For earlier talks on
Field Quality and on
Common Coil Magnets,
please visit:
http://vlhc.org/mtworkshop.html

Review of Field Quality in Accelerator Magnets

Ramesh Gupta, LBNL

VLHC Workshop on Accelerator Physics
Lake Geneva, Wisconsin
Feb. 22-25, 1999

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.

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:

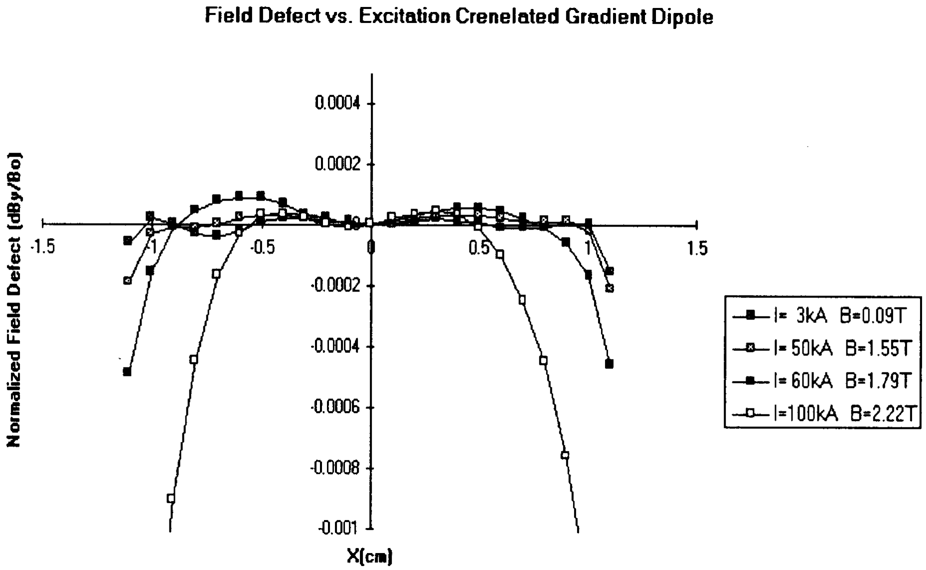
A few parts in 10^{-4} up to

~70% of horizontal aperture.

High Field (2T):

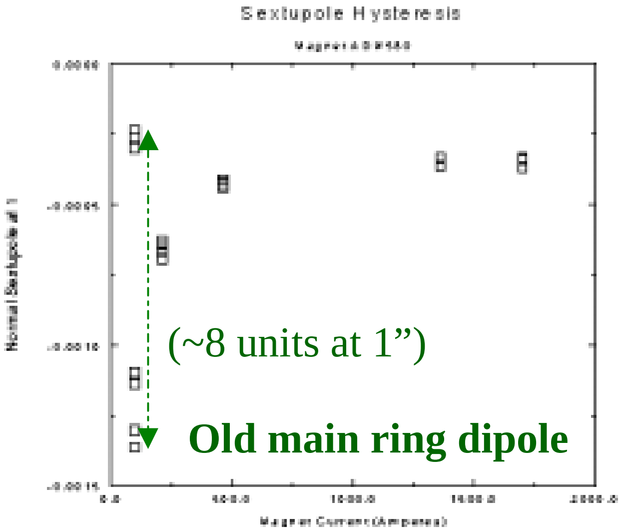
A few parts in 10^{-4} up to

~50% of horizontal aperture.



Field Defect vs. Excitation Crenelated Gradient Dipole

Improvements in Iron Dominated Magnets



(~8 units at 1”)

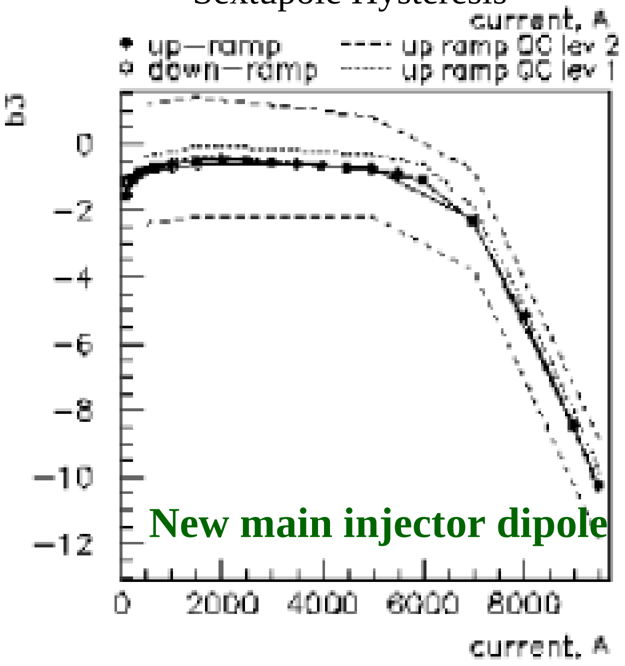
Old main ring dipole

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	Sext Down	Sext diff
	400 g	400 g	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.

Sextupole Hysteresis



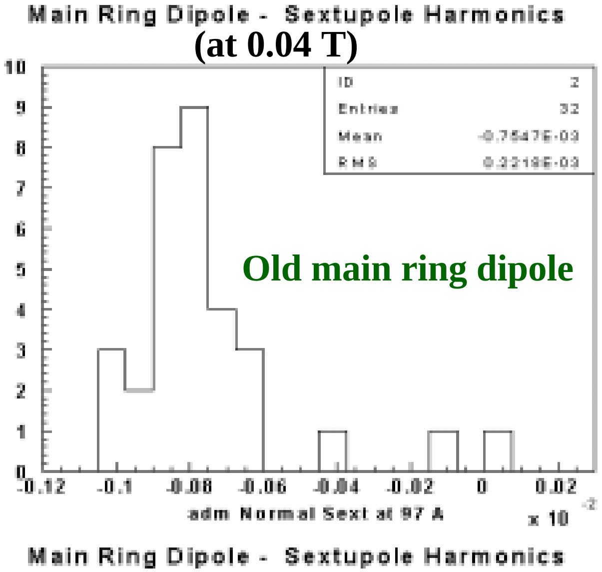
New main injector dipole

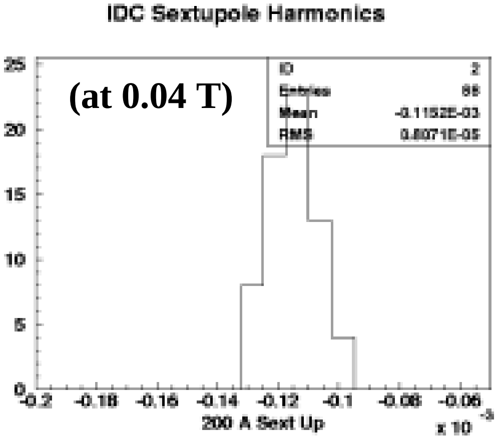
Figure 2: Normalized sextupole harmonics $\times 10^4$ at 1″ reference radius integrated through Main Injector dipole IDC023-0. Injection is at 1000 Gauss at a current of 500 A. Measurements with a full length probe are taken at the fixed currents plotted with both up ramp and down ramp measurements 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)
$\langle b_2 \rangle \sim 1$; $\sigma(b_2) \sim 1.6$

FNAL Main Injector Dipoles
Aperture: 2 inch X 6 inch

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

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

Review of Field Quality in SC Magnets

Major improvements in last 10-15 years

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

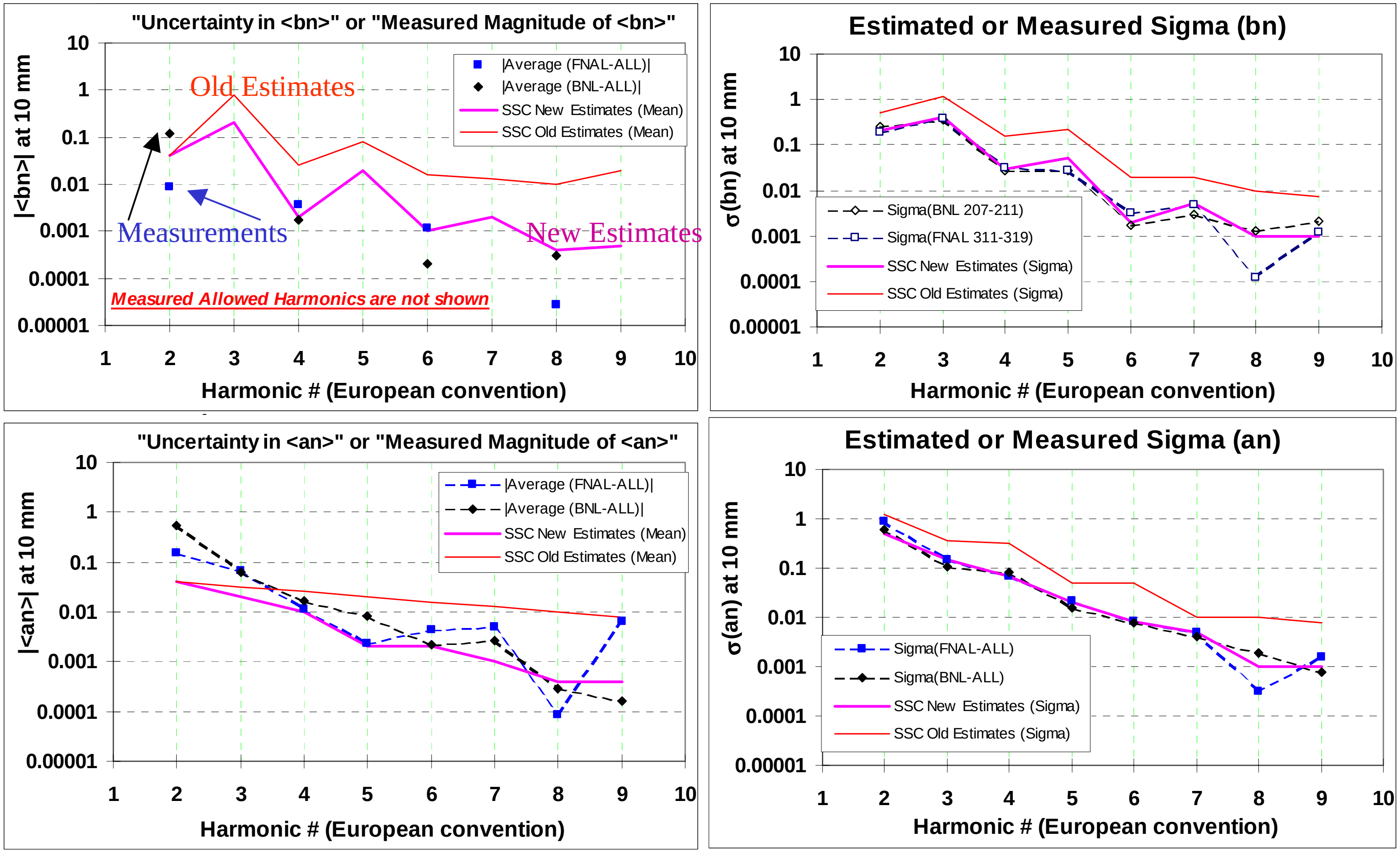
Most of this presentation (specially on SC magnets) will deal with the field quality measurements in "*actual magnets*";

and <u>not</u> just the theoretical expectations.

Field Quality in SSC Magnets (Lab built prototype dipoles)

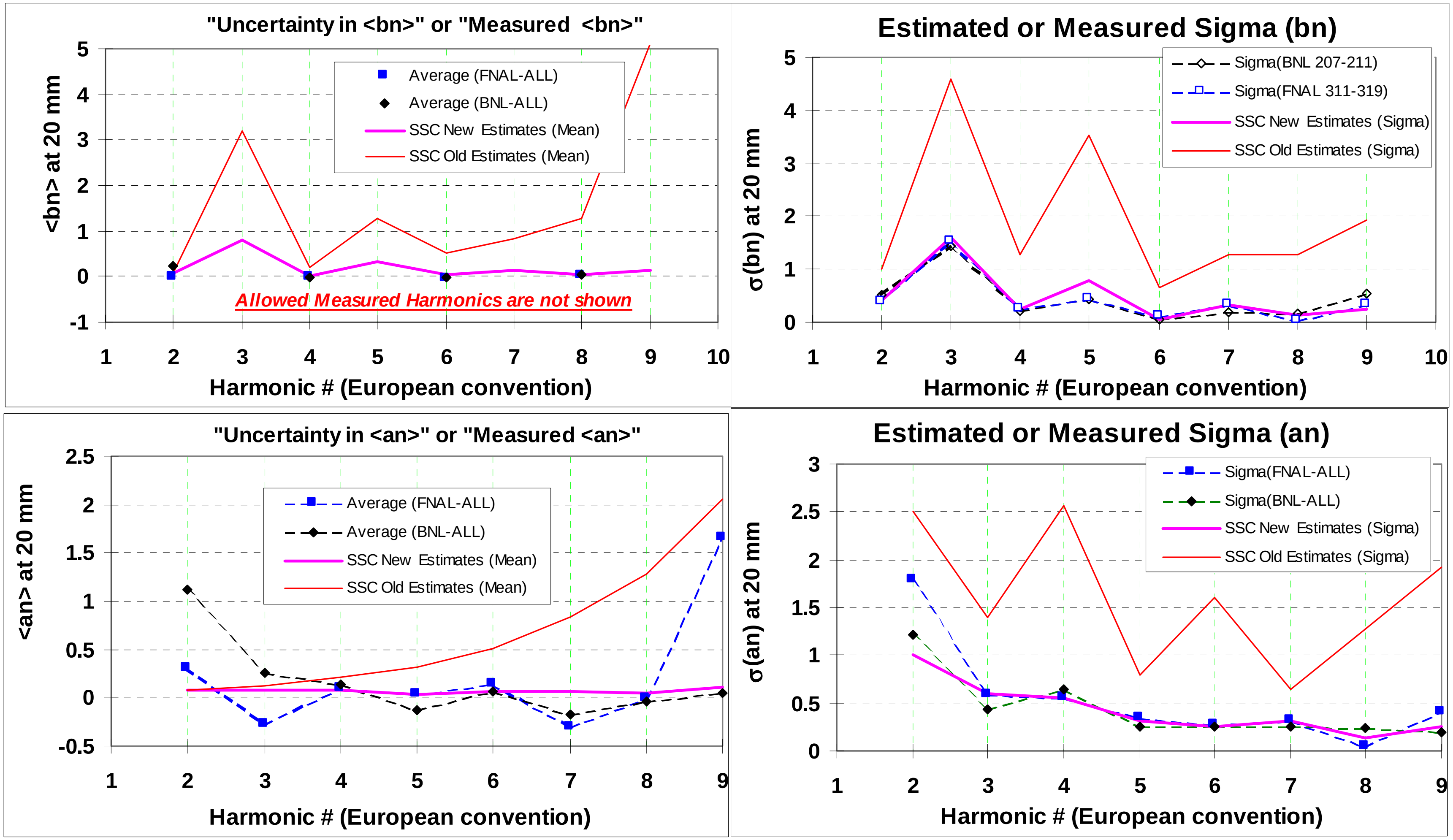
Note:
A general improvement by a factor of 3-10.

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



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)


"Uncertainty in <bn>" or "Measured <bn>"

Allowed Measured Harmonics are not shown

Estimated or Measured Sigma (bn)

"Uncertainty in <an>" or "Measured <an>"

Estimated or Measured Sigma (an)

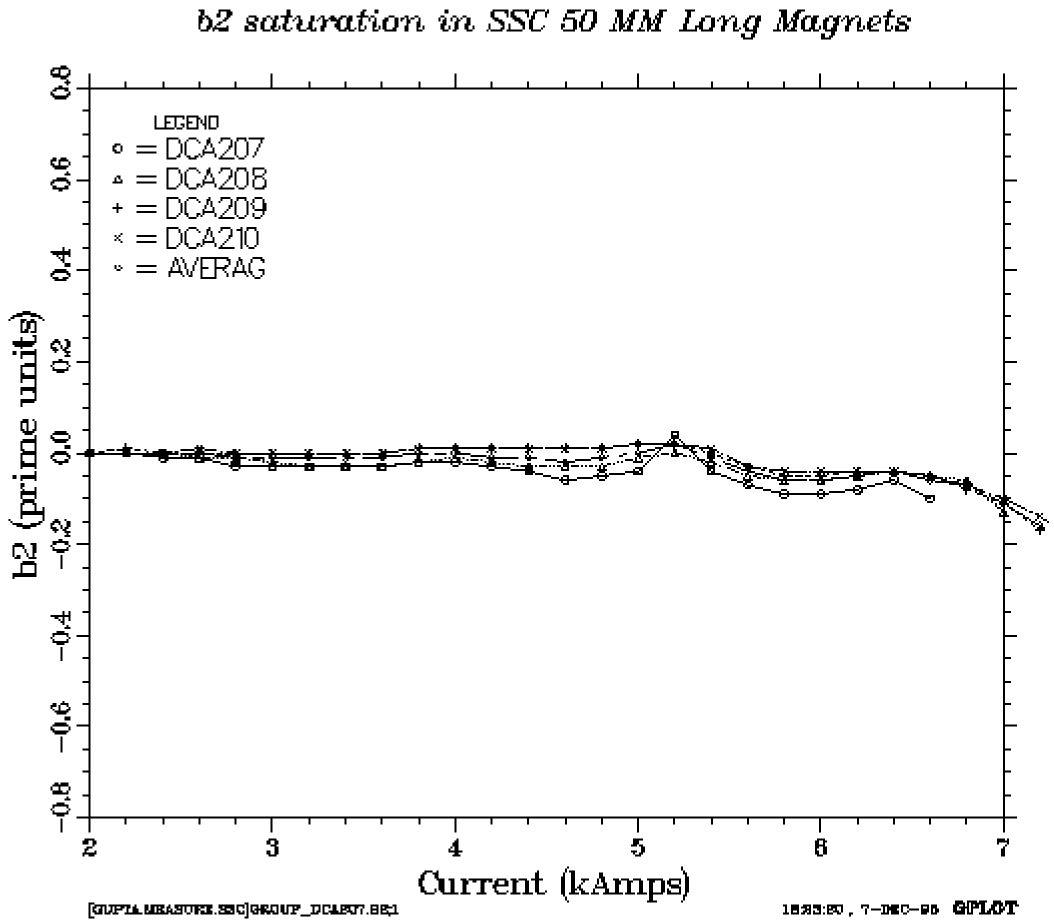
Measured Current Dependence in BNL-built SSC Magnets

Specifications was 0.8 unit.

These BNL built magnets had almost zero current dependence.

Earlier magnets had larger current dependence.

Major progress has been made in reducing the current dependence in field harmonics.



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").

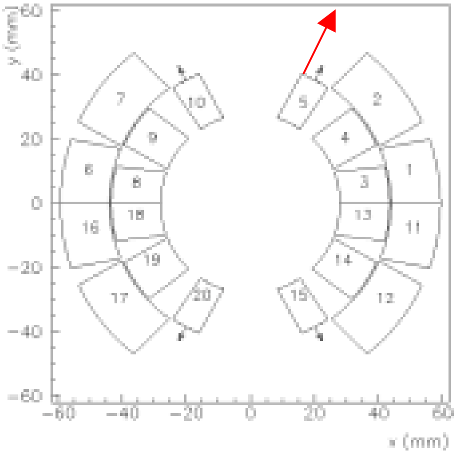
Therefore, the results (measurements) are appropriate for objectively evaluating/reviewing

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

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

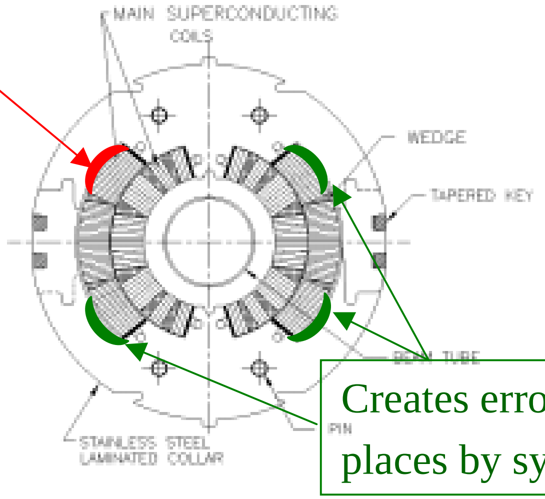
Symmetric model: 4 black arrows

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.

Error in collar here



Creates error at other places by symmetry

Three magnets with similar apertures
Tevatron, HERA and RHIC

Tevatron Dipole

(76.2 mm bore)

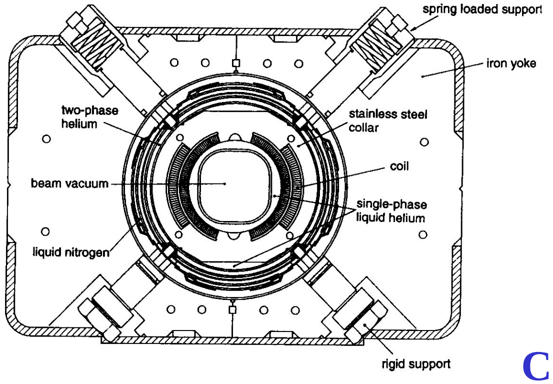
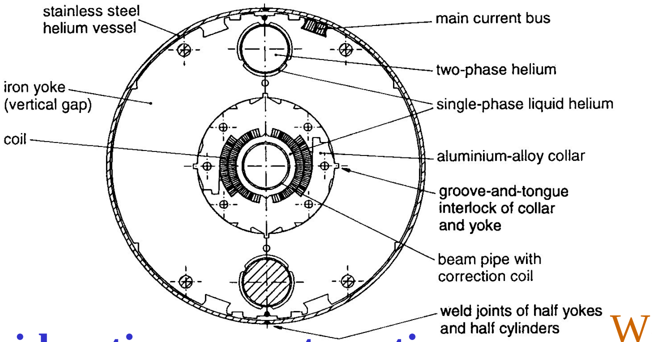


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

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

HERA Dipole

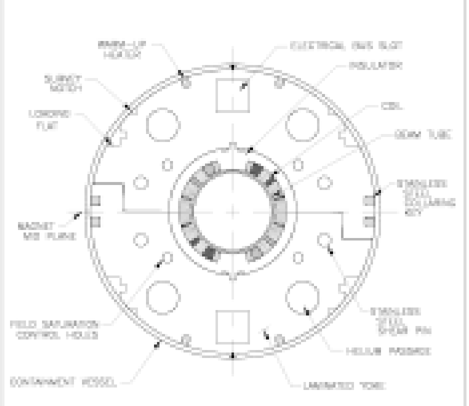
(75 mm bore)



Consideration on systematic errors

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

RHIC Dipole
(80 mm bore)



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**).

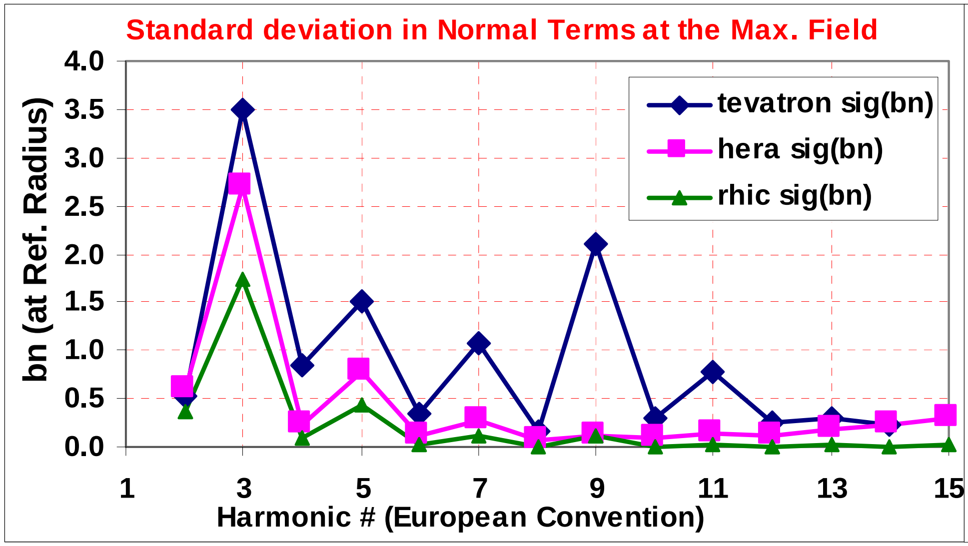
Collars used in Tevatron and HERA dipoles have smaller part-to-part dimensional variation (RMS variation ~10 μ) as compared to RX630 spacers (RMS variation ~50 μ) used in RHIC dipoles.

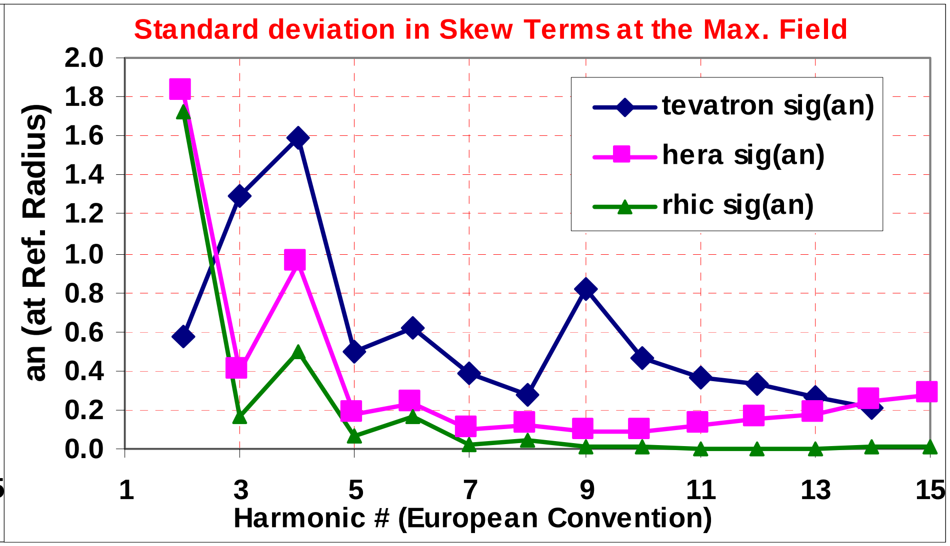
Conventional thinking : RHIC dipoles will have larger RMS errors. But in reality, it was opposite.

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


Standard deviation in Normal Terms at the Max. Field


Standard deviation in Skew Terms at the Max. Field

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

Lower Order Harmonics generally due to Construction Errors

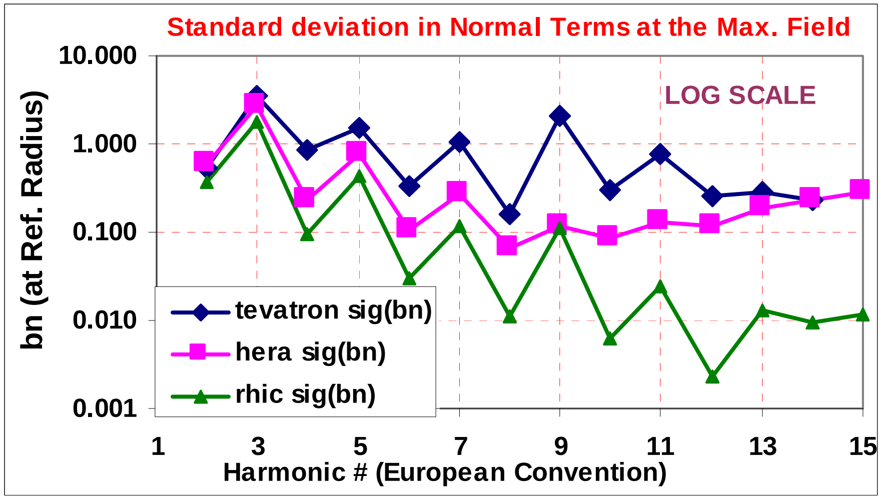
Higher Order Harmonics generally due to Measurement Errors

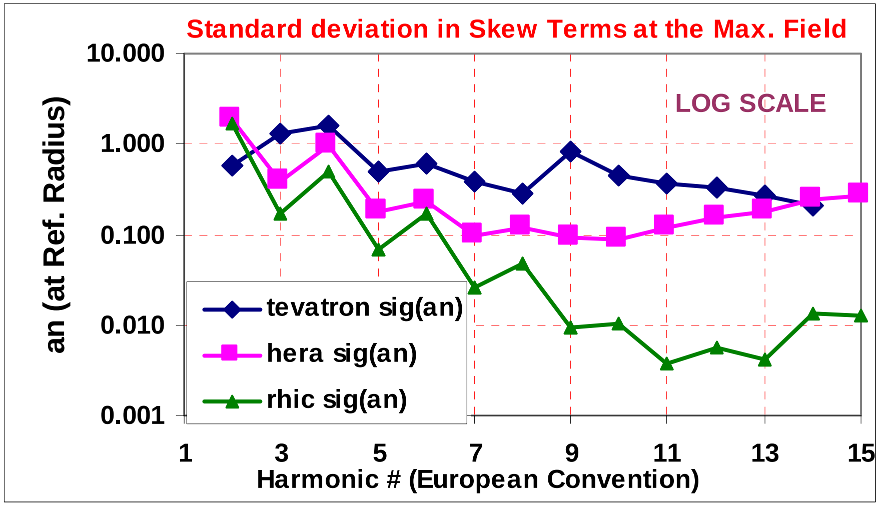
Comparison of Field Quality in Tevatron, HERA and RHIC dipoles

(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

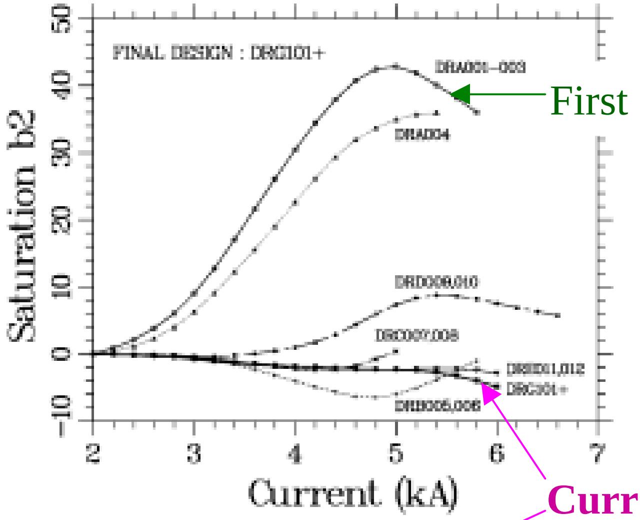
Saturation in RHIC Arc Dipoles

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

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

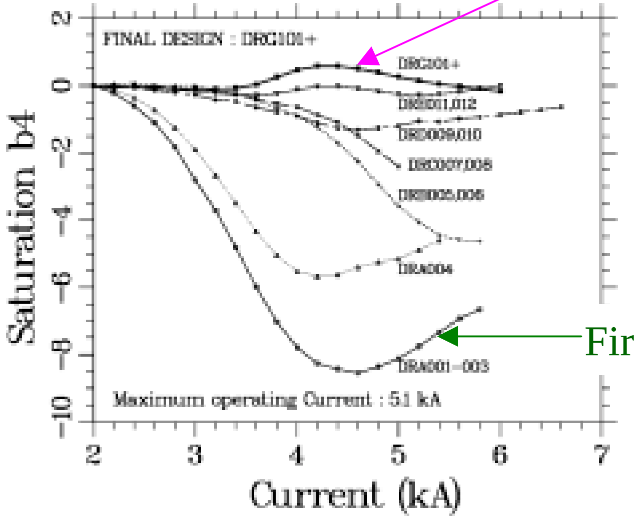
Initial design had bad saturation (as expected from conventional wisdom), but a number of developments made the saturation induced harmonics nearly zero!

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



First Design

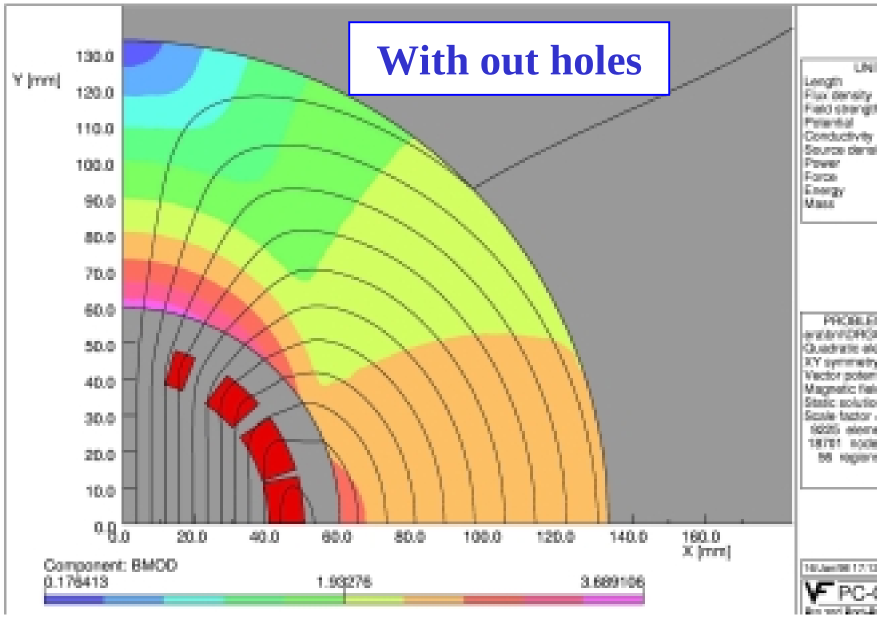
Current Design

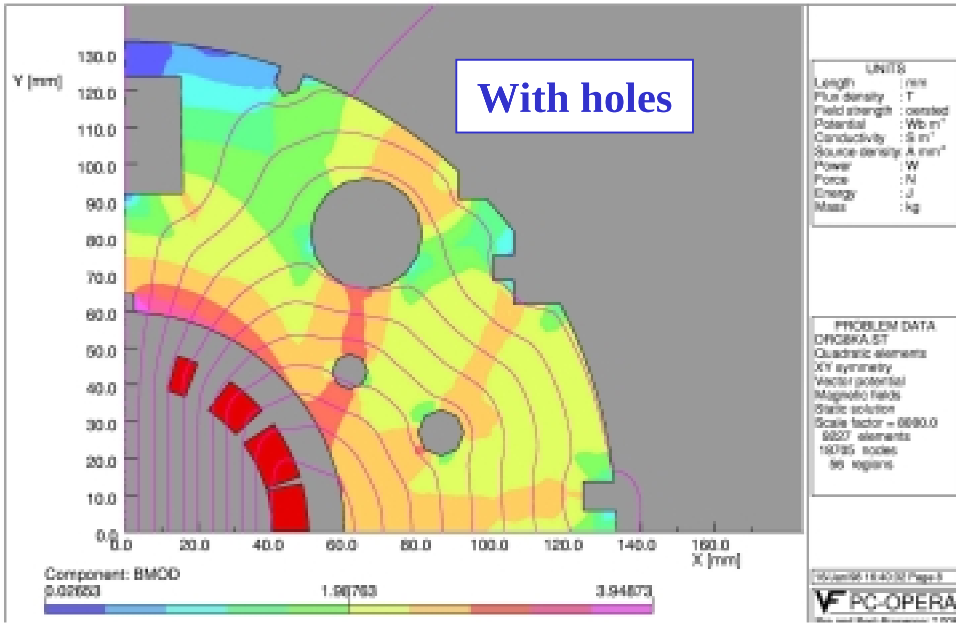


First Design

Saturation Control in RHIC Dipoles

Variation in |B| in Iron Yoke

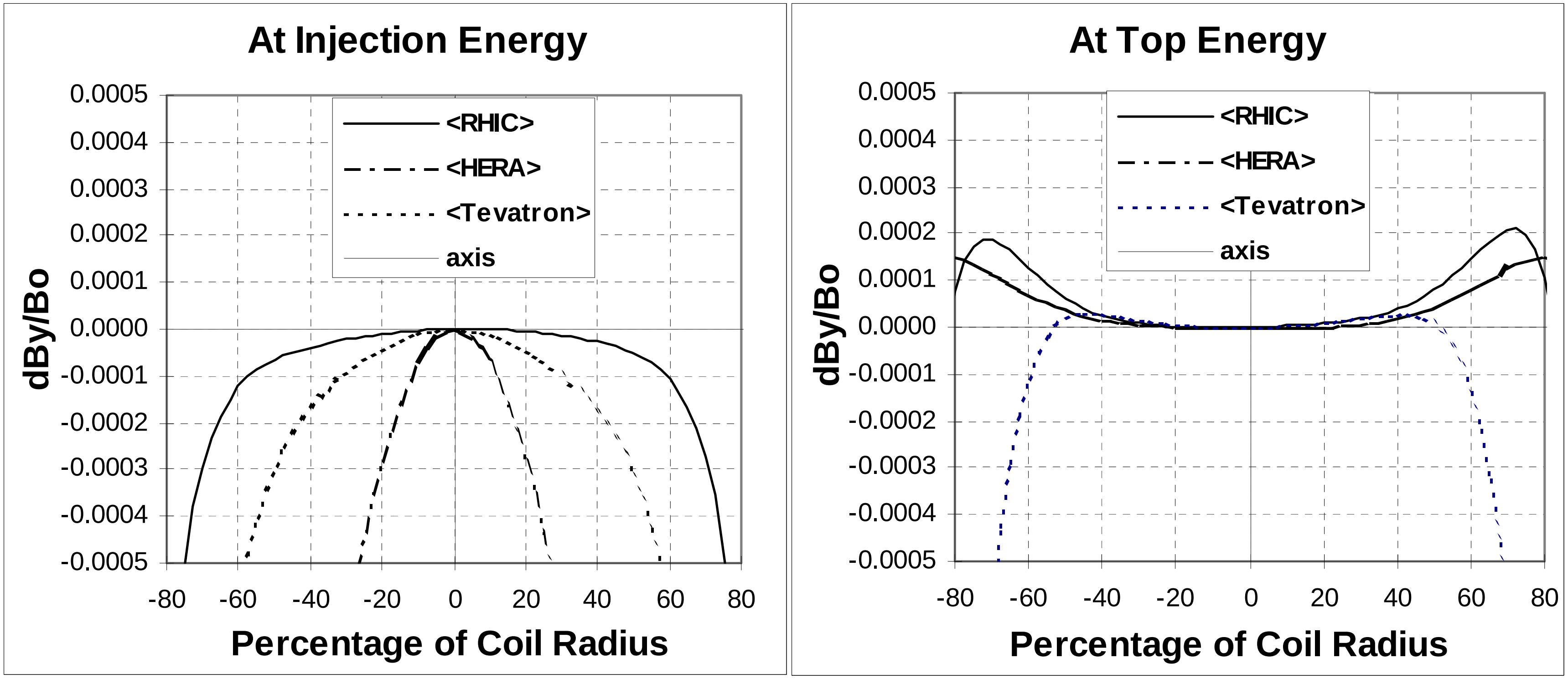

With out holes


With holes

- 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.

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.

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.

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.

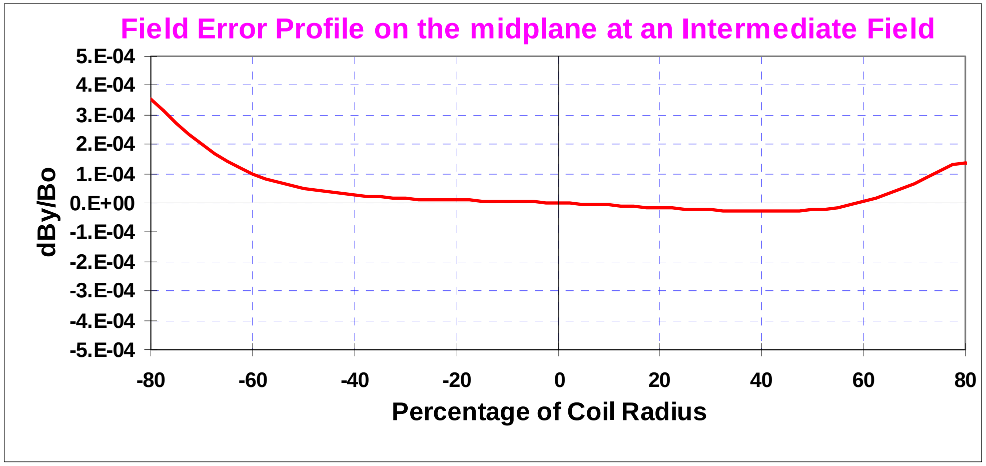
The sextupole magnets will be used for persistent current induced b_2 and for other beam dynamics purpose (chromaticity correction); may also be used for removing a relatively small residual b_2).

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


Field Error Profile on the midplane at an Intermediate Field

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

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

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

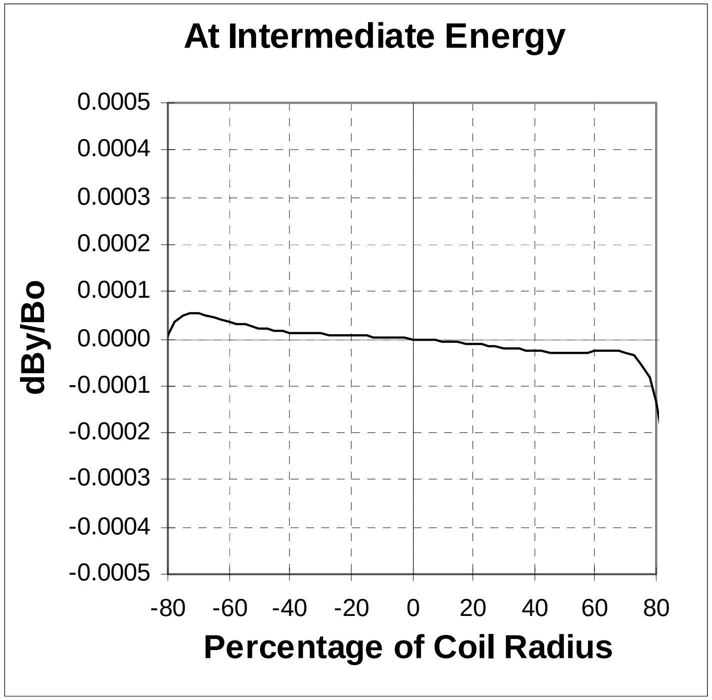
All harmonics are within or close to one sigma of RHIC arc dipoles.

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 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)

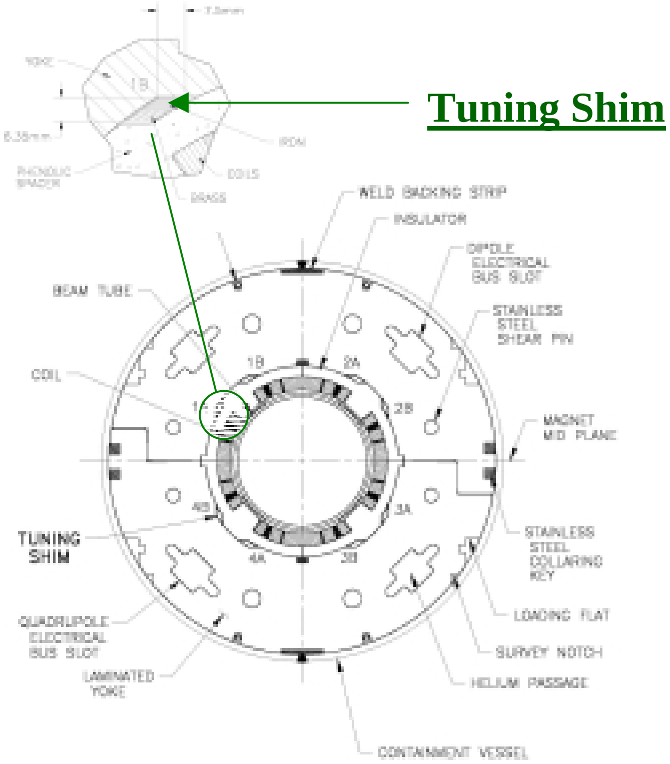
Tuning Shims for 10^{-5} Field Quality at 2/3 of coil radius

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.

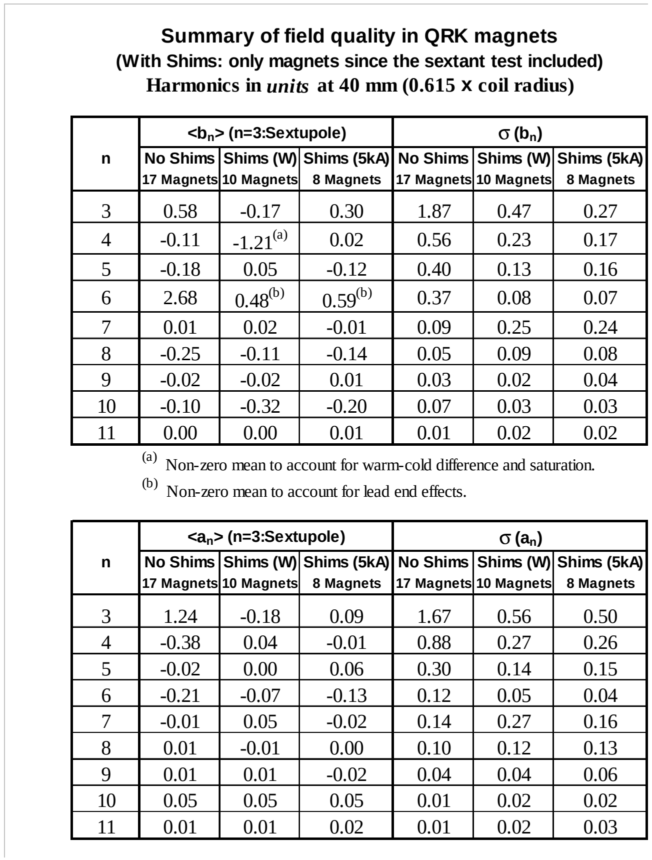
3. Install tuning shims. The tuning shims are inserted without opening the magnet (if the magnet is opened and re-assembled again, the field harmonics may get changed by a small but a significant amount).

4. Measure harmonics after tuning shims for confirmation.

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:



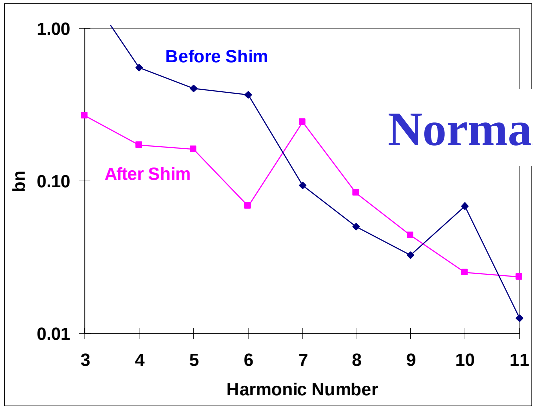
Summary of field quality in QRK magnets
(With Shims: only magnets since the sextant test included)
Harmonics in *units* at 40 mm (0.615 x coil radius)

n	$\langle b_n \rangle$ (n=3:Sextupole)			σ (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

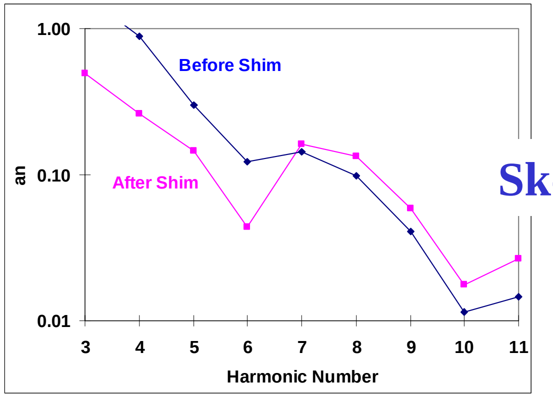
(a) Non-zero mean to account for warm-cold difference and saturation.

(b) Non-zero mean to account for lead end effects.

n	$\langle a_n \rangle$ (n=3:Sextupole)			σ (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} .

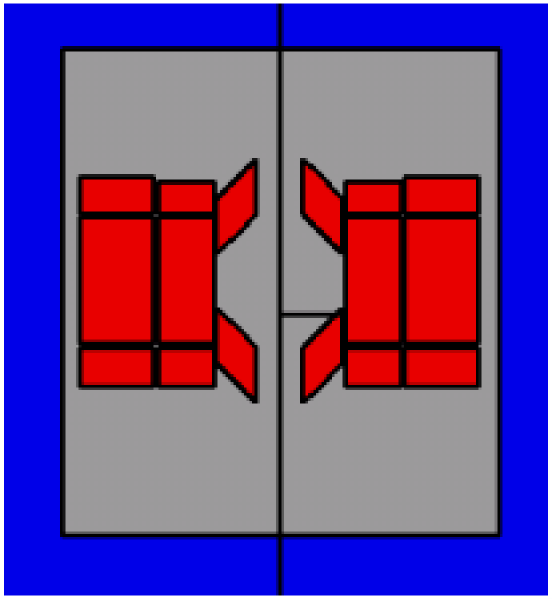
Harmonic measurements provided by Animesh Jain, BNL

Preliminary Calculations in a Common Coil Design Magnet

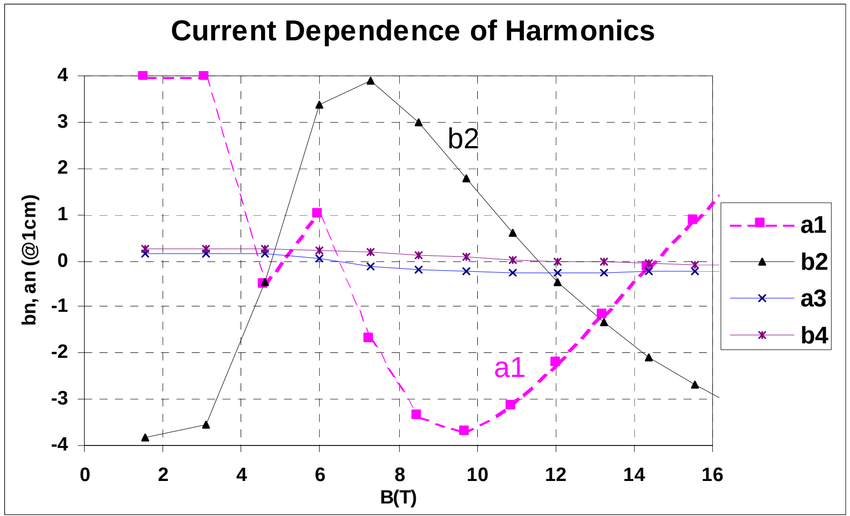
<u>Post "*Port Jefferson Workshop*" Update</u>: One wedge and adjustments in block positions generates a cross-section where all geometric harmonics are less than 2 parts in 10^5 at 10 mm reference radius.

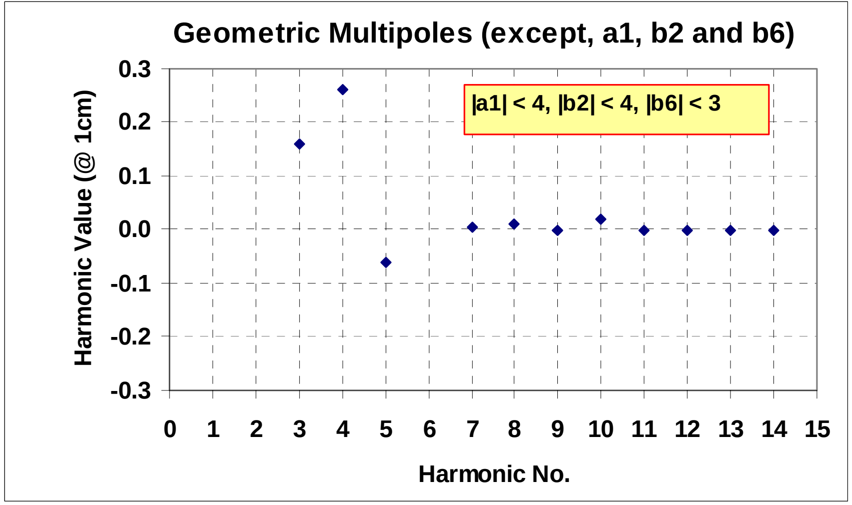
Saturation needs to be reduced in skew quad and normal sextupole (current high field value ~20).

How important are the high field harmonics? They <u>might</u> have an influence on the size of the magnet.



Results (old) presented at Port Jeffersons in Nov. 98.





|a1| < 4, |b2| < 4, |b6| < 3

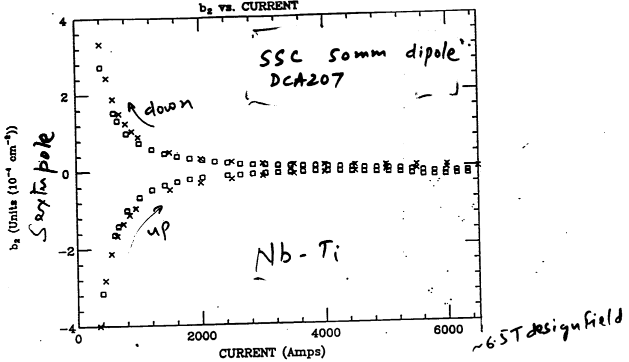
Persistent Current-induced Harmonics

(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).

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

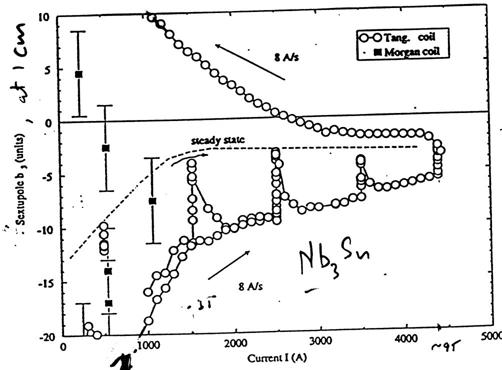


Fig. 6. Measured sextupole at low field (direction of arrow indicates up or down current).

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

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 magnetization

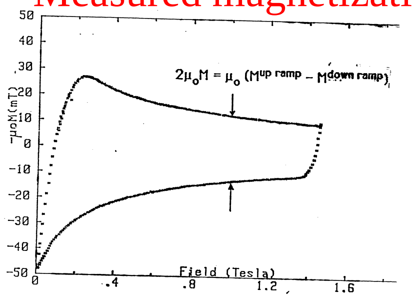


Fig. of a typical magnetization loop.

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.