Field Quality as a Tool to Monitor Magnet Production

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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 potential vunerable situation

Recently all magnets in entire ring were ramped to RHIC design energy

All magnets made it (what a relief)

But we did find several flaws, some of them fatal

They were detected by monitoring field quality

Lorentz forces in ssc

Reference: MT 15 Paper

Field Quality Analysis as a Tool to Monitor Magnet Production*

R. Gupta[1], M. Anerella, J. Cozzolino, D. Fisher, A. Ghosh, A. Jain, W. Sampson, J. Schmalzle, P. Thompson, P. Wanderer, E. Willen
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Why field Quality is important?

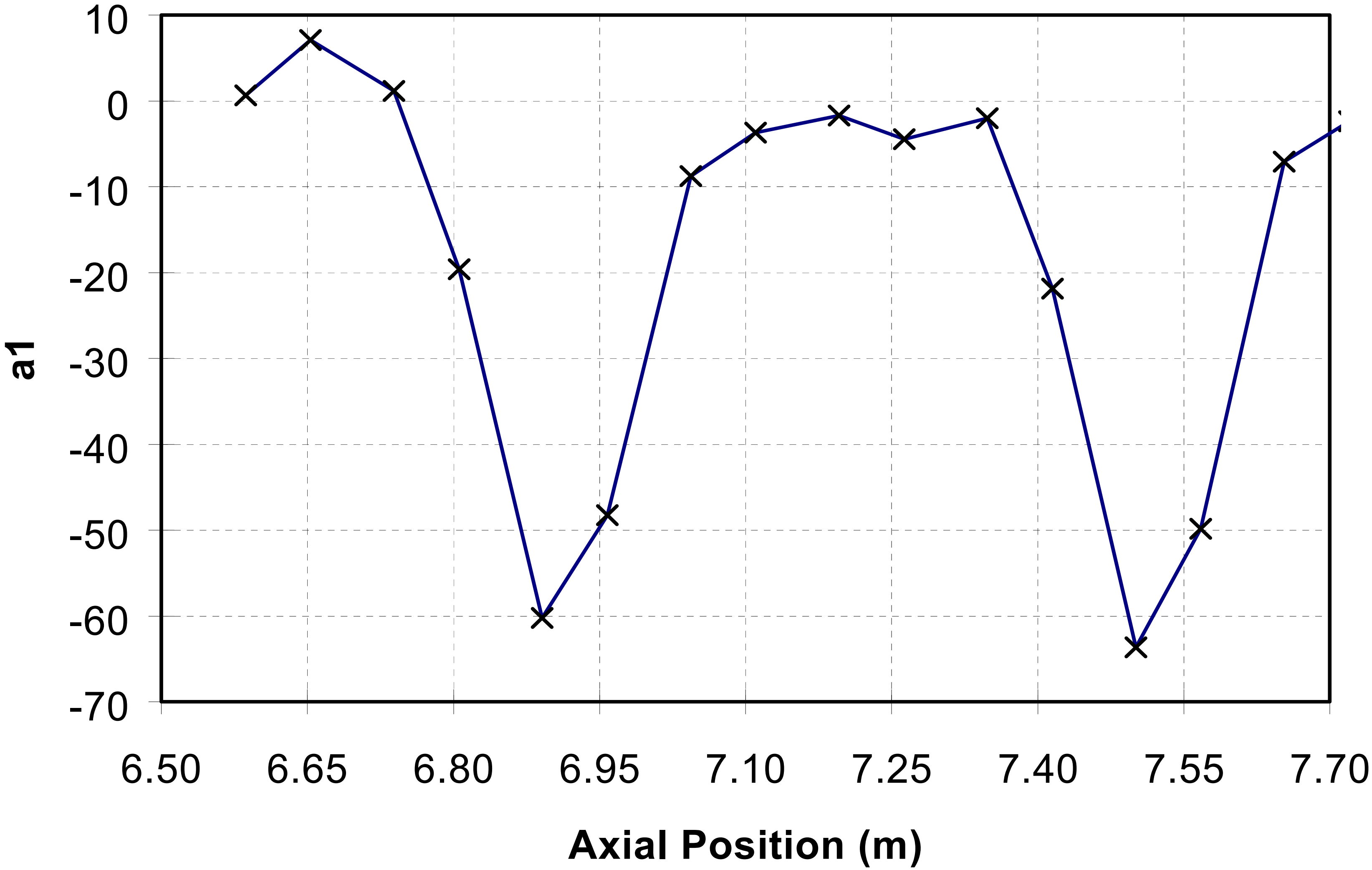
- Influences the performance and cost of the machine
  - At injection: **Main dipoles - large number** - impact performance, magnet aperture and hence the machine cost.
  - At storage: **Insertion quadrupoles - small number** - determine luminosity performance.
  - Corrector magnets + associated system - ease of operation and overall machine cost.
  - Tolerances in parts and manufacturing - translates in to cost.

A proper understanding is important for reducing cost while assuring field quality:

1. Conventional Wisdom: Reduction in random errors is due to smaller variation in cable thickness
   - NOT so. Will be shown based on the theoretical arguments & experimental data.
2. Conventional Wisdom: Need 1 mil (25 micron) tolerances at most places
   - Experimental Results and Analysis: NOT so. Such realization may reduce tolerance specifications of certain parts - cost savings while maintaining a good field quality.

- A bonus from field quality (used extensively during RHIC magnet production)
  - Field Quality as a tool to monitor production. Powerful, rapid feedback to manufacturer.

RHIC Arc Dipole Missing Pole Section in Spacer Case



RHIC Arc Dipole Missing Pole Section in Spacer Case

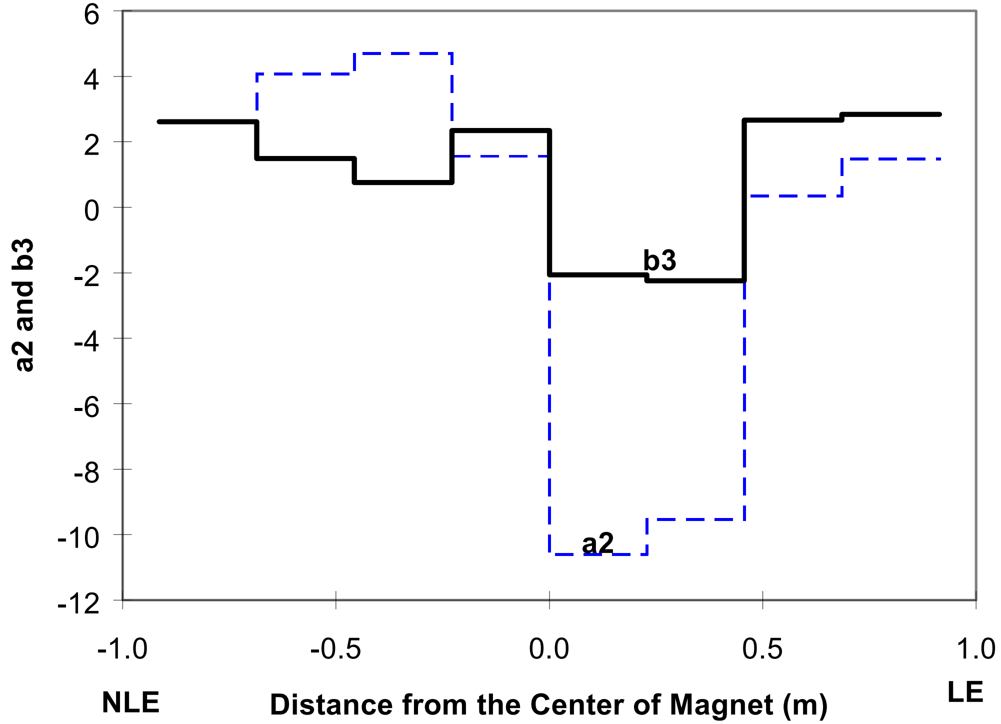
INTEGRATED DEVIATIONS IN HARMONICS IN TWO METER LONG SECTION IN THE SUSPECTED REGION OF RHIC ARC DIPOLE MAGNET DRG189.

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

RHIC Insertion Quadrupole Missing Shim Case

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



Results from Present Day Magnets (Real Magnets)
What has a major impact on random field errors? Is it cable thickness or some thing else?

Note: NO computer calculations and direct experimental correlation has shown that cable thickness is the major cause of reduction in random field errors in modern magnets.

It is just a common perception, NO proof!

How to disprove something that is not proved.

Scientific Method

Make a large amount of "bad cable" and make many magnets (for statistics). Compare results with similar magnets made with good cable.

Interesting, scientific but not practical.

Alternate Method:

Examine measurements. Find correlation. Determine what has the pre-dominant effect.

Is it cable thickness or some thing else?

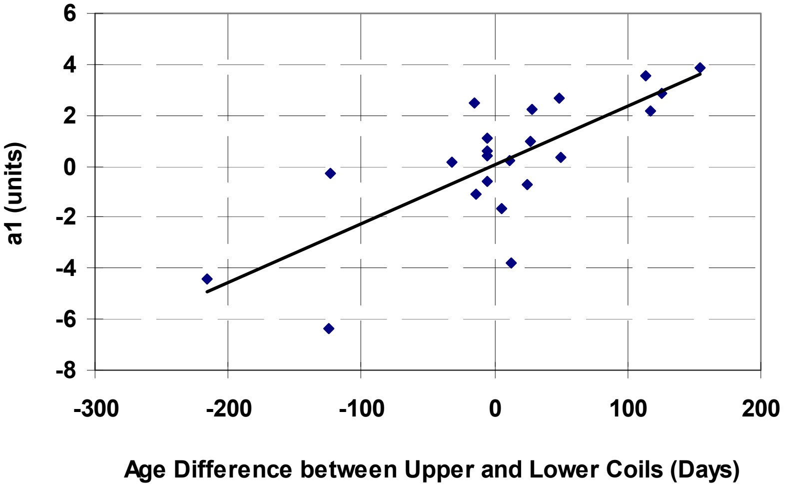
Example 1:

Compare RHIC 80 mm and 100 mm aperture dipoles. Both used same cable and similar designs.

Conventional Wisdom: Smaller random errors in 100 mm.

Reality: NOT so. Bigger in larger aperture dipoles. Why?

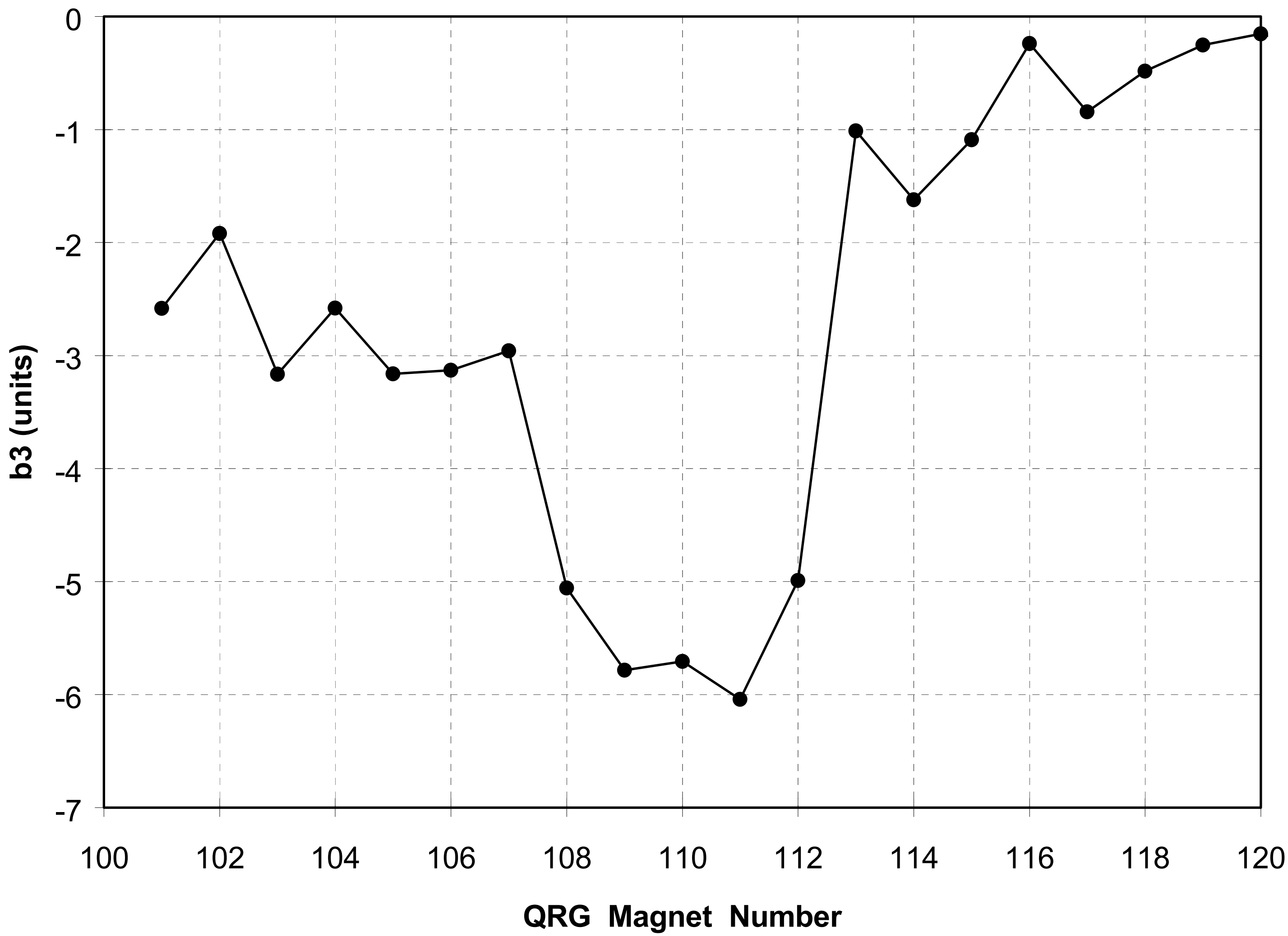
Results of investigations: The coils were matched based on the size measured when made/cured. Coils grew in time. Correlation found.



Overall control on coil rather than just cable thickness is more important.

Kapton insulation plays a major role in assuring a uniform coil production.

RHIC Arc Quadrupole with Wrong Shim Adjustment Case



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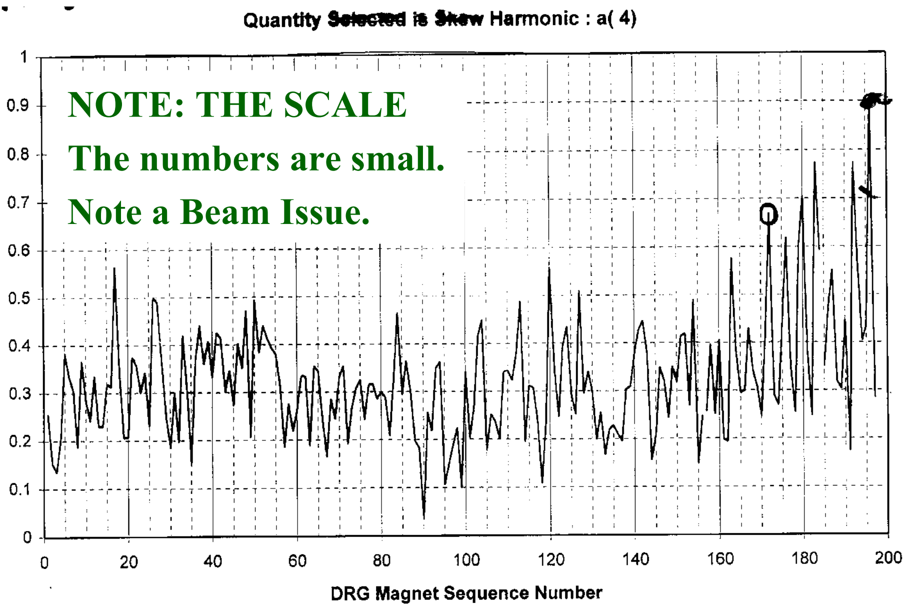
Superconducting Magnet Division

Results from Present Day Magnets (Real Magnets)
What has a major impact on random field errors? Is it cable thickness or some thing else?

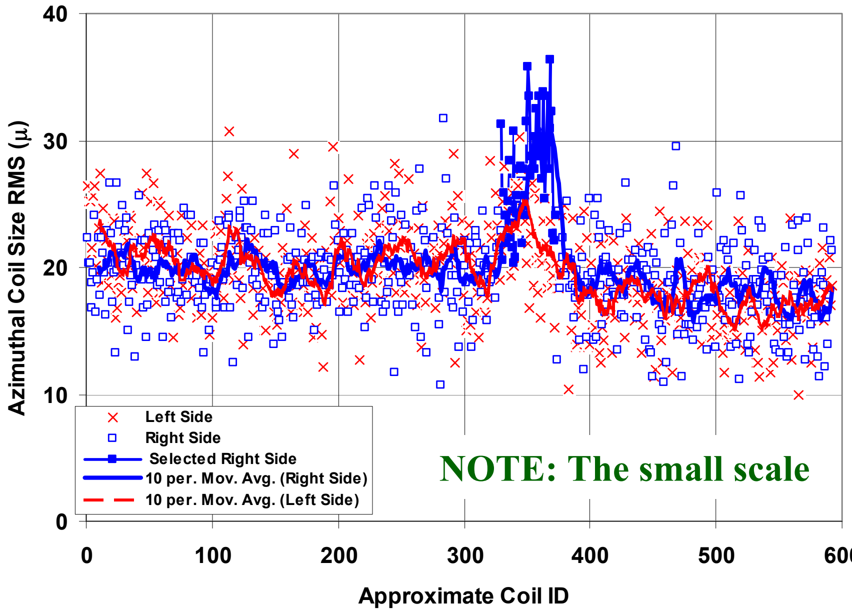
Example 2:

During RHIC main dipole productions, the axial variation of harmonic became relatively large.



An investigation, led by field error analysis, found a change in coil size in a small section was caused by a small dirt (a few mil) in curing press.

Curing press cleaned, problem solved.

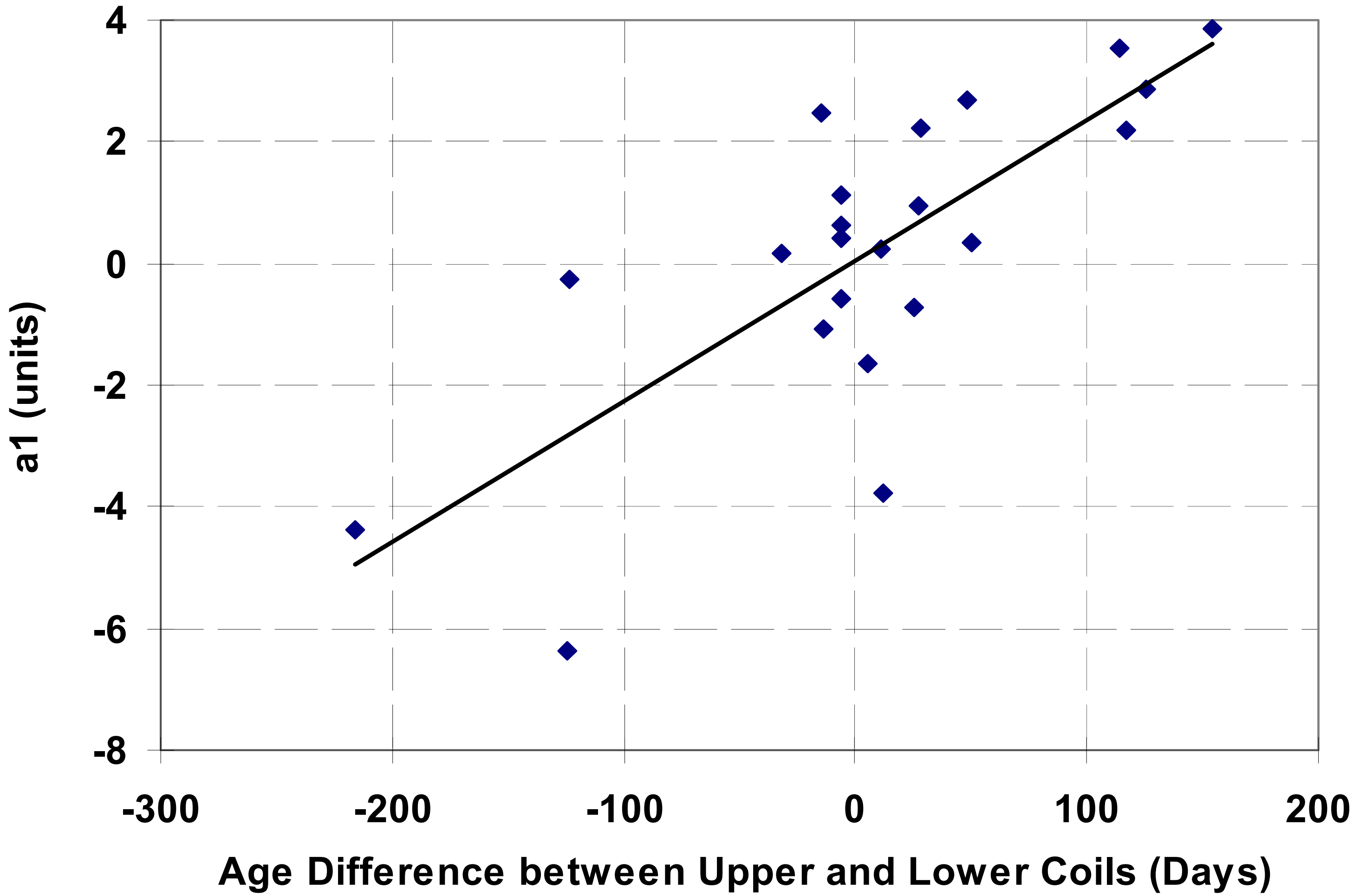


Cable thickness didn't change but the cured coil size changed and harmonics changed due to small human error which are always possible. Stay Vigilant.

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

A SIDE NOTE: The power of "Harmonic Analysis" in monitoring magnet production.

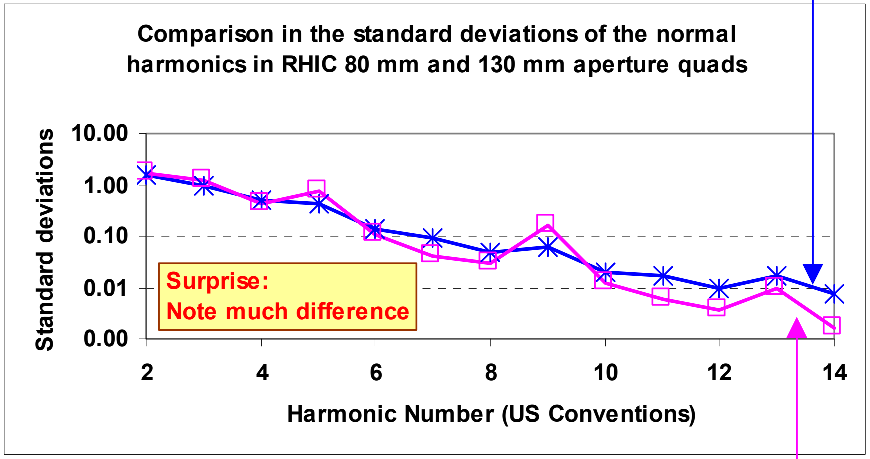
RHIC Insertion Dipole Coil Fabrication Date Case

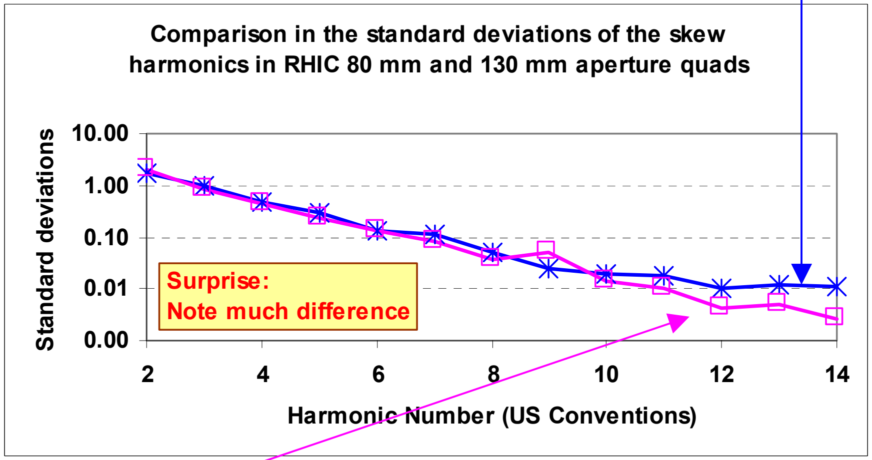


Conventional Wisdom: Increasing Aperture Reduces Standard Deviation at 2/3 of the Coil Radius.

Warm Harmonic Measurements in 2 types (apertures) of RHIC Quadrupoles:

80 mm aperture ARC Quads (25 mm reference radius)



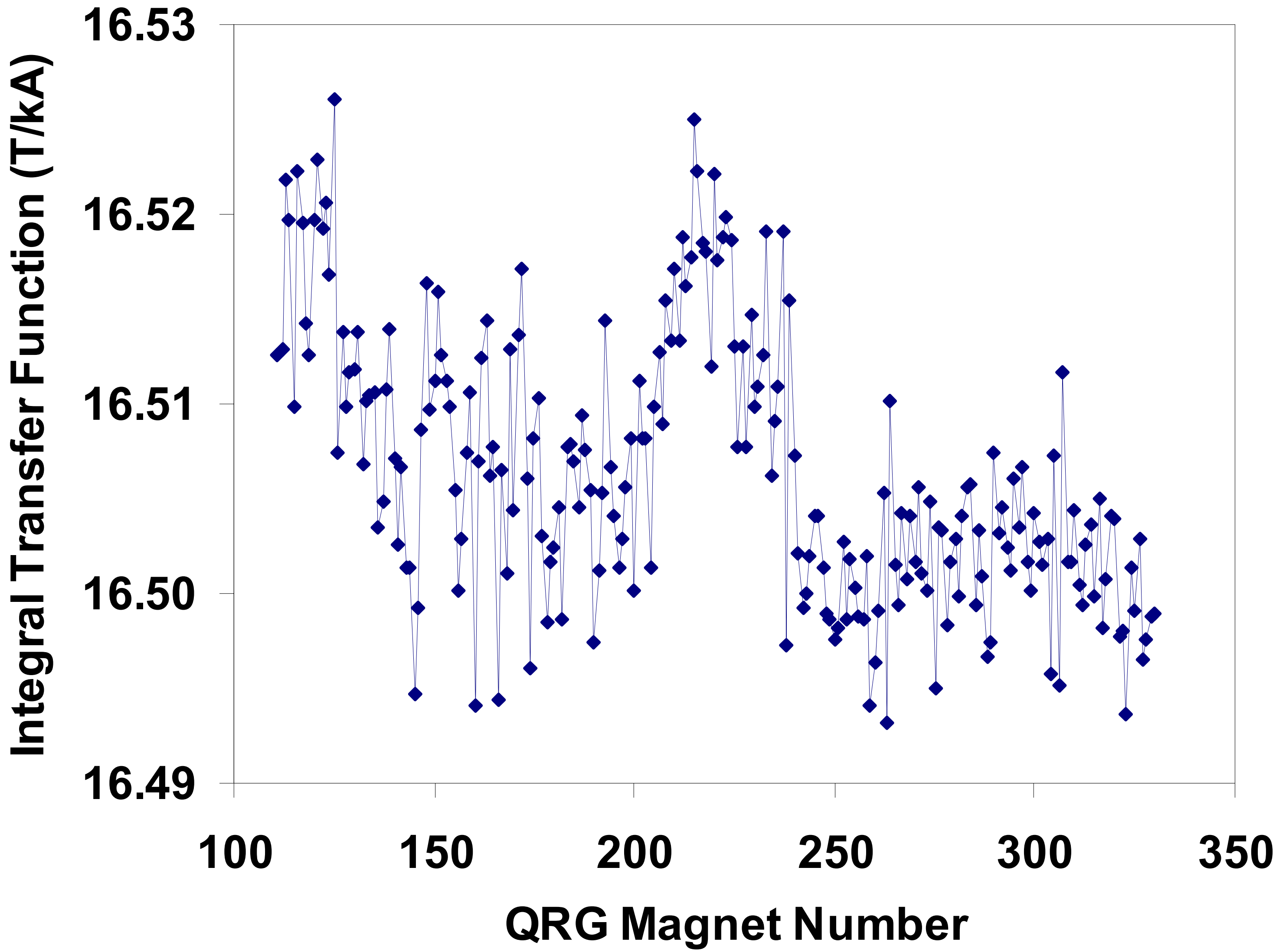


Normal Harmonics

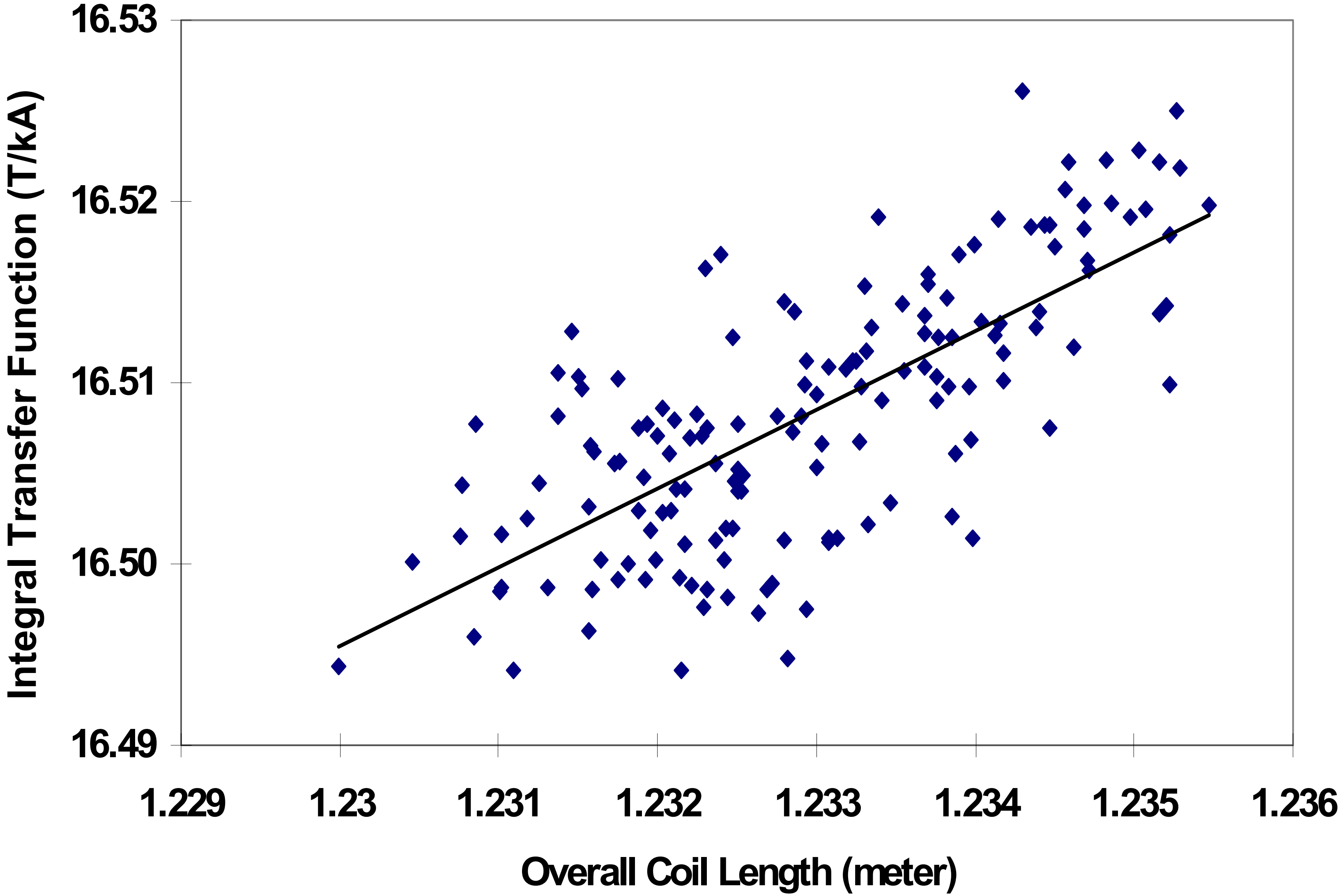
Skew Harmonics

130 mm aperture IR Quads (40 mm reference radius)

RHIC Arc Quadrupole Coil Length Variation Case



RHIC Arc Quadrupole Coil Length Variation Case



Influence of magnet components on field errors (From: R. Gupta, LHC Collective Effects Workshop, Montreux, 1995. Published in Particle Accelerators)

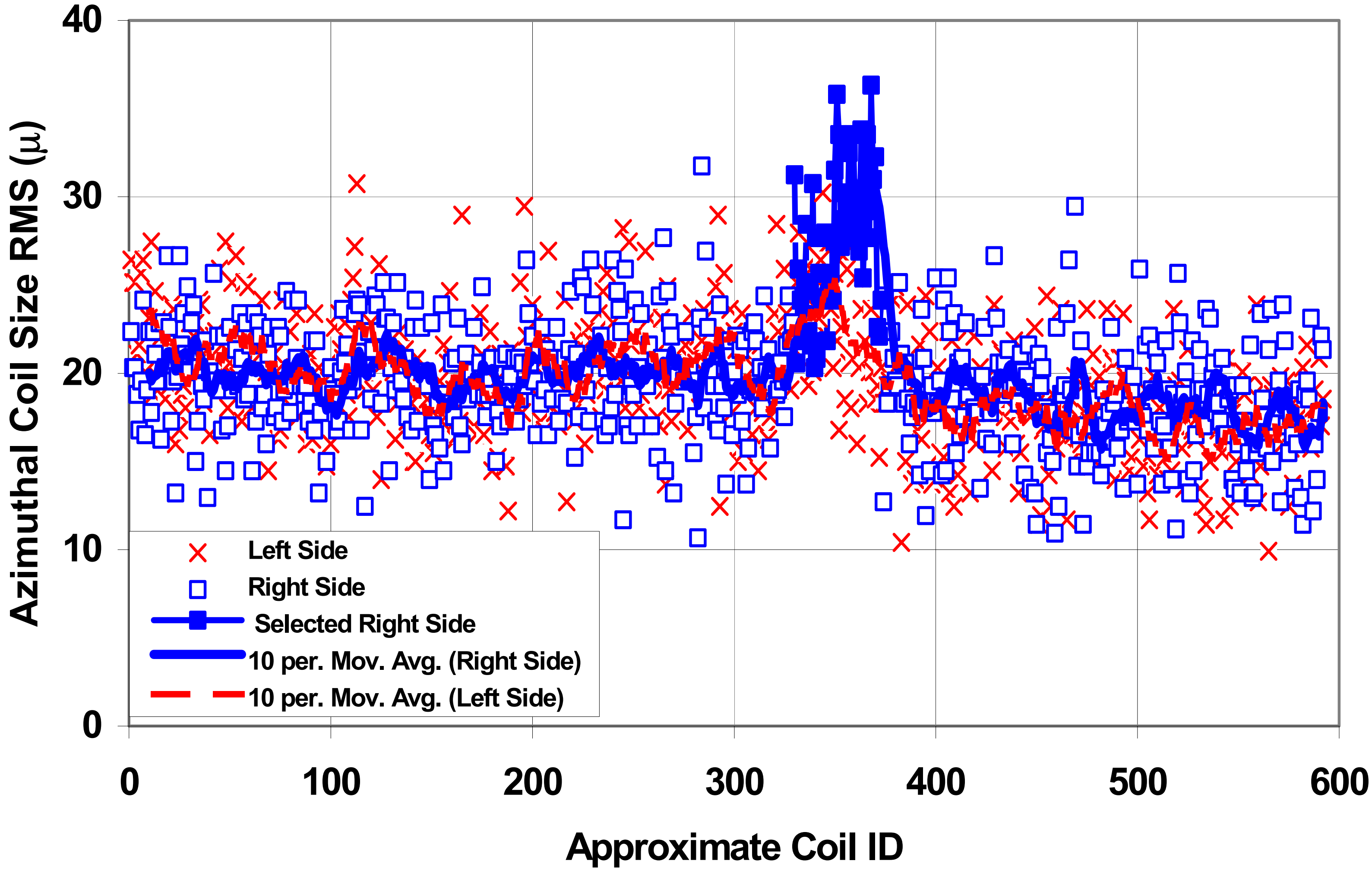
Cable and Insulation size have a major impact on coil size and hence pre-stress on the coil in the magnet. They don't influence odd b_n's and even a_n's and the influence on odd a_n's can be made negligible if the azimuthal coil size between the upper and lower halves is matched to $25\mu m$. Unless the variation in cable or insulation thickness is so large that the change in pre-stress on the coil is unacceptable, the influence on even b_n's is also negligible.

Other Components primarily influence only the allowed harmonics as long as a large quantity of them is used in the magnet. Non-allowed harmonics may be generated if the quantity is small or the mechanical design prevents randomizing in a 4-fold dipole symmetry.

Coil Curing Tooling generates only skew harmonics because of the way coils are installed in a dipole magnet. A difference between left and right side of the coil size or curing conditions generates even a_n's and an average variation generates odd a_n's. The influence of the coil curing press on harmonics may be significant (both on RMS and systematic) if it is not stable or uniform.

Coil Collaring Tooling creates primarily odd b_n's in a horizontally split design and odd a_n's in a vertically split design. A significant variation in the collaring process may also create even b_n's. In a reasonably well constructed collaring press, it should have only a small impact on harmonics.

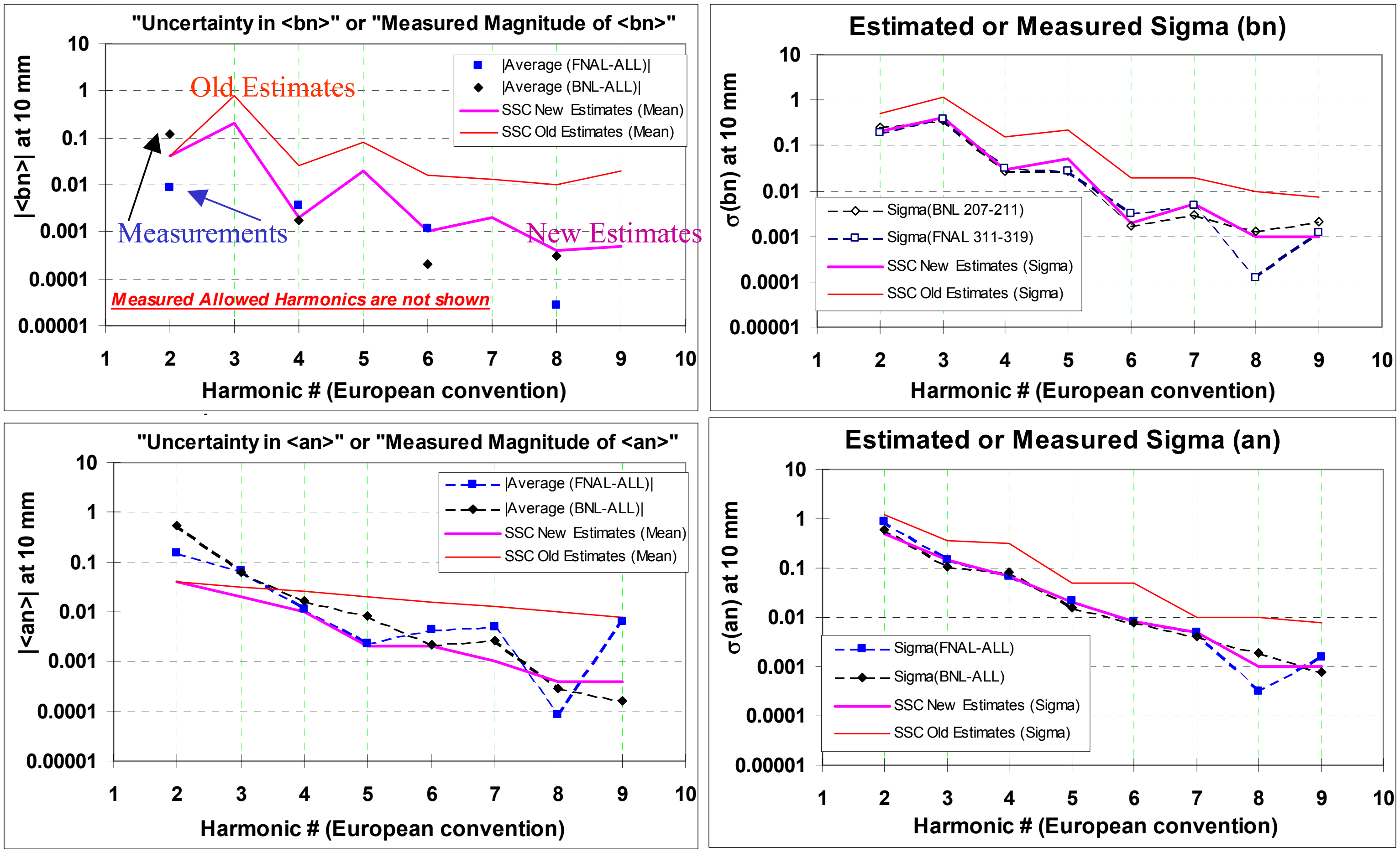
RHIC Arc Dipole Curing Press Case



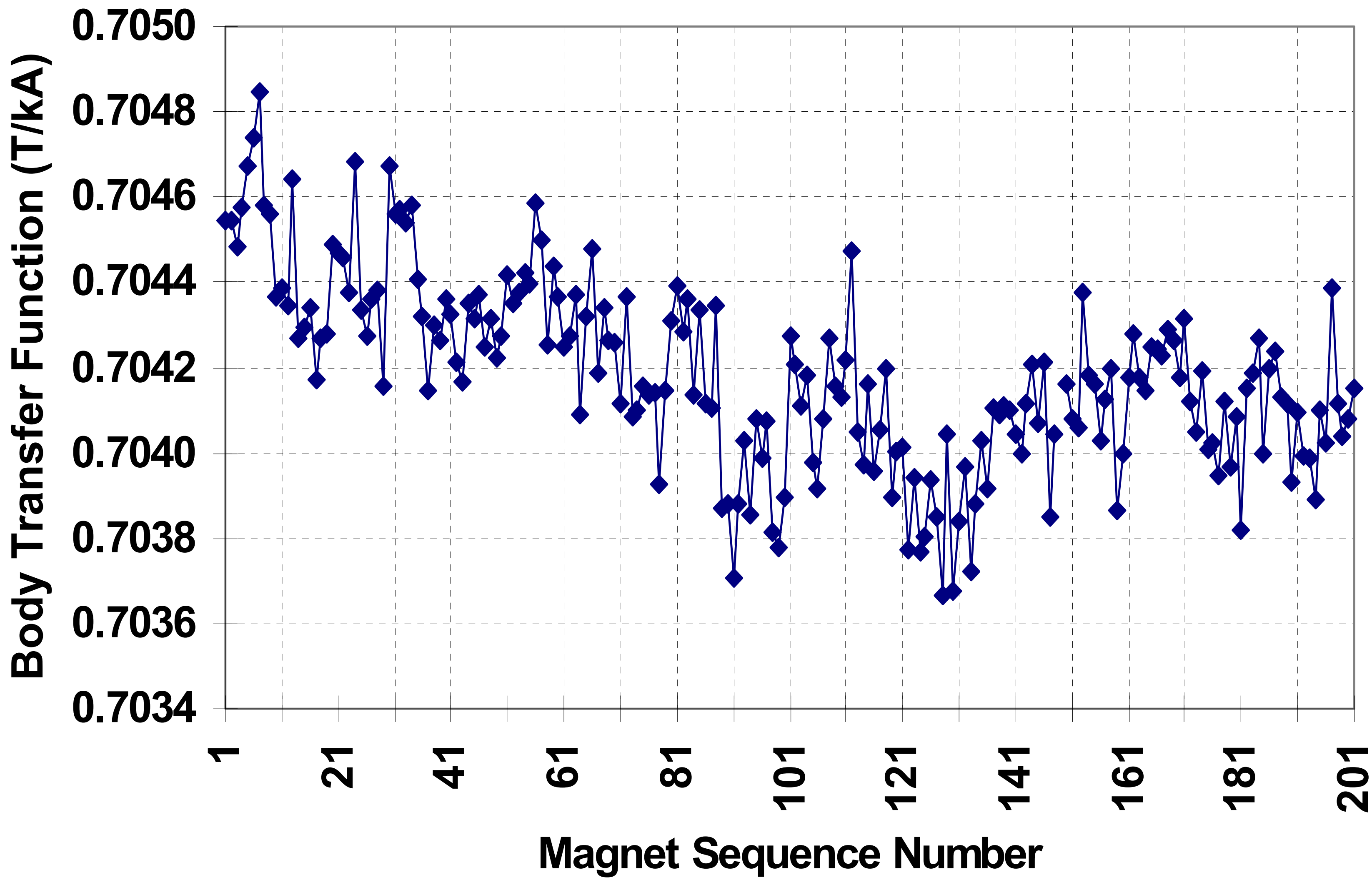
Field Quality in SSC Magnets (Lab built prototype dipoles)

Note:
A general improvement by a factor of 3-10.

Expected and Measured Harmonics at 2 T in BNL-built and FNAL-built SSC 50 mm Aperture Dipoles

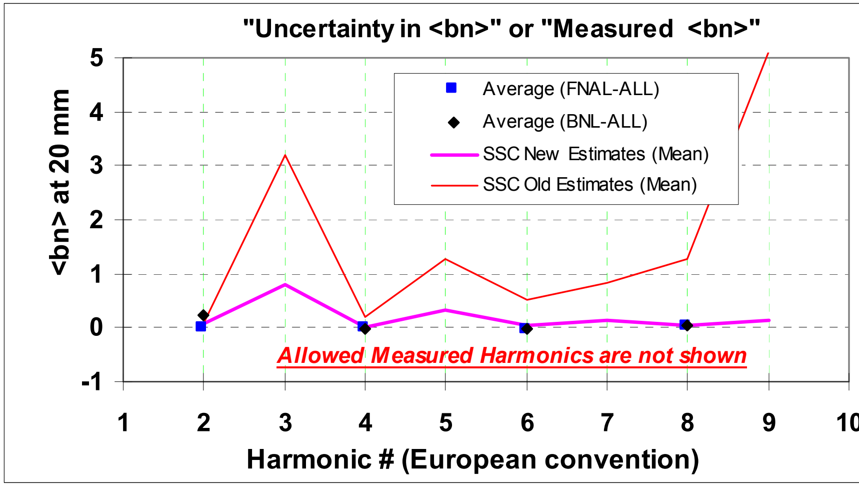


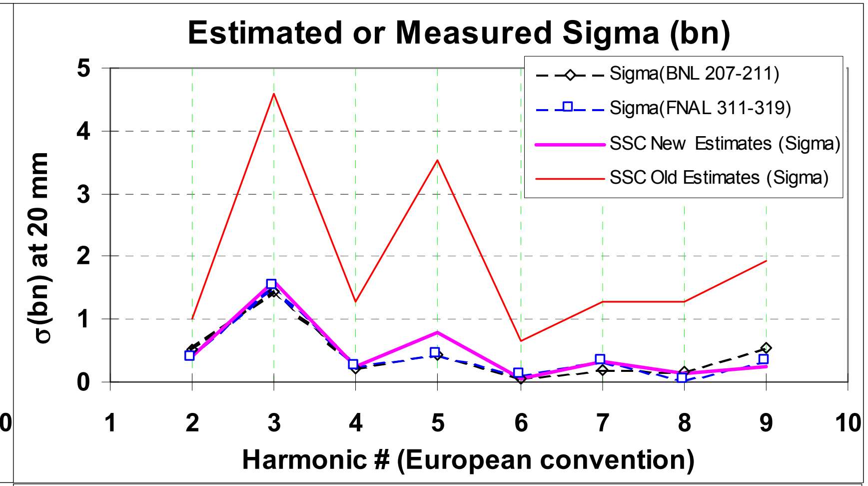
RHIC Arc Dipole Insulator Thickness Case

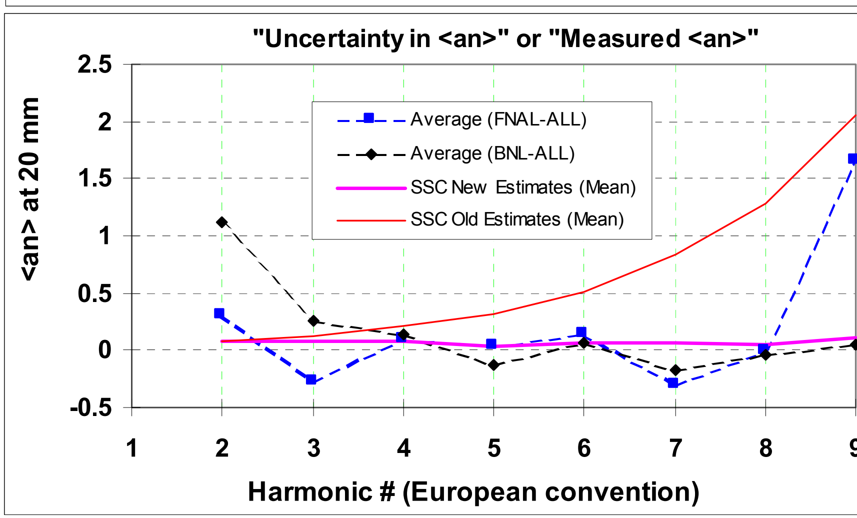


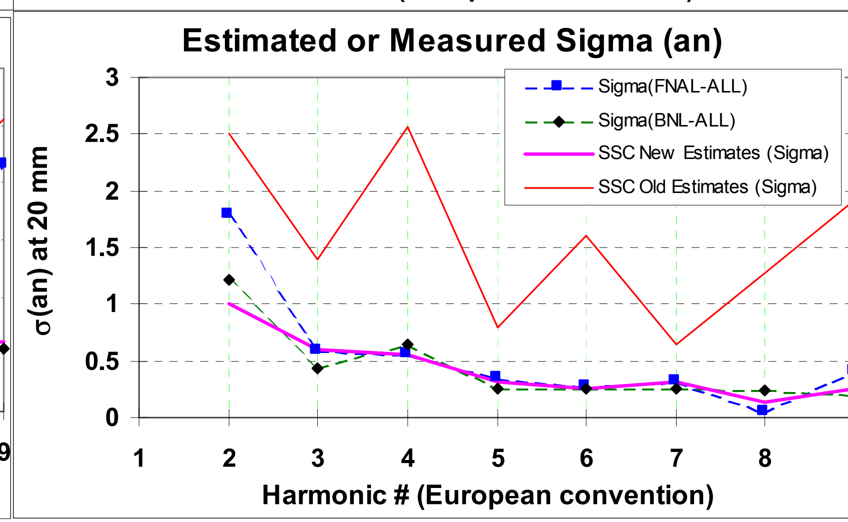
Field Errors in SSC dipoles
How off we were from reality?

Expected and Measured Harmonics at 2 T in SSC Dipoles (previously shown in LOG scale at 10 mm)







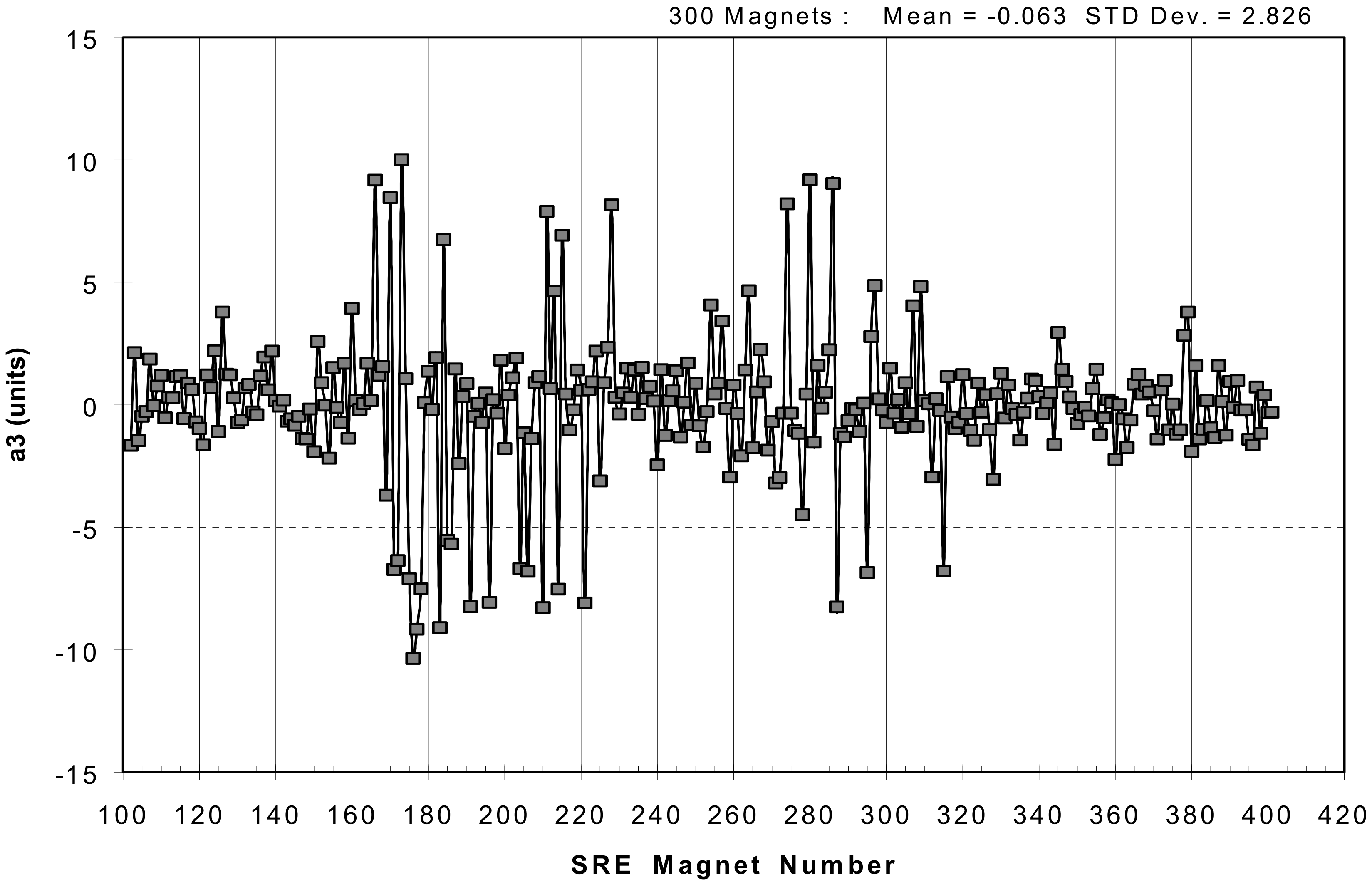


Incorrect Tuning Shim Installation Case

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

RHIC Sextupole Yoke Heat Case

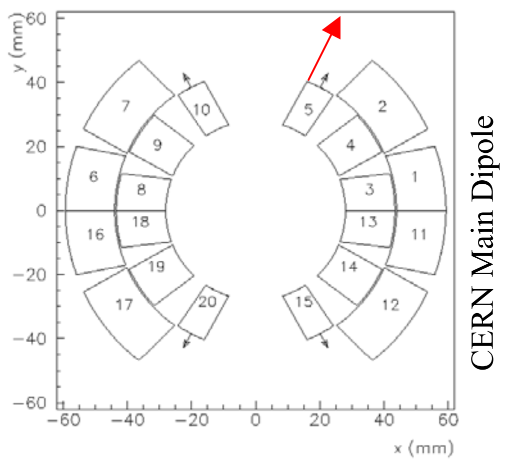


Why were we so wrong in estimating field errors in SSC dipoles?

Popular Models

Ignore the source of error and displace various conductor blocks at random by 25-50 micron Assumption: it simulates the error in parts and construction on field harmonics.

Add the resultant field errors in an RMS way.



Movement in popular models: one red arrow

Symmetric model: 4 black arrows

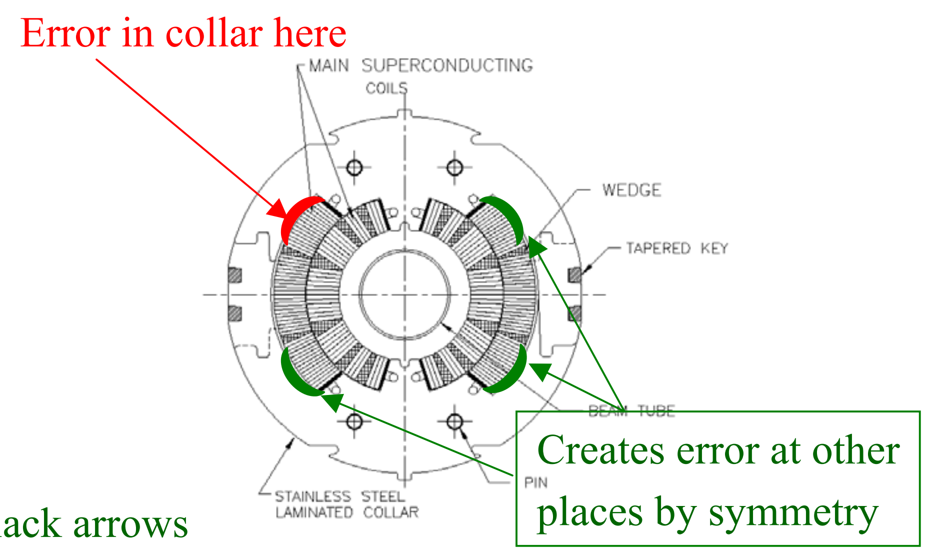
Realistic model: some thing in between but closer to black arrows

A More Realistic Model

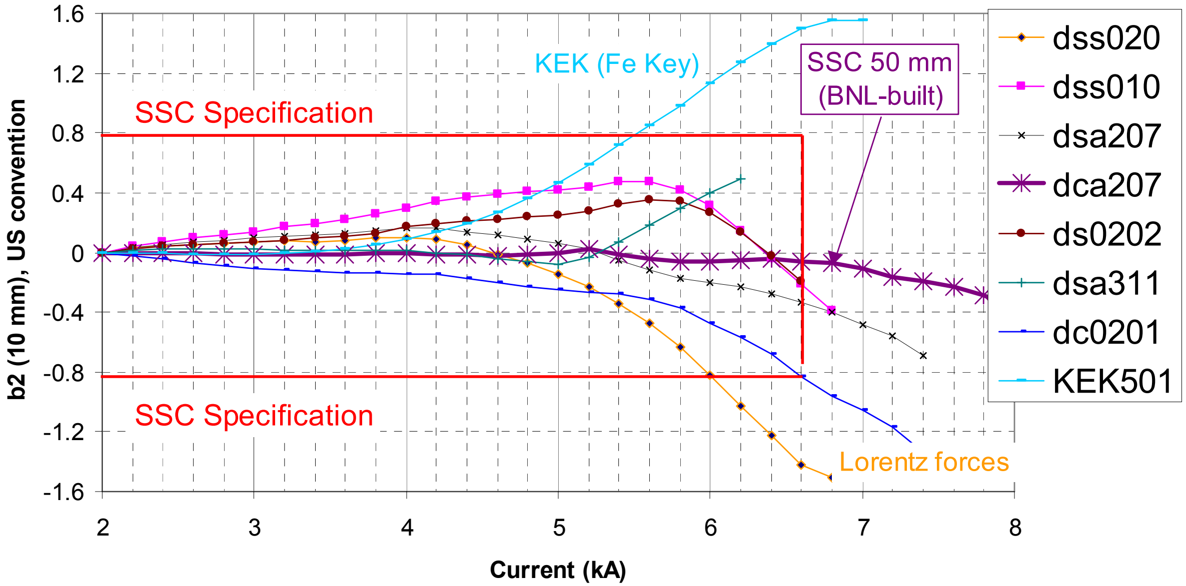
The errors in parts do not necessarily translate to the error in field harmonics. The effect of geometric errors gets significantly reduced in magnets due to averaging and symmetry considerations.

For example consider how a systematic or random error in collar, wedge or cable works in a magnet.

How about the critical coil curing?

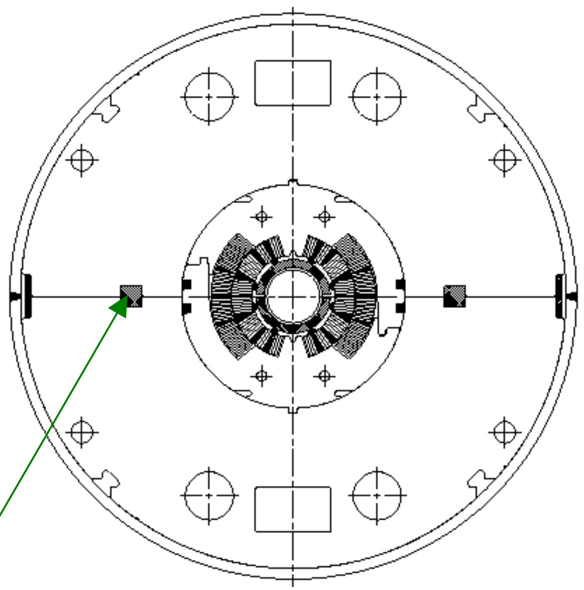


Measured Current Dependence in Sextupole in SSC Magnets



Cross section of SSC 50 mm Dipole

Yoke optimized for low saturation



Near zero current dependence in sextupole in first 50 mm design itself in BNL built long magnets.

Specifications was 0.8 unit.

Earlier magnets (40 mm) had a much larger value.

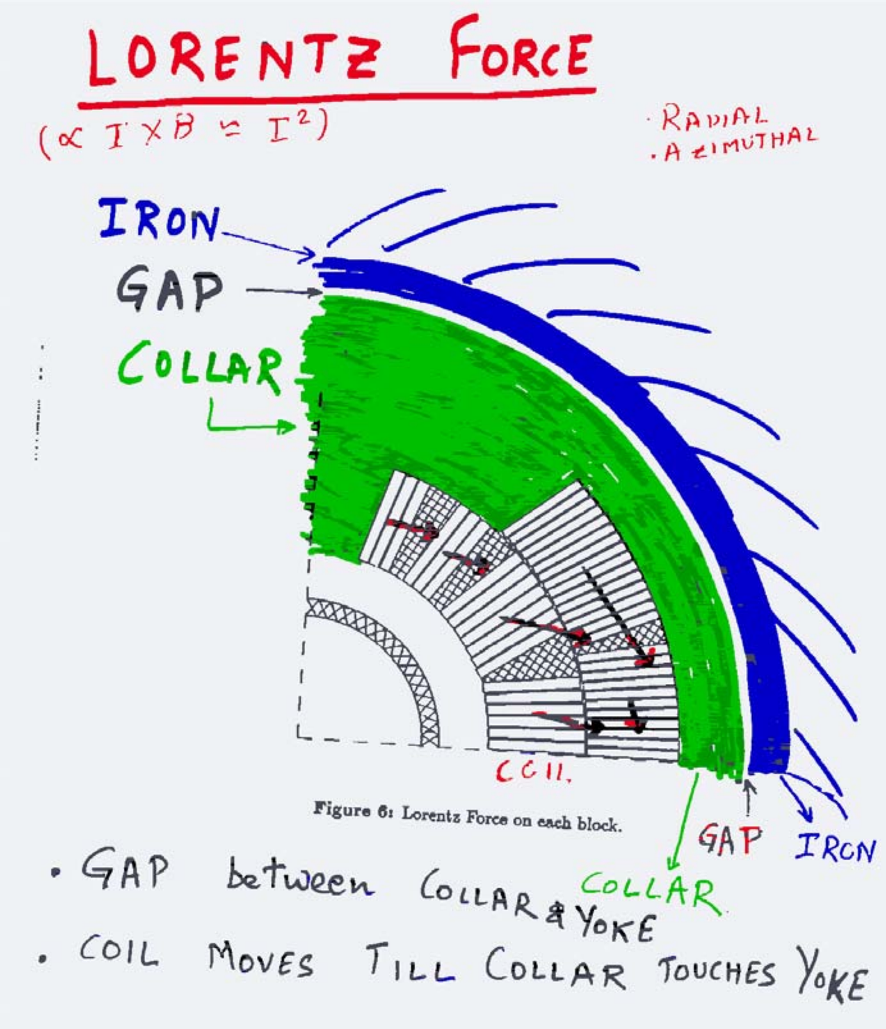
(Source: Iron saturation and Lorentz forces)

Non-magnetic key to force uniform saturation

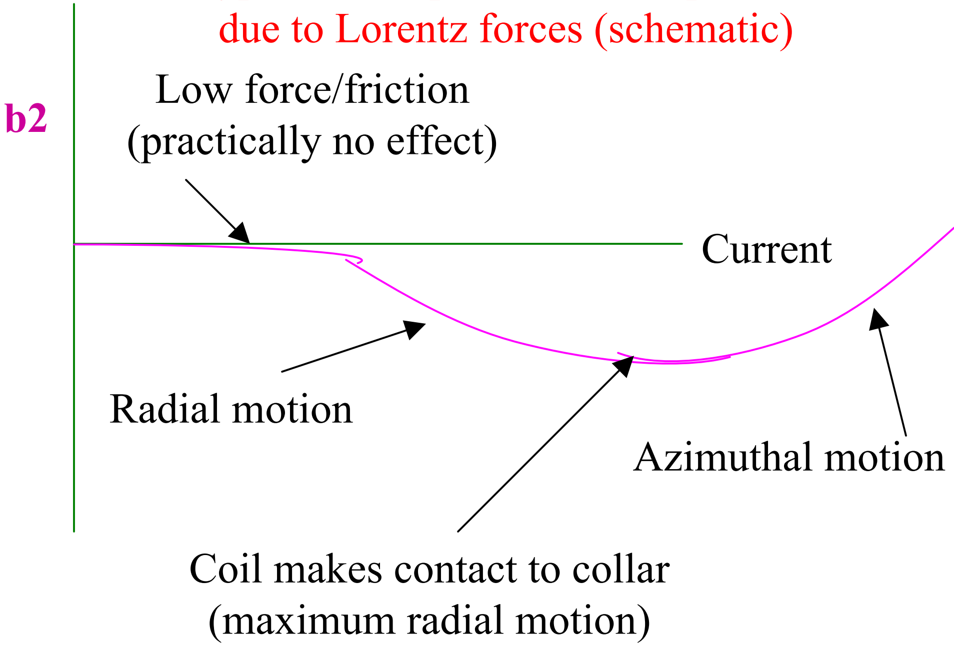
Can also be used to adjust current dependence during production (done in RHIC magnets).

Major progress in reducing the saturation induced harmonics.

Influence of Lorentz Forces



A typical Sextupole current dependence due to Lorentz forces (schematic)



A small radial gap inn some SSC prototype magnets (75-100 micron, almost allowed by errors due to spec) gave about 1 unit of negative sextupole. Such things can be accommodated in a flexible design.

Note: The measured current dependence is a combination of saturation induced harmonics and Lorentz force induced harmonics.

Feedback in design from HERA experience: The Real Magnet Vs. Paper Design

Note: Integral B.dl

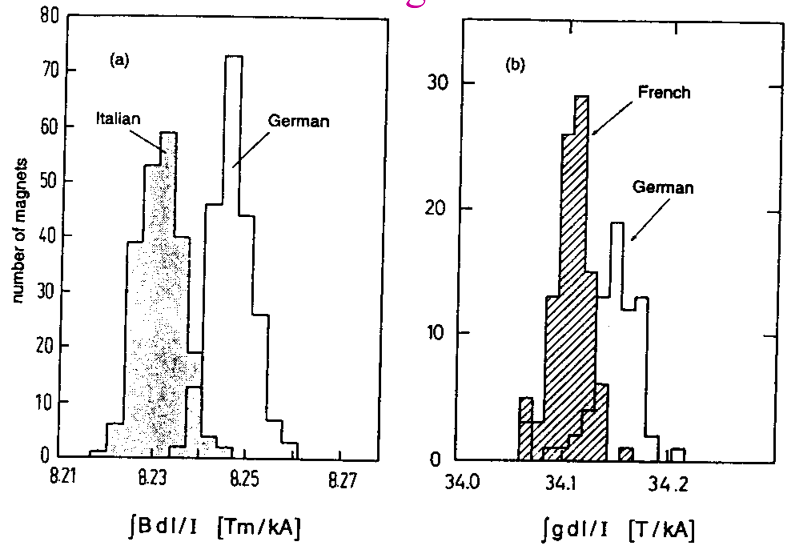
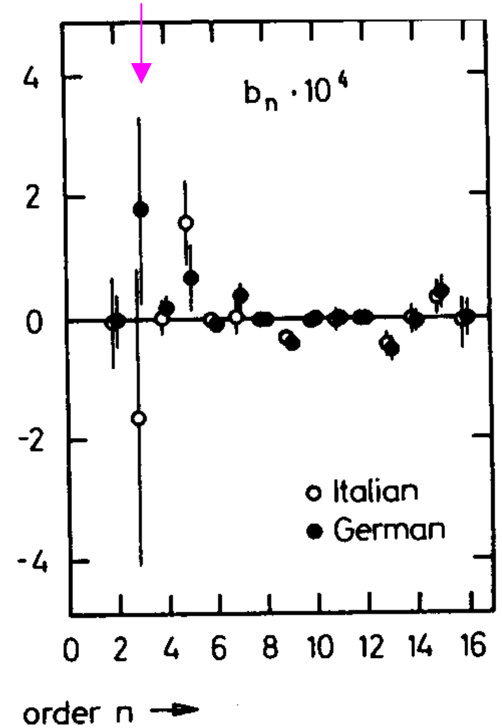


Figure 5.5: (a) Field integral of all HERA dipoles, normalized to coil current. (b) Integrated gradient of all quadrupoles, normalized to coil current (Brück et al. 1991).

Note: Sextupole



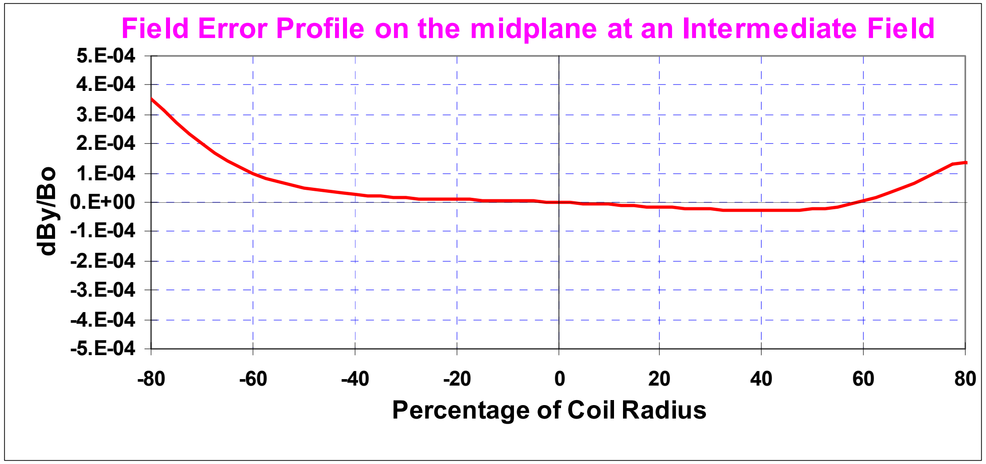
- Parameters do deviate from nominal value.
- It takes time to locate the cause of the problem and then fix it (conventionally that included a cross section iteration). Takes too long and the magnet production can not stop.
- A good design strategy would anticipate such deviations.
- Make a flexible design that assures good field quality despite such deviations.

RHIC 100 mm Aperture Insertion Dipole: The first magnet gets the body harmonics right

Geometric Field Errors on the X-axis of DRZ101 Body

First magnet and first attempt in RHIC 100 mm aperture insertion dipole

A number of things were done in the test assembly to get pre-stress & harmonics right



Note: Field errors are within 10^{-4} at 60% of coil radius and ~$4*10^{-4}$ at 80% radius.

Later magnets had adjustments for integral field and saturation control.
The coil cross-section never changed.

Harmonics at 2 kA (mostly geometric).

Measured in 0.23 m long straigth section.

Reference radius = 31 mm

b1	-0.39	a2	-1.06
b2	-0.39	a3	-0.19
b3	-0.07	a4	0.21
b4	0.78	a5	0.05
b5	-0.05	a6	-0.20
b6	0.13	a7	0.02
b7	-0.03	a8	-0.16
b8	0.14	a9	-0.01
b9	0.02	a10	0.01
b10	-0.04	a11	-0.06
b11	0.03	a12	-0.01
b12	0.16	a13	0.06
b13	-0.03	a14	0.03
b14	-0.10	a15	0.02

All harmonics are within or close to one sigma of RHIC arc dipoles.

Average Field errors ~10^{-4} up to 80% of the coil radius

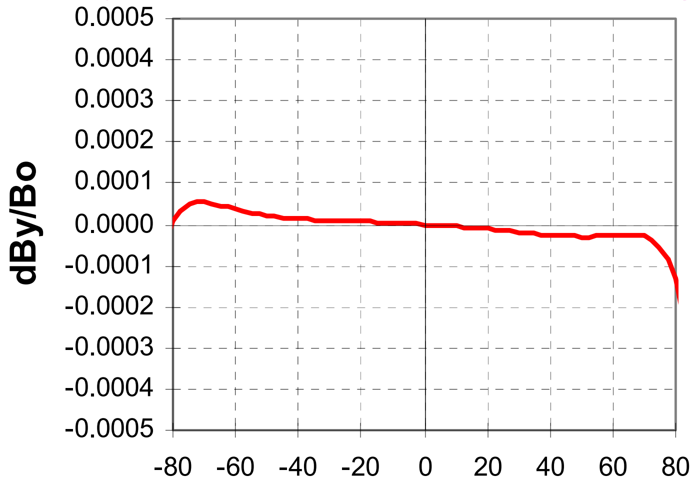
Geometric Field Errors on the X-axis of RHIC DRZ magnets (108-125)

Coil Cross section was not changed between prototype and production magnets

A Flexible & Experimental Design Approach Allowed Right Pre-stress & Right Harmonics

At Intermediate Energy

Small systematic due to advances in design



Note: No R&D Prototype magnet program.

Estimated Integral Mean in Final Set
(Warm-cold correlation used in estimating)
Harmonics at 3kA (mostly geometric)
Reference radius is 31 mm (Coil 50 mm)

b1	-0.28	a1	-0.03
b2	-0.26	a2	-3.36
b3	-0.07	a3	0.03
b4	0.15	a4	0.48
b5	0.00	a5	0.04
b6	0.32	a6	-0.24
b7	0.00	a7	0.01
b8	-0.08	a8	0.05
b9	0.00	a9	0.00
b10	-0.12	a10	-0.02
b11	0.03	a11	-0.01
b12	0.16	a12	0.06
b13	-0.03	a13	0.03
b14	-0.10	a14	0.02

***Raw Data Provided by Animesh Jain at BNL**

Field errors are 10^{-4} to 80% of the aperture at midplane.

(Extrapolation used in going from 34 mm to 40 mm; reliability decreases)

Ultimate Field Quality in SC Magnets

A magnet properly designed with "Tuning Shims" should theoretically give a few parts in 10^5 harmonics at 2/3 of coil radius (i.e. practically zero).

Animesh Jain at BNL found changes in harmonics between two runs in RHIC insertion quadrupoles.

First thought that the changes were related to the tuning shims.

Later, an experimental program found that the harmonics change after quench and thermal cycles in other magnets also. These changes perhaps put an ultimate limit on field quality.

Changes may be smaller in magnets made with S.S. collars.

Note: n=2 is sextupole