Field Quality Analysis as a Tool to Monitor Magnet Production*

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***Abstract*— Field harmonics offer a powerful tool to examine the mechanical structure of accelerator magnets. A large deviation from the nominal values suggests a mechanical defect. Magnets with such defects are likely to have a poor quench performance. Similarly, a trend suggests a wear in tooling or a gradual change in the magnet assembly or in the size of a component. This paper presents the use of the field quality as a tool to monitor the magnet production of the Relativistic Heavy Ion Collider (RHIC). Several examples are briefly described. Field quality analysis can also rule out a suspected geometric error if it can not be supported by the symmetry and the magnitude of the measured harmonics.**

I. INTRODUCTION

Field harmonics are measured warm (at room temperature) in all superconducting accelerator magnets to determine if these are acceptable for RHIC [1]. These warm harmonics are also a reflection of the magnet geometry and can be used to monitor the mechanical structure of the magnet. The current passing through the cable gives the magnetic signal which reflects the coil geometry. The image current of the coil due to iron reflects the geometry of the iron yoke. The field harmonics are the Fourier analysis of this signal. A large departure from the nominal value may indicate an unacceptable part or assembly of the magnet. This paper presents the use of field harmonics as a tool to determine possible defects or irregularities in the magnets. The presence and absence of several harmonics is used to determine the nature, size and location of the defects. In most cases, the warm (room temperature) measurements were sufficient to pinpoint the defect, but in some cases cold measurements were also used.

The field harmonics in RHIC magnets are expressed in terms of the normal and skew harmonic coefficients, b_n and a_n in "units", defined by the following expansion

$$B_y + iB_x = 10^{-4} \times B_R \sum_{n=0}^{\infty} (b_n + ia_n)[(x+iy)/R]^n$$

where x and y are the horizontal and the vertical coordinates, R is the "reference radius" and B_R is the field strength at $x=R$ (on the midplane) due to the most dominant harmonic. The reference radii for field harmonics are 25 mm for 80 mm aperture arc dipole and quadrupole magnets, 31 mm for 100 mm aperture insertion dipole magnets and 40 mm for 130 mm aperture insertion quadrupole magnets.

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II. RHIC MAGNET PRODUCTION CASES

In this section, a few selected examples (cases) during the RHIC magnet production [2] are given, where the field quality analysis was used to determine a defect in the magnet. A systematic analysis of the harmonics, when they deviated significantly from their typical values, determined the defect. In some cases, further measurements were required to find the exact nature and location of the defect. The necessary steps were taken either to remove the defect or to prevent it from occurring in subsequent magnets.

A. *RHIC Arc Dipole Missing Pole Section in Spacer Case*

The warm magnetic measurements are performed [1] in all RHIC arc dipoles DRGnnn (where nnn is a three digit number starting from 101) in ten steps using a one meter long measuring coil to cover the entire coldmass length of 9.7 meters. During such a measurement in magnet DRG189, it was found that several harmonics deviated from the average straight section value by about a factor of 3 or more. One neighboring section also deviated by about half of this amount.

The integral value of these harmonic deviations is given in Table I for this two meter long straight section. These deviations can not be explained based on nominal construction errors. Large values of odd skew harmonics show that the normal up-down symmetry of dipole magnets is significantly broken here. No deviation in odd normal harmonics indicates that the left-right symmetry is still present. Similarly, no deviation in even skew harmonics indicates that the magnitude of difference between the first and the third quadrants is the same as that between the second and the fourth quadrants. The presence of large even normal terms indicates that the structure as a whole has changed. Moreover the change of sign in alternate harmonics (see Table I) suggests that the error is closer to the pole than to the midplane. When put together, these symmetry arguments mean that turns have significantly and symmetrically moved upward towards the vertical axis.

The magnet was transported from the vendor to the Laboratory for more measurements and analysis. The measurements were repeated with another one meter long rotating coil with smaller axial steps, to derive the axial profile of field harmonics with better resolution. Fig. 1 shows the axial variation in the skew quadrupole harmonic derived from such a procedure based on the 0.15 m step size. The sextupole harmonic was also measured directly with a Hall probe array (effective length ~1 mm) to verify the procedure used.

TABLE I
INTEGRATED DEVIATIONS IN HARMONICS IN TWO METER LONG SECTION IN THE SUSPECTED REGION OF RHIC ARC DIPOLE MAGNET DRG189.

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**
a_n	-22	0	2.7	0	-0.9	0	+0.3
b_n	0	-10	0	1.3	0	-0.5	0

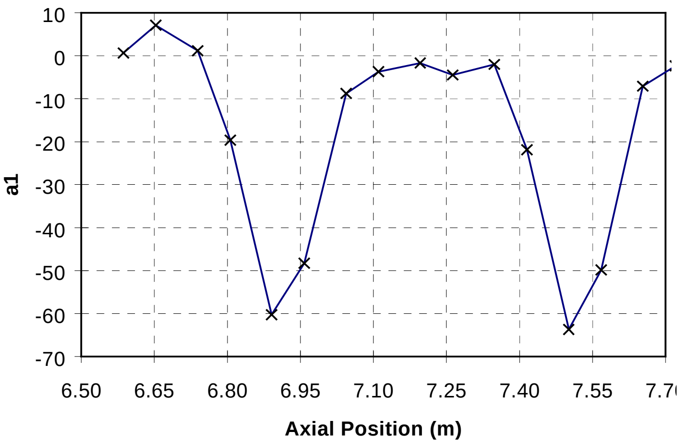

Figure 1: The axial variation in the skew quadrupole harmonic in RHIC 80 mm aperture dipole DRG189 in the suspected region.

The RHIC magnets use two types of 0.15 m long phenolic spacer (brand name RX630) as insulators between the coil and the yoke. Those used in the body have a pole to compress the coils and those used in the ends have no pole. Based on Fig.1 and based on the parts used in magnets, it was postulated that end-type of pole spacers may have been inadvertently used in two places in the body of the magnet. Furthermore, calculations showed that with missing compression (and therefore a change in the effective turn thickness), the turns have moved upward symmetrically towards the vertical axis with a maximum displacement of 1.7 mm. This was consistent with the expected uncompressed coil size. The magnet was partly disassembled to verify this scenario and upon inspection it was indeed found to be the case. A magnet with such a large discontinuity in the superconducting coil is expected to have a poor quench performance, and was not accepted for RHIC. A similar error was discovered in another magnet, DRG226.

B. *RHIC Insertion Quadrupole Missing Shim Case*

The field quality in the lead-end and non-lead end halves of 2.1 m long (magnetic length), 130 mm aperture RHIC insertion quadrupoles QRJnnn (where nnn is a three digit number starting from 101) is separately obtained from a series of measurements with a 2.78 m long coil. The magnet QRJ105 was found to have large differences in harmonics in the two halves. These differences could not be explained by the allowed tolerances in parts and assembly. The harmonics were measured in smaller steps of 0.225 m with the same measuring coil. The axial variation in a_2 and b_3, obtained using a procedure similar to the one discussed in the previous section, is shown in Fig. 2. A discontinuity (or a change much more than what can be explained by allowed tolerances) in the section between 0.0 to 0.5 meter can be seen in the lead-end half.

TABLE II
MEASURED AND COMPUTED CHANGE IN HARMONICS FOR A ~0.45 M LONG 0.36 MM THICK MISSING SHIM ON THE VERTICAL AXIS OF 130 MM APERTURE RHIC INSERTION QUADRUPOLE QRJ105. THE MEASURED HARMONICS ARE THE DIFFERENCE BETWEEN THE AVERAGE VALUE IN THE NORMAL REGION AND THE AVERAGE VALUE IN THE SUSPECTED REGION.

	a_2	b_3	a_4	b_5	a_6	b_7
Measured	-11.0	-4.5	3.0	1.3	-0.5	-0.35
Computed	-11.3	-5.8	2.5	1.2	-0.6	-0.4

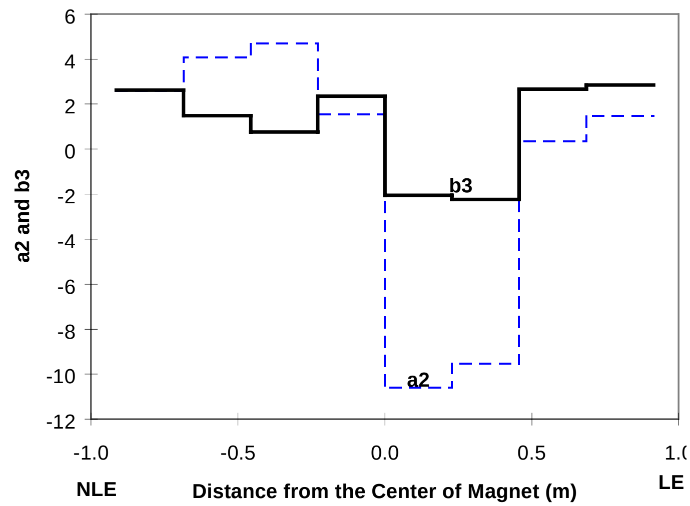

Figure 2: The axial variation in skew sextupole and octupole harmonics in RHIC 130 mm aperture quadrupole QRJ105.

The magnet symmetry arguments, similar to those used in the last section (in quadrupoles a_2 reflects up-down asymmetry), indicate that the two coils in the upper half have moved closer to the vertical axis of the magnet. The coldmass was disassembled and a visual inspection revealed that a ~0.45 m long part of 0.36 mm thick shim on the vertical axis on the upper half had fallen off. The measured and computed change in harmonics affected by this symmetry are given in Table II. Given the normal measurement errors and construction tolerances, a deviation was neither expected nor observed in the harmonics not listed in this table.

C. *RHIC Arc Quadrupole with Wrong Shim Adjustment Case*

Since 80 mm aperture RHIC arc quadrupoles (4-fold symmetry) are collared like dipoles (2-fold symmetry), a large positive octupole term (b_3 ~ +7 units at 25 mm radius) is created. To compensate for this asymmetry, the coil-to-midplane gap on the horizontal and vertical axes were made 0.25 mm and 0.15 mm respectively [6]. The measurements (see magnets 101-107 in Fig. 3) indicated that this difference had over compensated the asymmetry, leading to a negative value of b_3. A request was made to the vendor to decrease this asymmetry by 0.025 mm which was also expected to help reduce the b_5 harmonic at injection. However, the change was made in the wrong direction and the asymmetry was increased. The measured b_3 (see magnets 108-112) showed an increase in the magnitude. This, and the new value of the b_5 harmonic confirmed that the change was indeed in the wrong direction. The problem was corrected in the subsequent magnets and the

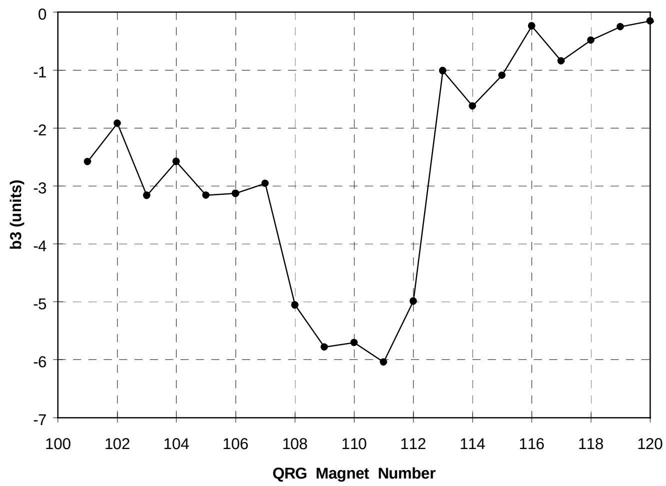

Figure 3: The measured octupole harmonic with the magnet number (first magnet named QRG101) in RHIC 80 mm aperture quadrupoles.

desired harmonics were obtained (see magnets 113 and onwards).

D. *RHIC Insertion Dipole Coil Fabrication Date Case*

During the warm magnetic measurements of RHIC 100 mm aperture insertion dipoles, it was found that the RMS (Root Mean Square) variation in the skew quadrupole harmonic (~2.5 units) was larger than the value obtained in 80 mm aperture arc dipoles (1.6 units). Since the two are built using similar design and construction techniques, one should expect a similar or smaller value in insertion dipoles due to their larger aperture. This large RMS was later traced to the storage of the coils for greatly varying periods of time prior to collaring. This allowed the coil azimuthal size to grow with time. The two coils in a particular magnet were matched in azimuthal size to 0.025 mm based on the size measured just after curing. In Fig. 4, we make a correlation plot between the difference in age (from coil curing to collaring) between the top and bottom coils and the measured a_1. One can conclude from Fig. 4 that the storage time between curing to collaring played a role.

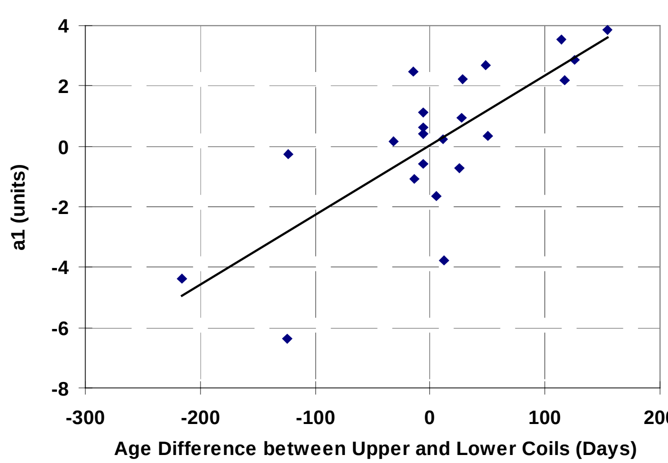

Figure 4: A correlation plot with a least square fit between the skew quadrupole and the age (from curing to collaring) difference between the upper and lower coils in 100 mm aperture RHIC insertion dipoles.

E. *RHIC Arc Quadrupole Coil Length Variation Case*

A pattern of variation was observed in the integral transfer function of 1.1 m long (magnetic length) 80 mm aperture arc quadrupoles (see Fig. 5). A careful examination of coil mechanical parameters revealed a similar pattern in coil length. This was later traced to an incorrect method employed by the vendor's subcontractor in assembling coil end parts. This resulted in the large variations of the coil ends and hence the overall coil length. Fig. 6 shows a correlation between coil length and integral transfer function. The assembly method was later corrected and the variations were reduced starting around magnet sequence number 240 in the magnets as shown in Fig. 5.

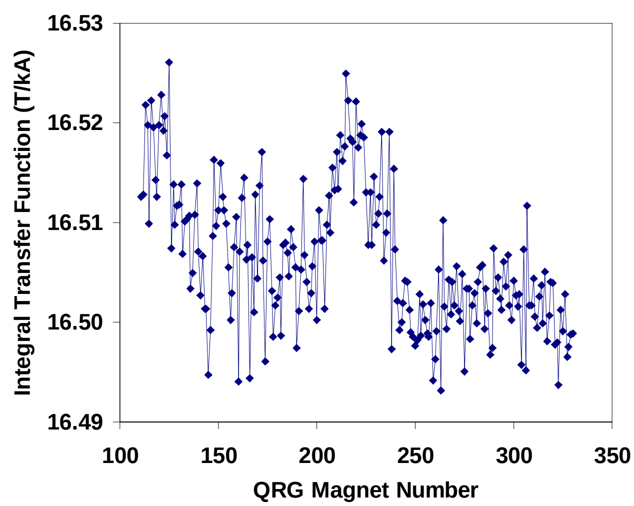

Figure 5: The measured integral transfer function with the magnet number in RHIC 80 mm aperture quadrupoles.

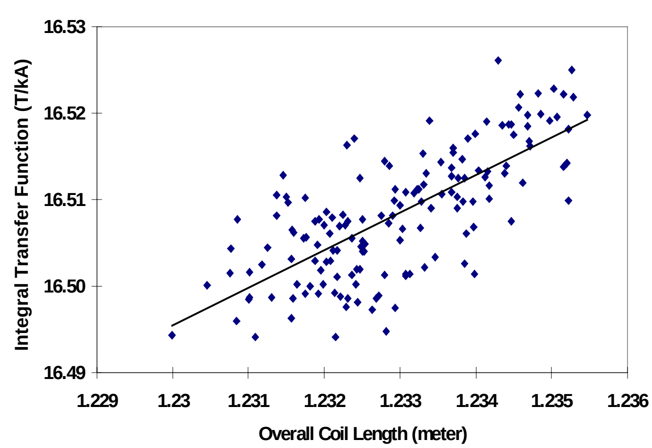

Figure 6: A correlation plot with a least square fit between the integral transfer function and the coil length in 80 mm aperture RHIC arc quadrupoles.

F. *RHIC Arc Dipole Curing Press Case*

In the middle of the production run of RHIC 80 mm aperture arc dipoles, a large axial variation in several field harmonics was observed in the body of a number of magnets. The harmonics which showed large variation were the odd normal and the even skew. By symmetry arguments, one can conclude that at certain places along the length, the left and the right coil do not have the same azimuthal size. By examining the harmonics carefully, the axial position, that was the source of this behavior, was located. The vendor was notified, who in turn reported overlapping curing shims in the press. This was corrected and the axial variation in the coil size (see Fig. 7), which had increased between approximate coil id numbers 320 to 370, returned to nominal values. The axial variations in harmonics also returned to their nominal values.

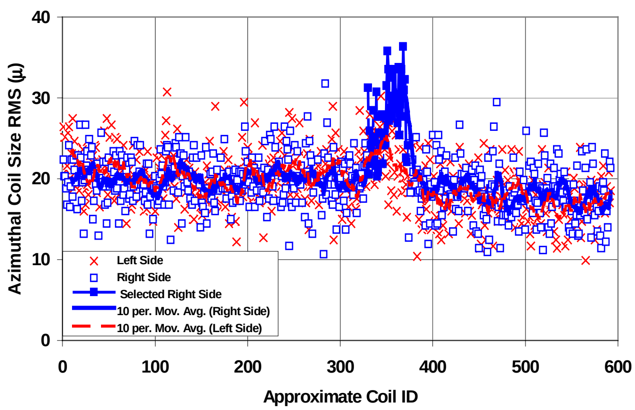

Figure 7: The standard deviation in the left and right azimuthal sizes (given in micron, μ) of the RHIC arc dipole coils.

G. *RHIC Arc Dipole Insulator Thickness Case*

In 80 mm aperture RHIC arc dipole magnets, the collaring load at which the yoke midplane closure takes place is monitored [3]. This is related to the azimuthal pre-stress on the coil and it depends on coil sizes, yoke inner diameter and the size of the RX630 phenolic spacer between coil and yoke.

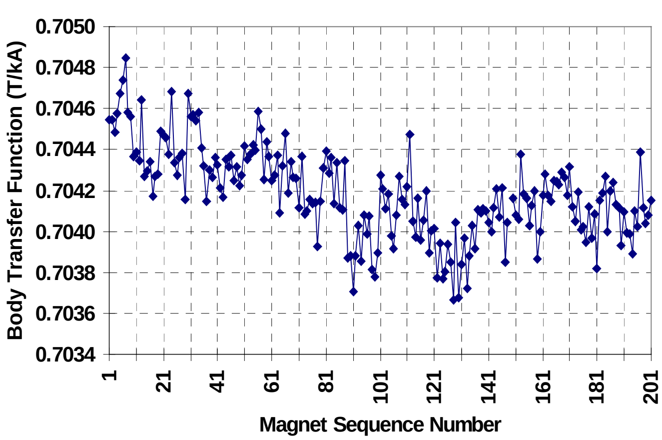

Figure 8: A trend plot of the transfer function in the body of the RHIC arc dipoles.

During the production after magnet sequence number 89, a low value of yoke midplane closure pressure was observed. Simultaneously, a lower value of transfer function in the magnet body was also observed (see Fig. 8). The two were correlated and determined to be caused by a change in RX630 insulator thickness, stemming from an unapproved change to the mold by the vendor's subcontractor. The mold was corrected and the problem was fixed starting with magnet number 137. Due to scheduling issues, parts from the existing inventory were used between magnet number 108 to 136 after inspection.

H. *Incorrect Tuning Shim Installation Case*

Eight tuning shims are used in 130 mm aperture RHIC insertion quadrupoles to remove eight selected harmonics after magnetic measurements [4]. The tuning shims are partly made of iron (magnetic) and partly of brass (non-magnetic). The magnetic design requires that the iron part of the shim be closer to the yoke inner surface. However, the mechanical design is such that the shims can also be inserted the wrong way, which would make the iron part of the shim further away. Here the magnetic measurements are used as a production tool to check the correct installation of these shims. An improperly installed shim would not only give wrong harmonics during warm measurements but would also have the wrong saturation behavior in the harmonics. One such case is given in Table III when a 25% iron-75% brass shim was installed in an incorrect orientation at a particular location. Table III lists the harmonics at a very low field (warm measurements). A large difference in harmonics means that it will be a reliable method. The method has been used effectively during the production to monitor proper installation of shims.

TABLE III
COMPUTED HARMONICS FROM A 25% IRON AND 75% BRASS TUNING SHIM WHEN IT IS INSTALLED IN A CORRECT AND IN AN INCORRECT ORIENTATION AT A PARTICULAR LOCATION.

	a_2	b_2	a_3	b_3	a_4	b_4
Correct	0.4	-2.7	-1.0	1.1	0.9	-0.3
Incorrect	4.7	-8.1	-5.6	2.7	3.7	0.5

I. *RHIC Arc Dipole Yoke Weight Case*

The RHIC arc dipoles have a systematic saturation of the skew quadrupole at high fields due to the asymmetrically placed cold mass in the cryostat. The actual saturation in a given magnet may differ from this systematic value based on the weight difference between the upper and lower yoke halves. These weights were recorded for all magnets and a good correlation was found between the yoke weight asymmetry and the skew quadrupole saturation [5]. In some magnets, the measured saturation behavior was inconsistent with the recorded yoke weights. An investigation by the vendor revealed that the scale used for recording the weights in these instances was out of calibration as a result of being struck accidentally. The scale was re-calibrated and the problem was corrected. This is an example where the problem would not have been detected without the cold measurements.

J. *RHIC Sextupole Yoke Heat Case*

The skew octupole term (a_3) in the sextupole magnets is an indicator of the top-bottom asymmetry. In the case of the

RHIC sextupoles, the mean value of a_3 is zero by design and the measured value for most magnets lies within ±2 units. Several magnets in the production, when measured warm, were found to have a_3 between 5 to 10 units, which is well outside the normal range (see Fig. 9). Nothing unusual was found in the geometric or electrical parameters of the coils in these magnets. Moreover, cold tests of some of these sextupoles revealed that the a_3 became quite small in the expected range of operation and practically disappeared at high fields. The large a_3 was later traced to the use of iron from two different heats for the upper and the lower yoke halves. The low field permeability value of the yoke in one particular heat was quite different from others. This explains the large measured value of a_3 harmonic only at very low fields. The sign of a_3 also correlated with whether the upper or the lower yoke half was from this heat. A value of 5 to 10 units is not of concern from the point of view of accelerator performance, however, the procedure shows the strength of the field quality as a technique to detect the deviations in the parts used in manufacturing magnets.

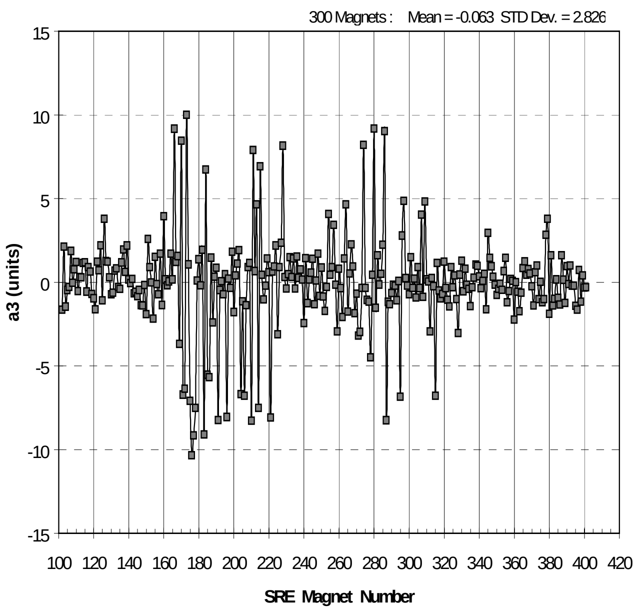

Figure 9: The measured skew octupole harmonic with the magnet sequence number in RHIC arc sextupoles.

III. CONCLUSIONS

Checks were instituted at BNL, its vendors, and their subcontractors to assure the quality of each magnet component and of the magnet as a whole. With the RHIC industrial dipole and quadrupole magnet production complete, all of these magnets delivered to Brookhaven (~800) were accepted and are suitable for machine use. However, either due to unauthorized work or faulty work, a few magnets were made outside the specifications. The field quality measurements and analysis part of the production testing revealed two magnets with flaws; these magnets were rejected before they left the factory.

The experience during the RHIC magnet program has shown the value of continuous monitoring of field quality not only for satisfying the machine requirements but also as a tool to monitor magnet production and to detect irregularities, if any. Given the enormity of the task, the number of instances has been rather small. The field quality measurements and analysis not only identified several of those cases in a timely manner but also isolated them to a particular part of the magnet. This helped remove the source and/or devise an appropriate course of action.

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