Field Quality Improvements in Superconducting Magnets for RHIC*

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Abstract

A number of techniques have been developed and tested to improve the field quality in the superconducting dipole[1] and quadrupole magnets[2,3] to be used in the Relativistic Heavy Ion Collider (RHIC). These include adjustment in the coil midplane gap to compensate for the allowed and non-allowed harmonics, inclusion of holes and cutouts in the iron yoke to reduce the saturation-induced harmonics, and magnetic tuning shims to correct for the residual errors. We compare the measurements with the calculations to test the validity of these concepts.

1 INTRODUCTION

The field harmonics are defined by the following relation:

$$B_y + iB_x = 10^{-4} B_{R_0} \sum_{n=0}^{\infty} [b_n + i\ a_n]\ e^{in\theta} \left(\frac{r}{R_0}\right)^n$$

where $b_n(a_n)$ is the normal(skew) n^{th} order harmonic and B_x, B_y are the components of the field at (r,θ). R_0 is the reference radius which is chosen to be 25 mm for the 80 mm aperture RHIC arc dipoles and quadrupoles and 40 mm for the 130 mm aperture insertion quadrupoles. B_{R_0} is the magnitude of the field due to the fundamental harmonic at the reference radius on the midplane.

The magnets for particle accelerators typically require a field uniformity of a few parts in 10^4. This implies that the magnet must be designed and constructed carefully and the parts used in the magnets must have tight dimensional tolerances. However, because of practical limitations and non-linear magnetic properties of the iron yoke, the cumulative errors may be larger than acceptable. In this paper we discuss an assortment of techniques developed during the RHIC magnet program to correct for these unwanted values of field harmonics. These techniques have been found quite effective and yet were simple to adopt and test on a short time scale with minimum changes in the magnet. Moreover, a method of *tuning shims* has been developed for the interaction region quadrupoles to meet the requirement that the field quality in these magnets be much better than expected from reasonable manufacturing tolerances.

2 FIELD QUALITY CONTROL

2.1 Octupole Term in Quadrupoles

The earlier designs of RHIC quadrupoles contained ~7 units of non-allowed octupole harmonic (b_3) in the magnets. These quadrupoles are collared like dipoles for design simplicity. However, in the process, the basic 4-fold quadrupole symmetry is broken and the octupole harmonic is generated. To compensate for this harmonic we deliberately introduced another asymmetry between the horizontal and vertical plane when the coils are assembled in the magnet. Two of the four coil to midplane gaps were increased from 0.1 mm to 0.2 mm on the horizontal plane but the other two were left unchanged at 0.1 mm on the vertical plane. An asymmetry of 0.1 mm between the horizontal and vertical planes generates b_3 and b_7, whereas an average 0.05 mm increase in the midplane gap generates allowed b_5 and b_9 harmonics. The size of this asymmetry is about right to cancel out the previously measured b_3. However, a small b_7 gets generated in the process. The allowed b_5 and b_9 harmonics are corrected in the regular coil cross section iteration. In Table 1, we compare the calculations and measurements in the experiment done to verify this technique in the 130 mm aperture quadrupoles. A similar fix has been used in the 80 mm aperture arc quadrupole design.

Table 1: *The change in field harmonics caused by an asymmetric increase in the coil to midplane gap in the 130 mm aperture RHIC interaction quadrupoles. The gap was increased by 0.1 mm in the horizontal plane only.*

	Δb_3	Δb_5	Δb_7	Δb_9
Computed	-6.8	-1.3	-0.45	-0.16
Measured	-6.5	-1.2	-0.30	-0.17

2.2 Adjustment of Coil Midplane Gap in Dipoles

During large scale production, there may be a systematic drift in harmonics due to, for example, wear in tooling. In the past it has been partly compensated by a change in the coil pole shim. The pole shims are eliminated in the RHIC arc dipole and quadrupole magnets to minimize the cost. A similar compensation can, however, be achieved by adjusting the thickness of the midplane insulation between the upper and lower halves of the coil. The concept was earlier tested when a pre-production short dipole was rebuilt with an increased midplane gap. We compare the results of calculations and measurements in Table 2. A small difference between the calculations and measurements can be explained by about 10% compression in the Kapton midplane insulation.

Table 2: *The change in field harmonics when the coil midplane gap is increased from 0.1 mm to 0.15 mm in the 80 mm aperture RHIC arc dipole magnets.*

	Δb_2	Δb_4	Δb_6	Δb_8
Computed	-3.3	-1.1	-0.31	-0.10
Measured	-3.0	-1.0	-0.29	-0.12

2.3 Cross Section Iteration with No Wedge Change

For a variety of reasons a significant difference is observed between the designed and measured values of allowed harmonics in the first magnet in a new series. Moreover, sometimes there is also a difference in the thickness of the insulated cable used in the original design computations and in an actual magnet. To handle such situations the coil cross section must be iterated. It is usually accomplished by changing the wedges and, therefore, other associated components used in producing the coil straight section and ends. This approach, however, requires a long lead time and could be relatively expensive for a small number of magnets.

In the RHIC interaction region quadrupole program, the cross section iteration for the allowed and non-allowed harmonics is accomplished by changing the size of the added midplane shims in addition to the size of the usual pole shims. This may change the pre-compression on the coil, but the change is negligible since the change in the effective cable thickness is only a few μm. However, for a larger change, the coil size must be adjusted in the coil curing process. A major advantage of this approach is the ability to iterate the cross section after the coils are made. In Table 3, we have listed a number of such iterations. In all cases, good agreement has been found between the calculations and measurements. The last iteration also accommodated a change in the cable thickness by about 9 μm.

Table 3: *Cross section iterations in 130 mm aperture quadrupole with no change in any wedge. The field harmonics are optimized at 5 kA. The pole and midplane shims were adjusted in all cases. In addition, case 3 accommodated a change in cable thickness by about 9 μm.*

	b_3	b_5	b_7	b_9
Case 1	0.0	+1.2	-0.3	0.60
Case 2	0.0	-1.2	-0.3	0.45
Case 3	0.0	-1.2	-0.15	-0.20
Goal	0.0	-1.2	0.0	0.0

2.4 Helium Bypass Holes for Saturation Control

In all RHIC magnets, the gap between the coil and yoke iron is very small. This would normally generate large values of allowed harmonics at high fields due to iron saturation. However, we have used a variety of techniques to reduce these saturation-induced harmonics by controlling the path of magnetic flux in the yoke. The location of the helium bypass holes was adjusted between DRC and DRD series 80 mm aperture RHIC arc dipole prototypes in order to reduce the decapole harmonic (b_4). A notch in the yoke aperture was also moved from midplane to pole which gives a significant positive change in b_2. The results of calculations for this experiment are shown in Fig. 1. The design operating current in this magnet is 5 kA.

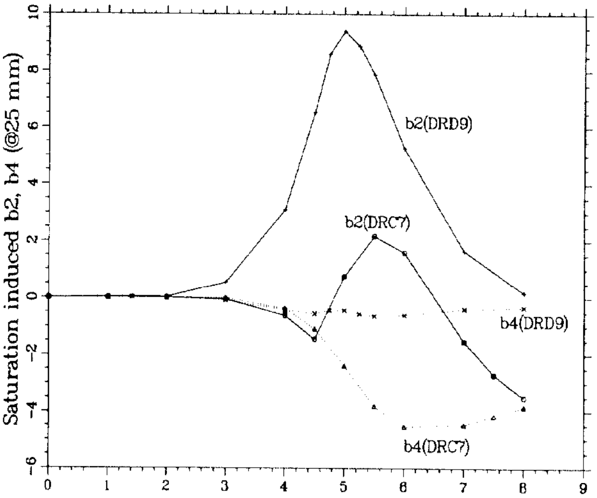

Figure 1: *The current dependence of b_2 and b_4 with two locations of helium bypass holes in RHIC arc dipoles.*

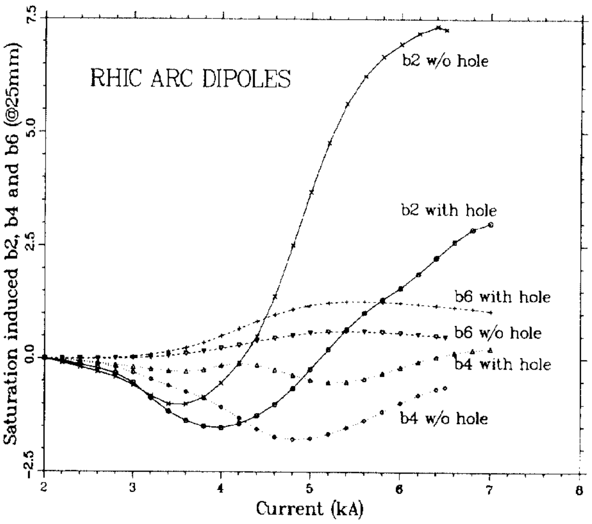

Figure 2: *The current dependence in b_2 and b_4 harmonics is significantly reduced by the saturation suppressor holes.*

2.5 Saturation Suppressor Holes

The saturation-induced sextupole (b_2) and decapole (b_4) harmonics were practically eliminated from the above design by punching an additional saturation suppressor hole in each quadrant of the yoke. These small holes (radius = 4.8 mm) are located quite close to the yoke inner surface. A short magnet was rebuilt to verify this technique. The results of the measurements are shown in Fig. 2. There is good agreement between the calculations and measurements. Though not important for machine performance, the saturation in b_6 harmonic is increased. In the similar 100 mm aperture RHIC interaction region dipole magnet design, we were able to reduce b_6 also by adjusting the location of the helium bypass hole in addition to optimizing the size and location of the saturation suppressor hole.

2.6 Two Radius Yoke Aperture for Saturation Control

In superconducting magnets, the yoke aperture is usually circular. The saturation characteristic of the yoke can be significantly altered if the yoke aperture is defined by two circular radii instead of one. The angular locations where the transition from one radius to another occurs and the difference between the values of two radii can be used as parameters to minimize the iron saturation. In Fig. 3, we present the calculations for the dodecapole harmonic (b_5) in the 130 mm aperture quadrupoles when the yoke inner radius is respectively 87 mm, 92 mm and a combination of 87 mm (at midplane) and 92 mm (at pole) with a transition at about 30°. The transfer function is higher and b_5 saturation is lower in the two radii case as compared to the one larger 92 mm inner radius case. There is a small increase in b_9 saturation by about 0.3 unit at 5 kA. The magnetic measurements confirmed that the two radii aperture technique indeed produced the results predicted by the computer codes.

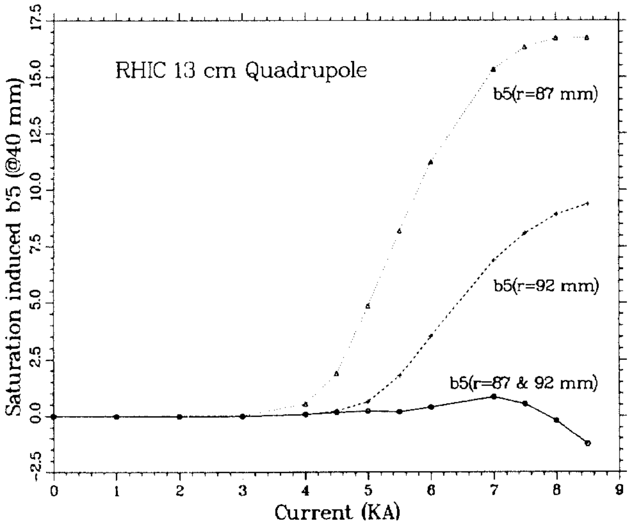

Figure 3: *The current dependence in the dodecapole harmonic (b_5) when the yoke inner radius is 87 mm, 92 mm and a combination of 87 mm and 92 mm.*

2.7 Tuning Shims for Extra High Field Quality

The luminosity performance of RHIC depends crucially on the field quality in the 130 mm aperture interaction region quadrupoles. In order to obtain a field quality much better than what is expected from normal construction techniques, a tuning shim scheme has been developed. These tuning shims are made of variable amounts of iron and are attached to the yoke at the eight places where the yoke inner radius changes. They are inserted in the magnet after collaring. The eight tuning shims will compensate the eight measured harmonics (a_2 through a_5 and b_2 through b_5) in each magnet by appropriately adjusting the thickness of the iron in each tuning shim.

The method has been tested recently when the field harmonics were measured with and without these tuning shims in the magnet QRI120. Harmonics due to tuning shims are obtained by taking a difference between the two cases. The calculations and measurements are given in Table 4, where we have compared the two at low current (warm measurements at 10 A) and at the maximum design operating current (cold measurements at 5000 A). The thickness of the iron in the eight tuning shims was either 2.8 mm or 3.3 mm and the configuration was chosen to produce only the harmonics listed in the table. The relative sign of b_3 and b_7 in this method is opposite to that in the asymmetric midplane gap method (see Table 1, section 2.1). In the final design of the 130 mm quadrupole magnets, we used a combination of the two methods to obtain small values of both b_3 and b_7.

Table 4: *A comparison of the calculations and measurements for the field harmonics produced by a set of tuning shims in the 130 mm aperture quadrupole QRI120.*

	Δb_3	Δb_5	Δb_7	Δb_9
Computed (10 A)	-1.7	-2.7	0.21	-0.29
Measured (10 A)	-1.5	-2.8	0.18	-0.27
Computed (5 kA)	-1.3	-2.0	0.15	-0.27
Measured (5 kA)	-0.8	-1.7	0.12	-0.27

3 CONCLUSIONS

The field quality in RHIC superconducting magnets has been significantly improved by the methods described in this paper. These techniques have been found to be quite simple to adopt and yet very powerful in controlling the field quality.

4 REFERENCES

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