STATUS OF THE QUADRUPOLES FOR RHIC*

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ABSTRACT

The proposed Relativistic Heavy Ion Collider (RHIC) will require 408 regular arc quadrupoles. Two full size prototypes have been constructed and tested. The construction uses the single layer, collarless concept which has been successful in the RHIC dipoles. Both the magnets attained short sample current, which is 60% higher than the operating current. This corresponds to a gradient of 113 T/m with a clear bore of 80 mm. The preliminary field measurements are in agreement with the calculations, with the exception of an unexpectedly large skew sextupole.

Introduction

The proposed RHIC[1] will generate colliding beams of ions as heavy as Au179 at energies up to 100 GeV/Amu. Because of the beam growth due to intrabeam scattering[2] the accelerator design is based on a lattice with only one dipole per half cell, and 90 degree phase advance per cell. In the machine there will be 486 quadrupoles (vis. 372 dipoles). 408 of these quadrupoles will be the "standard arc" quadrupoles discussed in detail in this paper. These quadrupoles are short (1.15 meter) medium gradient (74 T/m) superconducting quadrupoles. To minimize the resources required to build the magnets, a coil design using a single layer of Rutherford type cable has been selected. For the same reasons, the mechanical design has been chosen to be very similar to that of the dipoles[2]. To date, two full size quadrupoles (designated QRA001 and QRA002)have been constructed and successfully tested.

Coil Design

The superconducting cable chosen is the same as that used in the dipole; in construction, it is expected that almost all of the cable used for the quadrupoles will be "scraps" from the dipole construction. This is a cable composed of 30 Cu(NbTi) wires which is "partially keystoned". The advantages of a single layer coil design include: 1) simplification of the coil winding and magnet assembly, 2) ability to run at the same nominal current (5000 A) as the dipoles. A two layer design could be approximately 400 mm shorter (out of a half cell length of 14.81 meter) but with a coil mean radius of 50 mm and an effective length of 700 mm, the importance of the end fields would be significantly increased. The margin between operation (5000 A) and quench currents (8000 A) is artificially large because the cable was chosen for the dipole application. Since most of the cable in the quadrupoles will be "free" there would no gain in using a lower critical current cable for the quadrupoles. It is feasible to design quadrupoles with only two separate coils instead of the normal four. The problem of compensating the ends of such a design is serious for a short quadrupole; also it appears to be incompatible with the two piece yoke discussed below. Hence the coil design is based on four separate coils. By placing two inert wedges in the coil, it is possible to essentially eliminate the systematic higher harmonics of the coil design. The 16 turn coil cross section chosen is shown in Figure 1; the difference between the partial (1.2 degree) keystone and the natural (1.7 degree) keystone can be seen. It is straight forward to generate an end design using the multiple thin spacer method developed by FNAL and used in the RHIC dipoles. Through the n=13 harmonic, the systematic harmonics generated by this design are all less than 0.02 "prime units" (see Appendix for units definition).

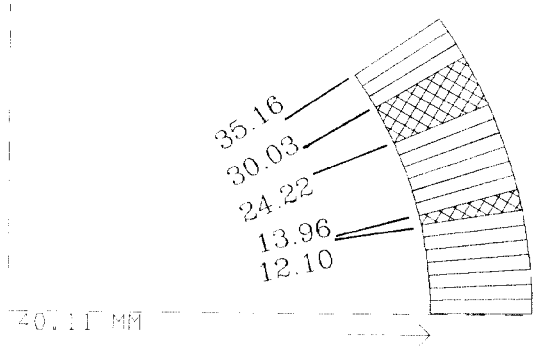

Fig. 1. Octant of Coil Cross Section

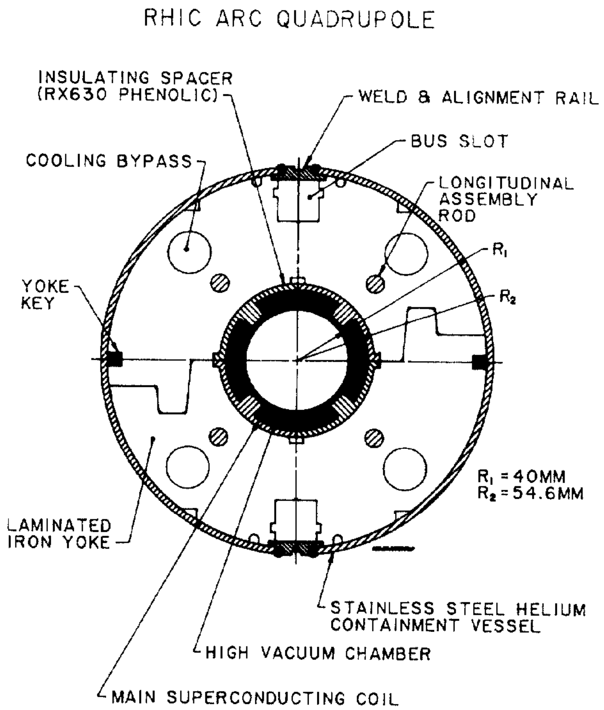

Fig. 2. Coil Assembled in Iron Yoke

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*Work performed under the auspices of the U.S. Department of Energy.

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Mechanical Design

The basic mechanical design of the dipole has proven quite satisfactory; hence the quadrupole design is based upon a modification of this concept. Specifically, the coils are positioned inside molded RX-630 spacers (see Figure 2) which serve to insulate the coil from the yoke and to accurately position the coil relative to the iron (which is the position reference for the magnet). The iron thus serves as both a magnetic return yoke and the mechanical constraint supplying the prestress to the coil. Because of the practical difficulties involved in assembling a four-part yoke, a two part yoke design is used, compatible with the dipole assembly process. The yoke is used to compress the coil to the design prestress (~8 kpsi). In this compression, the dimensions of the coils change; this means that the poles move relative to the iron yoke. This is accommodated by dividing the insulator into four sections which move independently until the yoke is closed. When the yoke is closed, the tabs on the ends of the insulator quadrants are held by the notches in the iron at the midplane. At this point in the assembly process keys are inserted in the outer circumference of the interlocking yoke halves. After removal from the press, a 4.8 mm stainless steel shell is welded over the yoke for helium confinement and additional mechanical strength. In the accelerator, the shell will be a continuous tube containing the quadrupole,a sextupole magnet,a corrector assembly and a pick-up electrode assembly. This "unit" assembly minimizes the possible relative motion of these components. The four holes (which provide a passage for helium flow) have been moved to quadrupole symmetric positions. In fig. 2 it is apparent that the square holes at the top and the bottom are not quadrupole symmetric. These holes are used for the bus work and it is not practical to split the bus work into four pieces to get through the quadrupoles. These asymmetries in the yoke produce potential perturbations in the magnetic field. The lowest order one seen in calculations is a b3'. The calculations indicate that at the operating field of 74 T/m this will below the allowable limit.

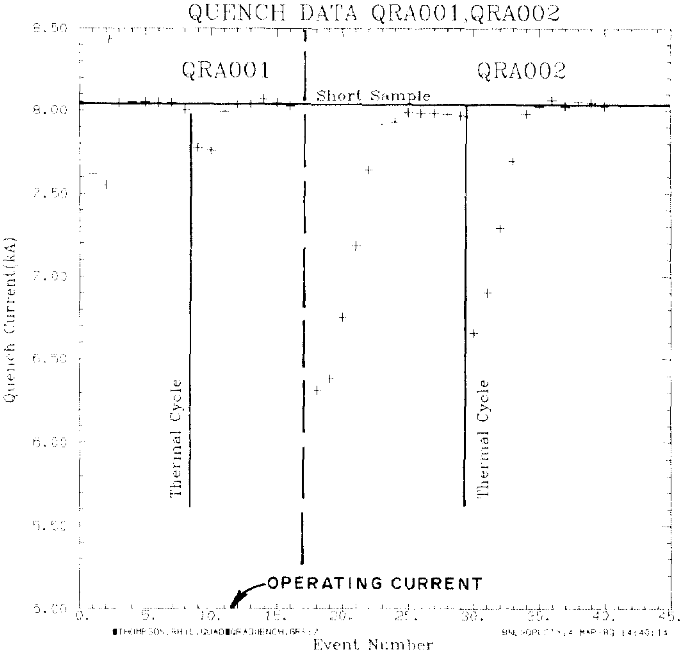

Fig. 3. Quench History for QRA001 and QRA002

Test Results

The currents at which natural quenches occurred as a function of event number are shown for the two full size magnets tested in Figure 3. Notice that the operating current (5000 A) is at the bottom of the graph. The short sample current is the measured critical current of the conductor used, compensated for the actual fields in the coils of the quadrupole. QRA001 shows negligible training. QRA002 shows moderate training which is lost during a thermal cycle. There were some anomalies in the readings of the strain gauges for this magnet. (Strain gauges are placed in the poles of the magnet to measure the coil prestress). It is possible that there was an error made in assembly. Both magnets reached short sample in a maximum of 6 quenches, and even the lowest quench observed is 25% above the operating current. The leads for the four coils are brought out to the end of the magnet for interconnection. This assembly is rather complex and poorly restrained mechanically. It may be the origin of some of the training; it is being redesigned for production magnets.

Field Quality

Detailed harmonic measurements have been made of both the magnets constructed to date. Because a quadrupole field is by definition non-uniform, these measurements are much more sensitive to position errors than the equivalent dipole measurements. The system used is in the prototype stage. High quality measurements were obtained for the quadrupole term and the first "allowed" harmonic (b5'). The measurement of the other harmonics was sufficient to indicate that the field quality was adequate for the accelerator.

Allowed Terms The quadrupole transfer function is shown in Figure 4. The measured values for the two magnets agree to approximately 5×10^{-4} which is equal to the expected random variation. The 1% difference between calculation and measurement is twice the variation seen in dipoles. The quadrupole field strength is inversely proportional to the square of the coil radius(twice the sensitivity of the dipole strength). The shape of the curve, produced by saturation of the iron yoke, is excellently predicted.

The first allowed harmonic is b5', whose behavior is shown in Figure 5a. The agreement between the two sets of measurements is extraordinary, the expected random fluctuation is 1.2. Since the disagreement with calculation of 2.5 units is reproducible, it can be trivially compensated for by minor coil modifications.

The measurements and calculations of b9' are shown in Figure 5b. The variation between magnets, 0.3 units, is 1 standard deviation. The difference between calculation and measurement (0.8 units) is consistent with the offset seen for b5'.

Octupole In a quadrupole with pure four-fold symmetry, all b3' terms would be identically 0. As explained above, the outer portion of the iron yoke has only dipole symmetry. Thus as the field increases, one would expect to see increasingly strong symmetry breaking terms. The lowest order such term is b3'. The calculations (see Figure 5b) predict 0.3 units of b3' at operating current and 0.8 units at quench. The measurements give much larger results. The shape of the curves exactly match those for b5', suggesting that it is feed-down due to incorrect corrections for positioning errors. In the accelerator design there are large octupole correction elements which can compensate for these effects.

Other Harmonics The harmonics at intermediate fields (where the effects of both magnetization and iron saturation are small) give information about the accuracy of coil fabrication and assembly. These are summarized in table 1 below. The column headed "rms" is the calculated random coil-coil variation, and "calc" labels the calculated harmonics for a perfect coil/iron assembly. The reproducibility of these first two magnets is extraordinary- for every harmonic the variation is less than the expected fluctuation. The only harmonic needing corrective action is the sextupole. The origin of this term is not understood. Possible sources include lead fields and a mid-plane gap in the iron.

Table 1: Base Harmonics

Harmonic	Rms	Calc.	QRA001	QRA002	
Grad/Amp	0.0006	1.481	1.496	1.496	(G/cm-A)
b2'	3.6	0	-7.4	0.6	
a2'	3.6	0	-4.3	-5.5	
b3'	2.3	0	-3.2	-2.1	
a3'	2.3	0	0.7	-0.5	
b4'	1.7	0	0	0.2	
a4'	0.1	0	0.2	-0.03	
b5'	1.2	1.0	-2.4	-2.0	
b6'	0.8	0	0.2	0.1	
a/b7'	0.6	0	0.4	0.2	
b9'	0.3	-0.05	0.7	0.5	

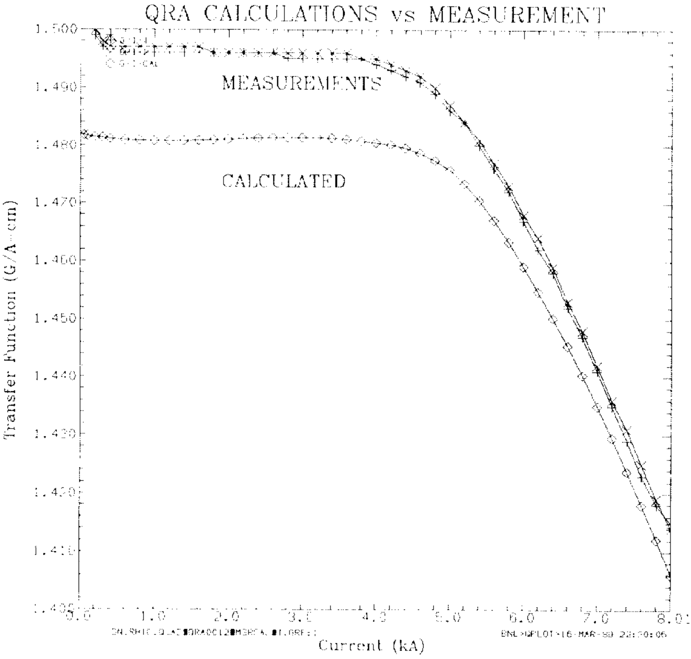

Fig. 4. Measured and Calculated Transfer Functions.

Conclusions

The first two RHIC quadrupoles, which were full size prototypes, were constructed without difficulties. After minimal training, they achieved gradients 60% higher than the design gradients. The field reproducibility is significantly better than expected. The sextupole term is unexpectedly large; the origin of this anomaly is being investigated. For production magnets, the lead assembly will be modified for better mechanical support.

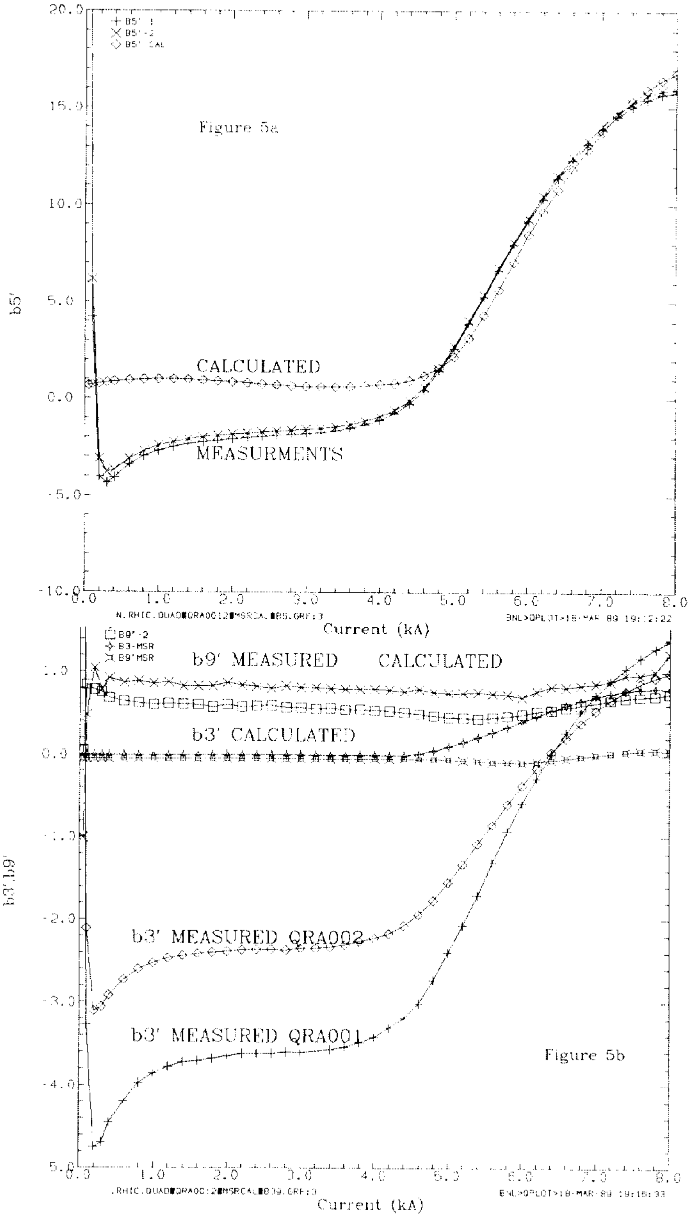

Fig. 5. Higher Harmonics: b5',b9' and b3'

Appendix Units Used

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

$$B_y = Grad*Rref \quad \sum b_n' \times 10^{-4} \quad (x/Rref)^n$$

$$B_x = Grad*Rref \quad \sum a_n' \times 10^{-4} \quad (x/Rref)^n$$

Grad = Quadrupole gradient

we use 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 at 25 mm.

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