© 1993 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

"B" Series RHIC Arc Quadrupoles*

P. Thompson, M. Anerella, G. Ganetis, M. Garber, A. Ghosh
A. Greene, R. Gupta, A. Jain, S.A. Kahn, G. Morgan, A. Morgillo
J. Muratore, A. Prodell, M. Rehak, W. Sampson, P. Wanderer, E. Willen

RHIC Project
Brookhaven National Laboratory, Upton, NY 11973

Table 1: RHIC Arc Quadrupole Parameters

Parameter	Value
Number of Turns/octant	16
Coil ID	80 mm
Design Gradient	71 T/m at 5000 A
Quench Gradient	107 T/m at 7650 A
Magnetic Length	1.11 m
Iron ID	109.2 mm
Iron OD	266.7 mm

ABSTRACT

A series of pre-production superconducting quadrupoles has been constructed at Brookhaven National Laboratory. These magnets have an operating gradient of 71 Tesla/meter with a coil bore of 80 mm. The eight magnets are exact prototypes of the quadrupoles which will be used in the arcs. These magnets were tested and measured and met the accelerator specifications.

1. 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 necessary focusing will be supplied by 492 superconducting main quadrupoles and 72 superconducting trim quadrupoles. Of these, 420 will have a coil inner bore of 80 mm, and design gradient of 71 Tesla/meter at a design current of 5000 A. The two accelerator/storage rings are divided into "regular arcs" and intersection regions. The arcs contain 276 quadrupoles of bore 80 mm and magnetic length 1.11 meters. In addition the insertion regions contain 144 additional 80 mm quadrupoles with lengths ranging from 0.93 to 1.81 meters. These magnets will use the same superconducting cable and mechanical configuration as the dipoles.

2. DESIGN CONSTRAINTS

The basic machine requirement is for quadrupoles with 80 mm bore and design gradient of 71 T/m. Practical considerations force maximum commonality with the dipole magnets. The same 30 wire copper stabilized NbTi superconductor has been used. Thus the quadrupole operating current is nominally equal (5000 A) to that of the dipoles (the quadrupoles are NOT in series with the dipoles). Overall parameters are specified in Table 1.

The overall mechanical structure is very similar to that of the dipoles; the single layer coil is spaced from the cold iron by a 5 mm thick plastic(RX-630) insulator which incorporates the pole spacers. The iron collars are compressed and keyed. Thus the iron serves the purposes of both return yoke and mechanical constraint. Mechanically, the iron has two fold(dipole) symmetry, allowing the use of the same press and techniques for assembly as the dipole. Calculations indicate that the coarser features of this symmetry breaking do not produce significant field perturbations. Detailed study reveals two problems:

Pole Motion In the dipole it is possible to key the pole directly to the iron because during assembly, there is no relative motion. This is not possible with a two part quadrupole assembly. The system used in these magnets is to key the insulators at the iron joints; during assembly the insulators and the coils slide within the iron until the tabs on the insulators contact the iron. This is less accurate and more complex than keying directly at the poles.

Iron Deformation The necessary prestress is applied with the iron collars. These collars bend under the applied load distorting the inner circumference and the coil. The same distortion occurs during dipole assembly, but produces dipole symmetric terms which are easily compensated by coil design. In the quadrupole this distortion produces $4\theta, 8\theta$, ... terms which can not be easily compensated for in the coil design.

3. MAGNETIC FIELD

The magnetic field is computed with a combination of analytic techniques for the coil cross section and finite element codes for the iron yoke. For the central section of the magnet, the allowed harmonics(2,6,10 θ) are readily calculated. Fig. 1 shows the calculations and the measurements for the fundamental and the first allowed harmonic(see appendix for definition of units used). The deviations are compatible with the mechanical uncertainties (50 μm) in the coil at 4 K.

The central harmonics are summarized in Table 2. Aside from the octupole(b_3) only the sextupole(b_2) is noticeable. The large fluctuation in this term indicates that it is due to some random variation in magnet construction.

0-7803-1203-1/93$03.00 © 1993 IEEE

Table 2: Quadrupole Central Harmonics Measured(average for QRB007-012) and Calculated. Values Measured at 3000 A, up ramp

n	b_n Calc	b_n ave	σ b_n	units
1	1.5107	1.522	0.006	G/A-cm
2	0	-0.822	0.949	b_2'
3	9.3[a]	7.443	0.681	b_3'
4	0	0.040	0.687	b_4'
5	-9.82	-8.732	0.425	b_5'
6	0	-0.072	0.096	b_6
7	0.05	0.095	0.051	b_7'
8	0	0.005	0.048	b_8'
9	-1.50	-1.752	0.050	b_9'
n	a_n Calc	a_n ave	σ a_n n	units
1	0		...	G/A-cm
2	0	0.600	0.537	a_2'
3	0	-0.535	0.730	a_3'
4	0	-0.207	0.188	a_4'
5	0	0.332	0.083	a_5'
6	0	0.035	0.143	a_6
7	0	-0.043	0.090	a_7'
8	0	0.023	0.050	a_8'
9	0	0.043	0.016	a_9'
a... see discussion of octupole moment				

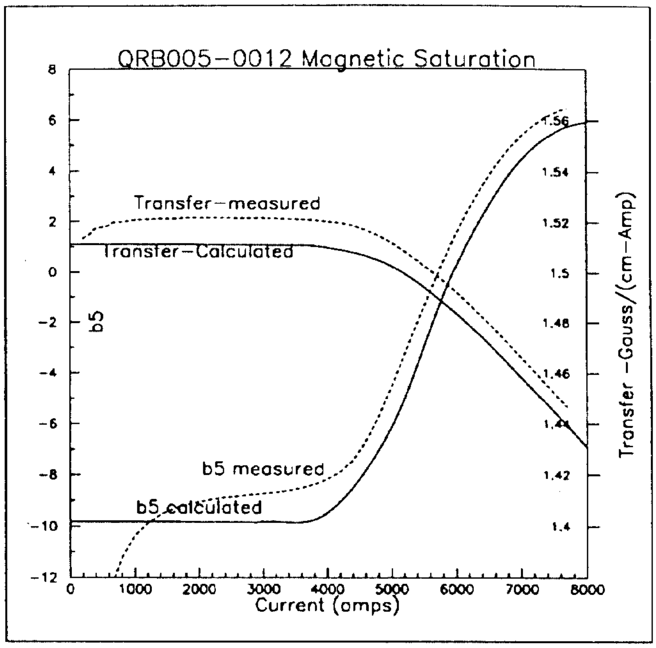

Figure 1: Central Section Fundamental(B1) and First Harmonic(B5) as a Function of Current, Calculations are Solid Curves.

4. END FIELDS

The ends of these magnets are discussed in more detail by Kahn et al[1]. The fields have been calculated with two different numerical integration programs, with rough agreement. There is significant uncertainty in the shape in the assembled magnet, in addition, one end of the magnet has external leads and cutouts in the iron to accommodate the leads. The fields are varying over distances comparable to the coil radius, which makes measurements difficult. The measurements have been carried out with a rotating coil 229 mm long, which is stepped through the magnet. Fig. 2 compares the calculations with the rotating coil measurements. Even though the calculations have been integrated over 229 mm they show rapid variations. The agreement for b5 is disappointing, but the large contribution from the leads is apparent. The cross section of this series of magnets was adjusted empirically to cancel the b5 contribution of the leads, so that the total would be ~ 0. The calculations can be integrated to produce full length harmonics. The equivalent measurements are done with a 2000 mm long coil. Table 3 presents these data. There are significant random b2/a2 and b4/a4 contributions from the ends. These can arise from differences ($\sim 2mm$) in the coil lengths and twisting of the ends. The difference for b5 is due to the discrepancy for the central section.

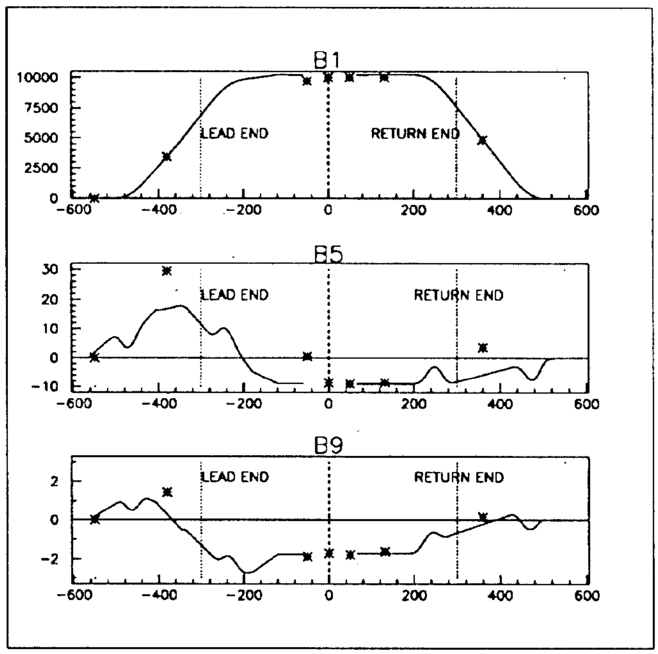

Figure 2: Comparison of 229 mm Coil Measurement and Calculations for length of magnet. * are measurements, solid lines END3D calculations. Vertical axis is b_n', horizontal is mm, the central region has been compressed to 600mm. Dotted lines show the ends of the straight section.

Table 3: Quadrupole Integral Harmonics Measured(average for QRB007-012) and Calculated. Values Measured at 3000 A, up ramp

n	b_n Calc	b_n ave	σ b_n	units
L	1.020	1.097	0.0002 ?	meter
2	0	-1.413	1.398	b_2'
3	9.3[a]	7.300	0.592	b_3'
4	0	0.672	0.613	b_4'
5	-0.228	2.2582	0.529	b_5'
6	0	-0.053	0.078	b_6
7	0.05	0.172	0.049	b_7'
8	0	-0.133	0.041	b_8'
9	-1.02	-1.167	0.342	b_9'
n	a_n Calc	a_n ave	σ a_n n	units
1	39	...	...	a_1'
2	0	-1.897	1.304	a_2'
3	0	-0.028	0.731	a_3'
4	0	2.738	0.522	a_4'
5	-1.6	-3.708	0.146	a_5'
6	0	0.172	0.114	a_6
7	0	-0.027	0.122	a_7'
8	0	0.048	0.087	a_8'
9	0.02	0.342	0.023	a_9'

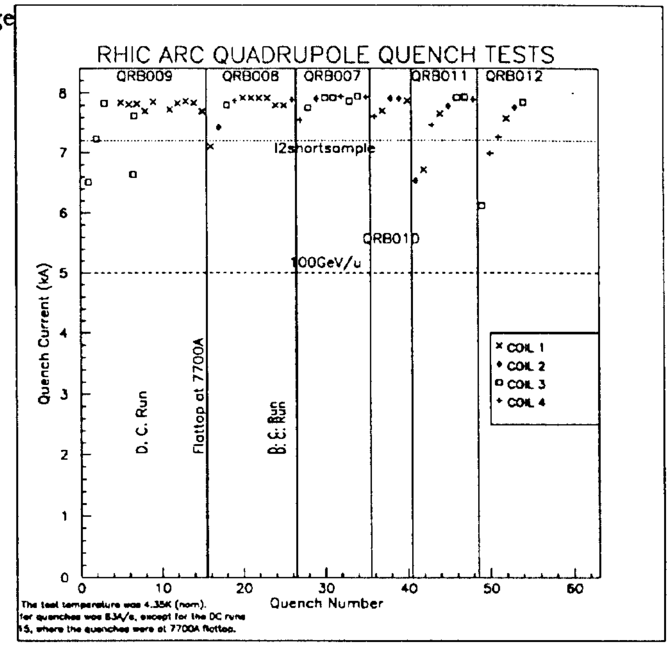

Figure 3: Quench Currents as a function of event number for these quadrupoles. Design current(5000 A) is indicated with dashed line, predicted critical current limit is shown with dotted line. Legend identifies which of the 4 coils in magnet quenched.

5. OCTUPOLE

Mixing quadrupole(2θ) and dipole(1θ) symmetries produces octupole(4θ) and higher 4n terms. Substantial octupoles have been observed in all RHIC quadrupoles[2]. In the process of clamping the coil with the steel collars the collars are distorted. Detailed measurements of this distortion have been made on a larger aperture quadrupole[3]. These show that the inner radius is reduced, and that the angle (nominally 180^o) swept by the half yoke is increased. This appears to account for the observed octupole in the 130 mm quadrupoles. The only mechanical measurements on 80 mm magnets are on dipoles. Since the assembly technique is the same, these are used to calculate the octupole. The measured deformation is 150 μm.

6. QUENCH PERFORMANCE

The quench behavior of these magnets is shown in Fig. 3. The design has a large margin, 44%, and the worst case quench is 22% above the design gradient. The I_{c_2} critical current limiting field is calculated in the same way as for dipoles, where it gives a prediction of quench plateau within 2%. Interestingly, these quadrupoles (and others constructed at this laboratory) consistently exceed this limit by $\sim$ 10%. The training may be due to the mechanical constraints on the leads. This will be investigated.

APPENDIX

The field on the midplane of a quadrupole can be expressed as:

B_y = Grad*Rref b_n' x $10^{-4}(x/Rref)^n$
(the $\cos(n+1)\theta$ term)

B_x = Grad*Rref a_n' x $10^{-4}(x/Rref)^n$
(the $\sin(n+1)\theta$ term)

Grad = Quadrupole gradient Rref = 25 mm.

With this definition, the "primed units" represent the field deviation measured at a radius of 25 mm as parts in 10^4 of the Gradient field at 25 mm.

7. REFERENCES

1. S.A. Kahn et al, *Calculations of Magnetic Field for the End Design of the RHIC Arc Dipole*, This conference poster Jc3, (1993).
2. P.A. Thompson et al, *Status of the Quadrupoles for RHIC*, IEEE Particle Accelerator Conf., pp. 504-506 (1989).
3. R. Gupta et al, *Large Aperture Quadrupoles for RHIC Interaction Regions*, this conference, paper N8,(1993).

---

*Work performed under Contract No. DE-A02-76CH00016 with the U.S. Department of Energy