center offset $X_0$ (Mean $\pm$ SD) (mm)	—	$0.03\pm 0.06$	$0.02\pm 0.09$
Center offset $Y_0$ (Mean $\pm$ SD) (mm)	—	$0.13\pm 0.06$	$0.03\pm 0.03$

magnets.

Two dipole magnets (DRG516 and DRG545) have so far been allocated as spare magnets. DRG516 has an excessive twist (2.5 mr standard deviation in body field angle) along the azimuthal axis. DRG545 has a large ( $-5.9$  units)  $a_1$  caused by a known coil size mismatch.

### B. Arc quadrupole (QRG)

The arc quadrupoles are also designed to operate at nominal current of 5 kA at top energy. Fig. 3 shows that the average

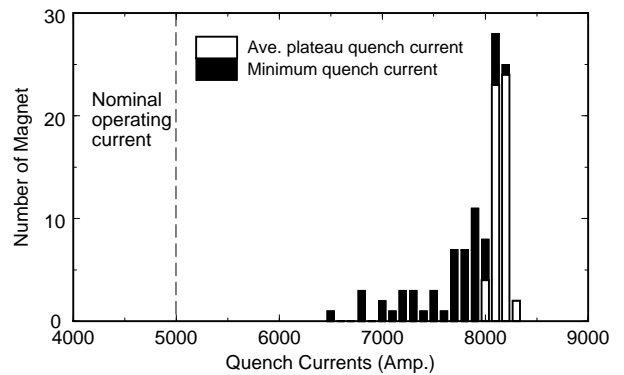


Figure 3. RHIC quadrupole magnet quench performance.

quench current after the plateau is reached exceeds the operating current by more than 60%.

The dominant multipoles of the quadrupoles are  $b_5$  and  $a_5$  resulting from the quadrupole symmetry of the coil and the end configuration, and  $b_3$  resulting from the asymmetry between the

horizontal and vertical planes, as shown in Table IV. From a beam dynamics point of view, the present values of  $b_5$  and  $a_5$  impose no significant impact on the particle motion due to the relatively small beam size in the arc.  $b_3$  has been compensated in the design by making the coil to midplane gap appropriately asymmetric,<sup>3</sup> while  $b_5$  has been reduced by compensating the body with the ends of the magnet.

During an early stage of industrial manufacture, midplane shims were incorrectly applied on 5 quadrupoles, resulting in a  $b_3$  of about  $-6$  units. These magnets were sorted and assigned to defocusing locations around the two rings to minimize their effects. So far, one quadrupole magnet (QRG156) with excessive  $b_2$  ( $-5$  units) has been allocated as a spare magnet.

### C. Sextupole (SRE)

In general, the performance of the sextupole magnets has exceeded the design goal. However, the epoxy contained in about 42 magnet coils is significantly weaker than normal. Consequently, the average quench currents (about 170 A) of these magnets, although exceeding the design operating current (100 A), are lower than the average of the regular magnets (above 200 A). To minimize possible long-term effects, these magnets have been sorted and allocated to the focusing locations around the two rings where the required strength of the sextupoles for chromaticity correction is about 50% of that at the defocusing locations.

### D. Trim quadrupole (QRT)

Ten of the trim quadrupoles (QRT) manufactured have been cold tested. The minimum quench currents of all the tested magnets are above 200 A, well exceeding the design operating current of 100 A. The field quality also exceeds the design goal.

### E. Arc correctors (CRB, CRC, CRD, CRE, CRF)

All of the five types of arc correctors (CRB, CRC, CRD, CRE, and CRF) will be cold tested. After initial training, all the magnets quench above the design operating current of 50 A. Since the dipole corrector layers are all powered individually, the variation in the integral transfer function (typically 1% standard deviation) is of little concern.

## III. MAGNET ASSEMBLY INSTALLATION

Since each arc dipole magnet is individually contained in its own cryostat, the magnet is immediately assigned to the ring for installation after it is approved and sorted. On the other hand, one arc quadrupole (Q), one sextupole (S), and one corrector (C) cold mass share a common cryostat, along with an attached beam

position monitor and (for some types) a recooler, becoming the CQS assembly. Individual corrector, quadrupole, and sextupole elements are assigned to CQS assemblies only after they have been reviewed and approved. The completed CQS assembly<sup>7</sup> is then assigned to the ring only after the overall unit has been separately reviewed and approved.

Each CQS is surveyed with the colloidal cell technique<sup>8</sup> to directly correlate the magnetic field center with the externally accessible mechanical fiducial positions. This information, along with the measurement data of the magnetic field angle, is used to align the magnets during and after installation.

## IV. CONCLUSION

The field quality and quench performance of the RHIC magnets well exceed design goals. Sorting has been applied to the arc dipoles to minimize the required maximum corrector strength, on the 5 arc quadrupoles with incorrectly applied shims, and on the 42 low-epoxy sextupoles to minimize possible long-term effects. By April 1995, 112 dipole magnets and 14 CQS assemblies have been installed in the RHIC tunnel.

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## V. REFERENCES

1. P. Wanderer, et al., these proceedings.
2. RHIC Design Manual, Brookhaven National Laboratory, revised Oct. 1994.
3. R. Gupta, et al., these proceedings.
4. S. Peggs et al., computer program MAGSTAT (1994).
5. S. Peggs, computer program SORT\_DIPOLE (1995).
6. J. Wei, R. Gupta, and S. Peggs, Proc. 1993 Part. Accel. Conf., p.258 (1993); J. Wei and M. Harrison, Proc. Int. Conf. on High Energy Accel., p.1031 (1992).
7. S. Mulhall, et al., these proceedings.
8. D. Trbojevic, et al., these proceedings.

Table IV

Some integral multipole harmonics of the RHIC quadrupole magnets measured at various test currents (mean $\pm$ standard deviation in prime units<sup>6</sup> at the reference radius of 2.5 cm).

	$b_3$	$b_5$	$a_5$
10 A (warm)	$-1.4\pm 1.2$	$1.4\pm 0.5$	$-3.7\pm 0.3$
660 A (cold)	$-0.7\pm 1.7$	$-1.9\pm 0.6$	$-3.7\pm 0.4$
1450 A (cold)	$-0.7\pm 1.7$	$0.5\pm 0.6$	$-3.7\pm 0.3$
5000 A (cold)	$-0.7\pm 1.7$	$5.6\pm 0.6$	$-3.8\pm 0.3$