FIELD QUALITY CONTROL THROUGH THE PRODUCTION PHASE OF RHIC ARC DIPOLES

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Abstract

The field quality in the arc dipoles built thus far for the Relativistic Heavy Ion Collider (RHIC) not only meets machine requirements[1] but is significantly better than that expected from scaling laws based on previous large scale superconducting magnet production for particle accelerators. In this paper we describe the evolution of the present cross section and the design philosophy that has led to these improvements. The techniques described here have been found quite efficient to adopt in the production environment, where schedule and cost considerations become important. Moreover, the techniques developed during the R&D program have resulted in making the saturation induced harmonics negligible, despite the fact that the iron is very close to the coil.

I. INTRODUCTION

The Relativistic Heavy Ion Collider being built at the Brookhaven National Laboratory will require 288 superconducting dipole magnets in the arcs. The cross section of these magnets is shown in Figure 1 and the basic design parameters are given in Table I. About half of them are already built by Northrop-Grumman Corporation and the field harmonics are measured[2]. The field harmonics are defined in the following relation:

$$B_y + iB_x = 10^{-4} B_0 \sum_{n=0}^{\infty} [b_n + i a_n] \left(\frac{x + i\, y}{R_0} \right)^n ,$$

where B_x and B_y are the components of the field at (x, y) and B_0 is the central field. a_n are the skew harmonics and b_n are the normal. R_0 is the normalization radius which is chosen to be 25 mm in these magnets.

Table I
Basic design parameters of RHIC arc dipoles

Coil inner, outer radius	40 mm, 50 mm
Yoke inner, outer radius	59.7 mm, 133.4 mm
Field, current at injection	0.40 T, 0.57 kA
Maximum design field, current	3.46 T, 5.09 kA
Computed quench at 4.5° K	8.25 kA
Magnetic length at 3.46 Tesla	9.44 m

The major sources of harmonic content in superconducting magnets are : (a) *Geometric multipoles* due to a non-ideal magnet geometry, (b)*Persistent current induced multipoles* due to the superconducting properties of the cable, (c)*Saturation induced multipoles* due to non-linear properties of the iron yoke, (d)*Coil deformation multipoles* due to changes in the shape of the collared coil due to Lorentz forces.

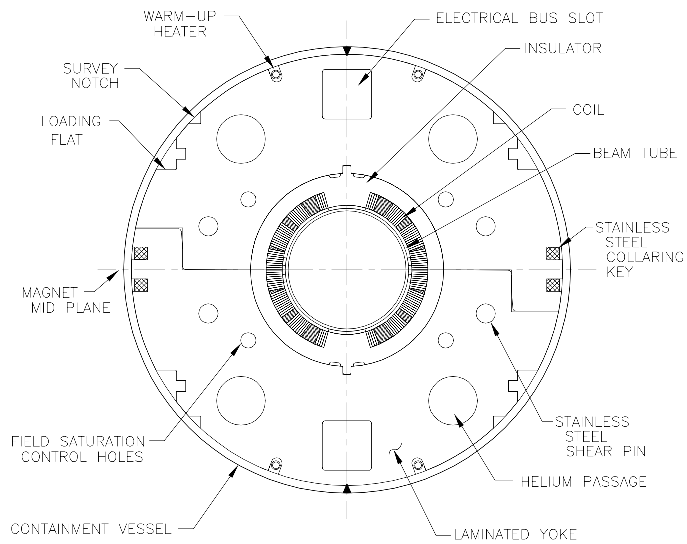

Figure 1. The cross section of the RHIC arc dipoles.

II. COIL DESIGN ITERATIONS

To obtain a high field quality such as that measured in RHIC magnets, the conductors must be placed at the appropriate location to an accuracy of ~50 μm $(0.002'')$. However, after the coils are manufactured, they go through significant deformation during curing, collaring and cool down processes and there is no direct control on where an individual turn will exactly go. The mechanical deformation in the coil and iron shape during manufacturing is not calculable to a combined accuracy of 50μm. To overcome this limitation, we empirically remove the influence of these distortions by calculating the offsets in measured field harmonics from the computed values after including all known sources. These offsets are subtracted out during the cross section iterations. In addition, the required changes in the iterated design are specified in terms of relative changes in dimensions as compared to the previous design so that the errors in tooling etc. get subtracted out.

The successful outcome of this approach is clear from Table II where the measured averages for the allowed harmonics are given for the Prototype, Phase 1, Phase 1A and Phase 2 dipoles. The Phase 1 cross section was the initial cross section used in the first 19 industry-built magnets which was based on the cross section used in the last two prototype magnets built at BNL. The coil midplane gap was deliberately made larger by 0.05 mm than the required[3] minimum value of 0.10 mm. This

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

was to compensate for a potential change in field quality associated with the change in tooling between the prototype and industry built magnets. An adjustment in the midplane gap is much more powerful than an alternate method of adjusting coil pole shim, particularly for the crucial b_4 harmonic. In fact, this adjustment got quickly implemented in the Phase 1A cross section (used in the next 86 magnets), when the coil midplane gap was changed from 0.15 mm to 0.10 mm to reduce b_4. The change in midplane gap back to 0.15 mm together with a change in one wedge by 63.5μm was incorporated in the Phase 2 cross section. The current production is proceeding on this design and 24 dipoles are included in Table II. In all cases good agreement has been found between the calculations and measurements.

Table II
The average and RMS values of field harmonics in various cross section designs for RHIC arc dipoles. The b2 harmonic is given at the maximum field (3.46 T) and the other harmonics at injection (0.4 Tesla). The measured warm cold correlation of 40 magnets is used to estimate harmonics in 129 magnets measured warm.

Design	b_2	b_4	b_6	b_8
Prototype	1.3±0.8	0.3 ±0.2	-0.1 ±0.05	0.40±0.03
Phase 1	0.4±1.6	-1.0 ±0.4	-0.38±0.09	0.20±0.06
Phase 1A	1.2±1.2	-0.4 ±0.30	-0.10±0.08	0.24± 0.03
Phase 2	-0.3±1.3	0.1 ±0.32	-.21±0.09	0.00 ±0.03a

Table III
The computed changes in the values of harmonics produced by a systematic azimuthal error of +25μm $(0.001'')$ in crucial parts in RHIC arc dipoles.

Parameter	δb_2	δb_4	δb_6	δb_8
Wedge 1	-0.98	-0.122	0.061	0.043
Wedge 2	0.69	0.423	0.022	-0.050
Wedge 3	1.42	-0.090	-0.068	0.041
Pole Width	-1.11	0.154	-0.039	0.014
Midplane Gap	-1.68	-0.557	-0.156	-0.050

In RHIC magnets, the specified tolerances in the dimensions of the most crucial parts are typically ±25μm (0.001$''$). In Table III we list the harmonics produced by a systematic +25μm azimuthal error in the three wedges, pole width and the coil midplane gap. The coil midplane can not have such a large error and is given for 25μm only for consistency. Moreover, field harmonics are also created by other parts used in the magnets, such as the errors in yoke dimensions etc., but they are generally expected to have a smaller impact on harmonics. In a few magnets the spacers used between the coil and iron were just outside the thickness tolerance and caused a noticeable change in the transfer function[2].

The harmonics in Table II are comparable to those in Table III. This suggests that the harmonics are not limited by the design and that these are probably the best harmonics one may hope for with reasonable values of mechanical tolerances and normal variations in the manufacturing process.

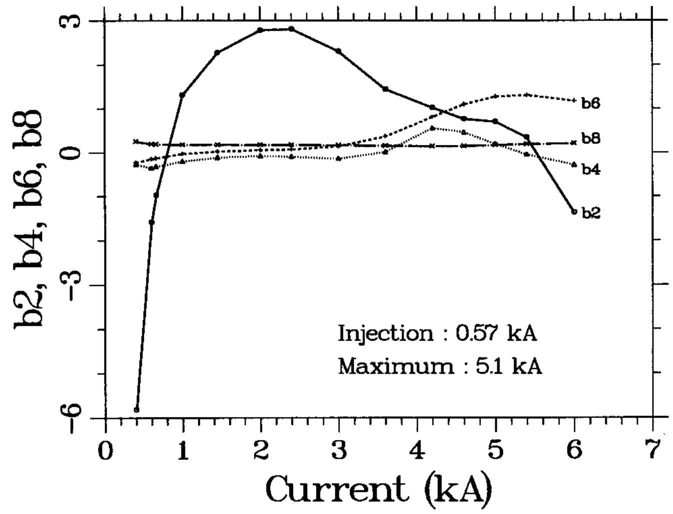

Figure 2. The measured current dependence of harmonics during up ramp (and 20 second wait) in RHIC arc dipoles.

III. YOKE DESIGN ITERATIONS

In RHIC magnet designs, the yoke has been brought very close to the coil in an attempt to get the maximum contribution from the iron. The conventional wisdom against such attempts in the past had been that the saturation induced harmonics would become unavoidably large. However, the results from RHIC magnets show that despite a high (∼35%) contribution from iron (50% to 100% higher than those used in major accelerator magnets) the saturation induced harmonics can be controlled to a small value. In Figure 2, we have plotted the average values of field harmonics as a function of current during the up ramp in 129 magnets. Only 40 of them are actually measured cold and for others an already well established warm-cold correlation from 40 magnets is used[2]. The dominant source for the current dependence below 2 kA is the persistent current in the superconductors, whereas above 2 kA it is the iron saturation and the change in coil and iron shape when Lorentz forces are unloading the pre-compression on the coil. In the present cross section, the deviation from the average in the design range of operation is ±2.5 unit in b_2 and ±0.4 unit in b_4. These values are comparable to those generated by $\pm 25\mu m$ error in more than one part (Table III). Except for the b_2 harmonic, all harmonics were optimized at the injection field. The b_2 harmonic was minimized at the maximum field where it is 2.5 units higher than at the injection. In addition, the variation in them is also minimized at the intermediate fields. The saturation induced b_6 harmonic was not optimized, as long as it did not become too large.

In Figure 3, we show the current dependence in the b_2 and b_4 harmonics in various yoke designs. The harmonics are an average of up and down ramps to remove the persistent current induced harmonics to first order. Also, an offset is added in each magnet so that they coincide at 2 kA for easy comparison. One can see an order of magnitude improvement.

The first yoke design was used in four (DRA series) magnets – the last one (DRA004) had a minor modification at the yoke outer surface. This cross section had a coil locating notch at the pole and a small coil-to-yoke gap of 5mm. Both of these features contributed to a large saturation. In the second design, used in two (DRB series) magnets, the coil-to-yoke gap was increased to 10 mm and the notch was moved to the midplane to reduce saturation. Then in the next two (DRC series) magnets, the material of the yoke-yoke alignment key was changed from non-magnetic stainless steel to magnetic steel. This made b_2 very small and b_4 significantly smaller but still large enough to require the external decapole correctors. Moreover, in order to improve the coil pole definition/location, it was decided to move the coil locating notch back to the pole from the midplane. At this stage, the yoke cross section was completely redesigned for the next two (DRD series) magnets and b_4 saturation was made small enough to consider dropping the decapole correctors from the lattice. However the pole notch, as expected, gave a relatively large b_2 saturation. Finally, a saturation control hole was added at a critical location near the yoke inner radius in the last two prototype magnets (DRE series) to make saturation induced b_2 and b_4 practically zero. However, in the DRG series yoke design, which is used in the industrially built magnets, the material of the yoke-yoke alignment key was changed from the magnetic low carbon steel to non-magnetic stainless steel to match the thermal contraction of the shell during cool down. The location of the saturation control hole was changed to compensate for extra saturation introduced by this change.

In the RHIC arc dipoles, the cold mass is not vertically centered in the cryostat. At high field this creates a skew quadrupole harmonic of ~ 2 units. In the present design, the yoke weight difference between the top and bottom halves is adjusted to compensate for this effect.

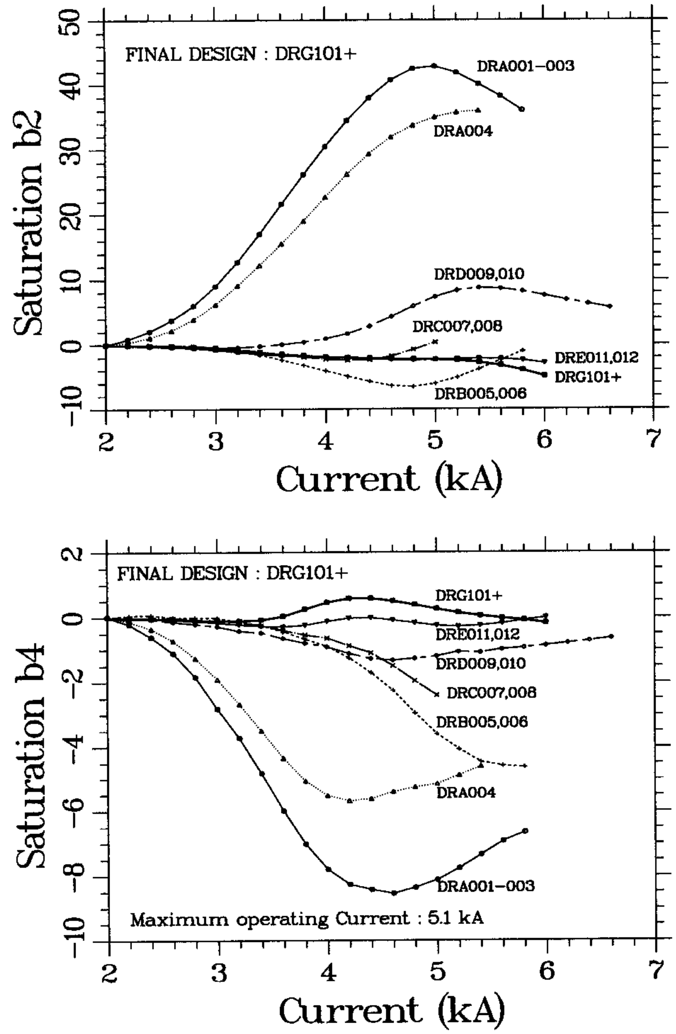

Figure 3. The current dependence of b_2 and b_4 in various designs of RHIC arc dipoles after removing the persistent current effects.

IV. CONCLUSIONS

The R&D program carried out at Brookhaven has resulted in a significant improvement in field quality of the critical arc dipole magnets for RHIC. In Figure 4 the net field error on the midplane in these magnets is compared with the similar aperture dipoles for other large accelerators.

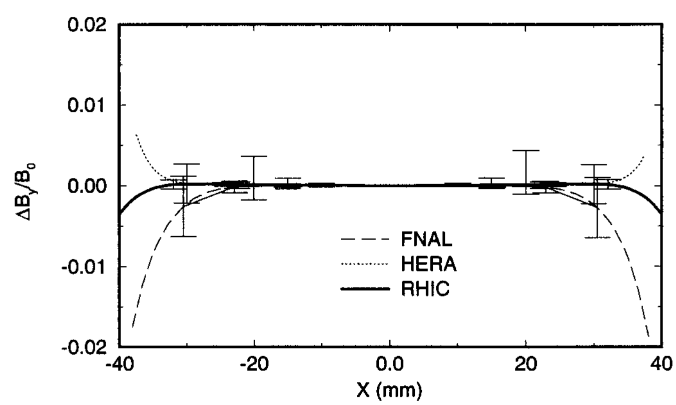

Figure 4. The field error at top operating field on the midplane of the 80 mm aperture RHIC arc dipoles compared with 76 mm aperture HERA and 76.2 mm aperture Tevatron dipoles. The error bars show the RMS variations. (Courtesy S. Peggs[4] and J. Wei).

References

[1] J. Wei, et al., "Field Quality Evaluation of the Superconducting Magnets for the Relativistic Heavy Ion Collider", this conference.

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[4] S. Peggs , "Private Communication."