BNL-68135

Field Quality Improvements in Superconducting Magnets for RHIC*

R. Gupta, A. Jain, S. Kahn, G. Morgan, P. Thompson, P. Wanderer, E. Willen
Brookhaven National Laboratory, Upton, NY 11973, USA

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

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

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.

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.

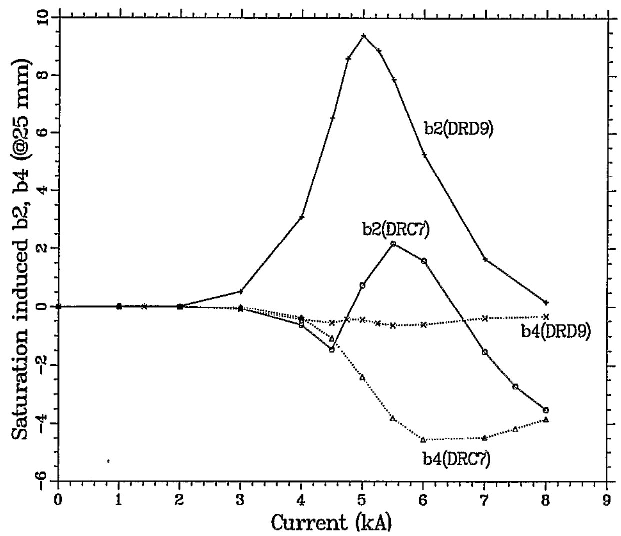

Figure 1: *The current dependence of b_2 and b_4 with two locations of helium bypass holes in RHIC arc dipoles.*

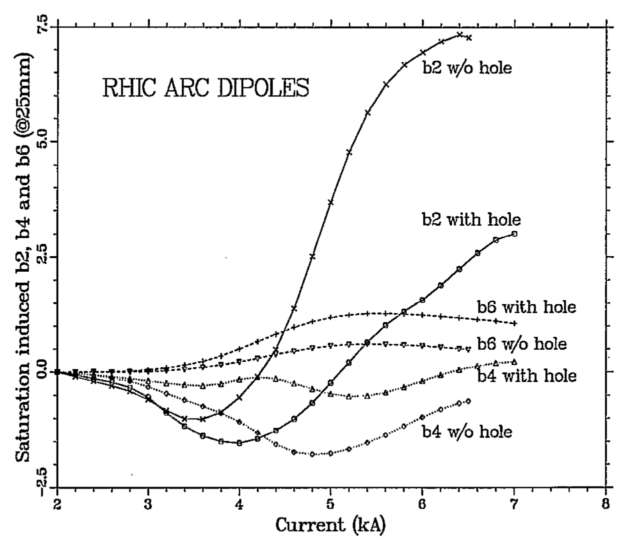

Figure 2: *The current dependence in b_2 and b_4 harmonics is significantly reduced by the saturation suppressor holes.*

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.

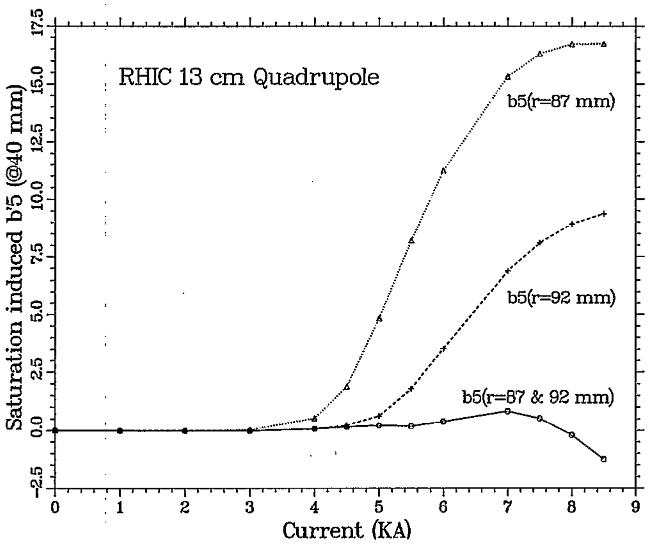

Figure 3: *The current dependence in the dodecapole harmonic (b_5) when the yoke inner radius is 87 mm, 92 mm and a combination of 87 mm and 92 mm.*

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

[1] P. Thompson, et al.,"Revised Cross Section for RHIC Dipole Magnets", 1991 Particle Accelerator Conference, pp. 2245-2247.
[2] P. Thompson, et al.," 'B' Series RHIC Arc Quadrupoles", 1993 Particle Accelerator Conference, pp. 2766-2768.
[3] R. Gupta, et al.,"Large Aperture Quadrupoles for RHIC Interaction Regions", 1993 Particle Accelerator Conference, pp. 2745-2747.

---

*Work performed under the auspices of the U.S. Department of Energy under contract No. DE-AC02-76CH00016.

The field measurements consist of axial scans at 660A (injection), 1450A (transition) and 5000A (storage). In addition, the complete current dependence from 50A to 6000A is studied at one location in the center of the magnet.

The current dependence of the skew quadrupole term measured in the axial center of two of the RHIC dipoles is shown in Fig. 2. In order to facilitate comparison between the two magnets, the geometric skew quadrupole term is removed by subtracting the value at 1450A. The possible sources leading to variation of a_1 with current in the SSC dipoles are discussed in an earlier paper [2]. In the case of the RHIC dipoles, the primary source of this variation is the asymmetrically located cold mass in the cryostat, as discussed earlier. The change in the value of a_1 between 1450A and 5000A will be referred to as "a_1 saturation" since the major source of this change is the saturation of the iron yoke. The skew quadrupole contribution at 1450A from superconductor magnetization is less than 0.1 unit in all the magnets.

III. Magnet to Magnet Variation in a_1 Saturation

The two magnets shown in Fig. 2 exhibit the largest (DRG125, filled boxes) and among the smallest (DRG113, solid line) skew quadrupole saturation. Based on the effect of the cryostat alone, all magnets are expected to show nearly the same current dependence in a_1. Such large magnet to magnet variations lead to uncertainties in predicting the values at high fields based on warm measurements alone.

The magnet to magnet variations can arise due to differences in the iron weights in the upper and the lower yoke halves. In the case of the SSC dipole prototypes, a good correlation was found between the top-bottom yoke weight asymmetry and the a_1 saturation [2]. Such a correlation is to be expected, because an asymmetry in the iron weights could either add to or cancel the effect of the cryostat, depending on the sign of the asymmetry.

In the case of the RHIC dipoles, the upper and the lower iron yoke weights are available in three different sections. We calculated the values of the skew harmonic terms integrated over each of these three sections in a magnet by appropriately summing the values measured in axial scans. Using axial scans at 1450A and 5000A, we can calculate the a_1 saturation in each of the three sections of a magnet.

Fig.3 shows the correlation between the yoke weight asymmetry and a_1 saturation in all the dipoles tested so far. The yoke weight asymmetry is defined as

$$\text{asymmetry} = \frac{\text{weight of Top part - weight of Bottom part}}{\text{Average weight of Top and Bottom parts}}$$

There are a total of 38 magnets in the plot shown in Fig.3, for a total of 114 (=3x38) points in the plot. A good correlation is seen between the yoke weight asymmetry and the saturation in skew quadrupole, as expected. The solid line shows a linear fit to the data points. A few of the data points are seen to lie away from the line. This lack of correlation in certain sections of a few magnets could be due to incorrect recording of the yoke weight. The linear fit shown excludes such data points (seven points in all, belonging to six different magnets). The linear fit gives an a_1 saturation of −1.9 units for zero asymmetry in yoke weight, in good agreement with

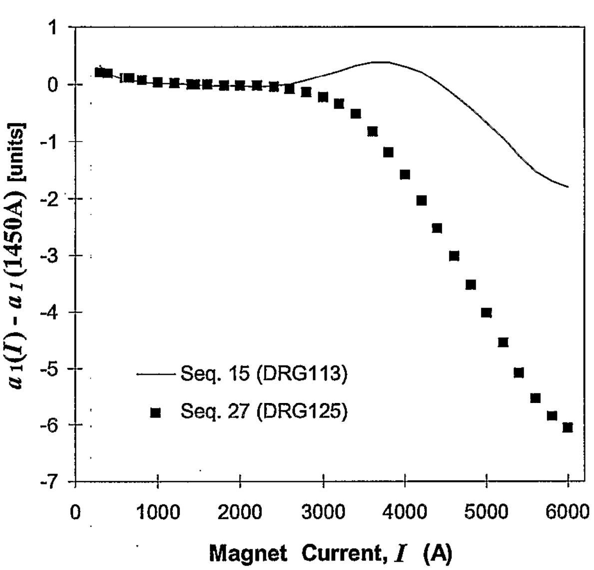

Fig. 2. Current dependence of the skew quadrupole term in the dipoles DRG113 and DRG125. The magnitude of change between low currents and 5000A is the largest in DRG125 and is relatively small in DRG113.

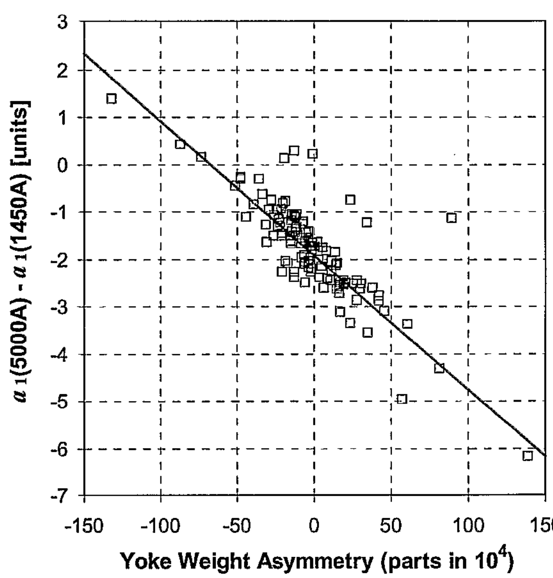

Fig. 3. Correlation between the yoke weight asymmetry and the saturation in the skew quadrupole term. There are three data points for each magnet corresponding to the three sections of the yoke blocks for which the weights are known.

theoretically calculated value of –2.0 units. Furthermore, the slope of the line gives a change of –2.8 units in a_1 saturation for 1% asymmetry in the iron yoke weight. This is also consistent with calculations. The calculated current dependence of the skew quadrupole term is shown in Fig. 4 for various values of top-bottom weight asymmetry. The calculated curves are similar to the measured current dependences shown in Fig. 2.

IV. CONTROL OF a_1 SATURATION

As seen from Fig.3, there is considerable magnet to magnet variation in a_1 saturation. This variation is a result of asymmetry in the top and bottom yoke weights. The production specifications for the RHIC dipoles specify that the total weight of the yoke be held constant within ±2 kg. The total yoke weight is approximately 2764kg. Ideally, the weights of the yoke halves should be controlled with little magnet to magnet variation. However, such a requirement is difficult to fulfill in practice. Since the yoke laminations are 6.35 mm thick with a tolerance of 0.25 mm, the weights of the yoke packs are expected to differ somewhat.

On the other hand, the systematic value of skew quadrupole measured at low fields in the RHIC production dipoles is close to zero. If the upper and the lower yoke blocks are exactly matched in weight, this would imply a systematic a_1 of –1.9 units at 5000A due to the cryostat. It is possible to reduce this systematic a_1 at high fields by counteracting the asymmetry of the cryostat by some other means. Various possible means to achieve this are suggested in [3].

The control of a_1 saturation essentially requires that additional iron be available in the bottom half of the yoke compared to the top half. We have utilized the natural variations in the weights of the iron yoke blocks to achieve this without incurring any additional cost in the production. In the dipoles now under production at the Northrop-Grumman Corporation, the yoke blocks are assigned in such a way that the heavier blocks are used for the bottom half and the lighter ones for the top half. A top-bottom weight difference of 0.5% is targeted to counteract the –1.9 units of systematic a_1 saturation.

Fig. 5 shows the asymmetry in the total upper and the lower yoke weights in all the dipoles delivered so far. The current scheme of yoke blocks assignment was implemented starting with dipole sequence number 63. For dipoles 1 through 62, no attempt was made to control the upper and the lower yoke weights separately. As can be seen from Fig. 5, most magnets in this group had a positive asymmetry, which only added to the effect from the cryostat. For dipoles numbered 63 onwards, it is attempted to make the lower half of the yoke heavier than the top half by approximately 1%. This is reflected in the negative values of asymmetry in Fig. 5 for sequence number 63 and higher. The additional iron on the bottom is expected to counteract the effect of the cryostat proximity on the top.

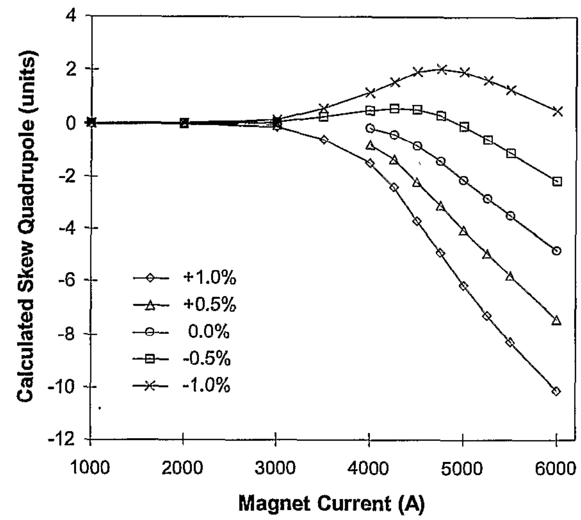

Fig. 4. The calculated current dependence of skew quadrupole term for various values of the asymmetry between the top and the bottom halves of the yoke.

The integral values of a_1 in the magnets were obtained by summing the fields measured in the axial scans. The saturation of integral a_1 was calculated using the integral values from the axial scans at 1450A and 5000A. The correlation between the integral a_1 saturation and the asymmetry in the total upper and the lower weights is shown in Fig. 6 for both the intial magnets (open boxes), and the current production (filled boxes). Once again, the correlation with iron weights can be seen to hold for most of the magnets. The solid line shows a linear fit to data. Some of the points do not fall close to the line. It should be noted that most of these points belong to the same magnets that did not show a good correlation in Fig. 3.

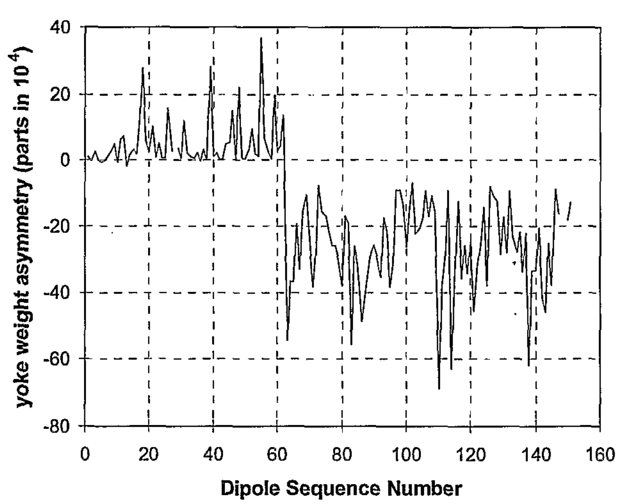

Fig. 5. The asymmetry in the weights of the upper and the lower yoke halves in the RHIC arc dipoles. Starting with magnet sequence number 63, the lower yoke half was made heavier than the top half.

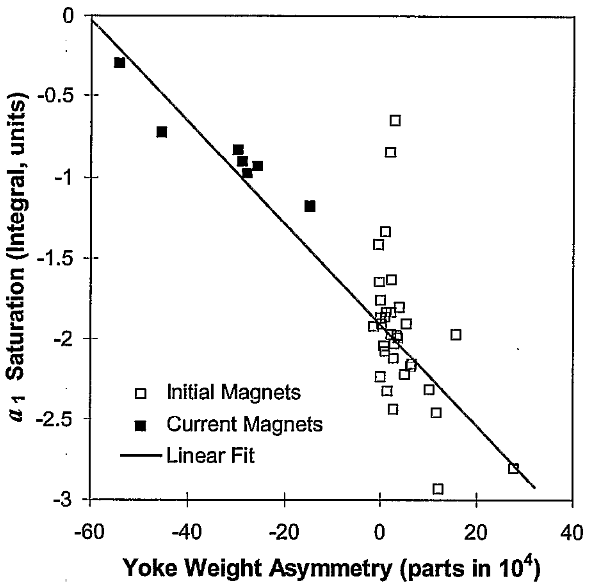

Fig. 6 Correlation between the integral a_1 saturation and the asymmetry in the total weights of the upper and the lower yoke halves.

It is clear from Figs. 5 and 6 that the magnets in the new scheme (production sequence 63 and higher) have a negative top-bottom asymmetry in yoke weight on an average. The saturation in a_1 is also correspondingly lower. The average a_1 saturation in the magnets 1 through 62 (cold data in 33 magnets) is -1.95 units, whereas the corresponding average for the magnets 63 onwards (cold data in 7 magnets) is only -0.83 units. Thus, a reduction of about 1.1 unit in a_1 saturation has been achieved.

V. Conclusions

A systematic change in the skew quadrupole is introduced in the RHIC dipoles at high fields by the asymmetrically placed cryostat. The variation in saturation of skew quadrupole term, a_1, has been seen to be well correlated with the top-bottom asymmetry in the iron yoke weight. The saturation of a_1 has been reduced by nearly a factor of 2 by selectively using the heavier yoke packs for the bottom half of the yoke. The scheme takes advantage of the natural variation in the weights, and assigns the heavier packs to the lower half. In other words, the reduction in a_1 saturation has been achieved without any additional cost. Furthermore, the good correlation between yoke weight asymmetry and a_1 saturation can be used to accurately predict the skew quadrupole term at high fields in the RHIC dipoles based on warm measurements.

Acknowledgment

We thank Mike Anerella, B. Erickson and the Northrop-Grumman Corporation for their contributions to this work. We also thank D. McChesney for his help in compiling the yoke weight data.

References

[1] R.Thomas et al., "Performance of field measuring probes for SSC magnets," Proc. 5th International Industrial Symposium on the Super Collider, San Francisco, California, May 6-8, 1993, in Supercollider 5, P. Hale, Ed. New York: Plenum, 1994, pp.715-718.

[2] R.C. Gupta and A.K. Jain, "Variation in a_1 saturation in SSC collider dipoles," Proc. Particle Accelerator Conference, Washington D.C., May 17-20, 1993, pp. 2778-2780.

[3] R.C. Gupta, "Correcting field harmonics after design in superconducting magnets," Proc. 4th International Industrial Symposium on the Super Collider, Atlanta, Georgia, March 4-6, 1992, in Supercollider 4, John Nonte, Ed. New York: Plenum, 1992, pp.773-780.