Lecture VII

Field Errors and Their Estimates in Modern Superconducting Magnets

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Field Errors in Superconducting Magnets RMS or Sigma

Sources of RMS Errors:

- Variations in parts and assembly

  (the process cannot be repeated exactly every time)

Examples of Variations:

- Electrical (e.g. J_c) and mechanical properties of superconductor
- Magnetic and mechanical properties of yoke laminations
- Mechanical tolerances in collars, wedges, spacers, etc.

Field Errors in Superconducting Magnets Systematic

Sources of Systematic Errors: Error in Design

Examples of Practical Design Errors:

- **Imperfect magnetic design**
- **Imperfect tooling design**
- **Imperfect manufacturing process**

Bad News:

Requires combined mechanical errors to be ~ 25 micron (difficult)

Good News:

Requires only minor corrections that in most cases can be implemented without a major impact on the design, cost and manufacturing

- **But only if thought and planned in advanced (this is the key)**

Conventional Models for Simulating the Influence of Mechanical Errors in Field Harmonics

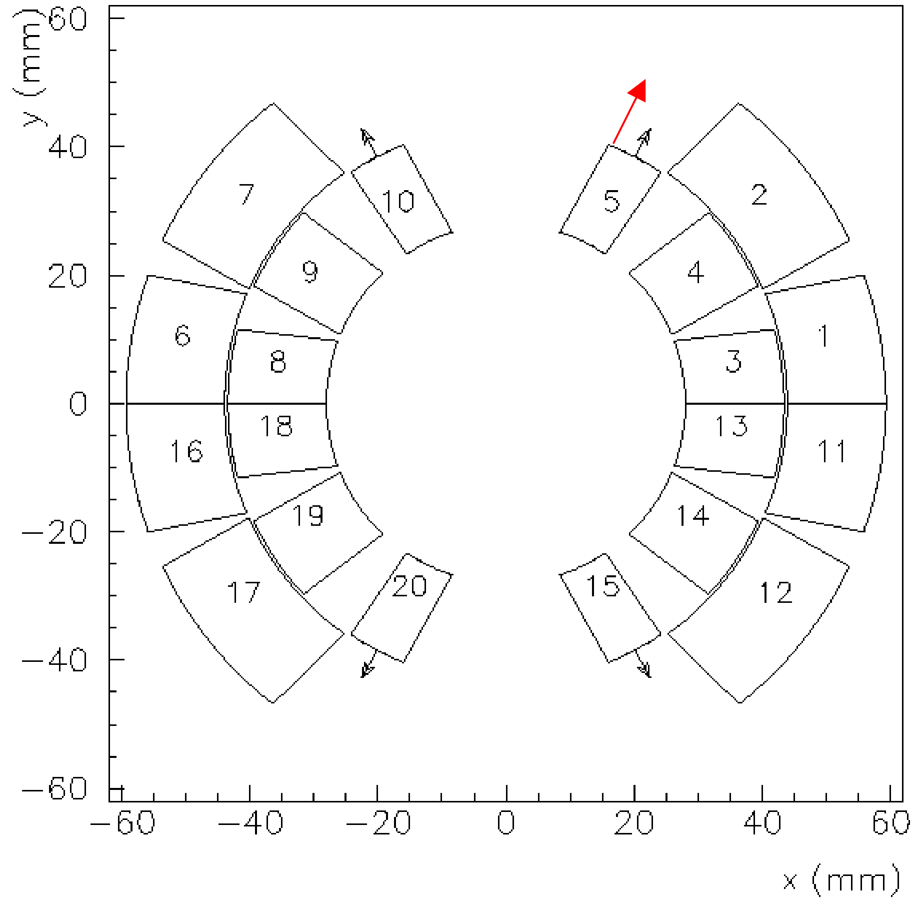
Conventional Models

(old but still popular in many cases)

Generally there are 25-50 micron (1-2 mil) errors in parts and construction.

Therefore, allow this kind of positional error in each of several blocks of conductors and then add their influence on error harmonics in an RMS sort of way.

Looks possible at first glance, but let's do a reality check (next two slides).

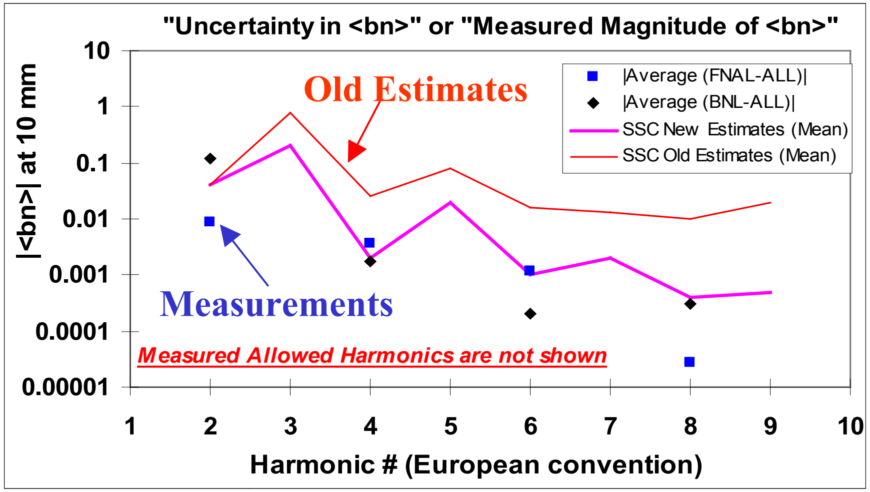


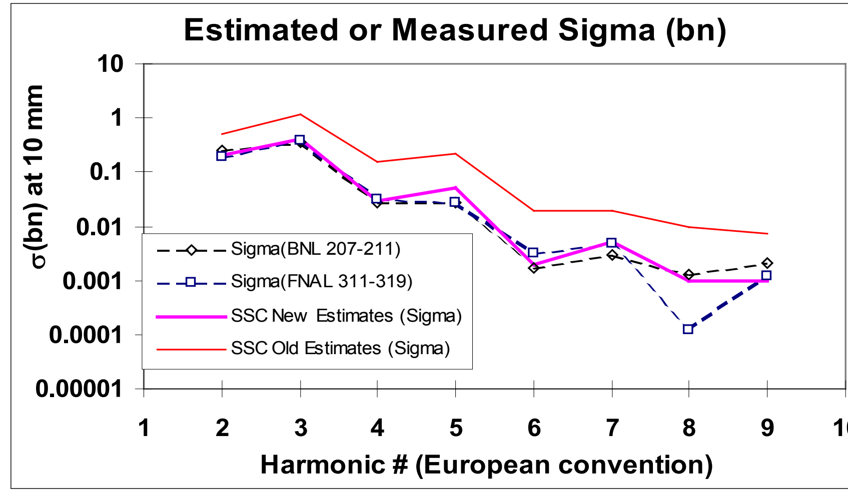
Symmetric model: 4 black arrows

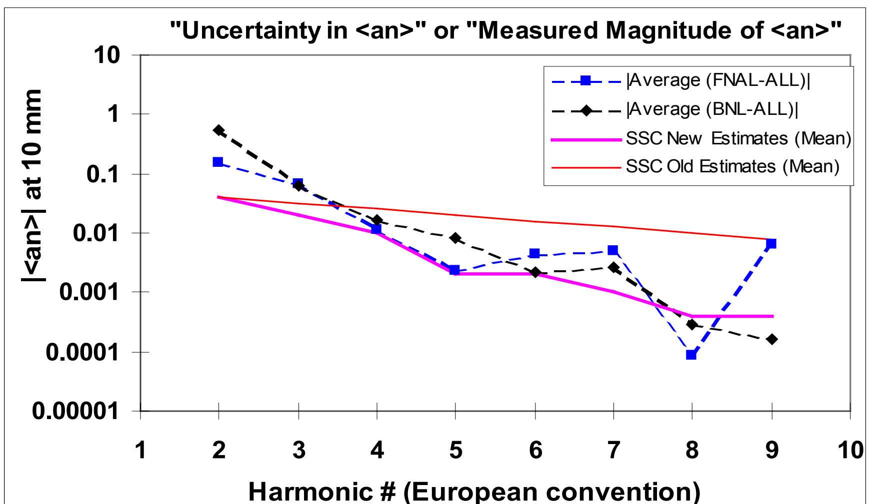
Block movement without symmetry: one red arrow

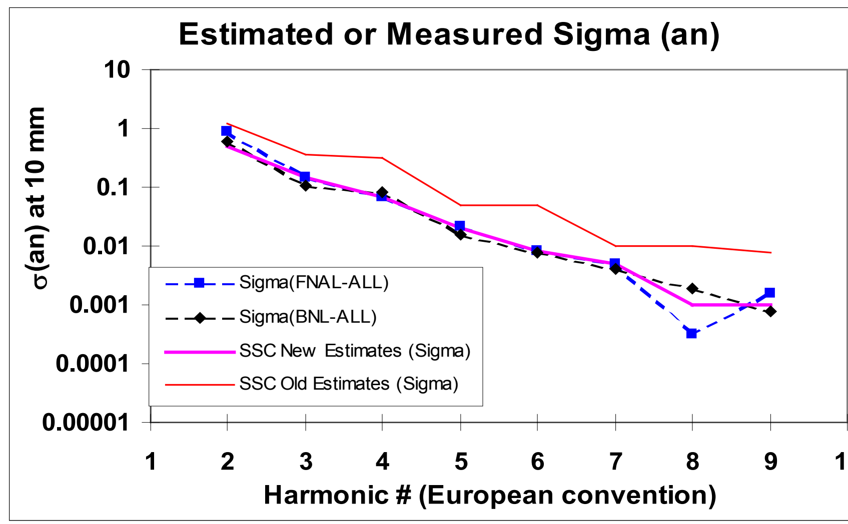
Field Quality in SSC Magnets
(Old model based estimates Vs. Measurements)

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





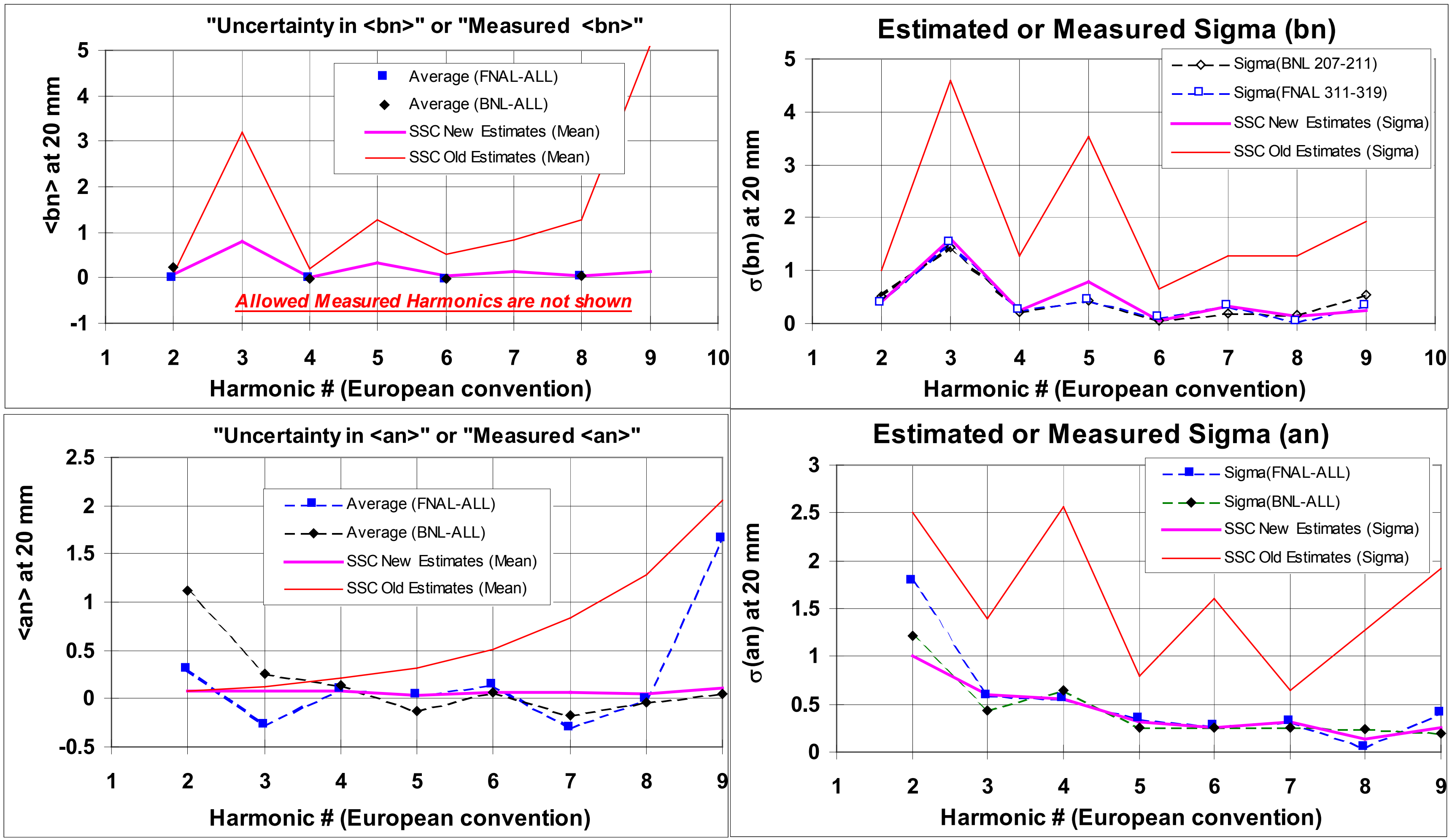




Note: Conventional (old) model over-estimated errors by a significant amount !

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

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



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 microns

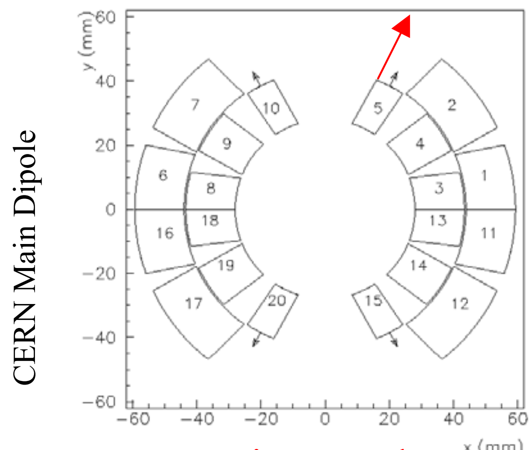
Assumption: it simulates the error in parts and construction on field harmonics. Add the resultant field errors in an RMS way.

A More Realistic Model

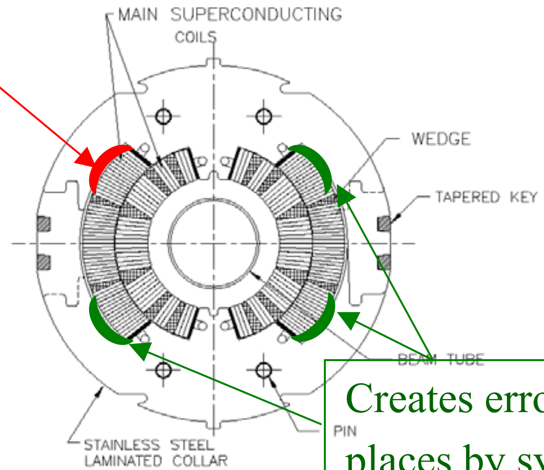
The errors in parts do not necessarily translate to the error in field harmonics. The effect of geometric errors gets significantly reduced in magnets due to averaging and symmetry considerations.

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

How about the critical coil curing?



Error in collar here



Creates error at other places by symmetry

Movement in popular models: one red arrow

Symmetric model: 4 black arrows

Realistic model: something in between but closer to the black arrows

Component Errors => Field Errors

The typical tolerances in parts and manufacturing process which define the coil cross section are specified such that the error from an individual component remains within 25 μm. The exception is the thickness of cable and insulation on it. The tolerances on them are generally an order of magnitude better. Uniform coil curing tooling also plays an important role in determining the location of the coil midplane in the magnet and hence in determining the values of non-allowed harmonics.

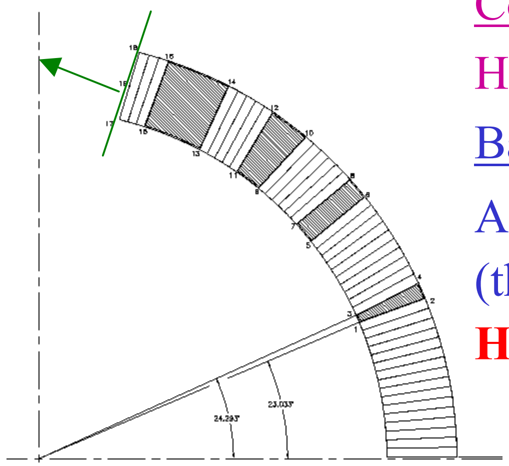
Cable and Insulation size have a major impact on coil size and hence pre-stress on the coil in the magnet. They don't influence odd b_n's and even a_n's and the influence on odd a_n's can be made negligible if the azimuthal coil size between the upper and lower halves is matched to 25μm. Unless the variation 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.

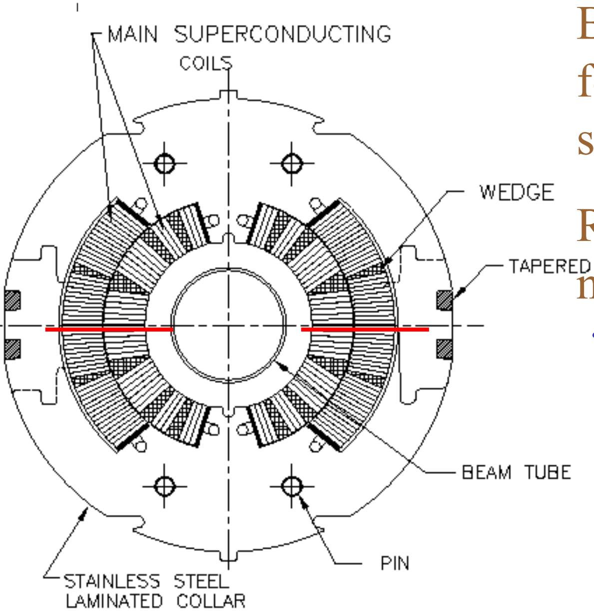
Other Components primarily influence only the allowed harmonics as long as a large quantity of them is used in the magnet. Non-allowed harmonics may be generated if the quantity is small or the mechanical design prevents randomizing in a 4-fold dipole symmetry.

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.

Impact of Cable Thickness on Field Quality





Common perception:

Has major impact on field errors, in particular on the random harmonics.

Basic Analysis:

A thicker cable makes bigger coils, as measured outside the magnet (though coil size can be controlled by adjusting curing pressure).

However, inside the magnet, the collars determine the coil geometry.

Cable thickness has a significant impact on the pre-stress on coils.

But to a first order, it does not have a major impact on field errors for a reasonable deviations in insulated cable thickness (the pre-stress variation will become a bigger issue before the harmonics).

Rapid variations in cable thickness are averaged out over a large number of turns and over the length of magnet.

The location of midplane has a major impact on field quality.

Though the overall cavity is well defined by collars, the location of coil midplane is not. It is determined by the relative size of upper and lower coils. If they are matched, the midplane will be OK.

Something other than the cable is more critical to harmonics.

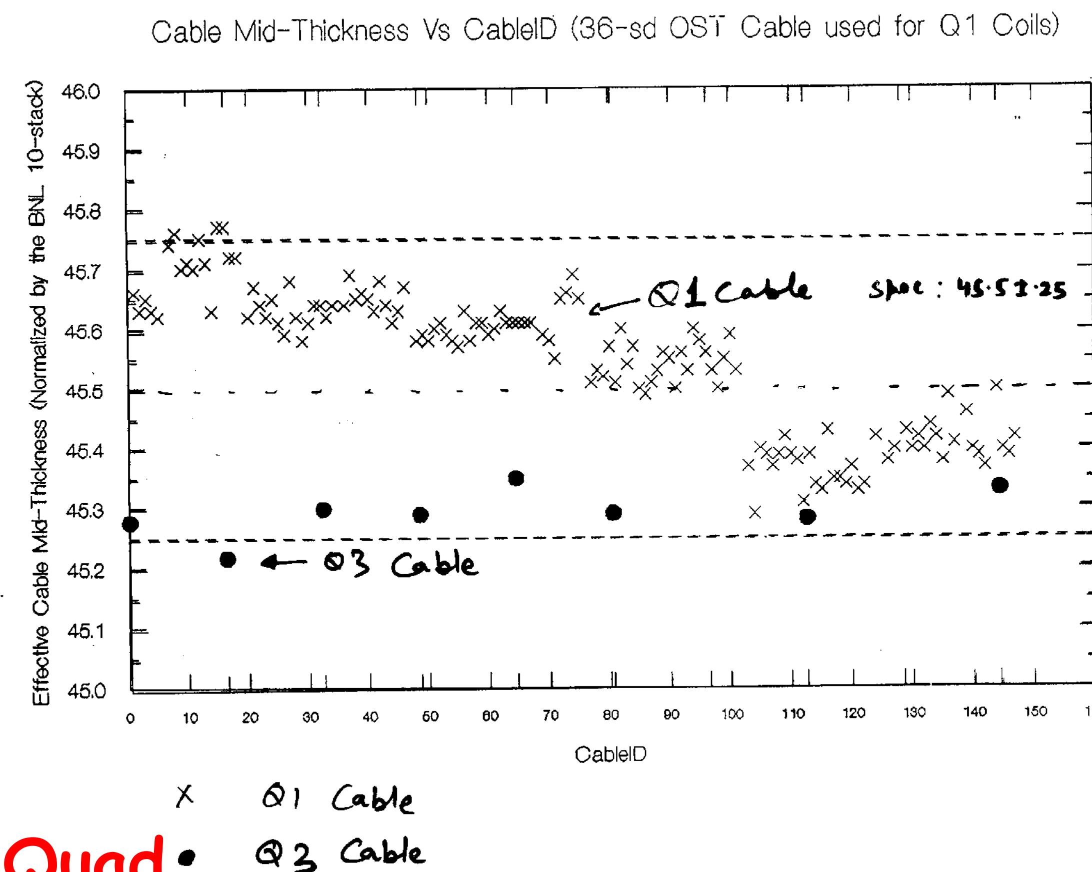
Different Size Cable (within spec) from Two Different Vendors

Specifications : +/- 0.25 mil (6.5 micron); 0.5 mil variation (13 micron)

Two vendors gave cable which differ systematically (but within specifications) by ~ 0.35 mil (however, had a small RMS)

27 turns => 9 mil (0.24 mm) much larger than desired.

A flexible design accommodated it!



RHIC 130 mm Insertion Quad

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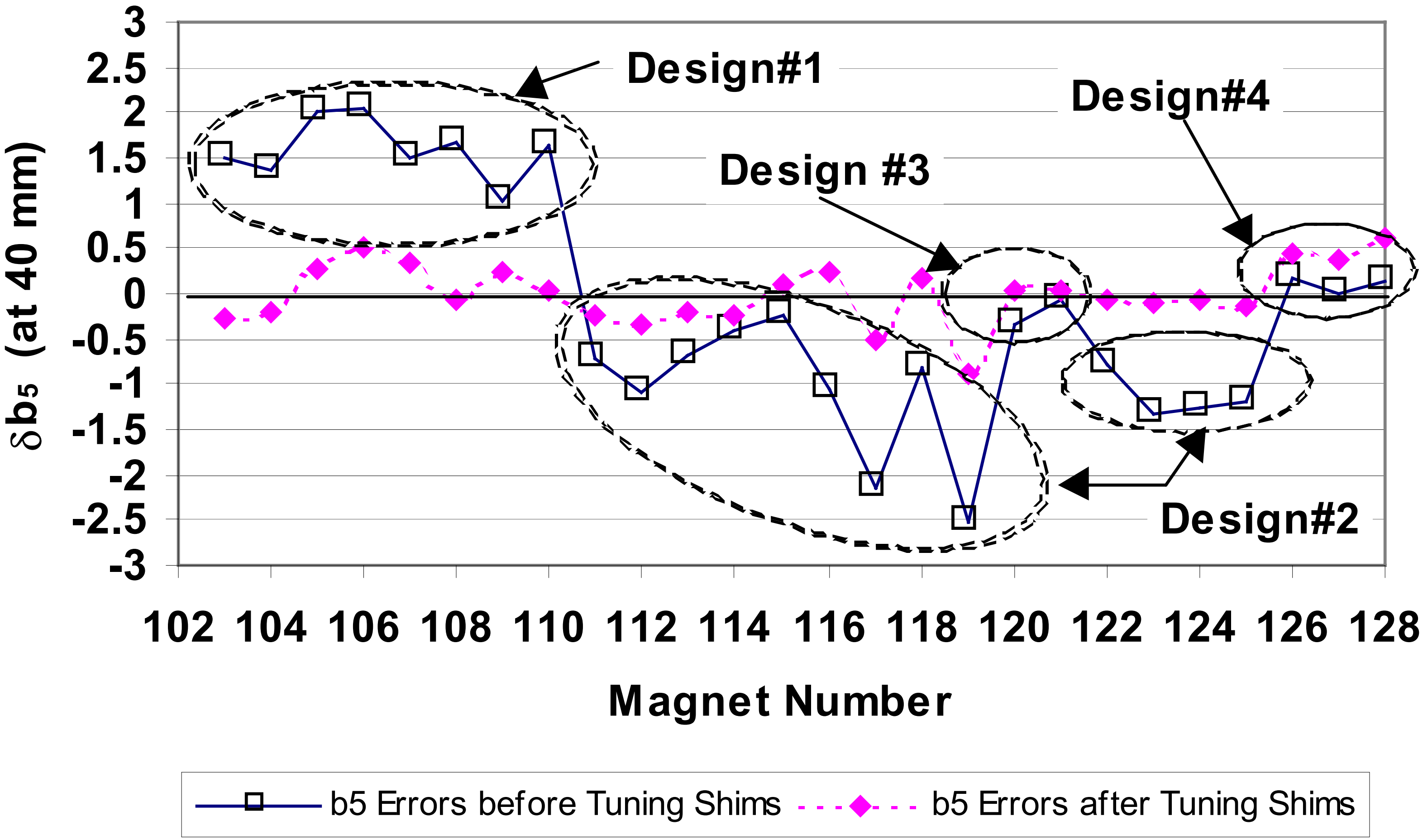
Superconducting Magnet Division

Flexible Design
(Adjustment in b_5 During Production in Q1)



- Accommodated large variations in cable thickness.
- Obtained a large change in field harmonic (b_5) after initial design.
  - ➢ The Magic of Flexible Coil Design and Tuning Shims

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

Note: Integral B.dl

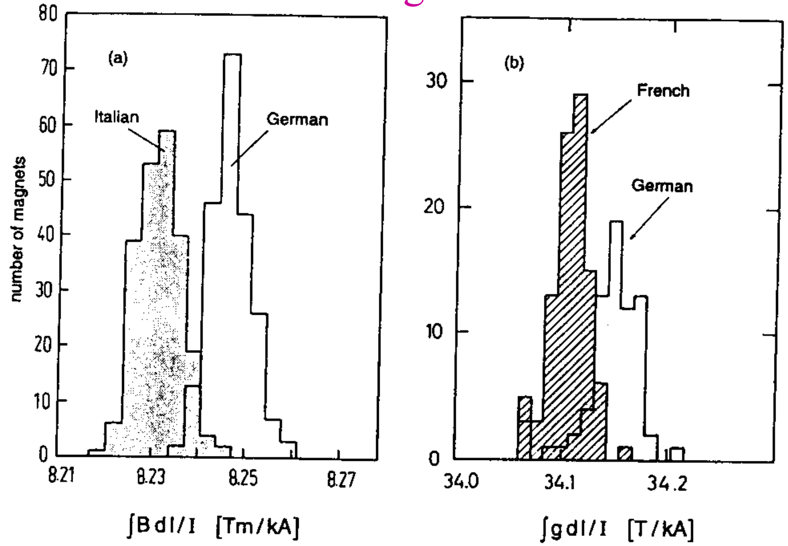
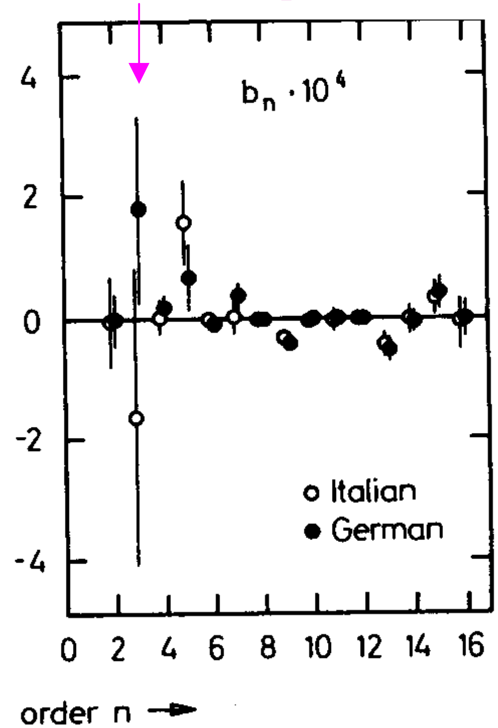


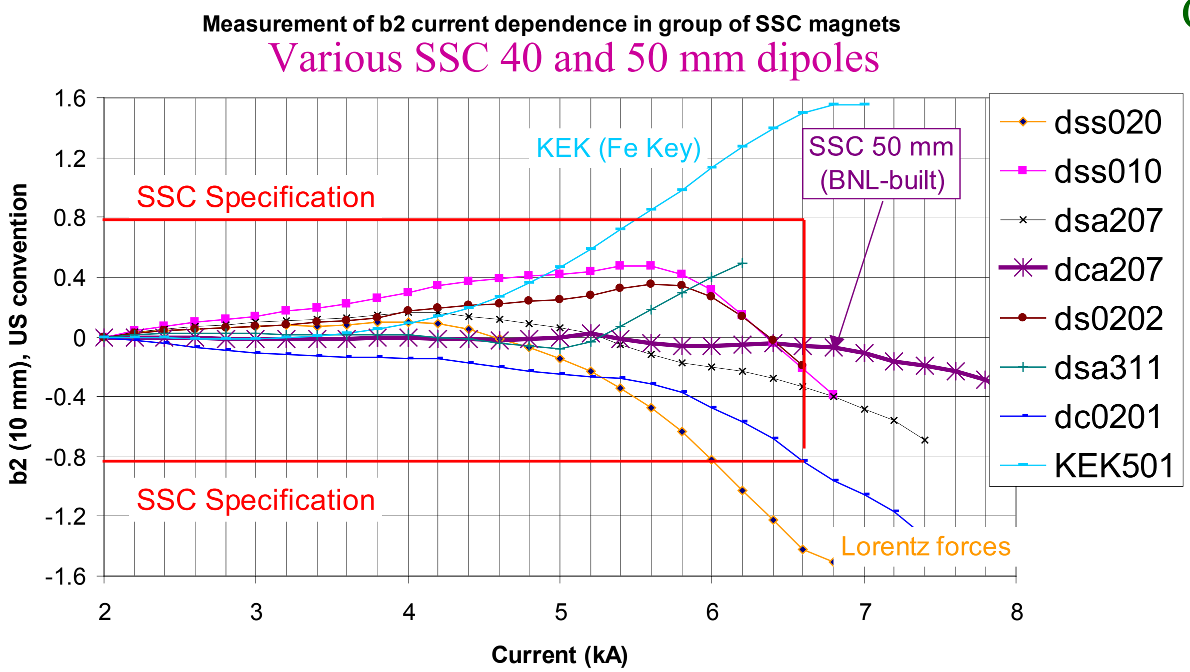
Figure 5.5: (a) Field integral of all HERA dipoles, normalized to coil current. (b) Integrated gradient of all quadrupoles, normalized to coil current (Brück et al. 1991).

Note: Sextupole



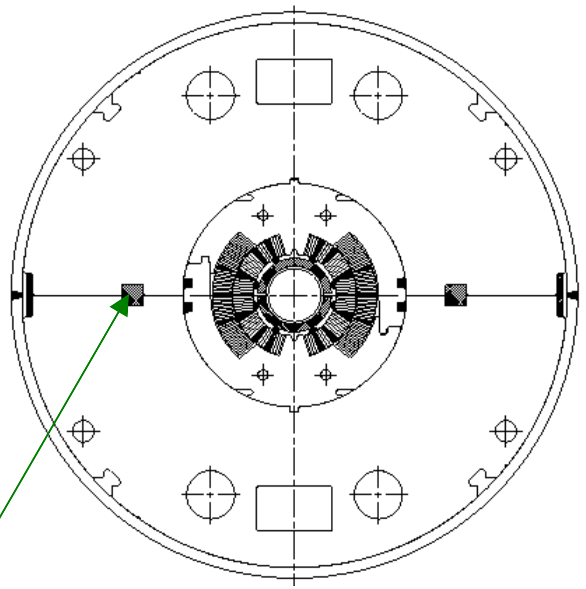
- Parameters do deviate from nominal value.
- It takes time to locate the cause of the problem and then fix it (conventionally that included a cross section iteration). Takes too long and the magnet production can not stop.
- *A good design strategy would anticipate such deviations.*
- *Make a flexible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

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.

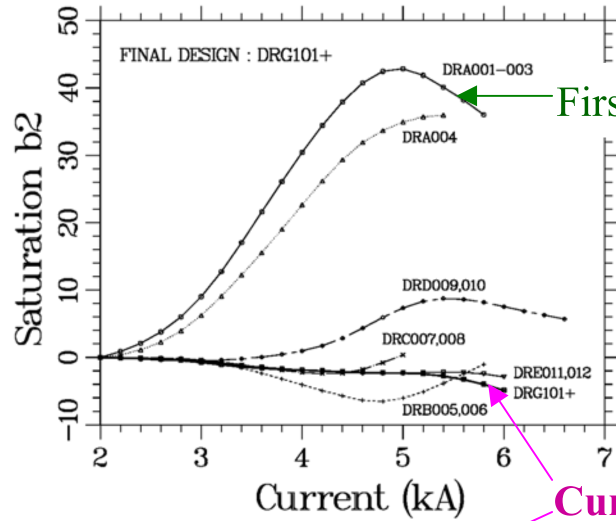
Saturation in RHIC Arc Dipoles

In RHIC iron is closer to coil and contributes ~ 50% of coil field

3.45 T (Total) ~ 2.3 T (Coil) + 1.15 (Iron)

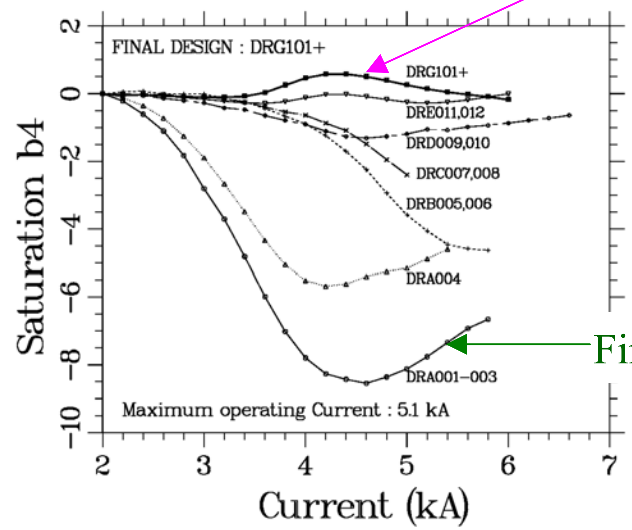
Initial design had bad saturation (as expected from conventional wisdom), but a number of developments made the saturation induced harmonics nearly zero!

Only full length magnets are shown.
Design current is ~ 5 kA (~3.5 T)



First Design

Current Design



First Design

Three magnets with similar apertures Tevatron, HERA and RHIC

Tevatron Dipole (76.2 mm bore)

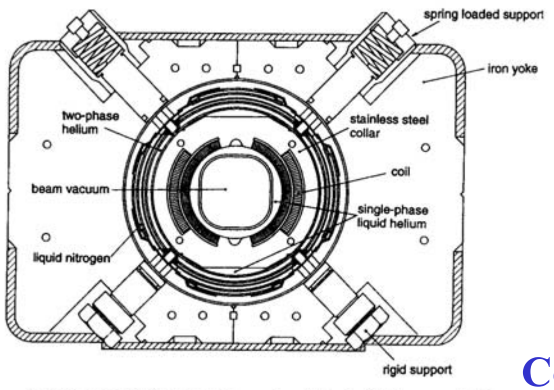
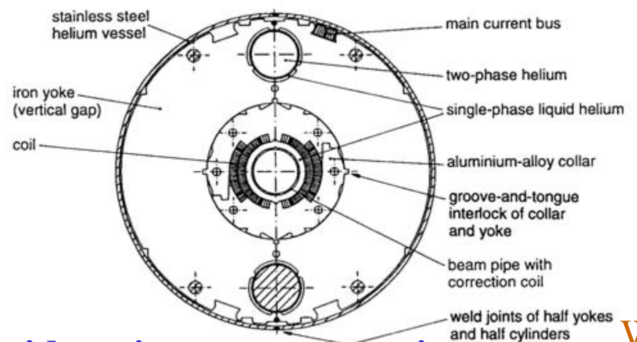
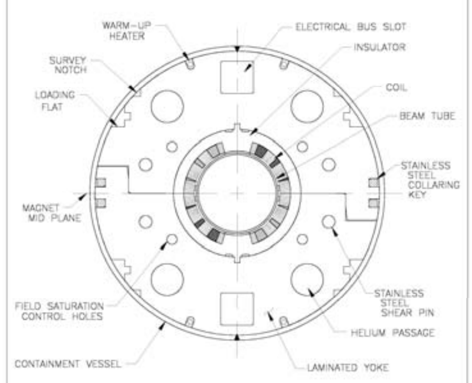


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

HERA Dipole (75 mm bore)



RHIC Dipole (80 mm bore)



Consideration on systematic errors

Tevatron: No Wedges (large higher order systematic harmonics expected). S.S. Collars - Iron away from coil (small saturation expected).

HERA: Wedges (small higher order harmonics expected). Al Collars - Iron away from coil (small saturation expected).

RHIC: Wedges (small higher order harmonics expected). Thin RX630 spacers to reduce cost - Iron close to coil (large saturation from conventional thinking. **But reality opposite: made small with design improvements**).

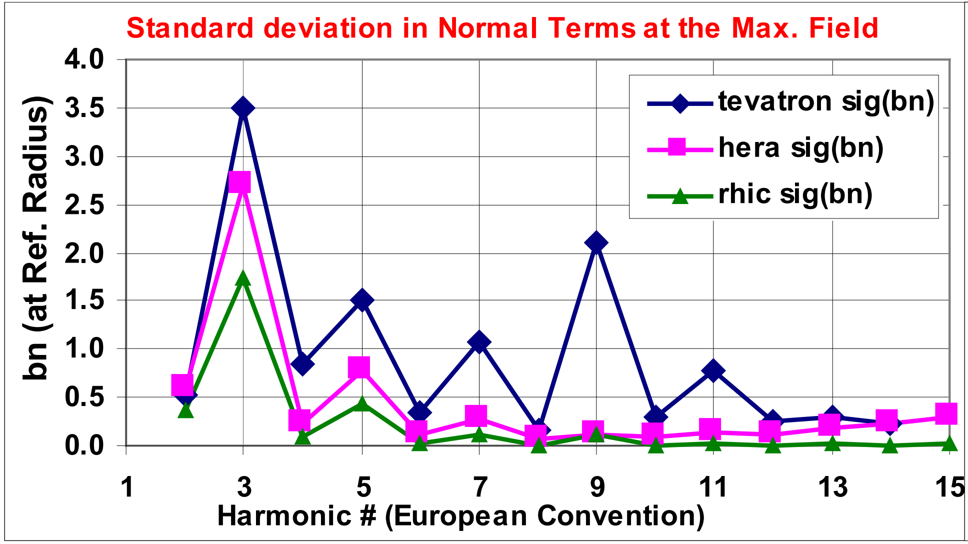
Collars used in Tevatron and HERA dipoles have smaller part-to-part dimensional variation (RMS variation ~10 μ) as compared to RX630 spacers (RMS variation ~50 μ) used in RHIC dipoles.

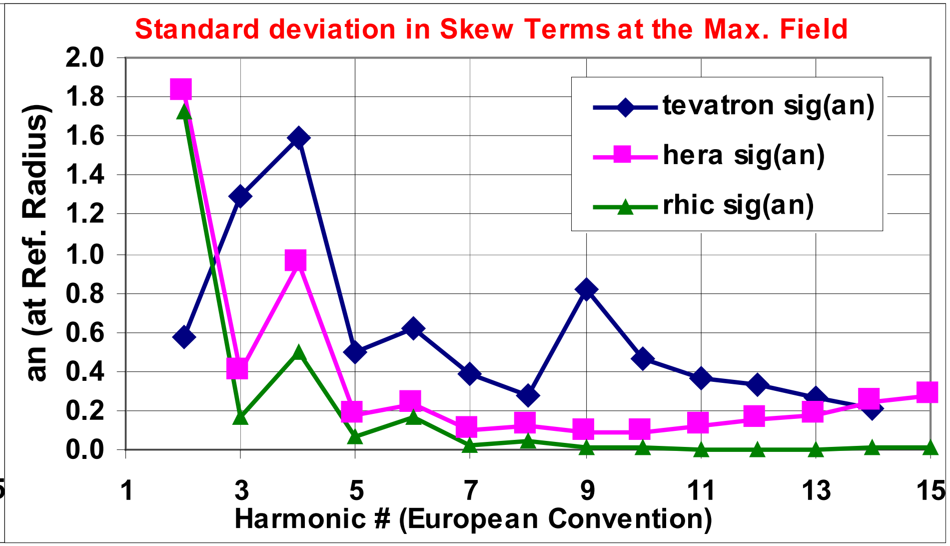
Conventional thinking : RHIC dipoles will have larger RMS errors. But in reality, it was opposite.

Why? The answer changes the way we look at the impact of mechanical errors on field quality !

Comparison of Field Quality in three similar aperture magnets

	Tevatron	HERA	RHIC
Reference Radius (mm)	25.4	25	25
Coil Diameter (mm)	76.2	75	80





RHIC has lower sigmas (except for a2 where tevatron used smart bolts)

Lower Order Harmonics generally due to Construction Errors

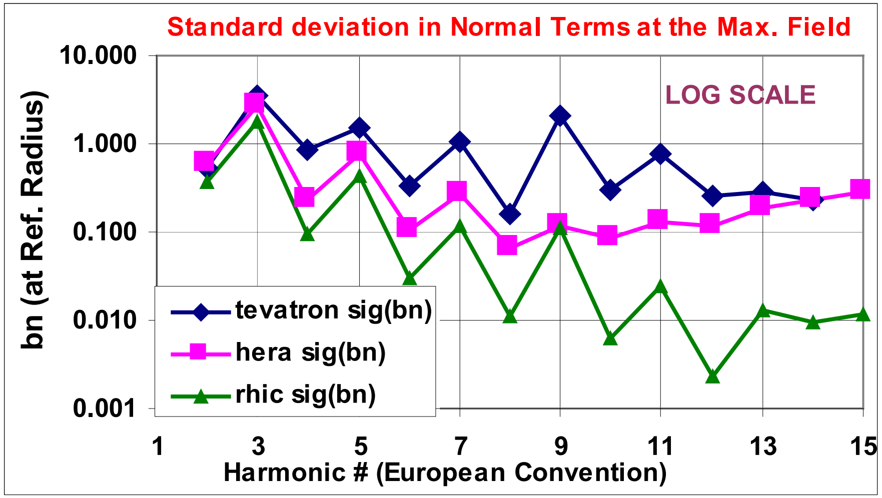
Higher Order Harmonics generally due to Measurement Error

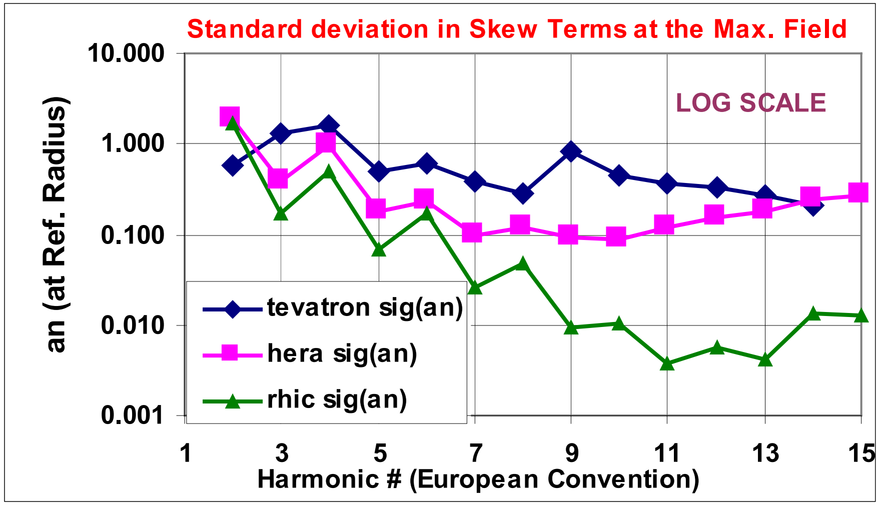
Comparison of Field Quality in Tevatron, HERA and RHIC dipoles

(Large scale production of similar aperture magnets)

Here the normal and skew harmonics are presented in LOG scale. They were shown earlier in linear scale.

	Tevatron	HERA	RHIC
Reference Radius (mm)	25.4	25	25
Coil Diameter (mm)	76.2	75	80





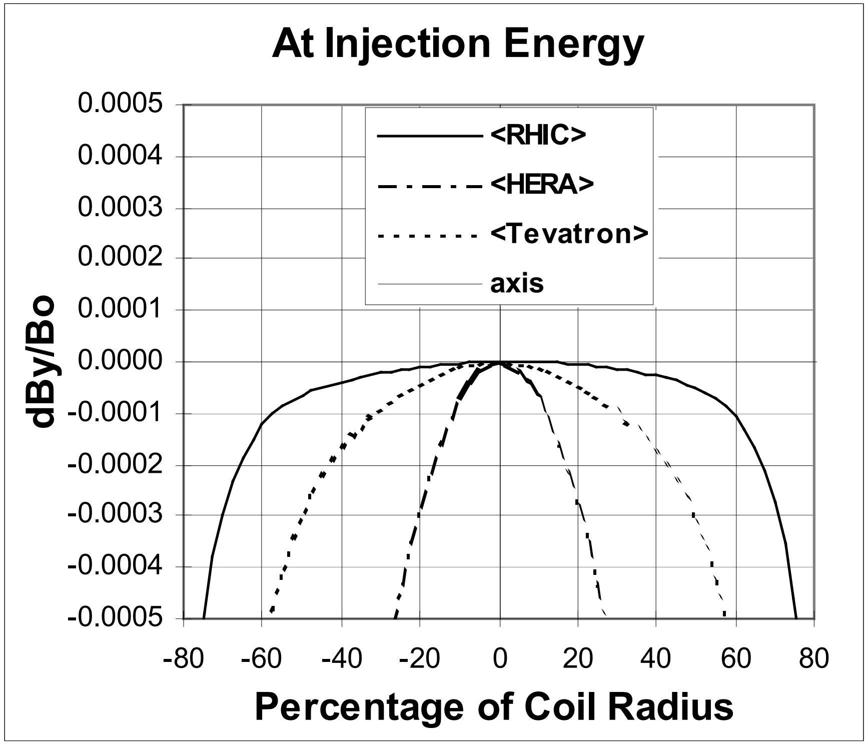
RHIC has lower sigmas (except for a2 where tevatron used smart bolts)

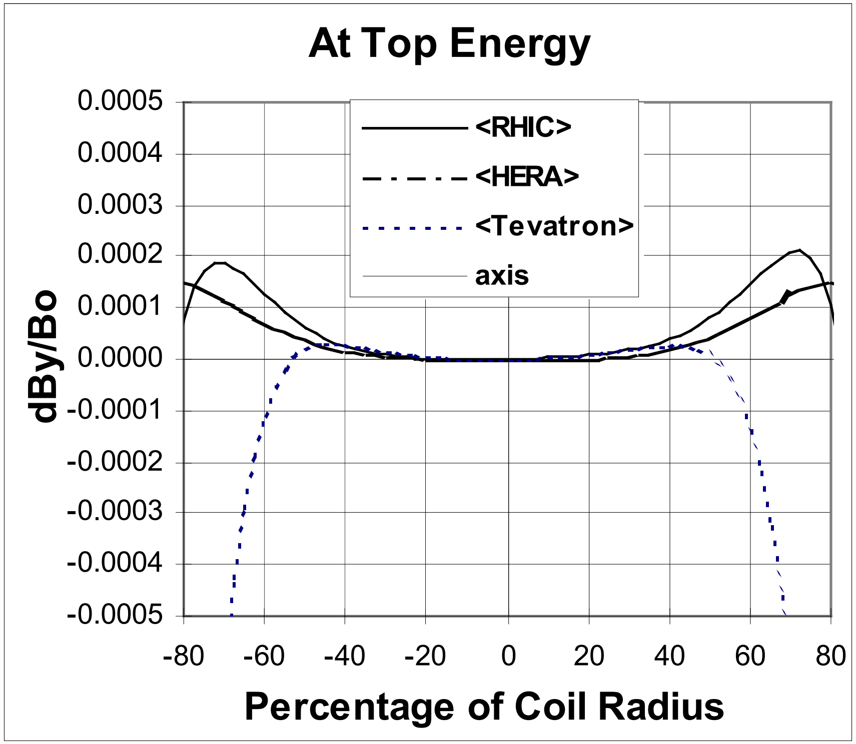
Lower Order Harmonics generally due to Construction Errors

Higher Order Harmonics generally due to Measurement Error

Average Field Errors on X-axis

COIL ID : RHIC 80 mm, HERA 75 mm, Tevatron 76.2 mm





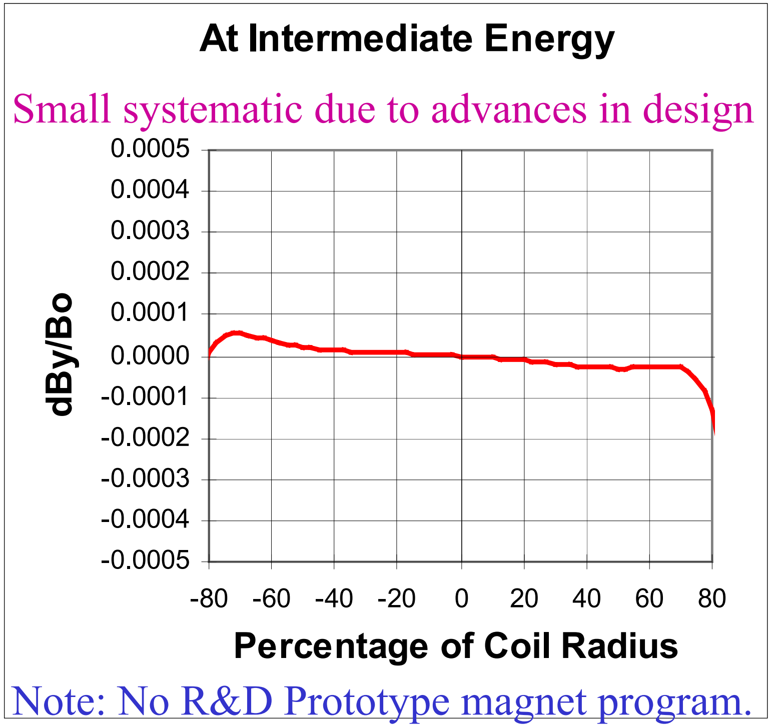
- **Warm-Cold correlation have been used in estimating cold harmonics in RHIC dipoles (~20% measured cold and rest warm).**
- **Harmonics b_1-b_{10} have been used in computing above curves.**
- **In Tevatron higher order harmonics dominate, in HERA persistent currents at injection. RHIC dipoles have small errors over entire range.**

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

Geometric Field Errors on the X-axis of RHIC D0 magnets (108-125)

Coil Cross section was not changed between prototype and production magnets

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



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)

Case Study: Coil Aperture and Random Field Errors

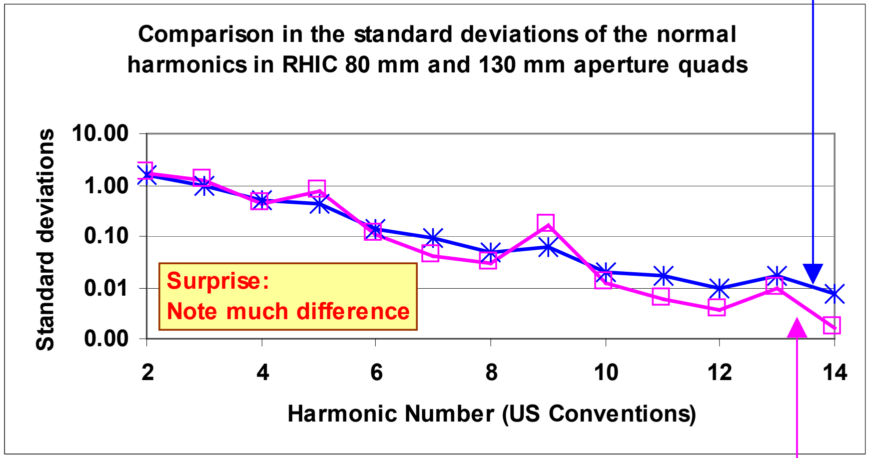
Conventional Wisdom:

Increasing aperture reduces random errors (normalized to at 2/3 coil radius) as the relative mechanical error decreases.

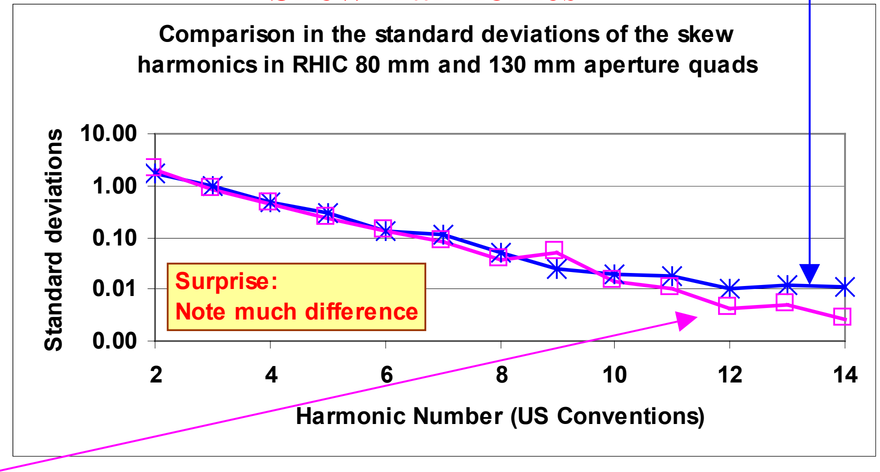
Warm Harmonic Measurements in 2 types (apertures) of RHIC Quadrupoles:

80 mm aperture ARC Quads (25 mm reference radius)

Normal Harmonics



Skew Harmonics



130 mm aperture IR Quads (40 mm reference radius)

Note: No major difference in random errors (sigma) as predicted by standard models.

Lessons Learnt:

Instead of using only general guidelines, one must look if there is a component (part) that may be driving the field errors. In case of RHIC Quads, it was Phenolic RX630 spacer.

Errors in Modern Measurement System

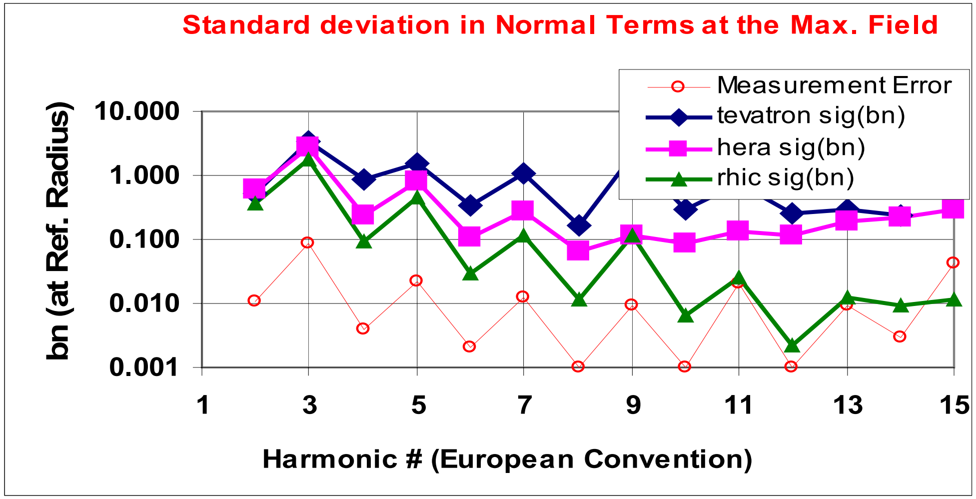
A. Jain and P. Wanderer, BNL

Summary of various contributions to measurement errors. The normal and skew harmonics are indicated using the US notation (b_1 = normal quadrupole, etc.)

Harmonic	Maximum error due to meas. coil construction/ calibration (units)	Effect of thermal cycle and/or quench (units)	Effect of time dependence, at 5kA (units)	Random error in measure-ment (units)	Total expected error (units)	Suggested value of total measurement uncertainty (units)
b_1	0.011	0.006	0.0	0.061	0.078	0.10
b_2	0.085	0.203	0.1	0.033	0.420	0.50
b_3	0.004	0.009	0.0	0.012	0.026	0.05
b_4	0.022	0.044	0.0	0.004	0.071	0.10
b_5	0.002	0.012	0.0	0.003	0.016	0.02
b_6	0.012	0.005	0.0	0.002	0.019	0.02
b_7	0.001	0.000	0.0	0.001	0.003	0.02
b_8	0.009	0.003	0.0	0.001	0.013	0.02
b_9	0.001	0.004	0.0	0.001	0.006	0.02
b_{10}	0.020	0.001	0.0	0.001	0.022	0.05
b_{11}	0.000	0.002	0.0	0.001	0.003	0.02
b_{12}	0.009	0.002	0.0	0.001	0.012	0.02
b_{13}	0.003	0.002	0.0	0.002	0.006	0.02
b_{14}	0.041	0.004	0.0	0.002	0.047	0.05
a_1	0.046	0.388	0.0	0.043	0.477	0.50
a_2	0.019	0.000	0.0	0.015	0.034	0.05
a_3	0.019	0.027	0.0	0.010	0.056	0.10
a_4	0.006	0.002	0.0	0.005	0.013	0.02
a_5	0.010	0.009	0.0	0.004	0.023	0.05
a_6	0.004	0.000	0.0	0.002	0.006	0.02
a_7	0.004	0.001	0.0	0.002	0.006	0.02
a_8	0.001	0.006	0.0	0.001	0.008	0.02
a_9	0.001	0.001	0.0	0.001	0.003	0.02
a_{10}	0.001	0.001	0.0	0.001	0.003	0.02
a_{11}	0.001	0.001	0.0	0.001	0.003	0.02
a_{12}	0.001	0.008	0.0	0.001	0.010	0.02
a_{13}	0.002	0.001	0.0	0.002	0.005	0.02
a_{14}	0.004	0.008	0.0	0.002	0.014	0.02

Very Small Measurement Errors in RHIC

Shows that errors in the measurement syste can be so small that it need not limit the expected or measured field harmonics in modern magnets.

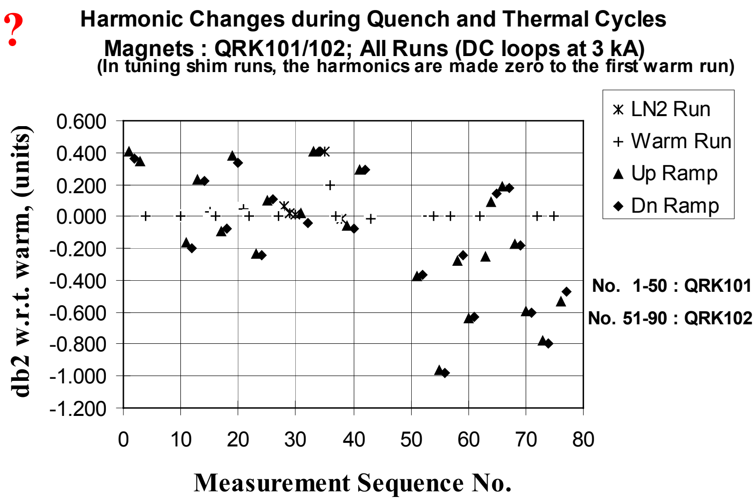


Ultimate Field Quality in SC Magnets

Is field quality limited by design & construction errors?

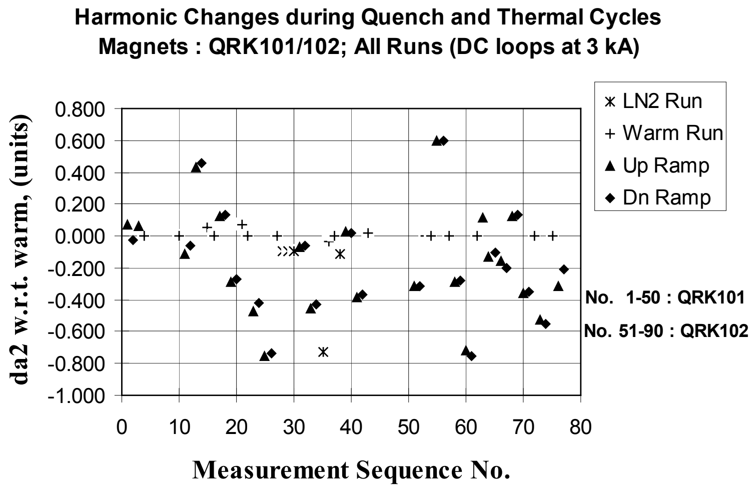
However, with the methods discussed previously (good designs with low computed harmonics and a flexible design to reduce the impact of errors in parts and manufacturing), one can make good field quality magnets.

•The error in harmonics (both random and systematic) can be further reduced with the help of tuning shims.



Therefore, such a magnet (with "Tuning Shims") should theoretically give a few parts in 10^5 harmonics at 2/3 of coil radius. This corresponds to an accumulated mechanical error of 5-10 microns.

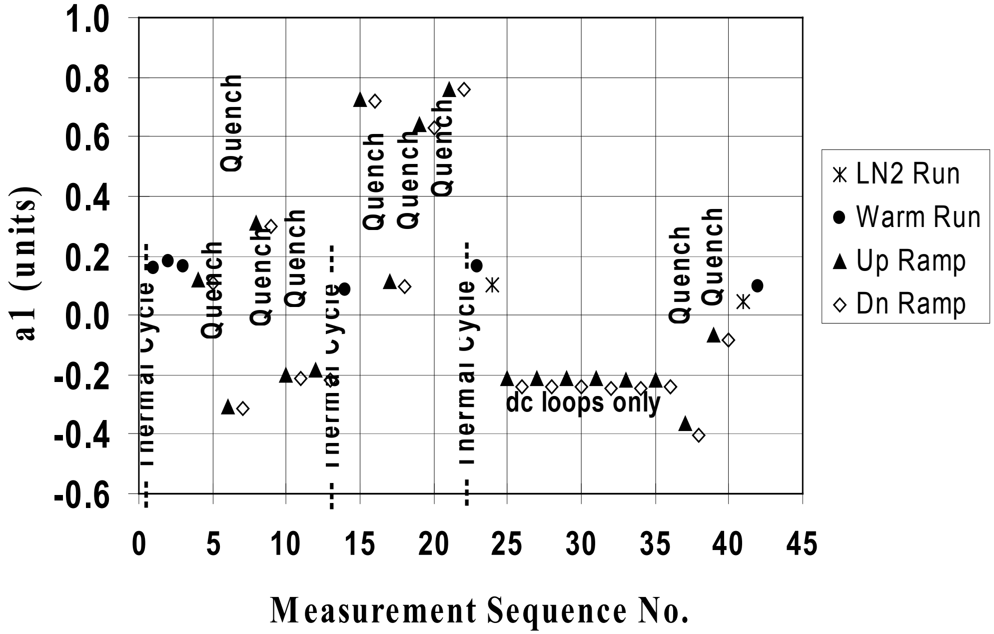
Note: n=2 is sextupole

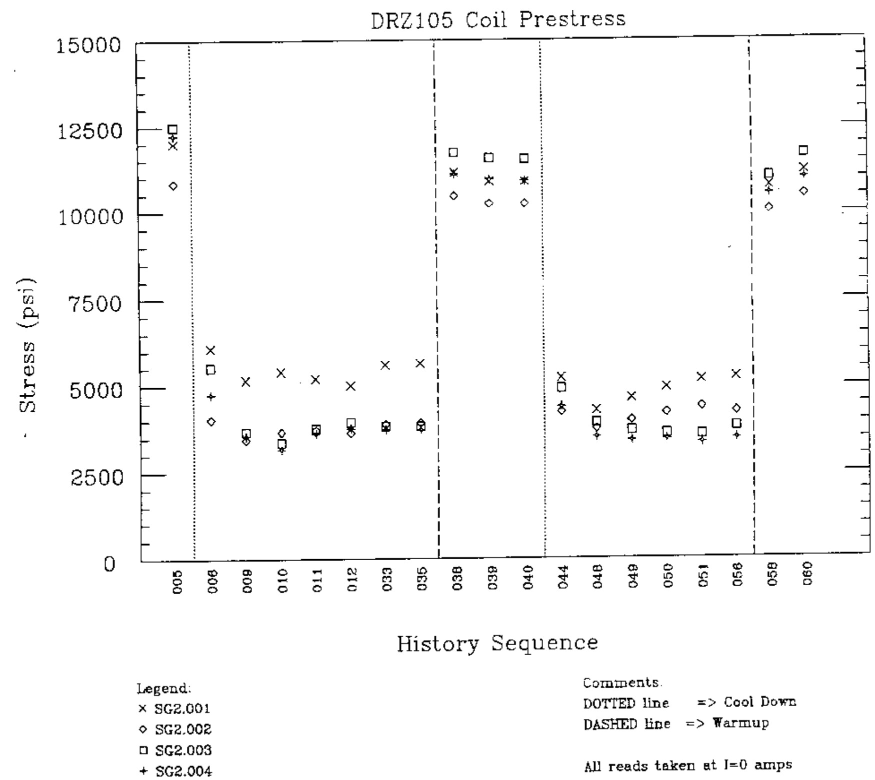


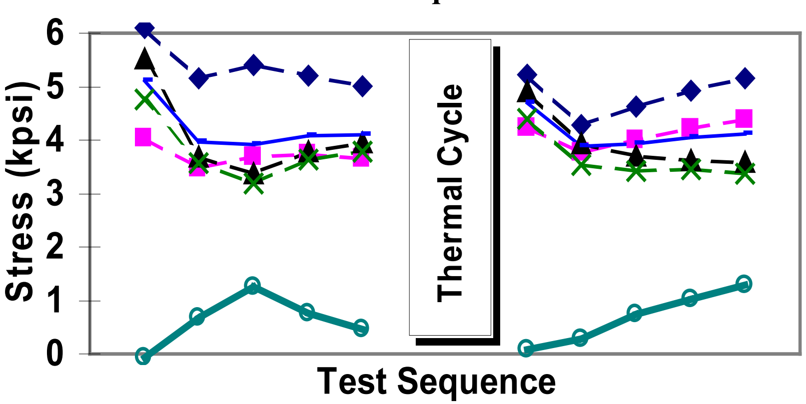
However, during the course of RHIC IR magnet program, it was discovered that the field quality is really limited by magnet not returning to its previous mechanical state. It was found that the harmonics change after quench and thermal cycles. This seems to put the ultimate limit on field quality!

Changes in Mechanical and Magnetic Behavior of RHIC Insertion Dipole

The relative variation in pre-stress and change in field harmonics both seem to be manifestation of the same thing: that the magnet may not be returning to its previous state after a quench or thermal cycle.







[illegible]

Summary

* The expected field quality in accelerator magnets has significantly improved over last decade or so.

* Systematic errors have been significantly reduced due to improvements in magnet designs.

* Systematic errors can be further reduced during the course of production if a flexible design approach is planned as an initial part of the design.

* Random errors have been significantly reduced due to improvements in construction techniques (parts and assembly).

* Many old codes (especially those that do not take into account of magnet symmetry, details of actual magnet construction, etc., tend to significantly over-estimate the expected errors. It is important that we make good estimates of the expected field errors so that machine builders can properly design the machine and determine what kind of corrector system is needed.

* We should examine if magnet costs can be significantly reduced by relaxing parts and manufacturing tolerances.