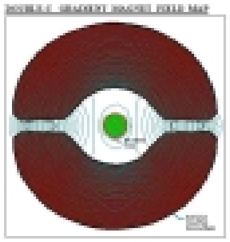
http://vlhc.org/mtworkshop.html

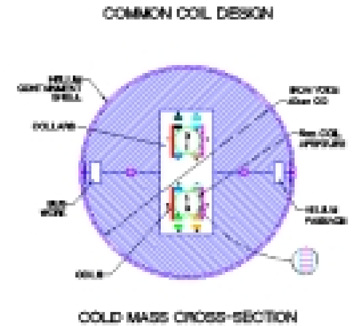
http://seminole.lbl.gov/rgupta/public/Field-Quality-presentation/

For a companion talk, please visit:

http://seminole.lbl.gov/rgupta/public/common-coil-magnet-system-presentation/



Field Quality Aspects of the Different Magnet Designs



FNAL Drawing

BNL Drawing

- **Iron Dominated Designs**

  Good at low field, trouble at high field

- **Conductor Dominated Designs**

  Good at high field, trouble at low field

Update on Field Quality

At a similar meeting some time ago, we over-estimated field errors in SSC magnets.

The technology and understanding of the field has improved since then. We should take advantage of that.

To make the above statement more credible, I would present mostly the measured data (in superconducting magnets) and review and explain the progress in the magnet technology in the field quality area.

Major Sources of Field Errors

- Superconductor Magnetization (persistent current induced)
- Iron Magnetization (saturation induced)
- Geometric (imperfect magnetic and tooling design)

❖ Iron Dominated Designs

(Good at low field, trouble at high field)

– Low Field conventional.

– Medium Field Superferric.

❖ Conductor Dominated High Field Designs

(Good at high field, trouble at low field)

– Cosine theta (penalty of experimental data).

– Block Type (yet to be demonstrated).

Field Quality in Iron Dominated Magnets

STATUS REPORT ON THE TRANSMISSION LINE MAGNET

G.W. Foster,
Fermi National Accelerator Laboratory, PO Box 500 Batavia IL 60510
September 29, 1997

Low Field:

A few parts in 10^{-4} up to

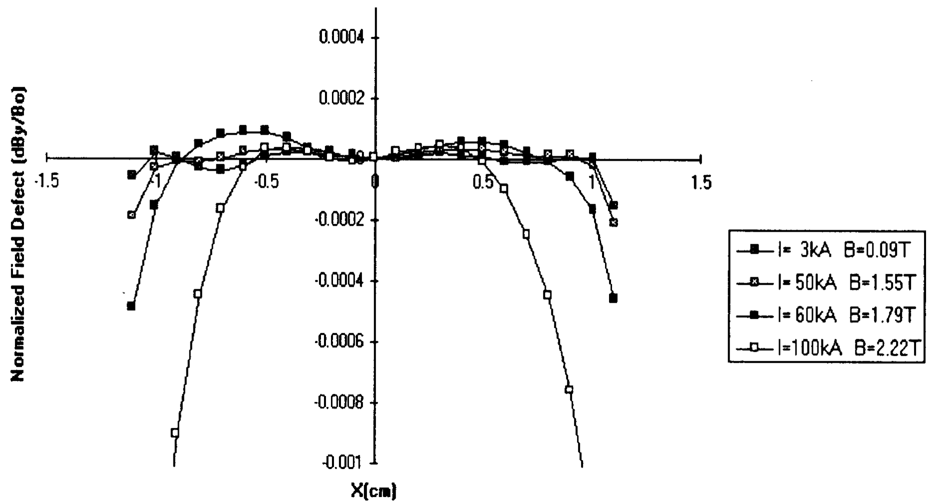
~70% of horizontal aperture.

High Field (2T):

A few parts in 10^{-4} up to

~50% of horizontal aperture.

Field Defect vs. Excitation Crenelated Gradient Dipole



Review of Field Quality in SC Magnets

Major improvements in last 10-15 years

>> Not just 10-20% but by several factors !!!

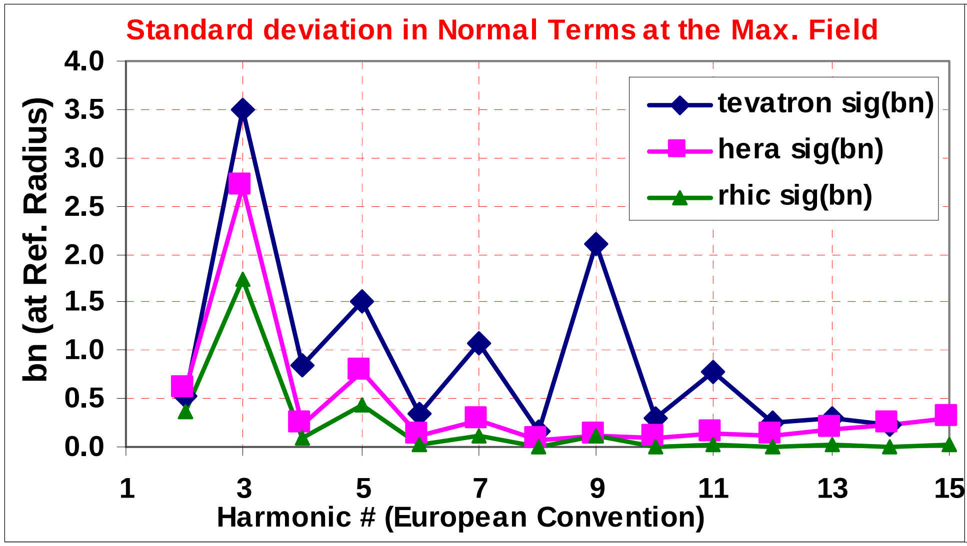
Most of this presentation (specially on SC magnets) will deal with the field quality measurements in "*actual magnets*";

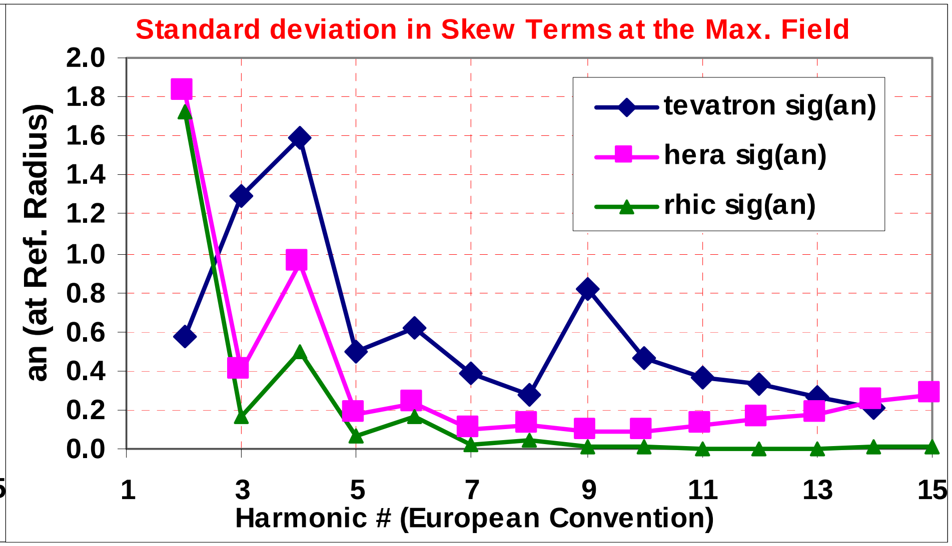
and not just the theoretical expectations.

First a brief overview and then a more detailed discussion.

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 Errors

Saturation in RHIC Arc Dipoles

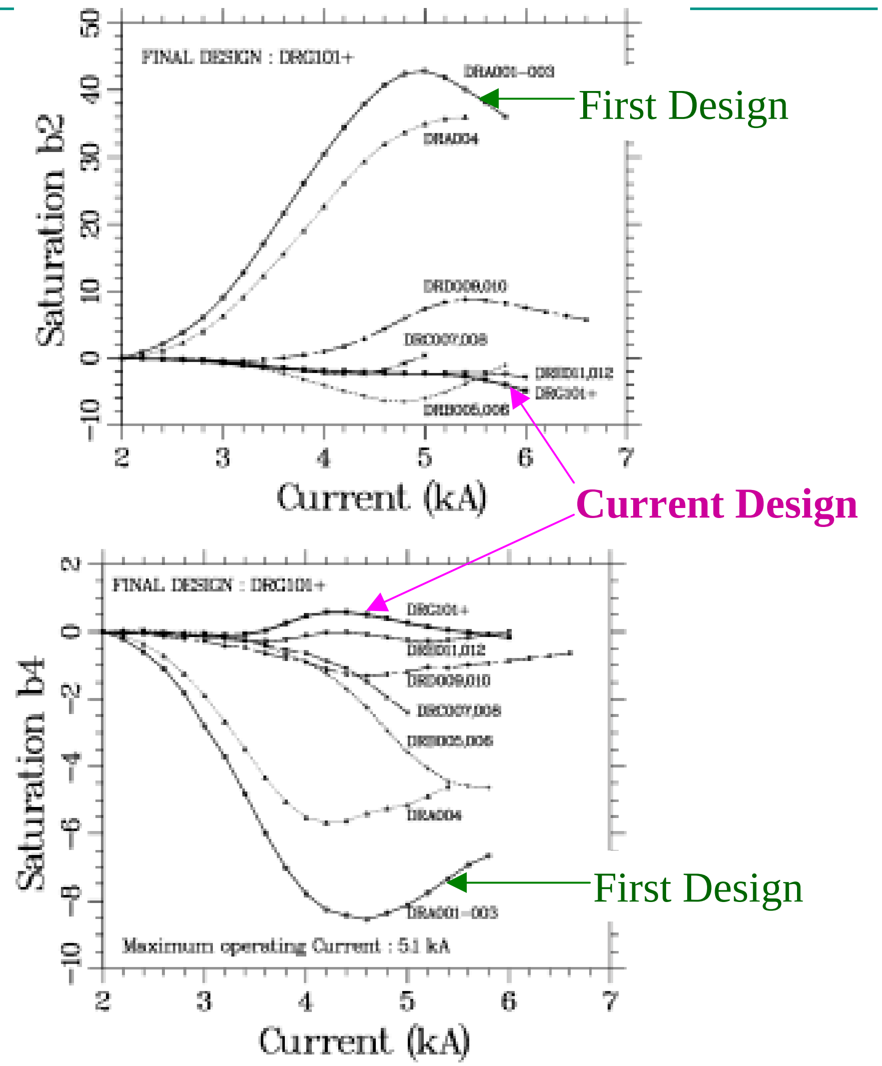
BERKELEY LAB

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)

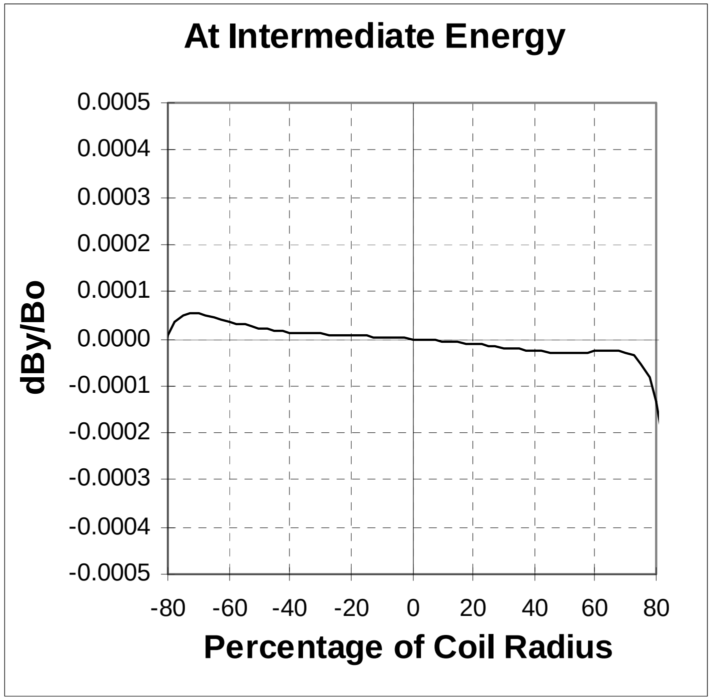


Average Field errors ~10^{-4} up to 80% of the coil radius

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

Coil X-section was not changed between 1st prototype and final production magnet

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

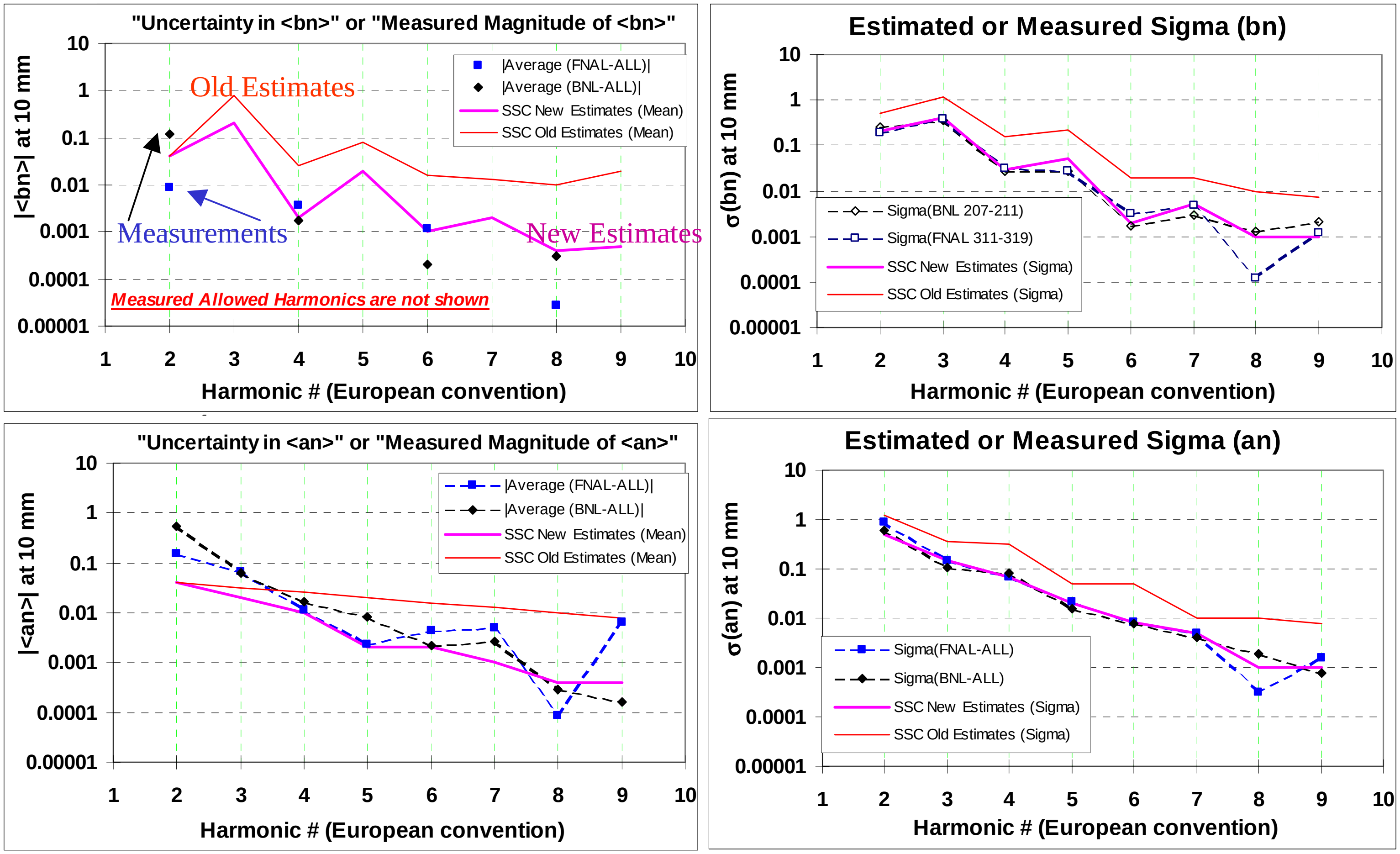
Field errors are 10^{-4} to 80% of the aperture at midplane.

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

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



The best in field quality with tuning shims
A few parts in 10^{-5} at 2/3 of coil radius

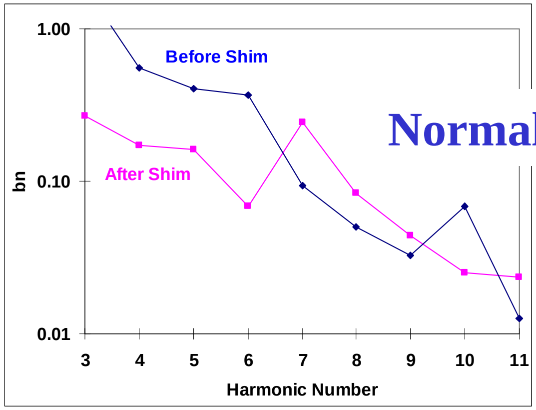
Field Quality in RHIC Insertion Quadrupoles
Improvements in field errors with tuning shims:

Summary of field quality in QRK magnets
(With Shims: only magnets since the sextant test included)
Harmonics in *units* at 40 mm (0.615 x coil radius)

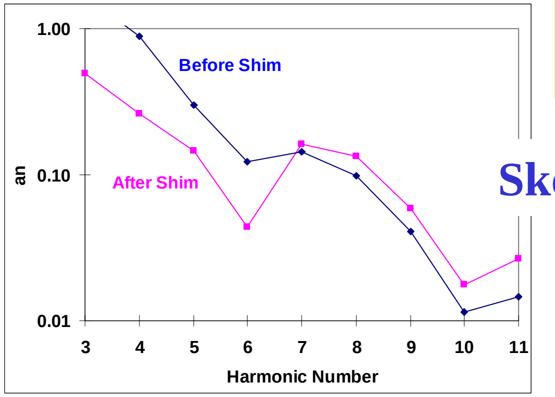
n	$\langle b_n \rangle$ (n=3:Sextupole)			$\sigma(b_n)$		
	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets
3	0.58	-0.17	0.30	1.87	0.47	0.27
4	-0.11	-1.21[a]	0.02	0.56	0.23	0.17
5	-0.18	0.05	-0.12	0.40	0.13	0.16
6	2.68	0.48[b]	0.59[b]	0.37	0.08	0.07
7	0.01	0.02	-0.01	0.09	0.25	0.24
8	-0.25	-0.11	-0.14	0.05	0.09	0.08
9	-0.02	-0.02	0.01	0.03	0.02	0.04
10	-0.10	-0.32	-0.20	0.07	0.03	0.03
11	0.00	0.00	0.01	0.01	0.02	0.02

[a] Non-zero mean to account for warm-cold difference and saturation.
[b] Non-zero mean to account for lead end effects.

n	$\langle a_n \rangle$ (n=3:Sextupole)			$\sigma(a_n)$		
	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets
3	1.24	-0.18	0.09	1.67	0.56	0.50
4	-0.38	0.04	-0.01	0.88	0.27	0.26
5	-0.02	0.00	0.06	0.30	0.14	0.15
6	-0.21	-0.07	-0.13	0.12	0.05	0.04
7	-0.01	0.05	-0.02	0.14	0.27	0.16
8	0.01	-0.01	0.00	0.10	0.12	0.13
9	0.01	0.01	-0.02	0.04	0.04	0.06
10	0.05	0.05	0.05	0.01	0.02	0.02
11	0.01	0.01	0.02	0.01	0.02	0.03



Normal harmonics



Skew harmonics

<< Plots for RMS errors.

The Mean error in harmonics is generally lower.

Note: Both Mean and RMS errors are a few parts in 10^{-4}.

Harmonic measurements provided by Animesh Jain, BNL

What brought these improvements?

(reporting BNL work, as most of it was done there)

What was <u>not</u> done?

– Specifications for tolerances in parts were <u>not</u> increased.

– Magnet production was <u>not</u> made more complicated.

– Magnets were <u>not</u> made more expensive.

What brought these improvements? (continued)

What was done?

A critical understanding of what is needed to make better field quality magnets was increased and incorporated in the magnetic and tooling design and in the construction process.

- Better tooling, cable size, cable insulation and overall coil size control, together with a better engineering reduced RMS errors.
- Improvements in measurement techniques also reduced RMS errors, as measured (relatively larger gain in higher order terms).
- An objective (and some time innovative), flexible and experimental approach reduced systematic errors and increased confidence that better field quality magnets can be made from the start.
- Support and encouragement from the management to such an Approach.

RELEVANCE TO VLHC MAGNETS

- INVEST EARLY IN THE DESIGN, ANALYSIS AND DEVELOPING TECHNOLOGIES.
- BUILDING MORE MAGNETS DOES NOT NECESSARILY BRING LARGER RETURNS IN LONG RUN. SOME TIME, IN PRACTICE, IT MAY EVEN COME IN THE WAY OF PROGRESS AS SCHEDULE PRESSURES MAY REDUCE NECESSARY DESIGN, ANALYSIS AND INNOVATIVE R&D WHICH IS MORE IMPORTANT AT THIS STAGE.
- BETTER FIELD QUALITY NEED NOT NECESSARILY COST MORE.
- USE UP-TO-DATE FIELD QUALITY INFORMATION BASED ON THE LATEST MEASUREMENTS IN MODERN MAGNETS FOR VLHC MACHINE (AP) STUDIES.

Now the Details
Three magnets with similar apertures

Tevatron Dipole
(76.2 mm bore)

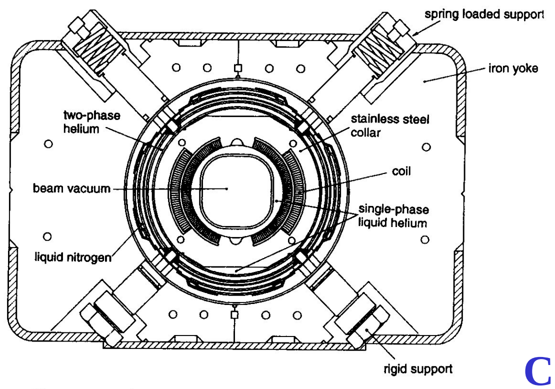
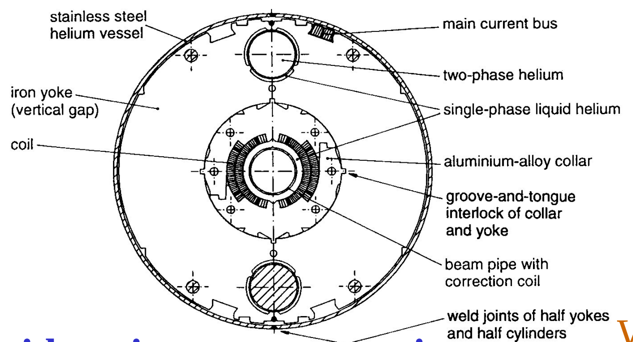
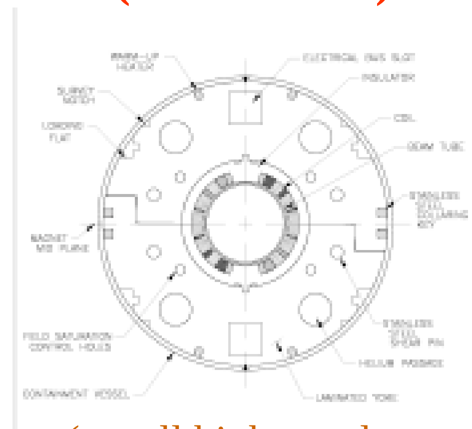


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

HERA Dipole
(75 mm bore)



RHIC Dipole
(80 mm bore)



Consideration on systematic errors

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

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

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.

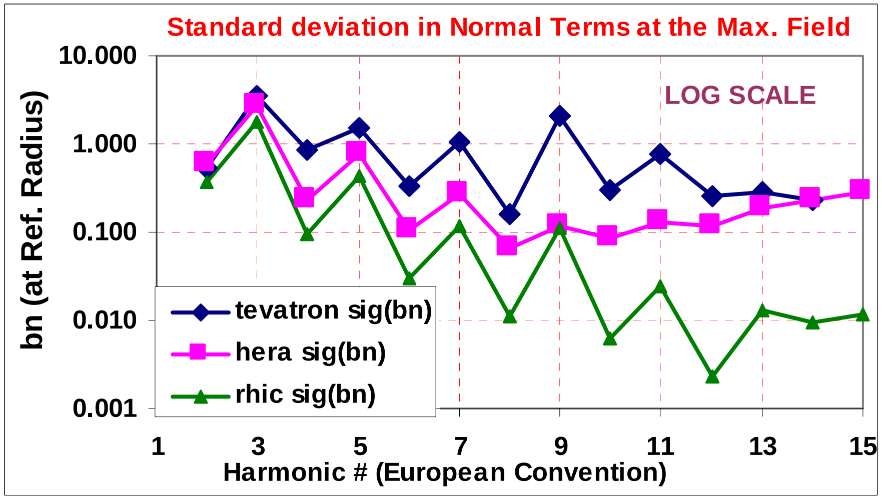
Why? The answer changes the way we look at the impact of mechanical errors on field quality !

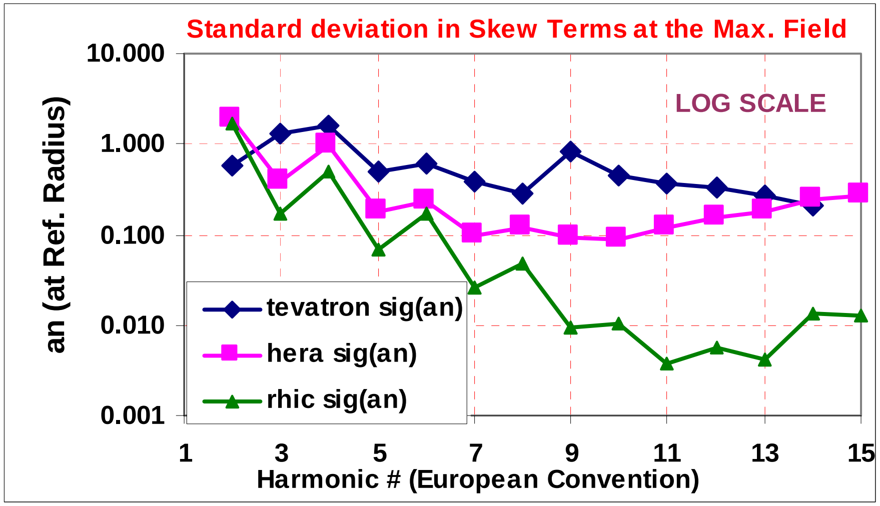
Comparison of Field Quality in Tevatron, HERA and RHIC dipoles

(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

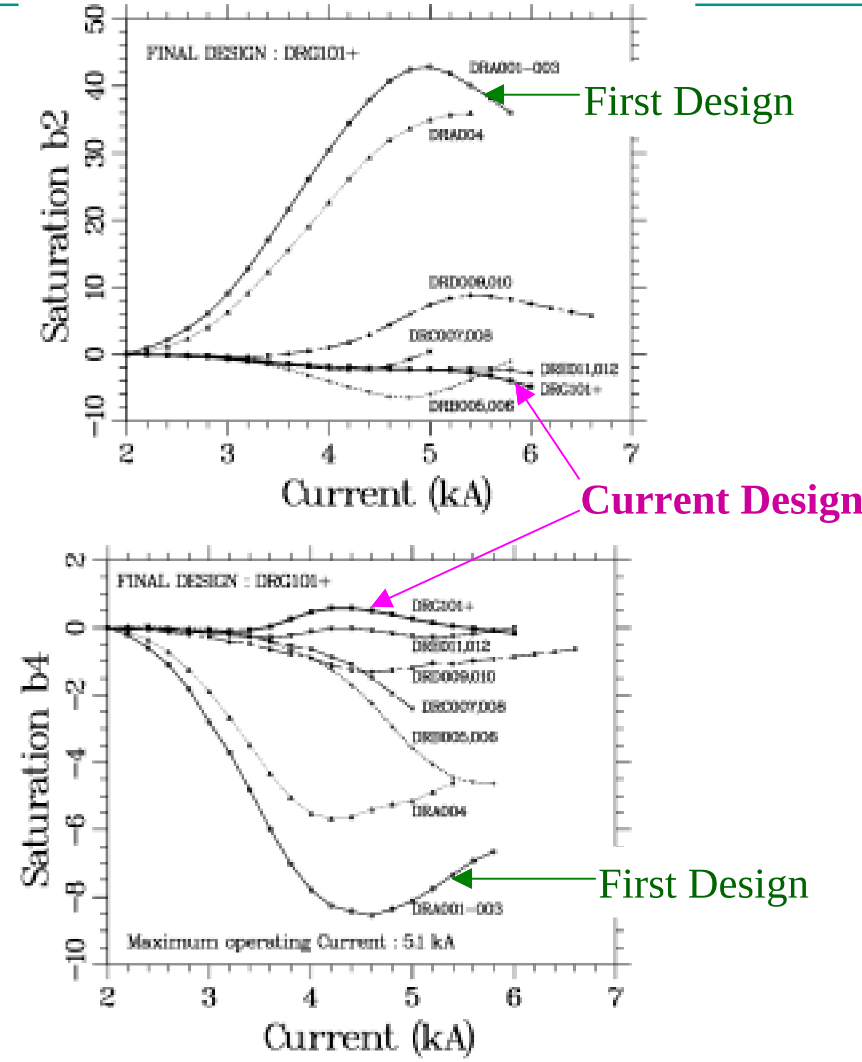




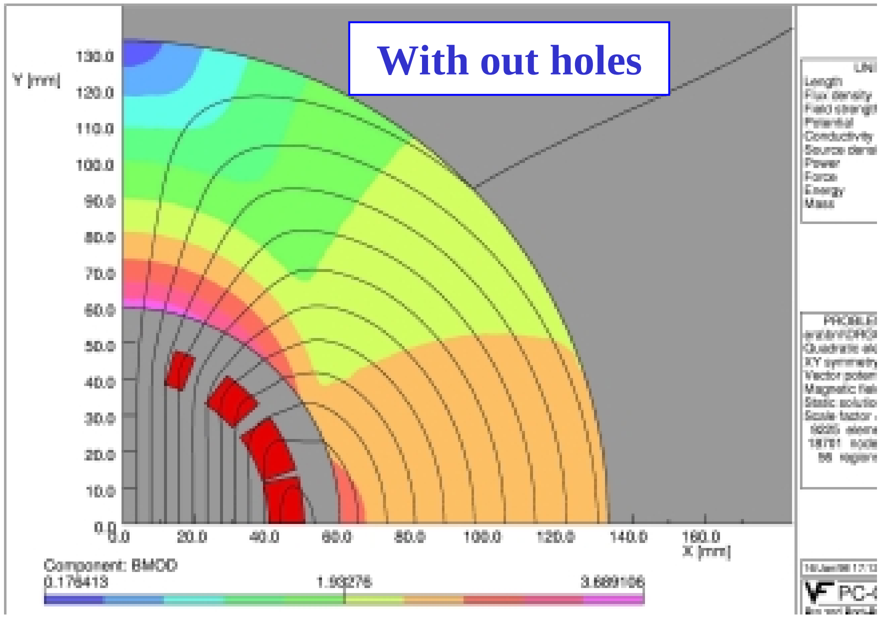
RHIC has lower sigmas (except for a2 where tevatron used smart bolts)
Lower Order Harmonics generally due to Construction Errors
Higher Order Harmonics generally due to Measurement Errors

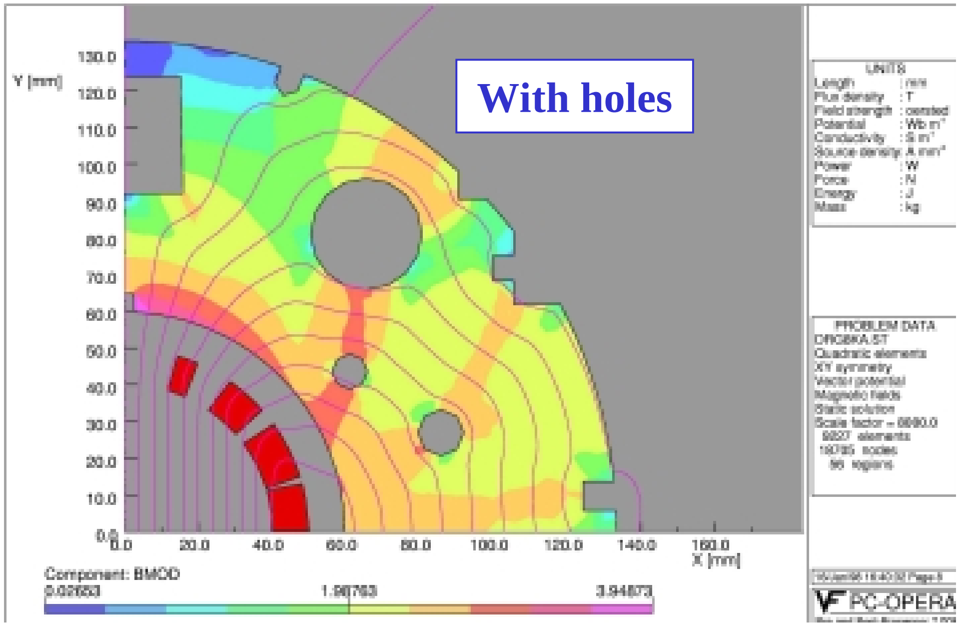
Approach for Reducing Saturation-induced Harmonics in RHIC Arc Dipoles

- An order of magnitude improvement over a period of time (only long magnets are shown here).
- Old approach: iron magnetization is non-linear; remove (reduce) iron from the higher field area.
- Approach used here: non-uniform saturation is bad and <u>not the saturation itself</u>; put holes etc. to increase iron saturation in the lower field area.
- Increase saturation at select places in iron to reduce saturation-induced harmonics. Also experimentally include the harmonics induced from coil deformation due to Lorentz forces.
- Techniques evolved through computer modeling and real magnet tests.
- An experimental approach that changed the conventional wisdom: expect large saturation-induced harmonics in close-in iron magnets.



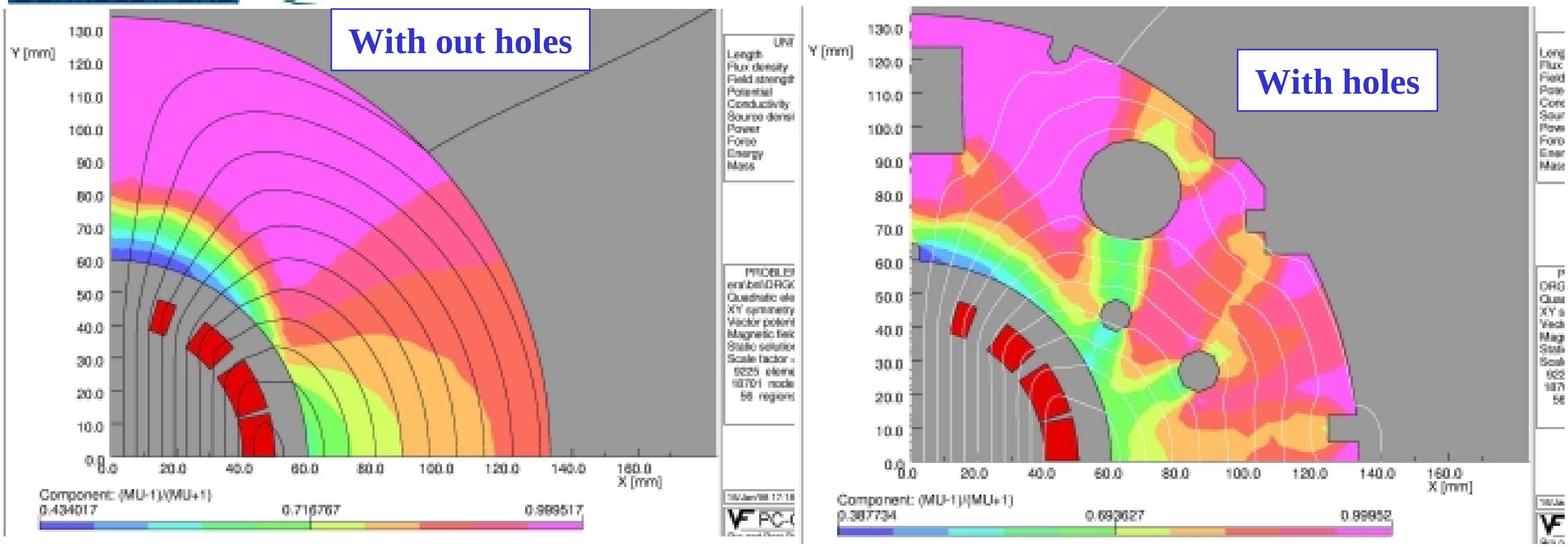
Saturation Control in RHIC Dipoles
Variation in |B| in Iron Yoke





- Compare azimuthal variation in |B| with and without saturation control holes. Holes, etc. increase saturation in relatively lower field regions; a more uniform iron magnetization reduces the saturation induced harmonics.
- Old approach: reduce saturating iron with elliptical aperture, etc.
- New approach: increase saturating iron with holes, etc. at appropriate places.

Saturation Control in RHIC Dipoles
Variation in (μ-1)/(μ+1) in Iron Yoke



- Better to examine (μ-1)/(μ+1) instead of |B|. It appears more in formula, e.g.

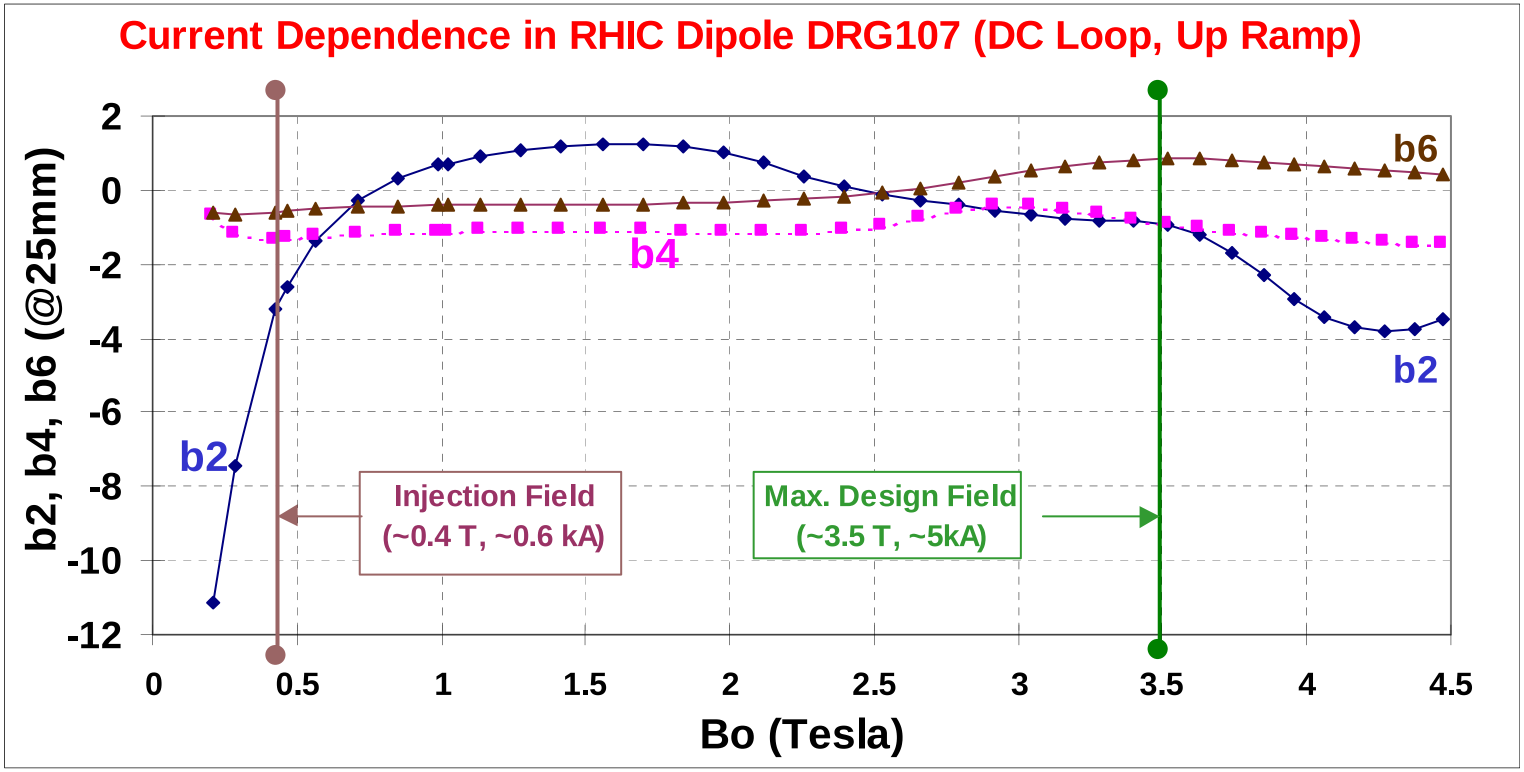
$$B_\theta = \frac{\mu_o I}{2\pi r} + \frac{\mu_o I}{2\pi a}\sum_{n=1}^{\infty}\left(\frac{a}{r}\right)^{n+1} cos\left(n\left(\phi-\theta\right)\right)\left[1-\frac{\mu-1}{\mu+1}\left(\frac{r}{R_f}\right)^{2n}\right]$$

and provides a better scale to compare (see pictures above).

- Compare the azimuthal variation in (μ-1)/(μ+1) with and without saturation control holes, particularly near the yoke inner surface. A more uniform iron magnetization reduces saturation induced harmonics.

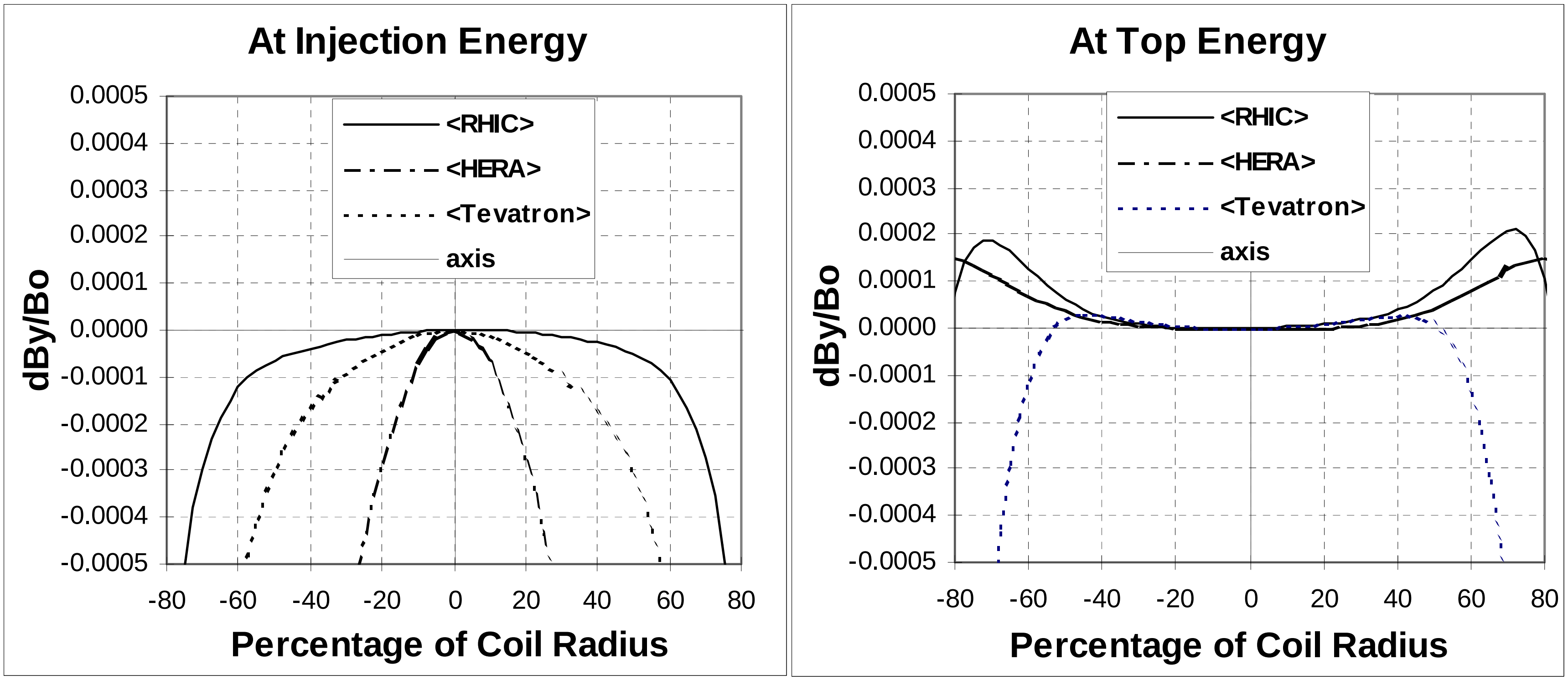
Current Dependence Beyond Design Field

- In all known major accelerator magnets (superconducting and iron dominated), the harmonics fall rapidly beyond the maximum design field. They are relatively flat in this design approach . Please note the difference in scale (50 units in previous slides in b_2 plots). It (a) shows a major impact of this design approach on field quality and (b) may have relevance to RHIC upgrade as most magnets in RHIC have ~30% quench margin over the maximum design field.



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.

Geometric Errors

- The RHIC dipole coil cross-section was optimized for small b_2 at design field and small b_4 at injection (yoke was optimized for small variations in between). The final phase of dipole production showed that on the average both were much smaller than the geometric tolerances (25 micron or 1 mil) in parts. Even a 10 micron systematic error in the critical wedge would have generated larger systematic harmonic errors than measured.
- The RHIC magnet design philosophy was based on a flexible approach where a mid-course correction in the manufacturing could be easily applied without disrupting the production. This approach accommodated geometric errors in individual parts, kept production line moving smoothly and made magnets with average field errors less than the geometric tolerances in parts.
- RMS errors (shown earlier) were also much smaller than previously thought possible. RHIC dipoles use phenolic RX630 spacers between the coil and iron. This is a critical component which defines coil geometry and hence influences the geometric errors in field harmonics. This component had part to part variation of 2-3 mils instead of 1 mil. However, the RMS errors in RHIC magnets (generated from this and other parts) were much smaller. Explanation: the field errors are smaller than the corresponding mechanical errors in parts thanks to averaging (if the quantity of those components is large) and symmetry effects (if the components are used in a symmetric fashion).
- Conclusion: Both systematic and random geometric field errors in magnets are much smaller than the geometric tolerances in parts.

Recap on Field Quality from the Latest Large Scale Production - The RHIC Dipole Production

- Reduction in random errors despite RX630 spacers (due to symmetry and averaging effects). Also the coil manufacturing and magnet tooling played a major role.

- Small overall systematic (and can be controlled during production).

- Small current dependence in harmonics despite the close-in iron. The current dependence (and hence saturation-induced harmonics) remains small beyond the design field.

- Such a good field quality means that the corrector magnets are NOT likely to be needed in RHIC for correcting field errors in arc dipoles.

The sextupole magnets will be used for persistent current induced b_2 and for other beam dynamics purpose (chromaticity correction); may also be used for removing a relatively small residual b_2).

On to a New Magnet

What happens when we go to a new magnet?

• Do we have to undertake a long R&D program to obtain a good field quality?

• In my opinion, that would be only a partial success of this experience.

• Ultimate in success: attempt to get the good field quality in the first magnet itself.

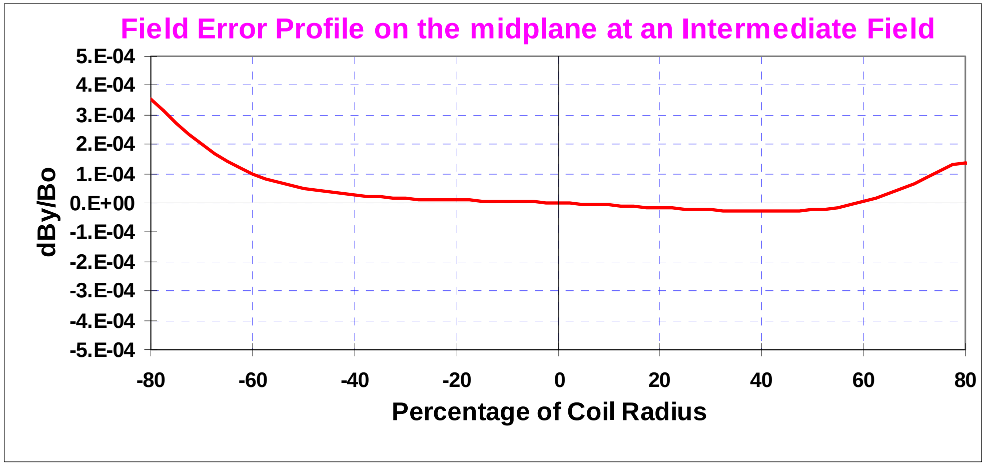
(A crazy and daring notion at that time; some thing never thought possible before)!

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.

What happens in a typical first magnet?

1. Pre-stress (and/or effective cable thickness) is not right by a significant amount. An attempt to get right compression messes up field quality.

2. Higher order harmonics are OK but lower order are not (generally first <u>two</u>).

> ➢ *Need 1+2 = 3 parameters to fix the above three quantities.*

But usually we are almost there: measured harmonics are 10^{-3} instead of required 10^{-4} . And corresponding relative mechanical errors are small as compared to the overall coil dimensions.

What is generally done?

Change cross-section (change wedges, cable size, coil tooling, etc.) which makes mechanical changes relatively large. As a result the process becomes time consuming and expensive and due to a large change it does not always converge in one iteration.

What was done in RHIC Insertion dipoles?

Approach used in RHIC insertion dipoles for faster progress (Goal: attempt to make the first magnet itself a field quality magnet):

- A flexible design (opposite to fixing parameters ASAP).
- Geometric: midplane caps, pole shims and wedge insulation.
- Saturation control: Holes in the iron, later filled with iron rods.

Moke up model showed wrong pre-stress and harmonics, as usual.

- Fixed in the first magnet assembly itself and obtain the desired pre-stress and small body harmonics.

- Used the adjustments (as planned and outlined above). The above adjustments were further used in later magnets for compensating end harmonics and for reducing measured current dependence (saturation-induced) in harmonics.

- The above adjustments are faster and cheaper than normal cross-section iterations. The coil cross-section was specified before the first magnet was tested and was never changed during production.

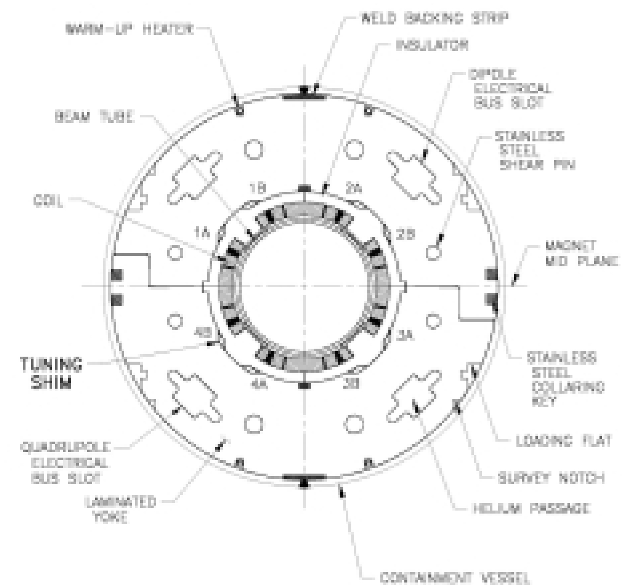
This shows the progress, confidence and the field getting matured.

The RHIC IR Quadrupoles
(The best field quality magnets ever built)

<u>At first glance, a very unlikely cross-section for building the best field quality magnet</u>

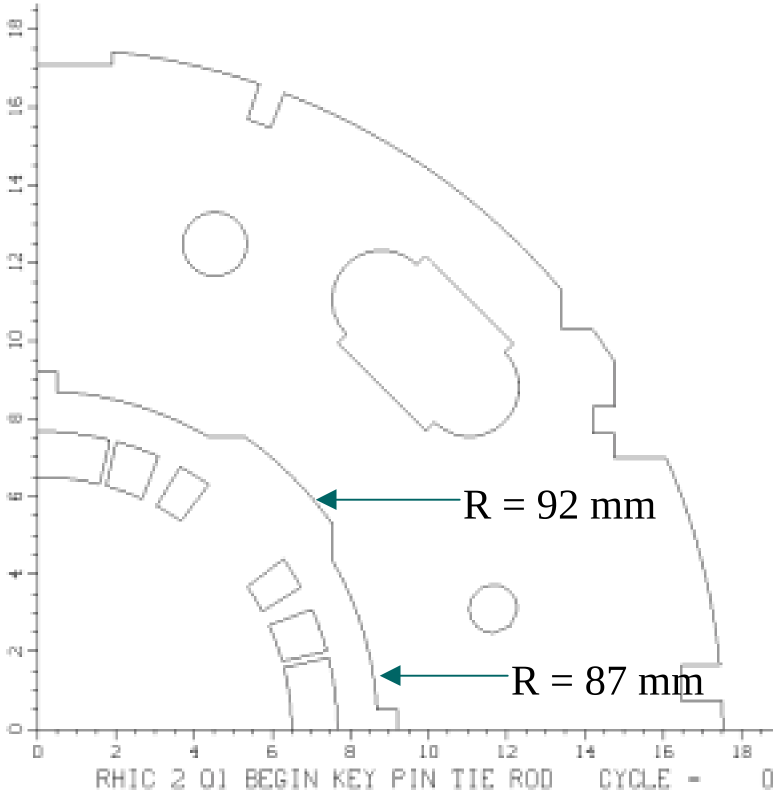
- Doesn't have the basic 4-fold quadrupole symmetry (large non-allowed harmonics).
- Close-in iron (large saturation-induced allowed harmonics).
- Uses RX630 spacers -large errors in parts (large geometric harmonics).

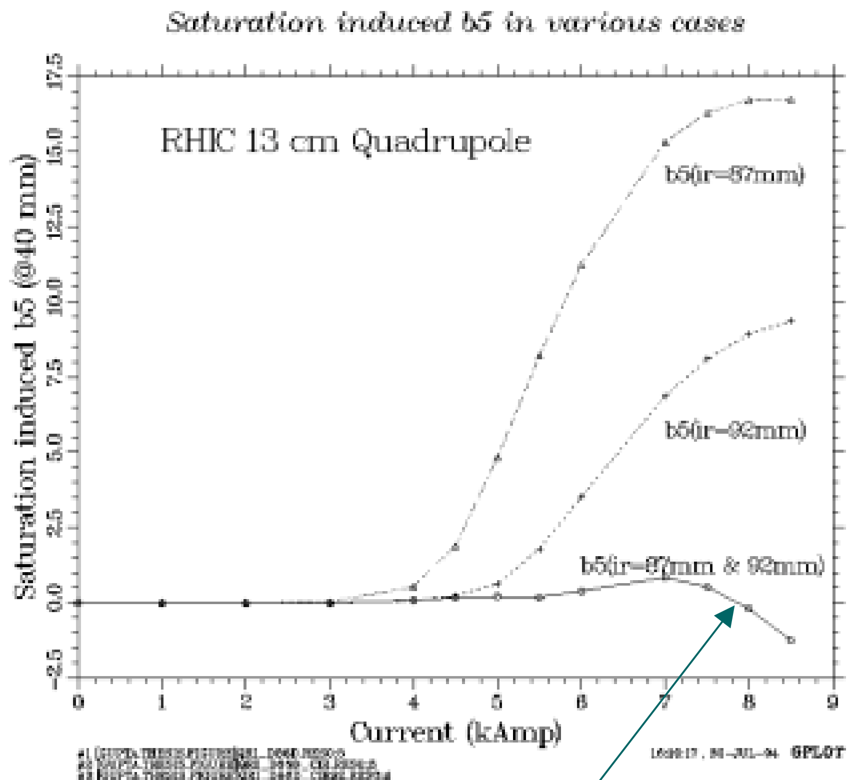
Moreover, it started out with ~ 1 mil uncertainty in insulation thickness (or effective cable thickness).
- Total ~27 mils (order of magnitude more than the typical 2 mil) in overall coil dimensions for 27 turns.
- Conventional thinking : Fix cable first.
- Done here : A flexible design which can absorb such large differences. This approach was used during production also for several adjustments in harmonics.



Cross section of the 130 mm aperture RHIC insertion quadrupole

Saturation control in RHIC IR Quad





Optimized design

POISSON model of a quadrant of the 130 mm aperture RHIC Insertion quadrupole.

Since the holes are less effective for controlling saturation in quads, a 2-radius method was used.

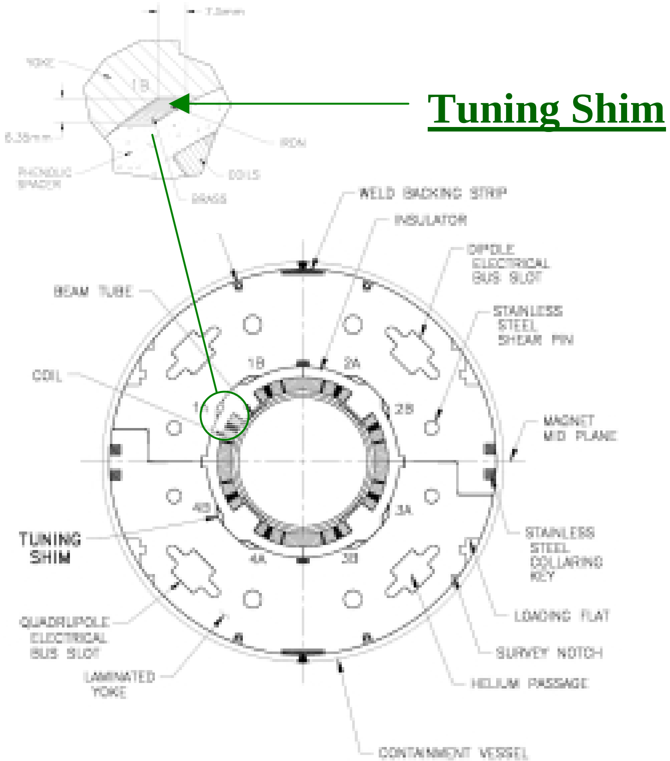
Tuning Shims for 10^{-5} Field Quality at 2/3 of coil radius

GOAL : Make field errors in magnets much smaller than that is possible from the normal tolerances.

Basic Principle of Tuning Shims:

Magnetized iron shims modify the magnet harmonics.

Eight measured harmonics are corrected by adjusting the amount of iron in eight Tuning Shims.



Procedure for using tuning shims in a magnet:

1. Measure field harmonics in a magnet.

2. Determine the composition of magnetic iron (and remaining non-magnetic brass) for each of the eight tuning shim. In general it would be different for each shim and for each magnet.

3. Install tuning shims. The tuning shims are inserted without opening the magnet (if the magnet is opened and re-assembled again, the field harmonics may get changed by a small but a significant amount).

4. Measure harmonics after tuning shims for confirmation.

Ultimate Field Quality in SC Magnets

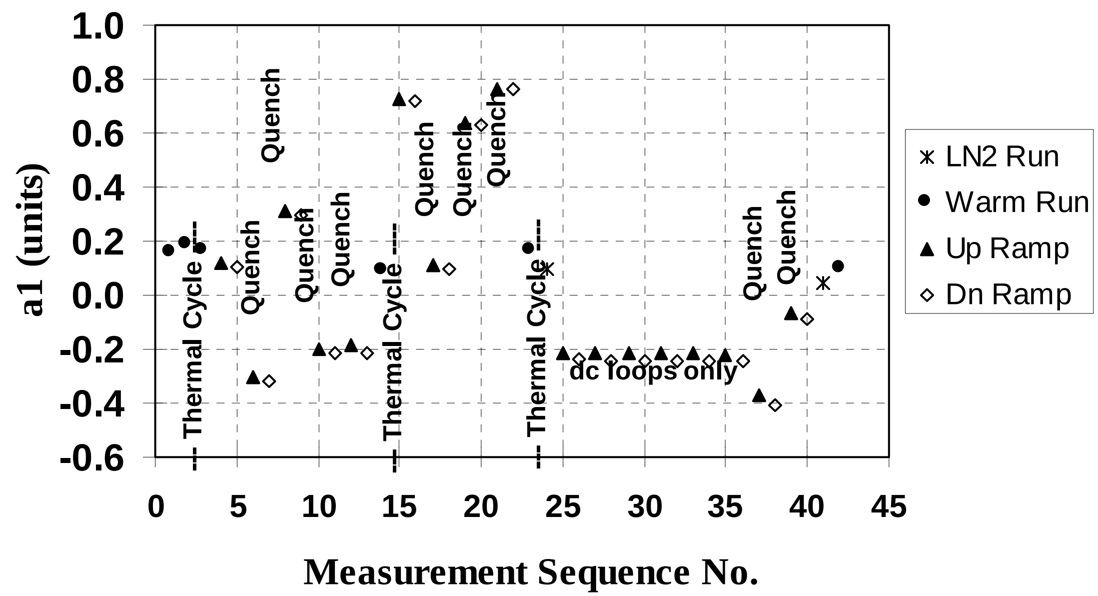
A magnet properly designed with "Tuning Shims" should theoretically give a few parts in 10^5 harmonics at 2/3 of coil radius (i.e. practically zero).

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.



Measured skew quadrupole harmonic in 100 mm aperture RHIC insertion dipole after repeated quench and thermal cycles. It appears (a possible explanation) that the harmonics change from a mechanical shock resulting from the quench and thermal cycles. Harmonics do not change during simple up and down ramps (dc loops) which do not produce such shocks. The change in the allowed b_2 harmonic showed a monotonic behavior.

Lessons from SSC Magnet Program

Never built a single field quality dipole magnet

- old conventional thinking style that
  - (a) it can not be done.
  - (b) fix other parameters first.

This contributed to retaining inaccurate estimates for a long time and to the conclusions drawn on the basis of those estimates.

However, built several 50 mm prototype magnets

– all wrong, but most by "a similar amount" ("important").

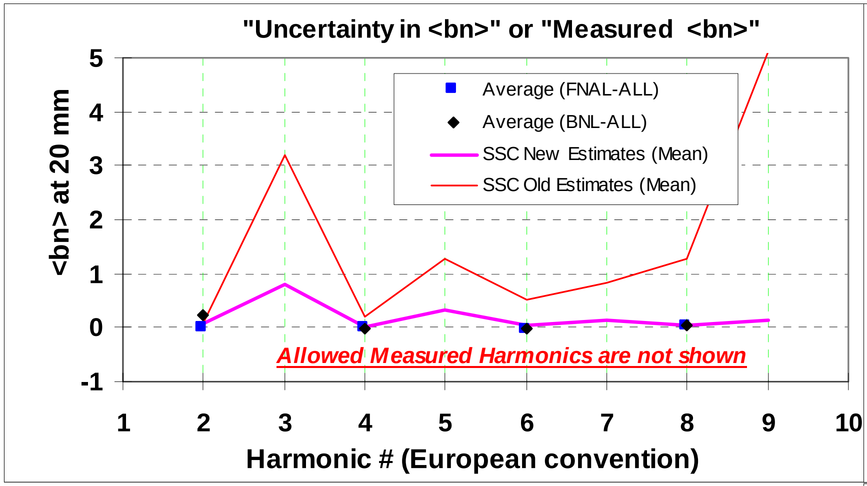
Therefore, the results (measurements) are appropriate for objectively evaluating/reviewing

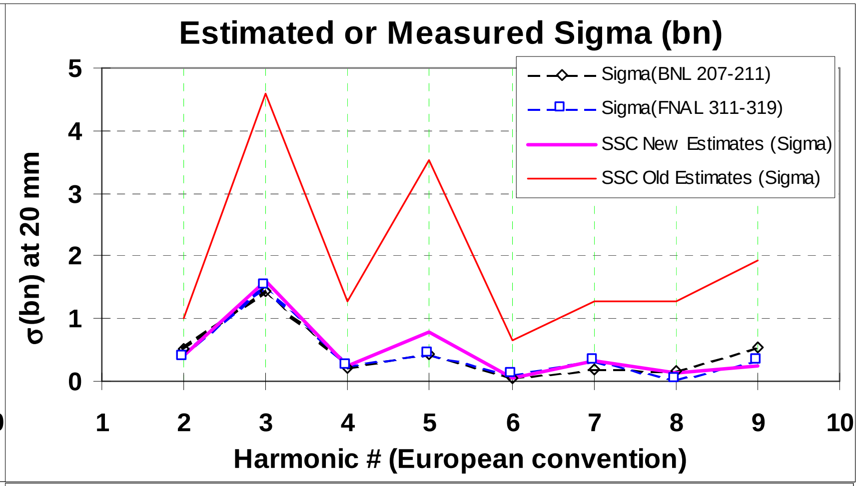
• RMS (superimposed over systematic) errors in field harmonics.
• systematic errors in most non-allowed harmonics.

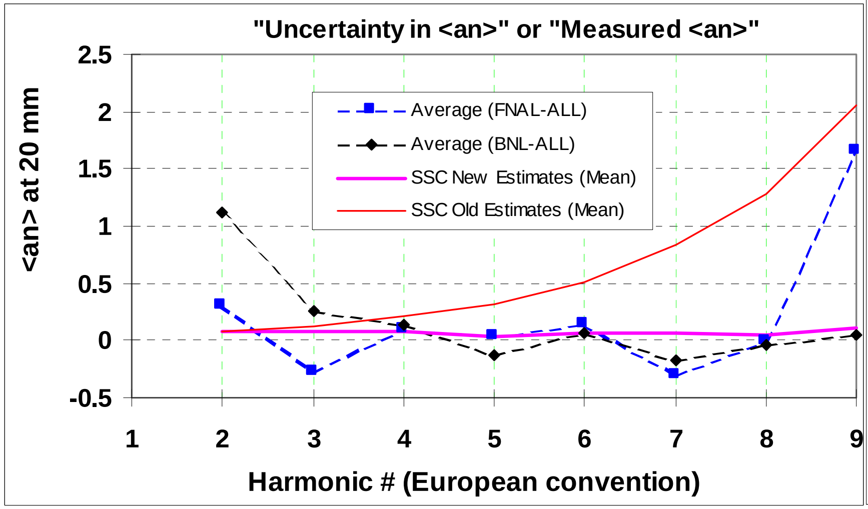
Field Errors in SSC dipoles

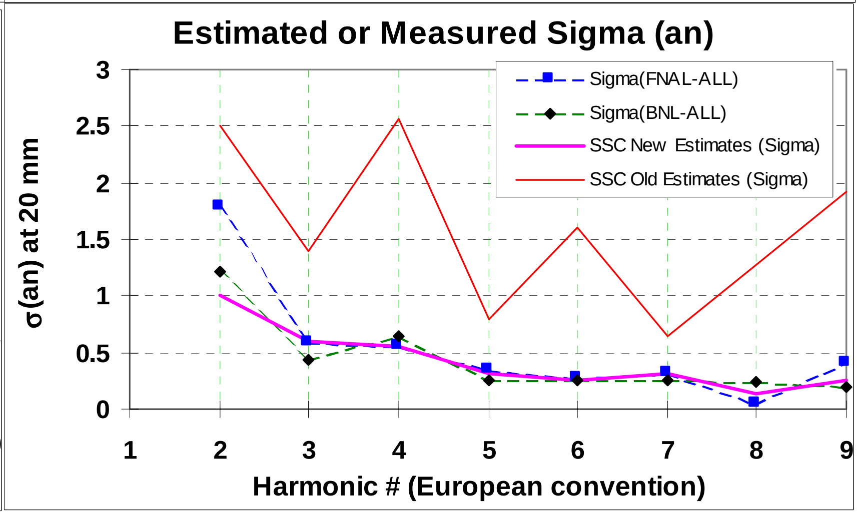
How off we were from reality?

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





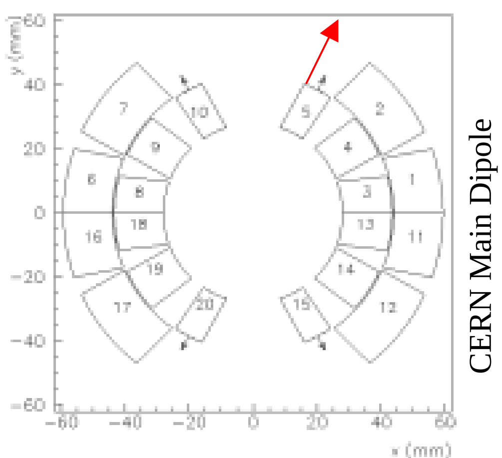




Why were we so wrong in estimating field errors in SSC dipoles?

Popular Models

Generally there are 25-50 micron (1-2 mil) error in parts and construction. Therefore, allow this kind of positional error in each of several blocks of conductor (see picture below) and then sum the resultant field errors in an RMS sort of way.



CERN Main Dipole

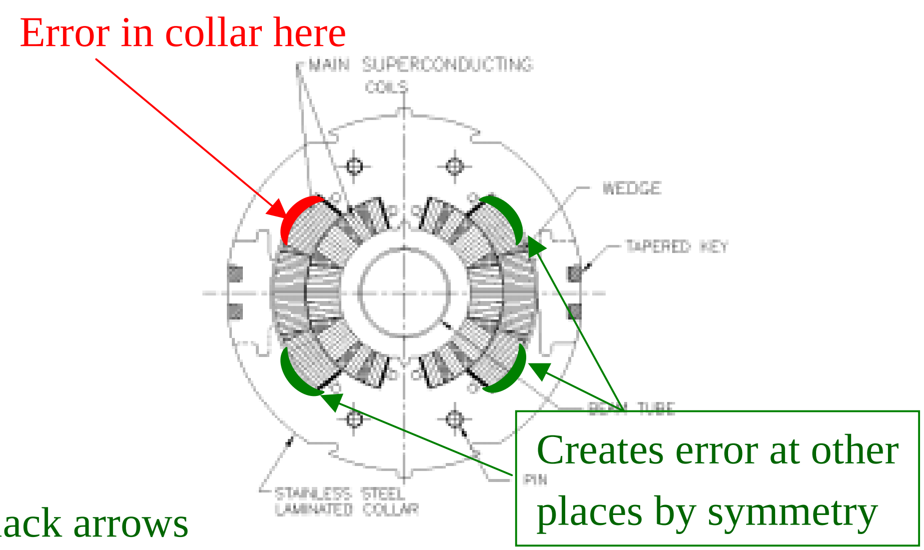
Movement in popular models: one red arrow

Symmetric model: 4 black arrows

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

Current Thinking (personal opinion)

The errors in parts do not necessarily translate to the error in field harmonics. The effect gets significantly reduced from averaging and symmetry considerations. For example consider how a systematic or random error in collar, wedge, cable, coil curing plays in a real magnet.



Improvements in Iron Dominated Magnets

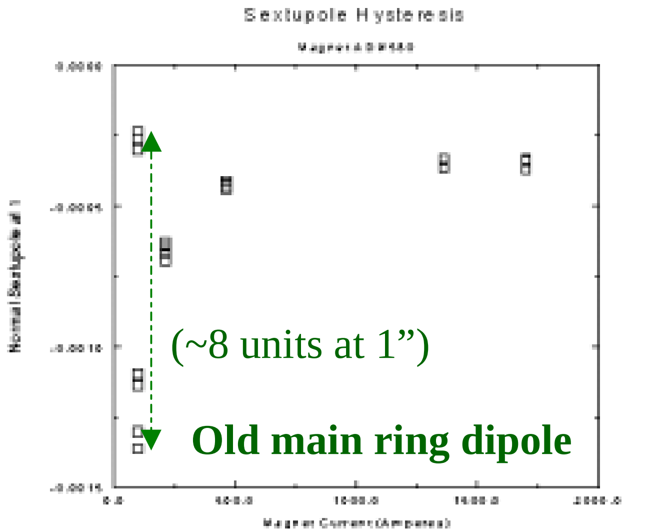


Figure 1: Normalized sextupole harmonics for a portion of the body of a Main Ring B1 dipole at transverse center. Injection field is about 400 Gauss at a current of about 97 A. All measurements are on an up ramp except for the more positive values shown at 97 A which are measured on a down ramp after a ramp to full field.

Magnet Series	Sext Up 400 g	Sext Down 400 g	Sext diff 400 g
ADM (B1)	-7.5E-4		
BDM (B2)	-4.6E-4		
ODM (B3)	-1.0e-4		
IDC	-1.15E-4	-1.15e-4	0.8E-6

Table II: Summary of mean values of the normalized sextupole harmonics at 0.04 T for a various series of accelerator dipole designs.

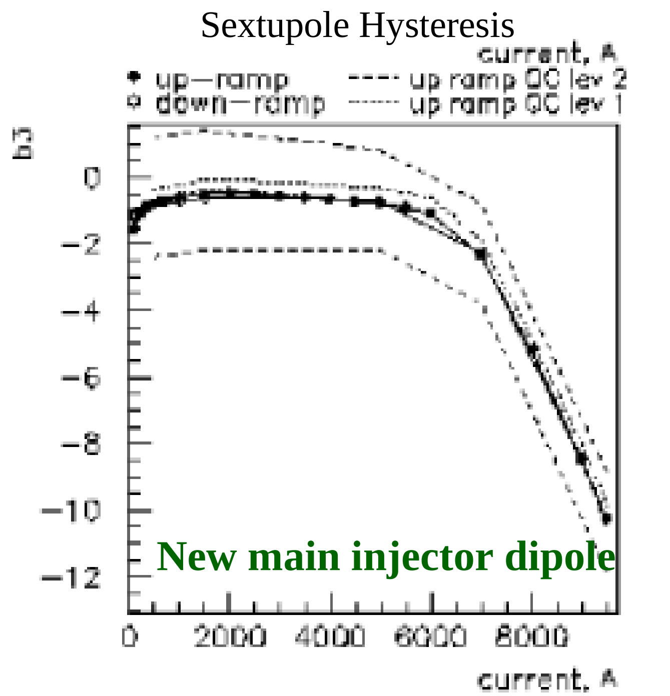
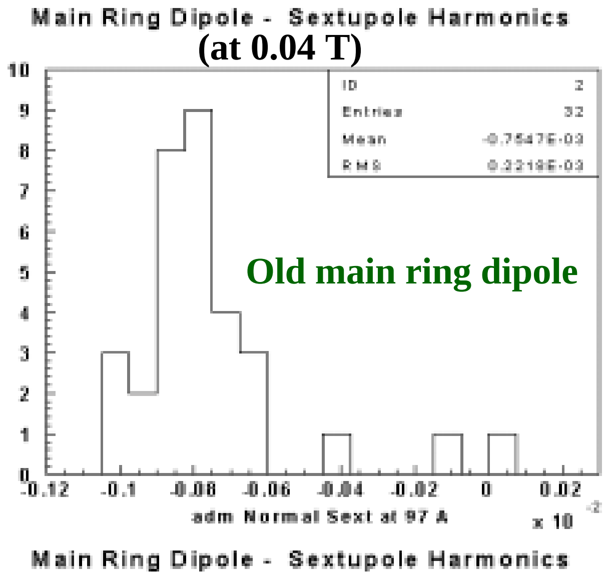


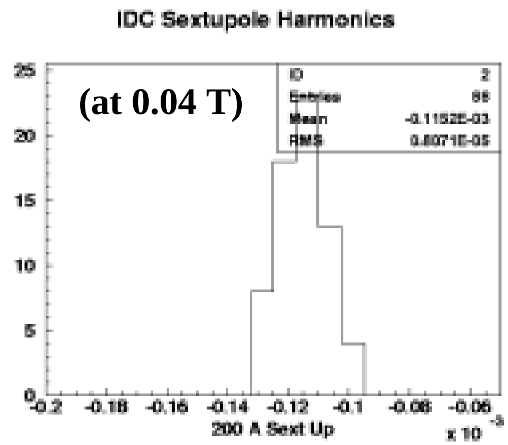
Figure 2: Normalized sextupole harmonics $\times 10^4$ at 1" reference radius integrated through Main Injector dipole IDC028-0. Injection is at 1000 Gauss at a current of 500 A. Measurements with a full length probe are taken at the fixed currents plotted with both up ramp and down ramp measurements shown. At most currents, the hysteretic fields produce a slightly more positive sextupole on the down ramp. Solid and dashed line are limits on the magnet-to-magnet variability expected based on previously measured dipoles.

- Data from Bruce Brown, FNAL. He claims that the main injector dipoles have shown that in iron dominated magnets now one can go to field as low as to 0.04 T (rather than 0.1 T), as the low field hysteresis errors are significantly reduced.

- AP issues?

Improvements in Iron Dominated Magnets (continued) - Comparison at 0.04 T (400G)





New main injector dipole

Figure 5: Histogram of normalized sextupole field at 200 A excitation for Main Injector IDC dipoles. Magnets prepared with 3 ramps to full field with resets to 0 A before ramp to 200 A for this measurement.

Data from
Bruce Brown, FNAL.

Can one can go to field as low as to 0.04 T for injection (rather than 0.1)?

If yes from field quality point of view, then how about the accelerator physics (AP) issues?

FNAL Main Ring Dipoles
Aperture: 3 inch X 5 inch

Sextupole at 1 inch
(40% of horizontal aperture)
$<b_2> \sim 1$; $\sigma(b_2) \sim 1.6$

FNAL Main Injector Dipoles
Aperture: 2 inch X 6 inch

Sextupole at 1 inch
(33% of horizontal aperture)
$<b_2> \sim 1.2$; $\sigma(b_2) \sim 0.08$

***Harmonic measurements are reliable up to b_6 (14 pole), as per Brown.**

Texas A&M Block Dipole (McIntyre)
(Current Programming to control saturation)

Current programming in three coil currents keeps the computed field harmonics within 1.5 parts in 10,000 at 10 mm reference radius over the entire operating range.

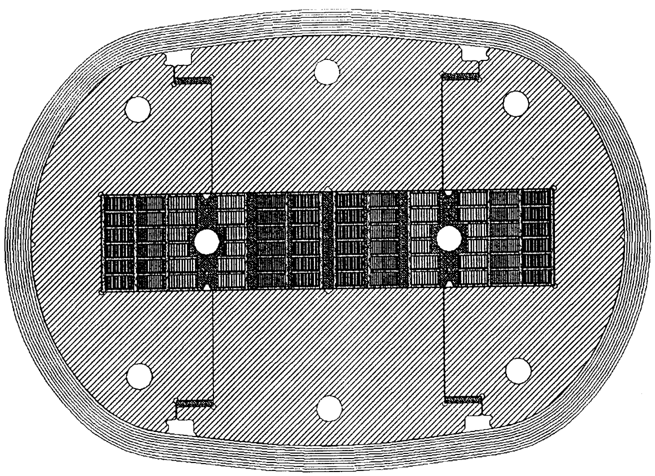


Figure 3. Block-coil Nb_3Sn dual dipole, vintage 1997.

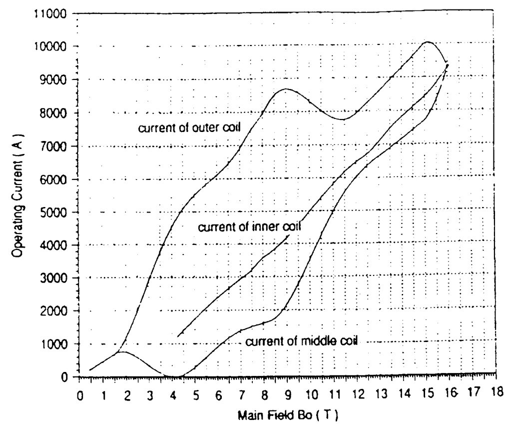


Figure 8. Current programming of three coil currents to produce optimum field quality.

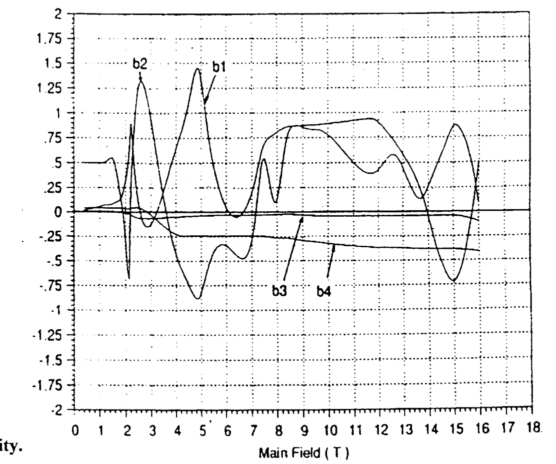
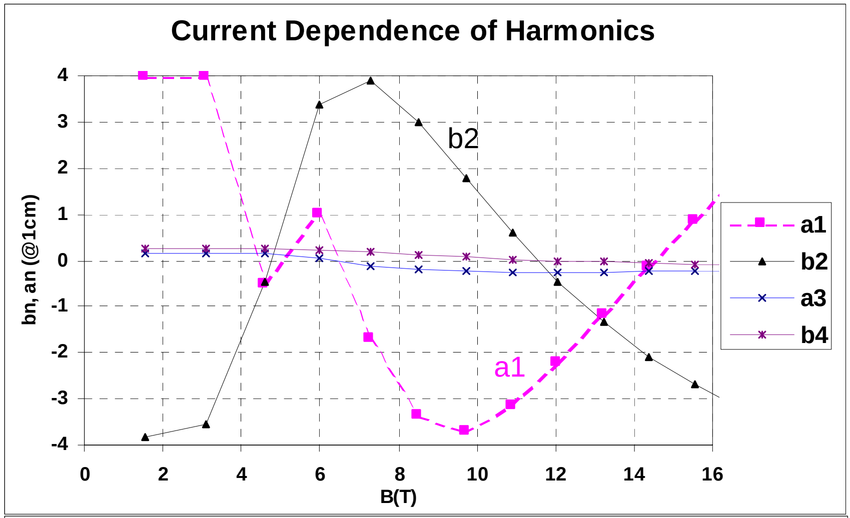


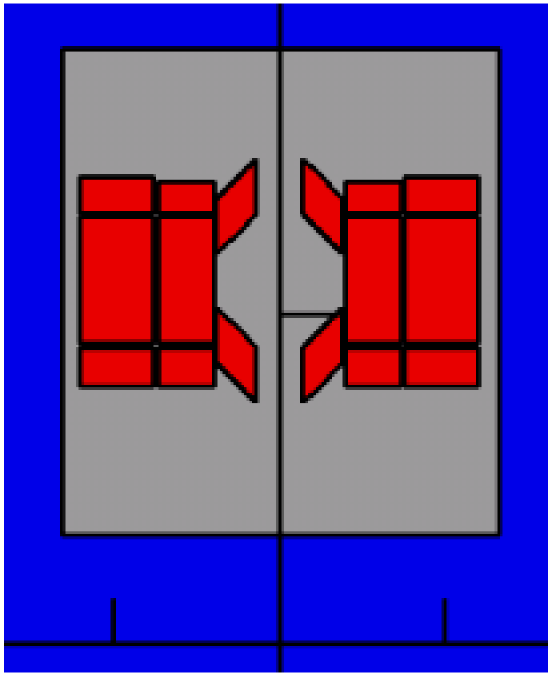
Figure 9. Calculated multipoles in the block dual dipole with current programming.

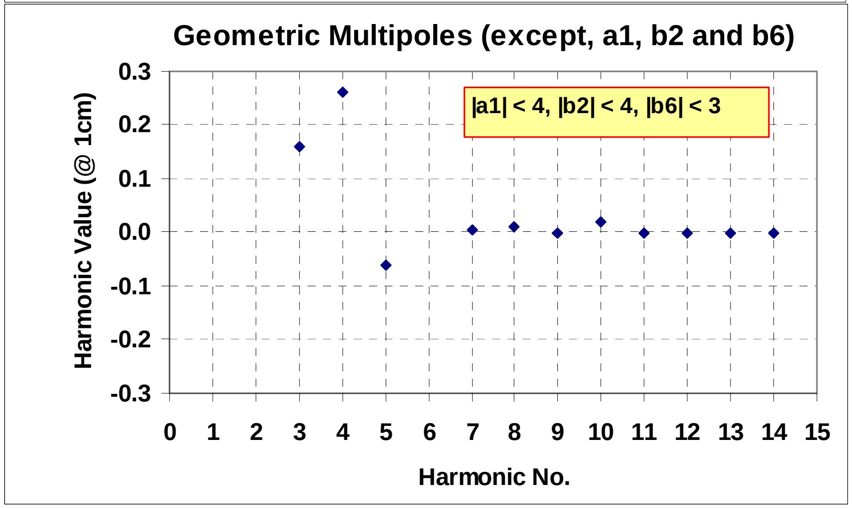
Preliminary Calculations in a Common Coil Design Magnet

A preliminary hand optimized design shows that even without any saturation control hole for reducing current dependence and without any wedge for reducing geometric harmonics, the harmonics are within 4 unit with a single power supply over the entire range.



Post Workshop Update: One wedge and adjustments in block positions generates a cross-section where all geometric harmonics are less than 2 parts in 10^5 at 10 mm reference radius.





Persistent Current-induced Harmonics

(may be a problem in Nb_3Sn magnets, if done nothing)

Nb_3Sn, with the technology under use now, is expected to generate persistent current-induced harmonics which are a factor of 10-100 worse than those measured in Nb-Ti magnets (due to about a factor of two higher critical current density and about a factor of 10 higher effective filament diameter). In addiction, a snap-back problem is observed when the acceleration starts after injection at study state (constant field).

Garber, Ghosh and Sampson (BNL)

Persistent current induced magnetization :

$$2\mu_0 M = 2\mu_0 \frac{2}{3\pi} \nu J_c d \quad (1)$$

J_c , CRITICAL CURRENT DENSITY

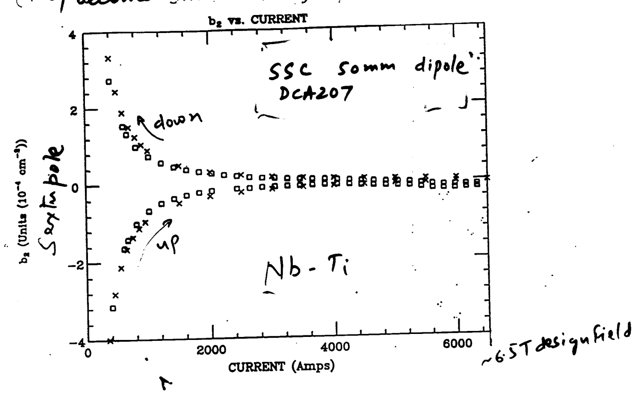
d , FILAMENT DIAMETER

ν , VOL. FRACTION OF NbTi

$$M_s = M/\nu \quad (2)$$

Measured of sextupole harmonic in Nb-Ti magnet

Persistant current induced harmonic depends on the property of superconductor (They become small at high fields) gupta



Measured of sextupole harmonic in Nb_3Sn magnet

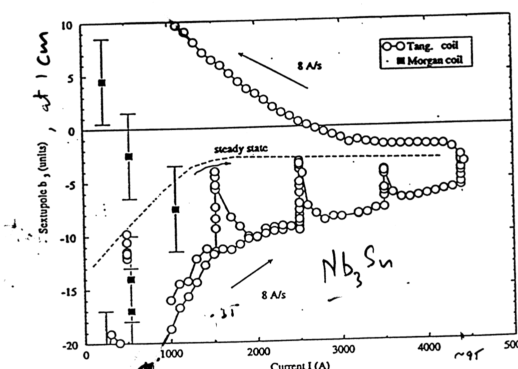


Fig. 6. Measured sextupole at low field (direction of arrow indicates up or down current).

LBL D20 50mm Dipole
World Record holder: 13.5
(@ 6700A)

Measured magnetization

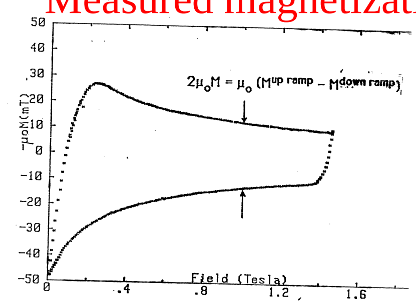


Fig. of a typical magnetization loop.

Acknowledgements

Most of the work on field quality in superconducting magnets reported here was done with my colleagues at the Brookhaven National Laboratory (BNL). I would like to take this opportunity to acknowledge all of them. In particular, Mike Anerella, Mike Harrison, Animesh Jain, Steve Kahn, Gerry Morgan, Pat Thompson, Peter Wanderer and Erich Willen played a major role in various ways (direct contribution, discussion, feedback, encouragement, etc.). Thanks. – Ramesh.

Summary and Conclusions

* This talk presented a sample of a few techniques (in reality a lot more was done), which have brought a significant (both in a qualitative and in a quantitative way) advances in the field quality in accelerator magnets.

* A design and analysis approach (which quite often ran against the conventional wisdom) worked well because of a systematic and experimental program.

* From a general guideline on field quality for VLHC (in reality, it is yet to be developed and should be done in close collaboration between accelerator physicists and magnet scientists, the RHIC model). However, it appears that all magnet designs should be useable in VLHC from field quality considerations.

* However, one should not take it for granted; a consistently good field quality in RHIC magnets was a result of several things. Moreover, it can be further improved with more innovative ideas. Given the time available for the next machine this is the time to explore the ways for reducing magnet costs while maintaining a field quality that is acceptable for VLHC . Conversely (and perhaps together), one should also examine if magnet costs can be reduced significantly by relaxing parts and manufacturing tolerances.