Lecture VIII

Field Quality as a Tool to Monitor Magnet Production

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Field Harmonics as a Diagnostic Tool (Field Harmonics -The MRI of Magnets)

Field Error Harmonics --- What do they represent?

➢ Harmonics are nothing but the reflection of magnetized geometry!

The internal magnet geometry cannot be measured mechanically after the construction, but:

- The current passing through the coil gives magnetic signals that reflect the details of the coil geometry.
- The equivalent signal of image current of the coil due to iron reflects the geometry of the yoke (at least of the yoke inner surface).
- The analysis of these signals (for example, Fourier analysis) can determine the deviations in the magnet geometry from the ideal design.

Thus the field harmonics will be used here as a diagnostic tool to determine the presence of a defect in the magnet, if any.

Mechanical Interpretation of Field Harmonics

Let us first consider the interpretation of harmonics measured warm:

- Magnet is not superconducting (no persistent current effcts)
- Field is low (no iron saturation effects)

In this case the field harmonics are the reflection of magnet geometry

In a typical magnet, most harmonics are less than a unit (10^{-4}) at 2/3 of coil radius.

1 unit in lower order harmonics generally reflects a ~25 micron error in parts or assembly.

Larger harmonics means large mechanical deviation from the nominal geometry.

If much larger error harmonics are observed, find out what out causing them.

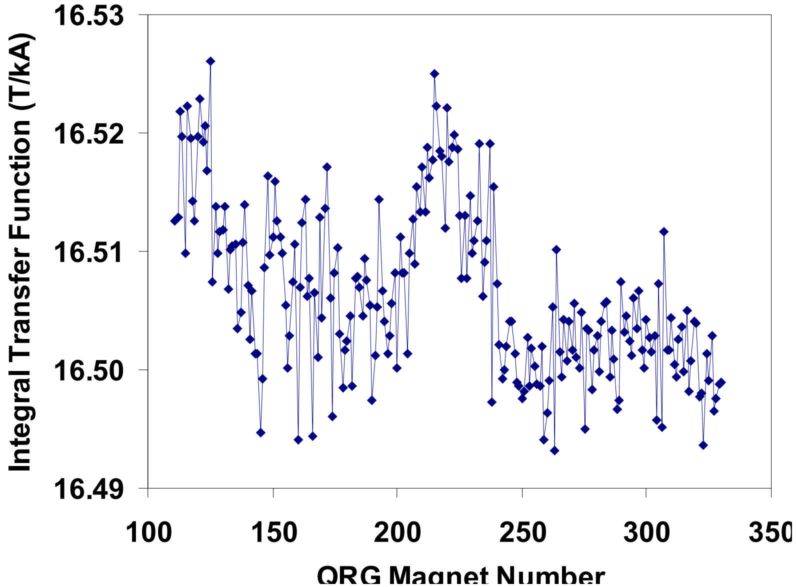
Remember, each harmonic reflects a particular symmetry (or a lack of it).

BNL/RHIC Experience

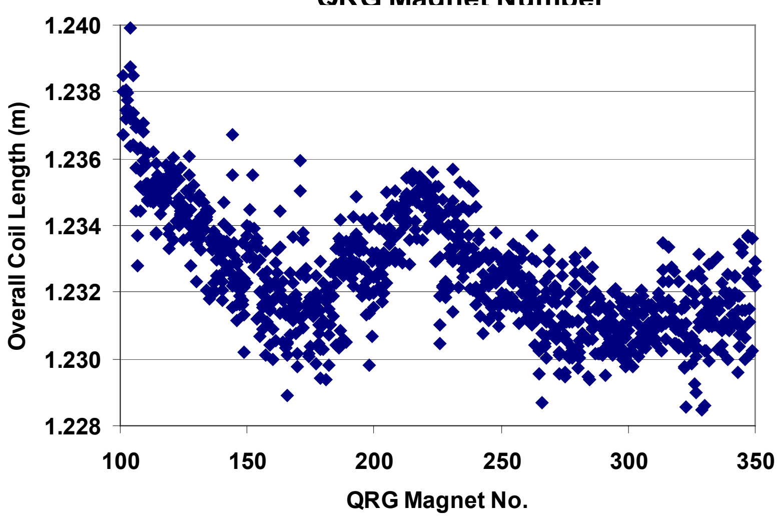
- RHIC uses a variety of superconducting magnets
- A large number of them were never tested cold before installation (cost considerations)
- This leaves a potentially vulnerable situation
- All magnets in entire ring were ramped to RHIC design energy and they all magnets made it (what a relief !)
- We did discover a few faulty magnets (some of them fatal), but obviously they were all discovered before sent to ring
- They were detected primarily by monitoring the warm harmonics

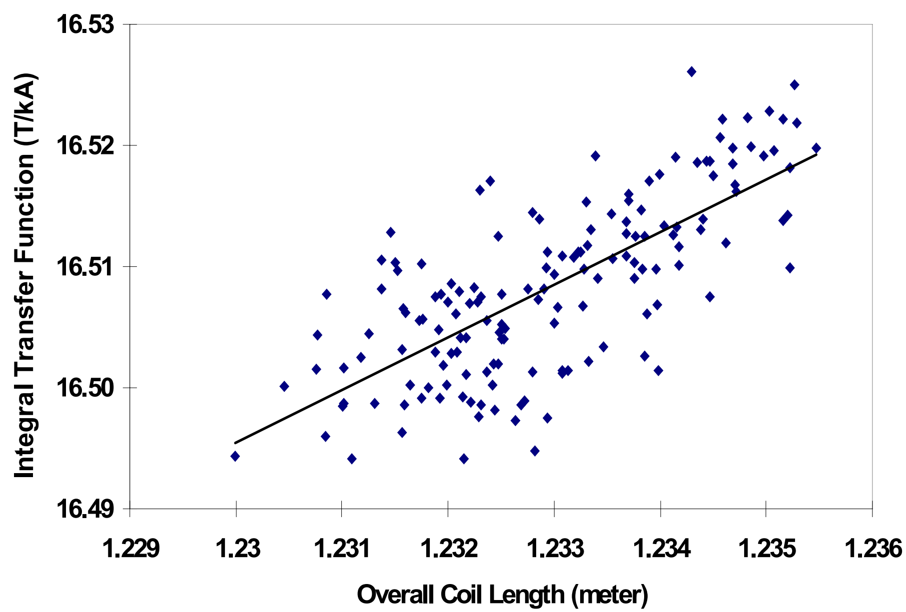
CERN is following a similar strategy and closely monitoring the warm harmonics in LHC magnets. They have also observed several interesting cases.

Integral Transfer Function and Coil Length in RHIC Quadrupoles



- During the course of RHIC quadrupole production, a pattern was observed in the integral transfer function of the magnet.
- All mechanical parameters of quadrupole (i.e. magnet components) were carefully examined.
- A correlation was observed between the integral transfer function and the overall coil length (essentially due to the variation in one end part).

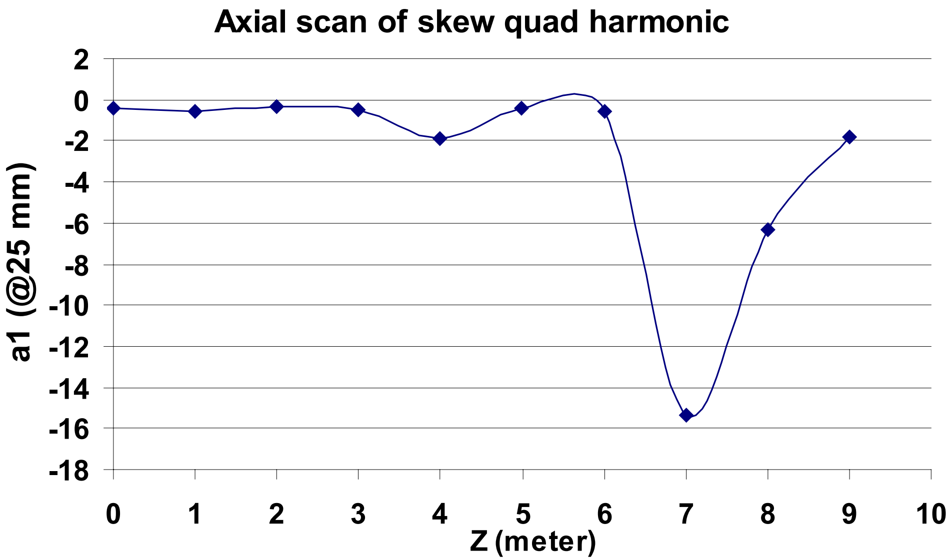


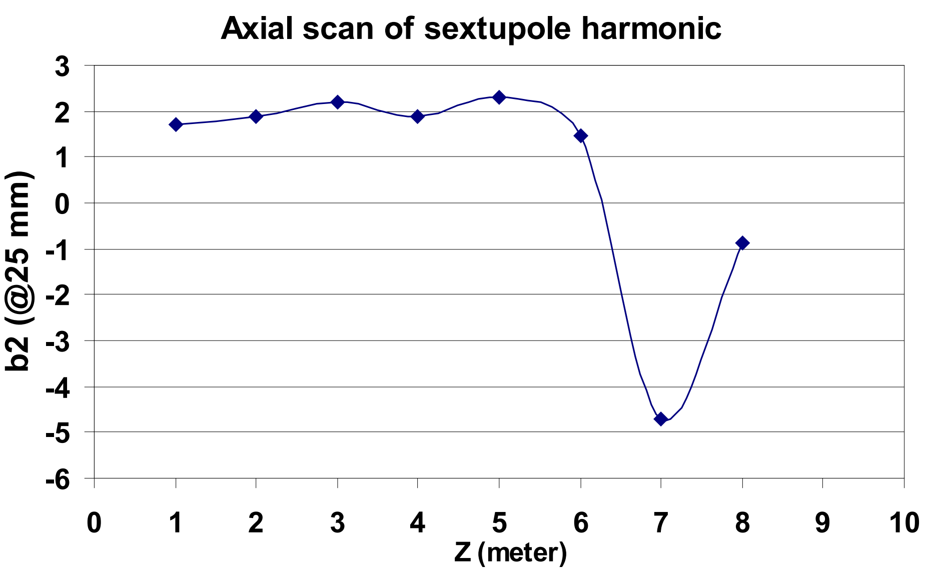


Unusual Harmonics in RHIC Arc Dipole DRG189 measured at Vendor

Warm magnetic measurements in 1 meter steps with a 1 meter long coil (harmonics measured at the manufacturer/vendor site).

- **An unusually large variation along the length observed (usually it was few units).**
- **Even though the overall integral field average error may have been acceptable from beam physics point of view, such large variation raised alarm about possible mechanical integrity or expected quench performance of the magnet.**
- **It is not sufficient to reject one magnet by telling the vendor that there was some large mechanical error.**
- **It is important to find out the source of that error (fault) to make sure that the error is not repeated again.**
- **This started an interesting and obviously challenging investigation.**





What Do the Field Harmonics in a Dipole Indicate?

If only B_o is present and no other harmonic is present:

It is a perfect dipole (but it's only a dream, in reality it never happens)

b_2, b_4, b_6 (even terms only):

Imperfect design

(and/or imperfect parts or tooling)

But a perfect dipole (4-fold) symmetry

b_1, b_3, b_5 (odd terms only):

Left-right symmetry is broken

a_1, a_2, a_3 , a_4, a_5 (skew terms only):

Top-bottom symmetry is broken

a_1, a_3, a_5 (odd skew terms only):

1^{st} quadrant is the same as 4^{th} quadrant

& 2^{nd} quadrant is the same as 3^{rd} quadrant

a_2, a_4, a_6 (even skew terms only):

1^{st} quadrant is same as the 3^{rd} quadrant

& 2^{nd} quadrant is the same as 4^{th} quadrant

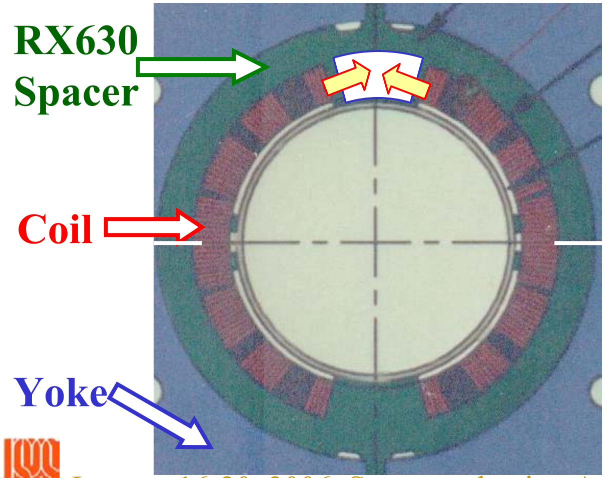
Detection of the Defect from the Analysis in RHIC Dipoles DRG189 and DRG226

Measured Harmonics in unit-m in 2 meter section

n	an	bn
1	-22	0
2	0	-10
3	2.7	0
4	0	1.3
5	-0.9	0
6	0	-0.45
7	0.3	0

These harmonics imply that the coil has moved towards the pole at the top half, because:

1. Large Odd an's => Large Top-Bottom Differences.
2. Odd bn's are zero => Left-Right Symmetry.
3. Even an's are zero => Difference between 1st and 3rd quadrant same as in 2nd and 4th.
4. Large Even bn's => Something is missing; (not just Displaced).
5. Sign and values of bn, an => The error is closer to the pole than the midplane.



COMPUTED MECHANICAL SIZE OF THE DEFECT :

Integral Size (Thickness X Length), side-to-side at the pole

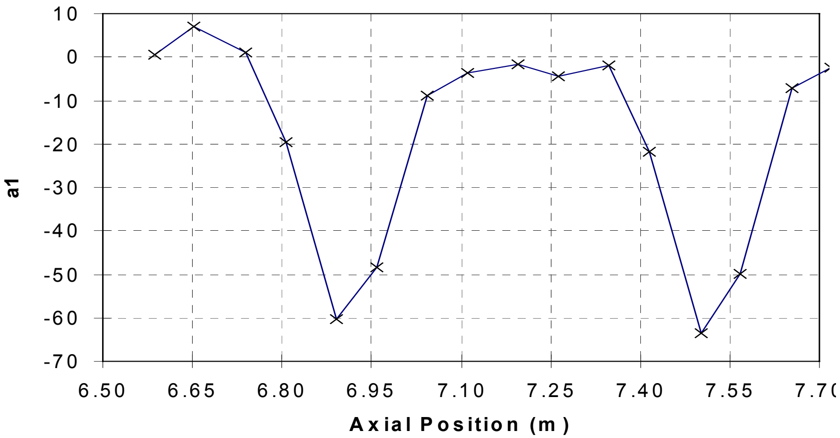
~0.8 Square Inch (Example : 2 places 0.067" X 6")

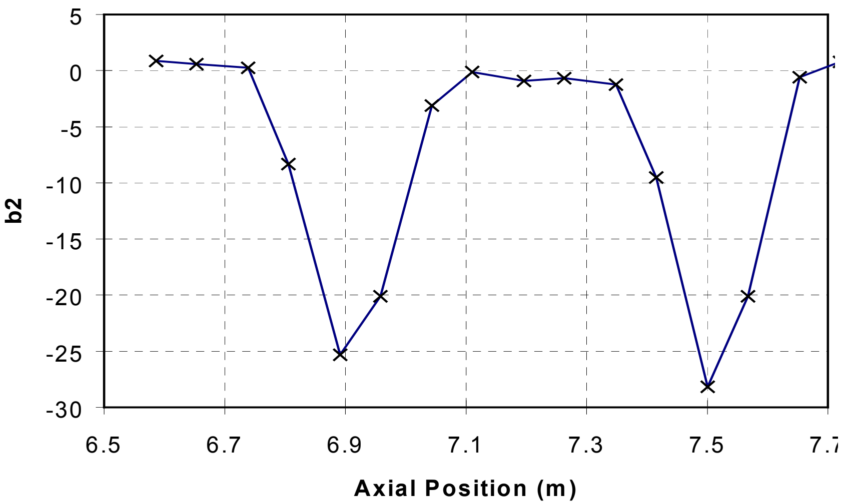
Z-scan in smaller step supports above.

Suspected Source : Possible use of "end spacers with no pole" instead of "body spacers with pole".

RHIC Arc Dipole - Measurement and Analysis of Defect at BNL

Warm measurements in 0.15 meter steps with a 1 meter long measuring coil





- **The symmetry and values of harmonics indicate that the upper coil is bigger than the lower coil by ~1.5 mm.**
- **Since uncompressed coils do not have such a difference in sizes, this must be due to coil not being properly compressed inside the magnet.**
- **This may be due to the use of end spacer (without pole) instead of straight section spacer (with pole).**
  - **There are Two Defects.**
  - **They are 0.6 meter apart (4 spacer length).**
  - **Size of each defect: ~0.15 m (length of spacer).**
  - **The location of these defects matches the location of the RX630 spacer (within few cm).**

A magnet with such large discontinuities in the coil (8 places, since each insulator gives 4 discontinuities) is expected to have a poor Quench Performance.

- **The theory was verified upon inspection.**

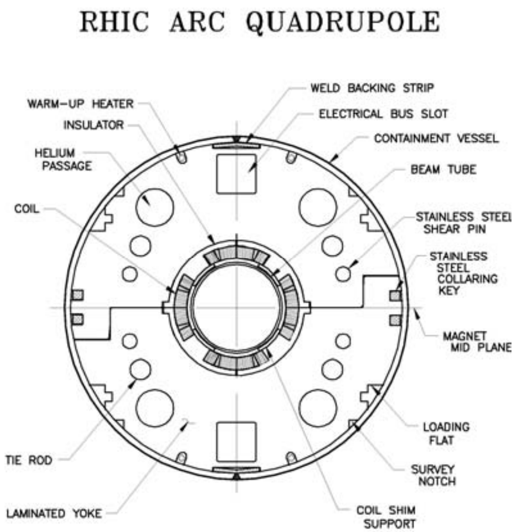
A major contribution to field that this tool can be so powerful !

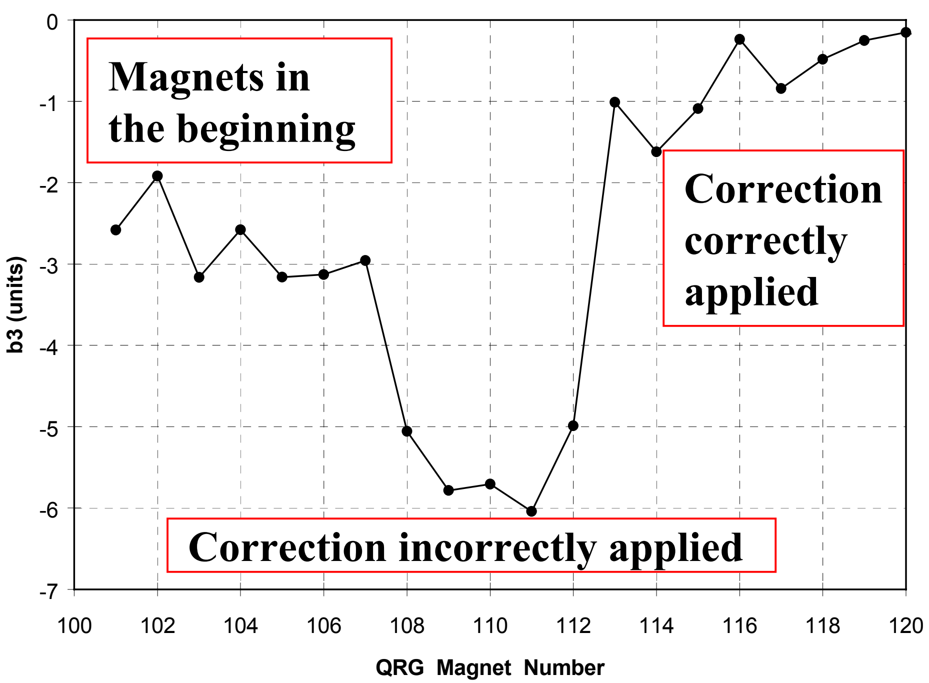
RHIC 80 mm Arc Quadrupole b_3 Adjustment During Production

Since RHIC quadrupoles are assembled like dipoles, therefore, have a large octupole ($b_3 \sim +7$ units)

Another deliberate asymmetry to cancel this term

Difference between the horizontal and vertical coil to midplane gap





- Initial design 0.1 mm gave too much correction
- Vendor was asked to decrease by 0.025 mm
- Vendor, instead, increased by the said amount
- Caught by harmonic measurements
- Vendor notified
- Problem fixed, desired harmonics obtained.

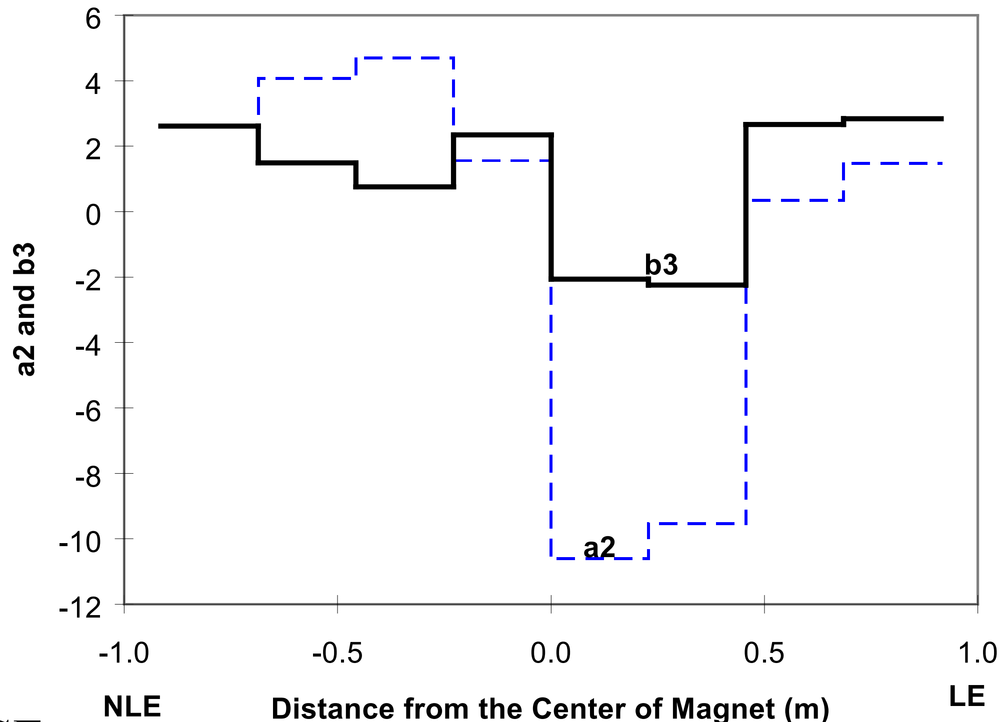
RHIC Insertion Quadrupole Missing Shim Case

RHIC insertion quadrupole magnet QRJ105 was found to have a large difference in harmonics between the lead and non-lead end halves.

The harmonics were measured in 0.225 m steps.

The coldmass, when dissembled, was found to have a broken shim in the suspected area (0.45 m).

Field Measurements in RHIC 130 mm Aperture Quadrupole QRJ105

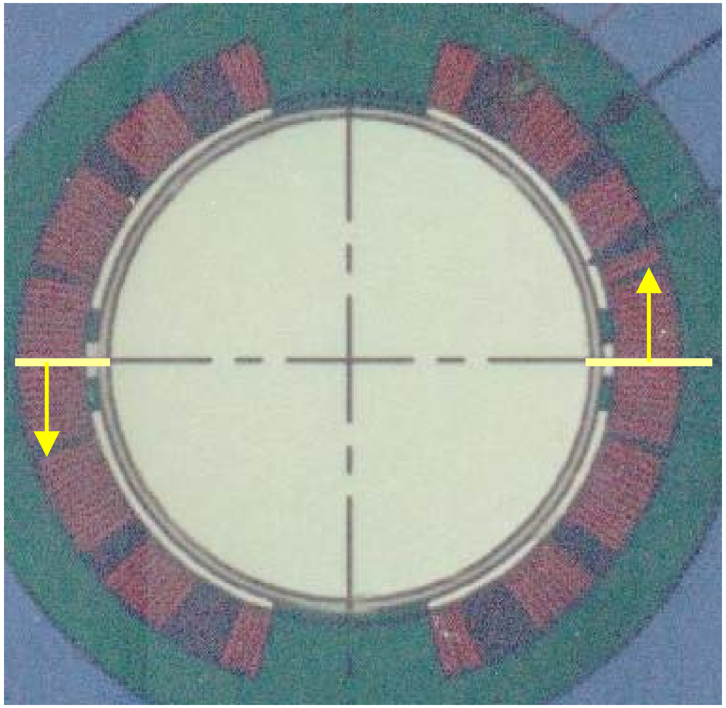


MEASURED AND COMPUTED CHANGE

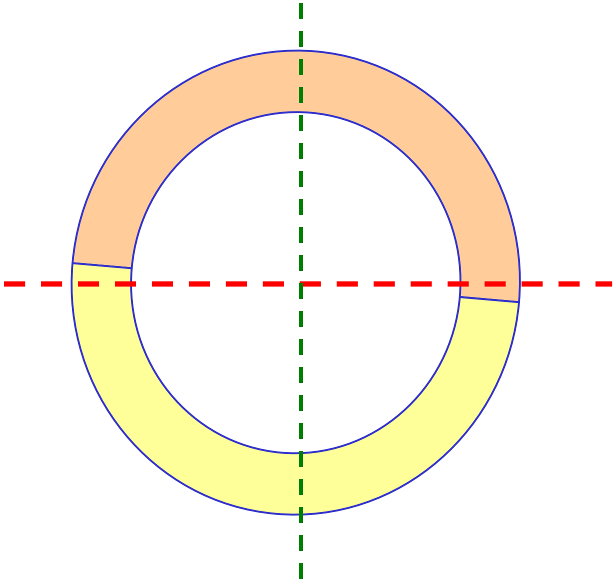
	a2	b3	a4	b5	a6	b7
Measured	-11.0	-4.5	3.0	1.3	-0.5	-0.35
Computed	-11.3	-5.8	2.5	1.2	-0.6	-0.4

Field Errors Due To Left-Right Size Differences Within A Coil

The coils are assembled in the magnet such that the right and left sides are flipped. Therefore the left-right size difference will create the following in the magnet:



Coil-to-coil midplane gap (1 in dipole)

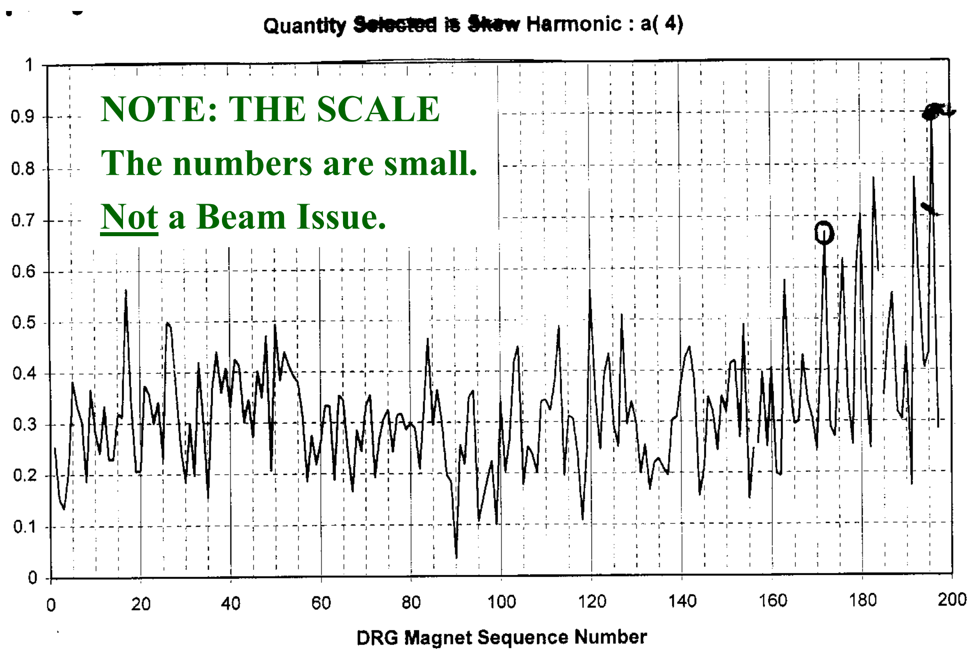


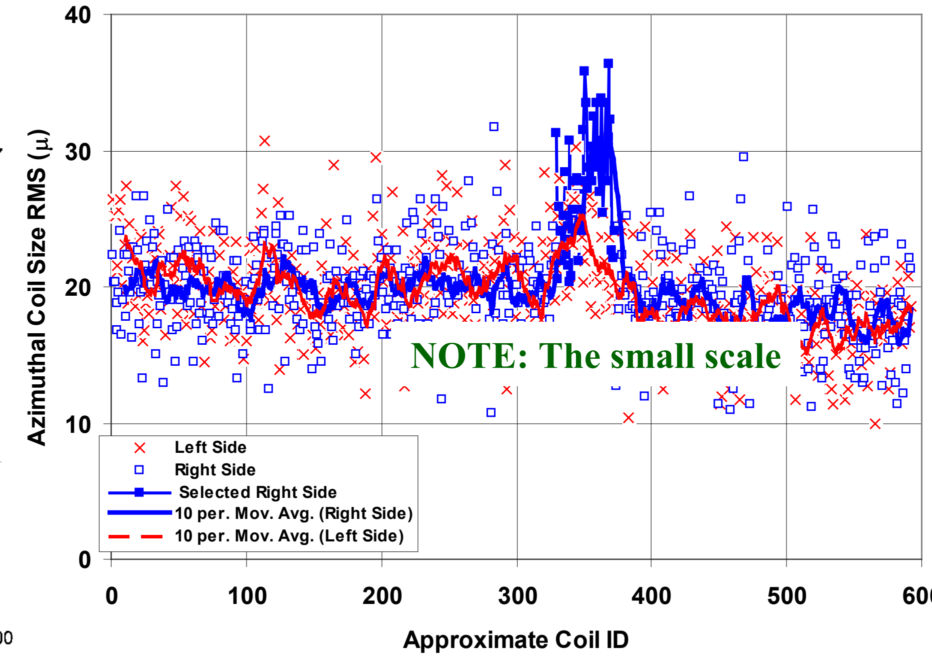
Class Assignment

In a dipole magnet, what harmonics will be created if all coils are made so that one side is consistently bigger than the other side?

Large Axial Variation in Skew Sextupole and Skew Decapole Harmonic

During RHIC main dipole productions, the axial variation of harmonics a_2 and a_4 became relatively large.





An investigation, led by field error analysis, found a change in coil size in a small section was caused by small amount of dirt (a few mil) in the curing press. ***Curing press cleaned, problem solved*** **!**

Theoretical argument and above observations indicate that careful control of coil manufacturing is critical for the reduction in RMS field errors.

RECAP: Field Harmonics and RHIC Magnet Production

• **Warm (room temperature) magnetic measurements were performed in all RHIC magnets.**

• **Field harmonic in magnets must meet the machine acceptance criterion (individual, systematic, random).**

• **If the field harmonics are significantly outside the normal production range, more investigation followed, even if it met the machine acceptance criterion.**

In several cases these investigations resulted in finding the source of these deviations and stopped the faulty magnets going in the machine.

SUMMARY

- **Field quality is a powerful tool to monitor magnet production.**

- **Field harmonics must be monitored continuously, not only for acceptance of magnets in the machine, but also to understand the sources causing the deviations from their nominal values.**

- **Field quality monitoring is an essential but not a sufficient tool to monitor magnet production. RHIC magnet program had a number of Q/A checks instituted at BNL, at vendors and at their subcontractors. A good database and establishing a correlation are essential for a timely response.**