BROOKHAVEN NATIONAL LABORATORY

RHIC

MEMORANDUM

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No:	565-1 (RHIC-MD-266)
Task Force:	Coil Geometry Analysis
Title:	Field Quality in Next Generation Accelerator Magnets

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Ramesh Gupta
Aug 1~~2~~4, 1997
(@CERN)

Field Quality in Next Generation Accelerator Magnets

- **Past Experience/Understanding**
- **Future Estimates/Planning**

Field Errors in SC Magnets

① • **RMS Errors** (σ)

Manufacturing (parts + assembly)

(Process can not be exactly repeated)

---

② • **Error in Mean** (systematic)

Design (x-section + tooling) ; parts & assembly

* Bad News: Difficult to get it right

Combined errors should be < 25 μm

But → In large production one can adjust (shift) the mean

* Good News

Only a small mechanical adjustment is required to change harmonics at 10^{-4}/le

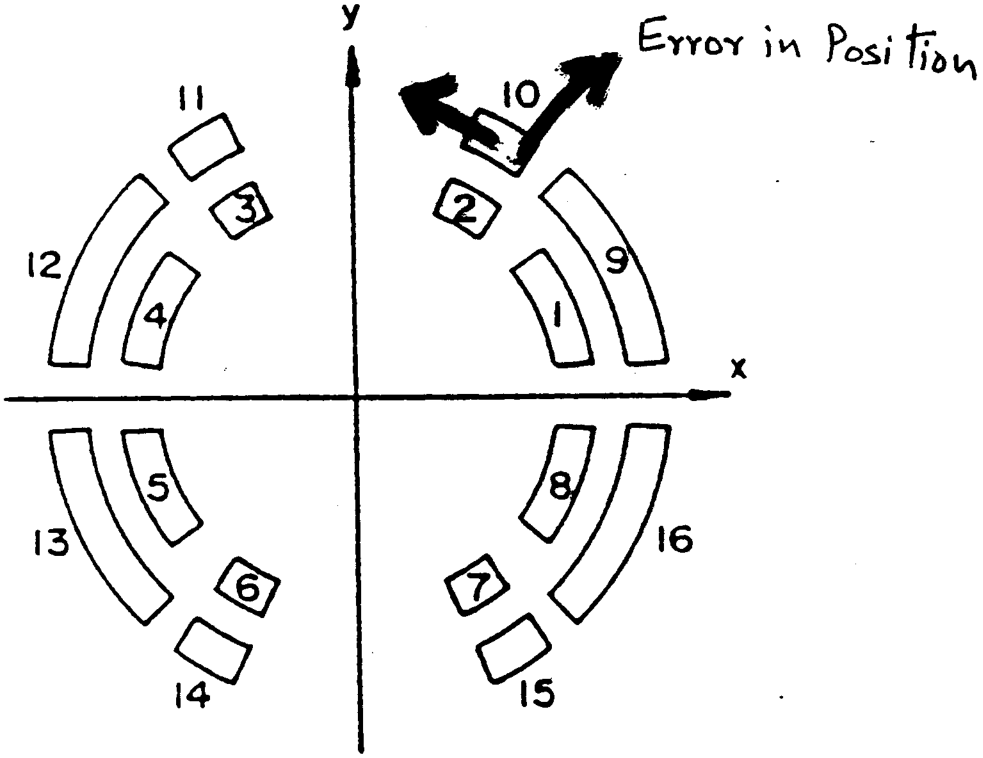
(such ~~changes~~ adjustments produce insignificant changes in the magnet mechanics)

Estimating Field Errors in SC Magnets

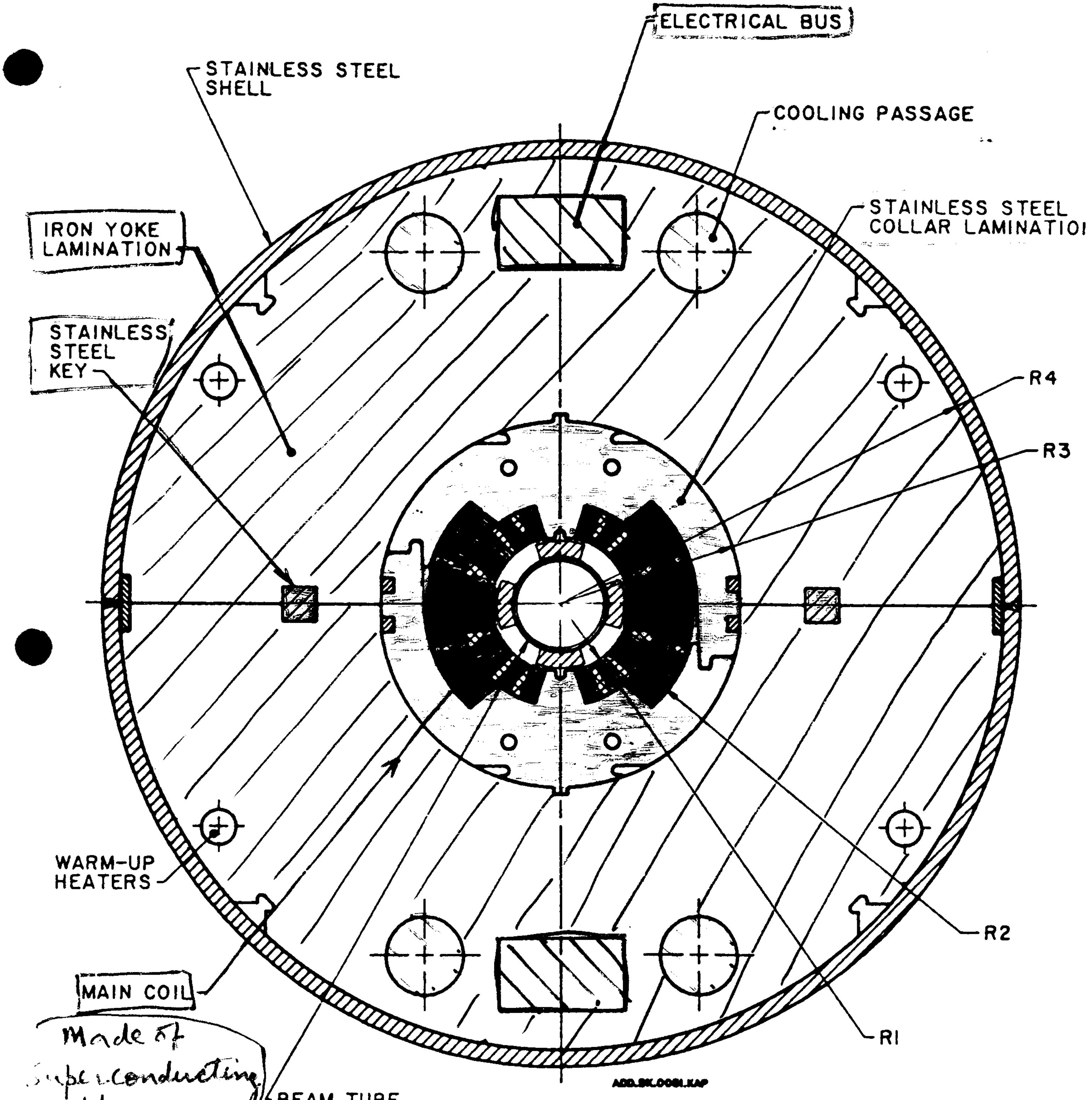
Popular Models

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

Therefore, allow this kind of positional error in each of several blocks of conductors and then sum the resultant error harmonics in an RMS sort of way.



Looks plausible but ...



RI = 24.77
R2 = 49.71
R3 = 67.79
R4 = 165.24

SSC 50mm COIL MAGNET CROSS SECTION

(Magnetically Important Features)

Comparison with Measurements

(@2000A, mostly geometric)

SSC 50 mm Aperture Dipole Magnets

(SSC magnets are closer to LHC magnets than RHIC magnets)

Vendor#1 **DCA207-DCA213 (7 built at BNL)**

DCA207-DCA211 (5 with no change)

Vendor#2 **DC311-DCA323 (13 built at FNAL)**

DCA311-DCA319 (9 with no change)

All had basically similar X-section (small differences in insulation, etc.)

(horizontally split vs. Vertically split

Use/combine statistics of measured harmonics appropriately.

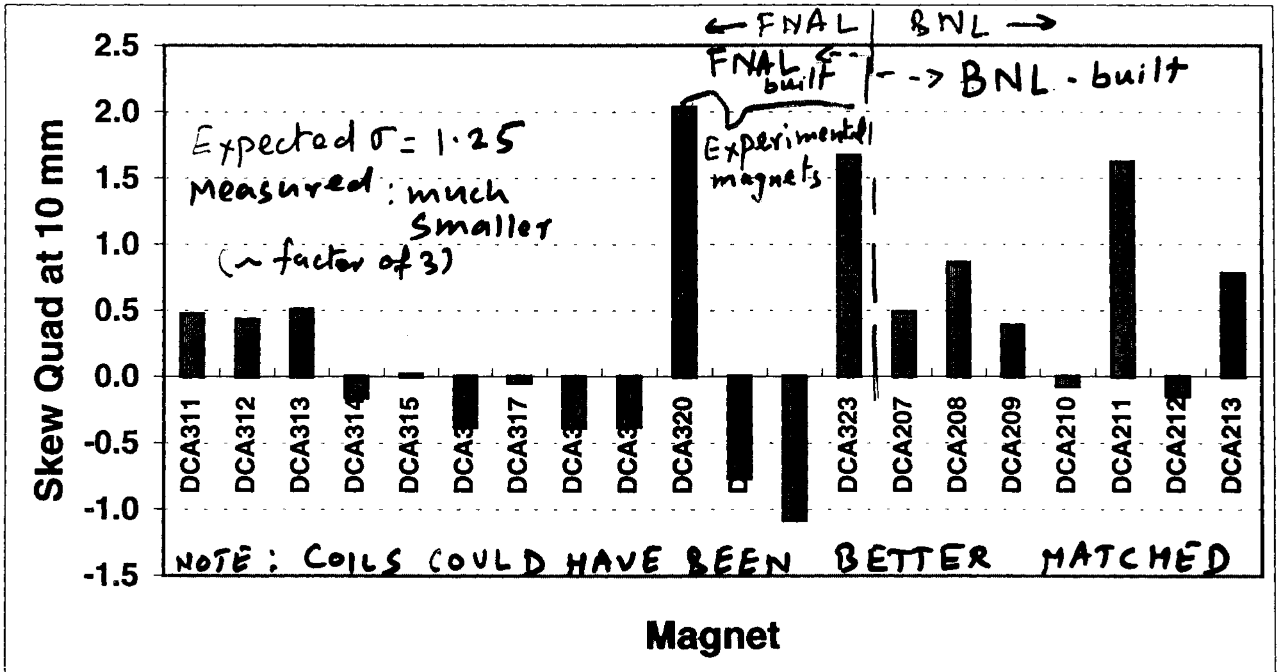
Note:

- These are laboratory-built magnets. [illegible] [illegible]
- Lab v/s Industry

Reality check*

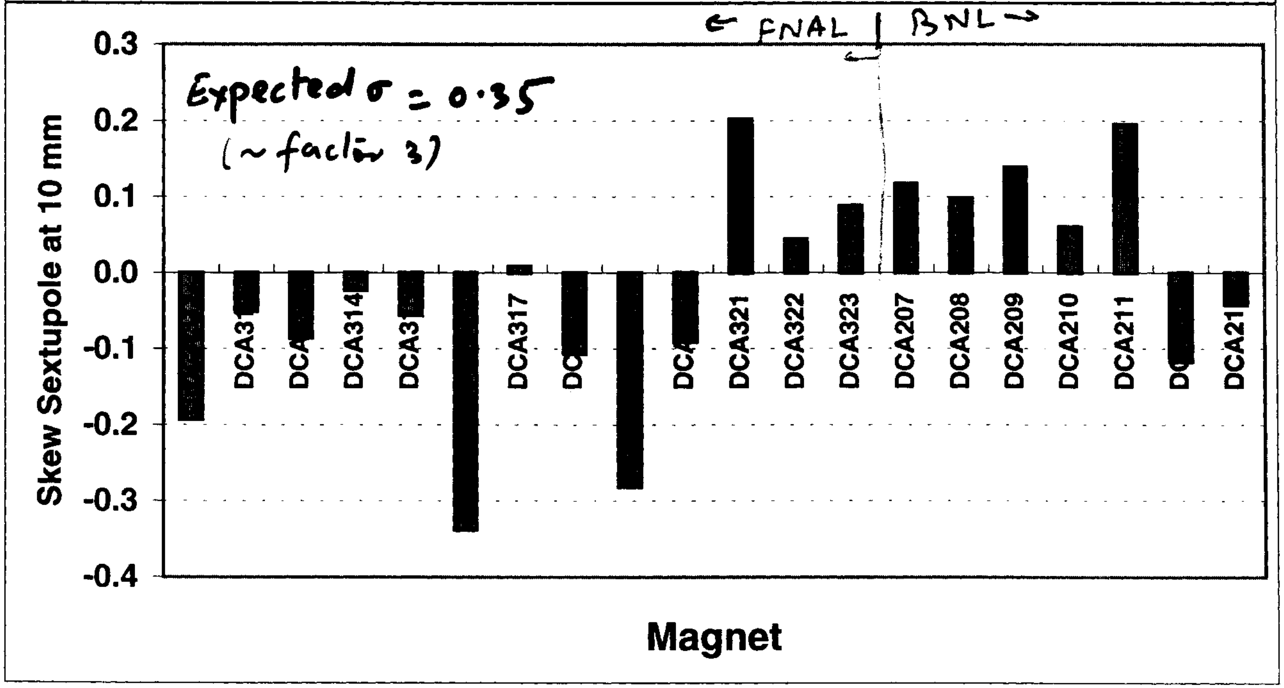
Measured Data in SSC 50 mm Dipoles (@ 2000A)

FNAL built DCA311-323 (320-323, experimental)
BNL built DCA207-213 (212 & 213, experimental)



Expected σ = 1.25
Measured: much smaller
(~ factor of 3)

NOTE: COILS COULD HAVE BEEN BETTER MATCHED



Expected σ = 0.35
(~ factor 3)

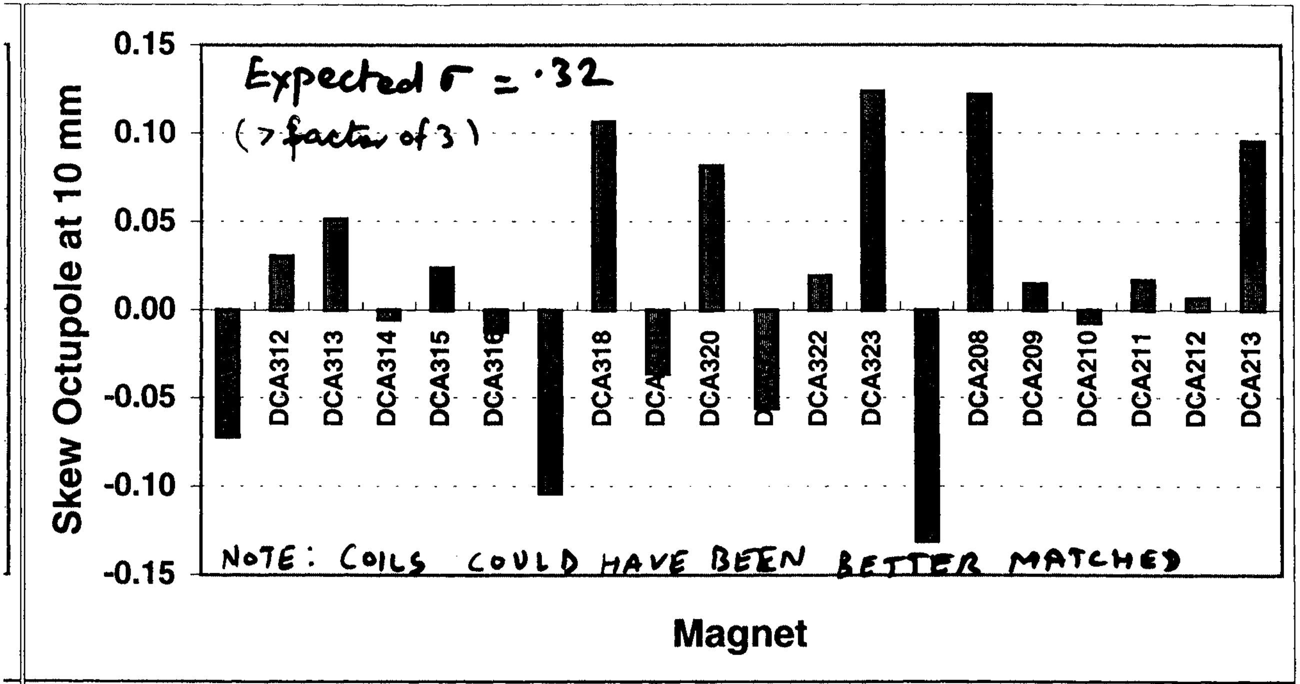
Critical to LHC
as per C. Wyss

1. Small skew quad harmonic except in experimental magnets
2. Systematic skew sextupole may be due to coil curing tooling
====> fix it in series production

Reality check *

Measured Data in SSC 50 mm Dipoles

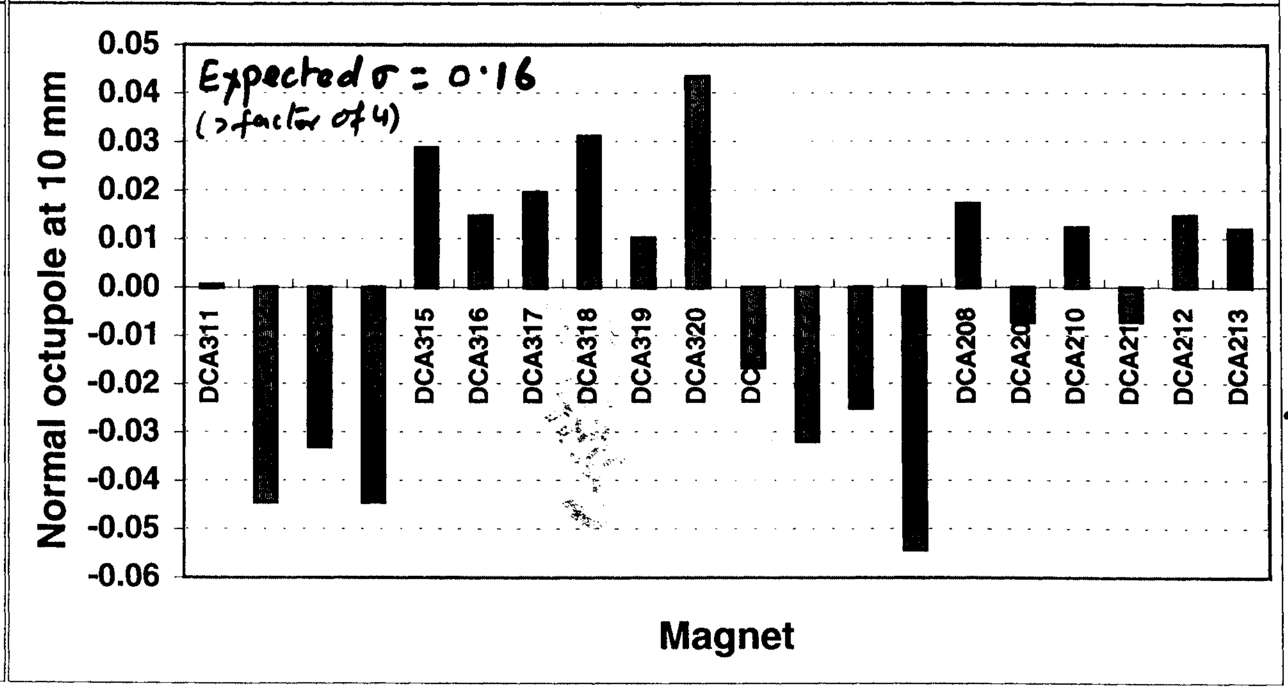
FNAL built DCA311-323 (320-323, experimental)
BNL built DCA207-213 (212 & 213, experimental)



Expected σ = ·32
(> factor of 3)

NOTE: COILS COULD HAVE BEEN BETTER MATCHED

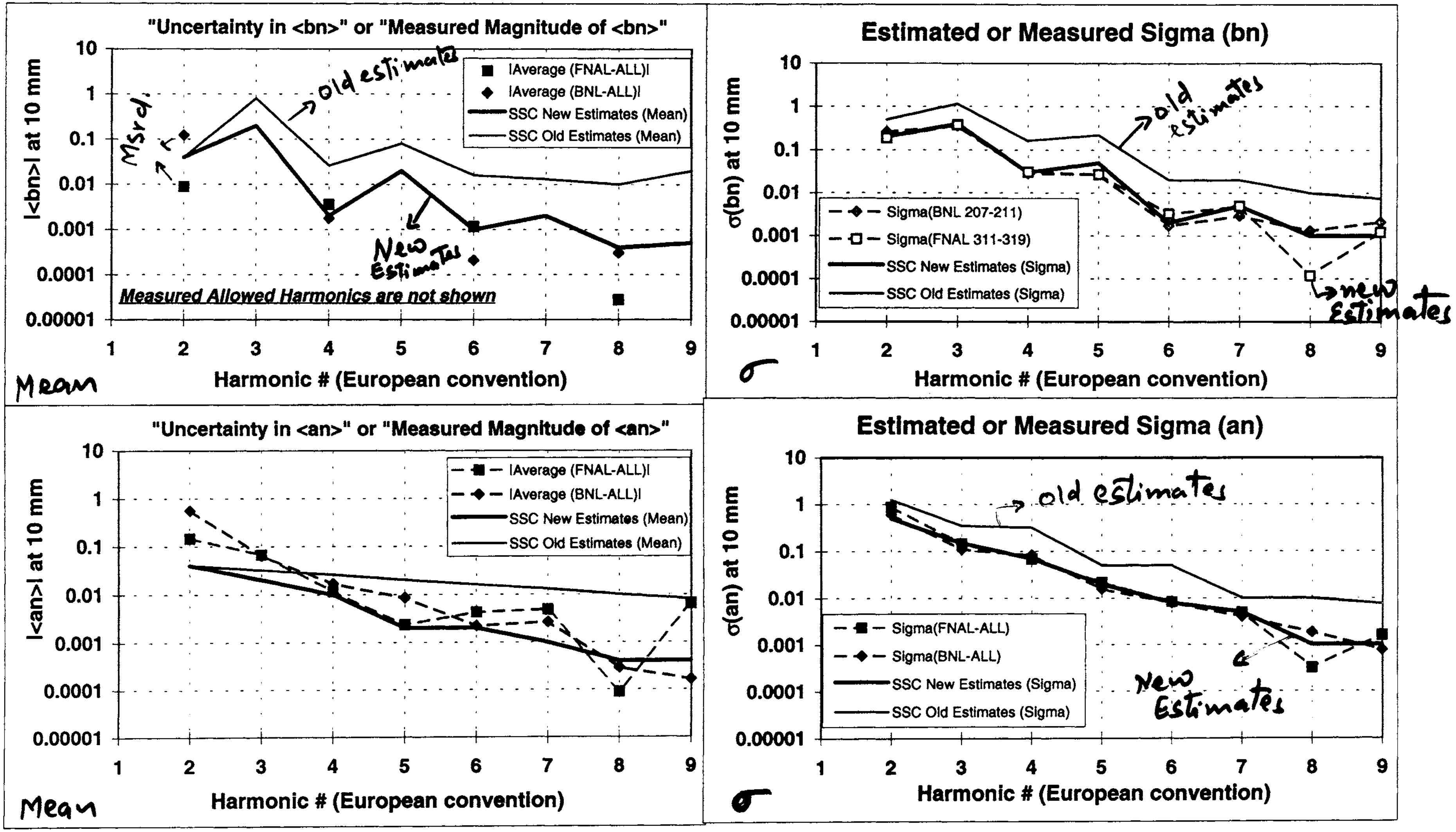
Critical to LHC

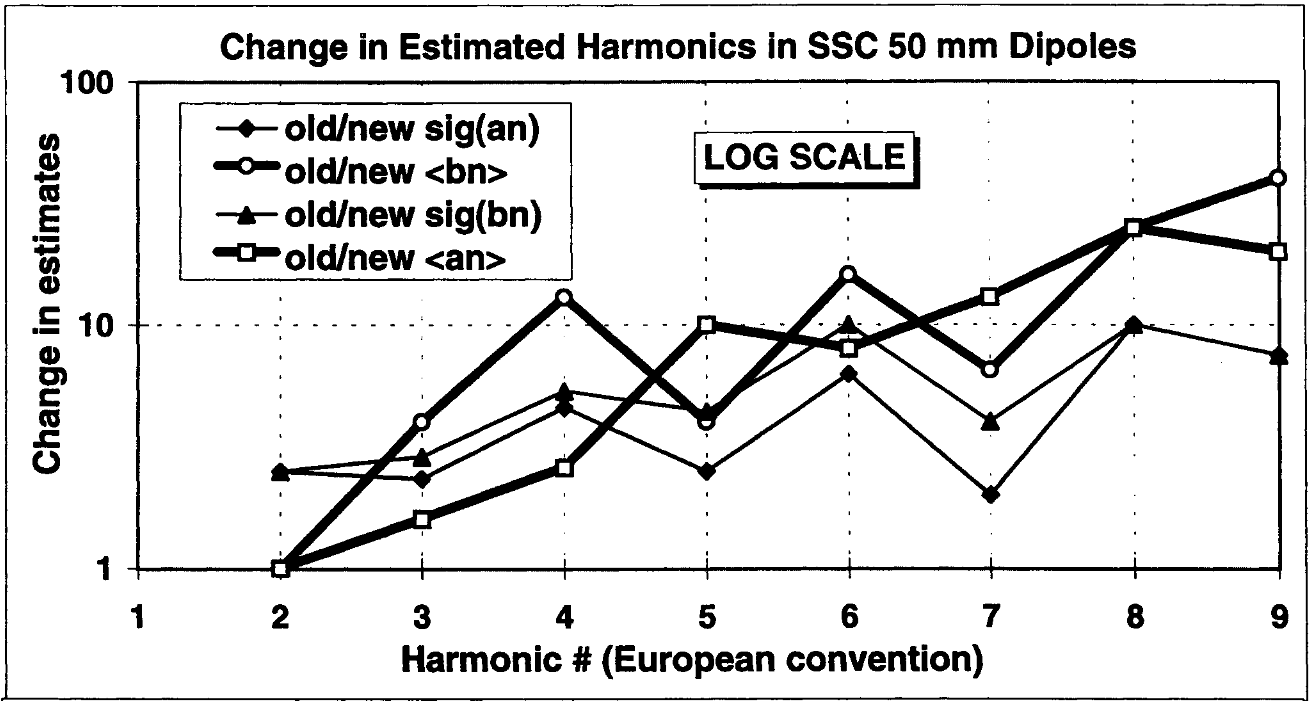


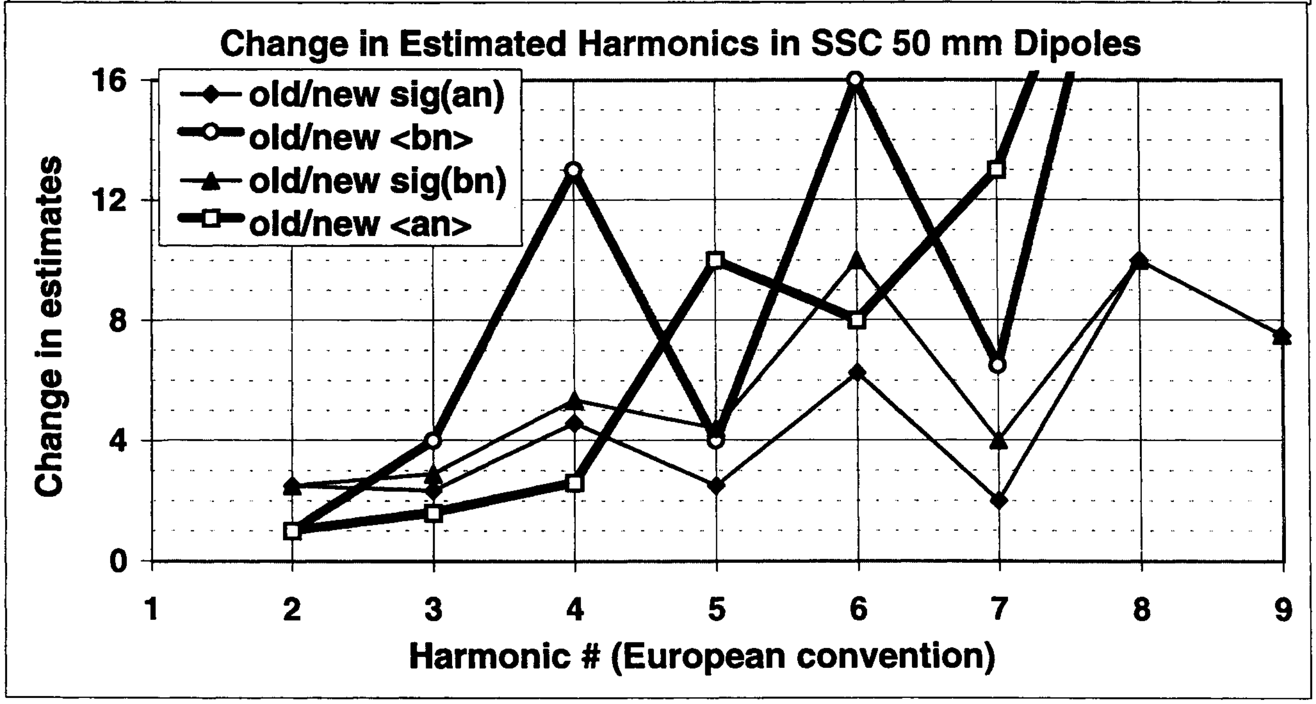
Expected σ = 0·16
(> factor of 4)

Critical to LHC

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




Change in Estimated Harmonics in SSC 50 mm Dipoles


Change in Estimated Harmonics in SSC 50 mm Dipoles

NOTE: THESE ARE RATIOS (NOT %)

NEW ESTIMATES BASED ON PREVIOUS DISCUSS

(more discussion off-line)

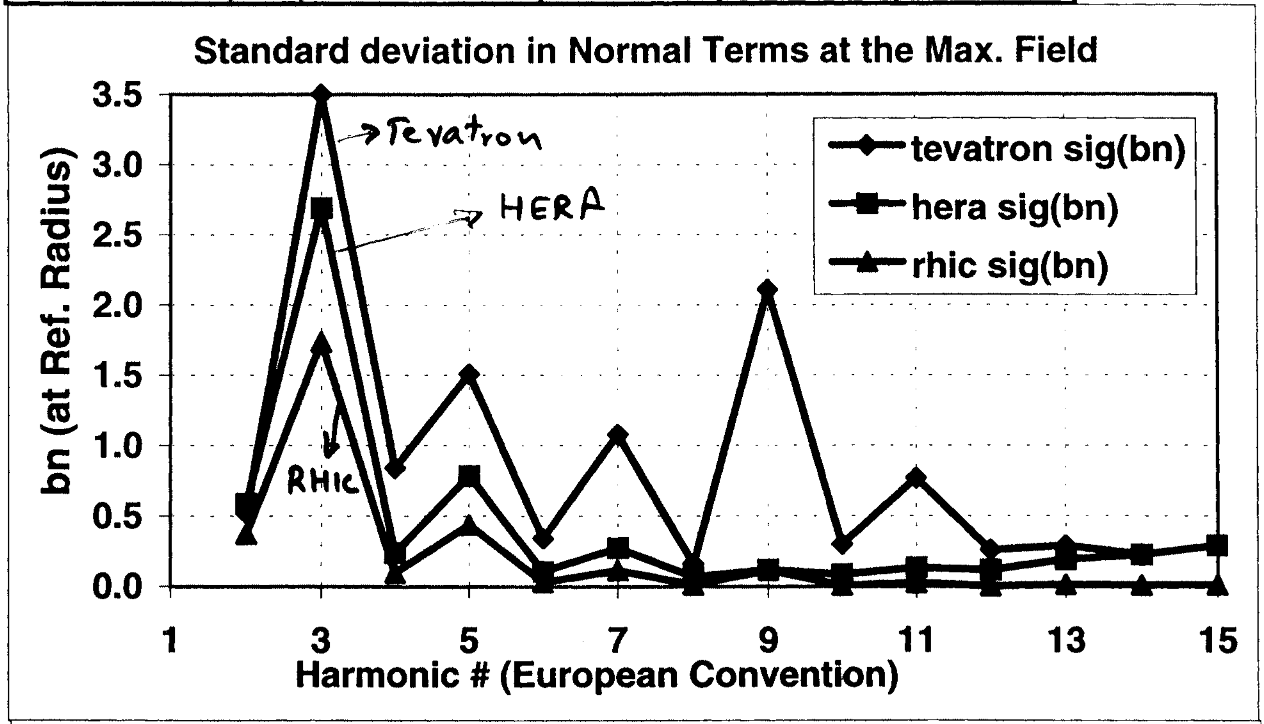
EPAC '96

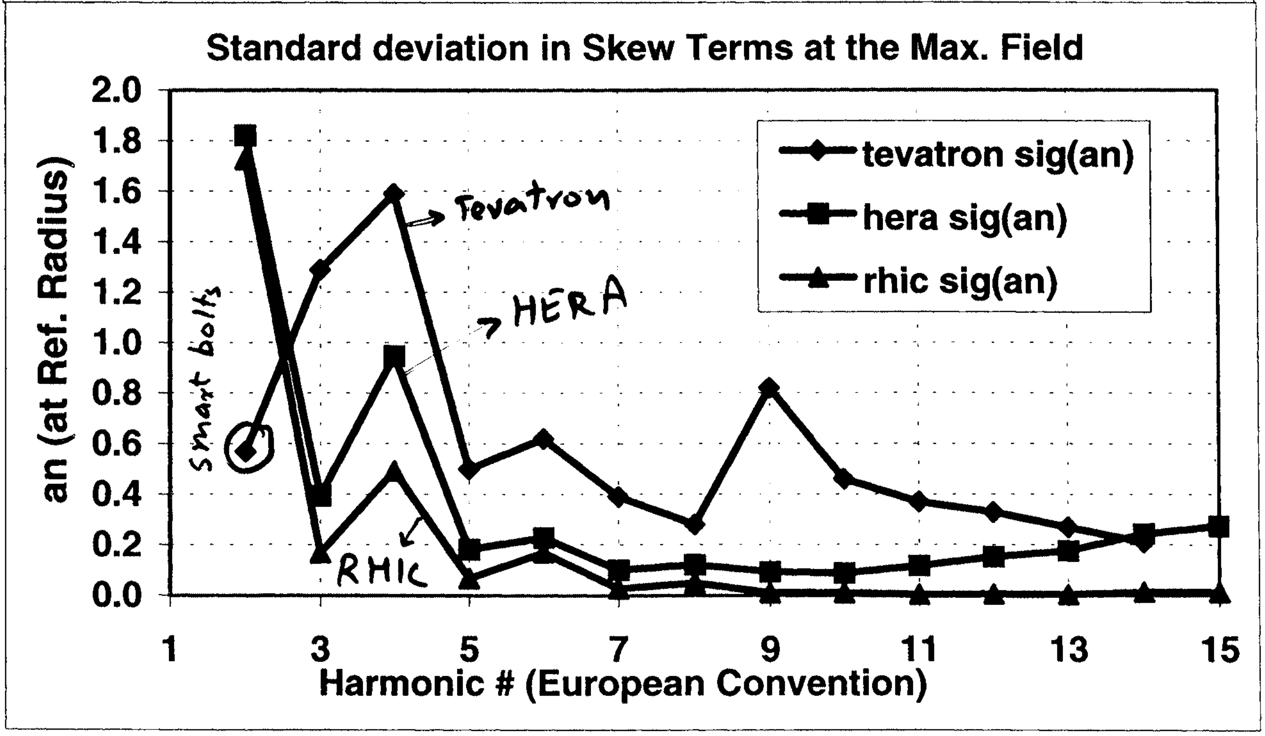
	SSC Expected Harmonics			SSC Tolerances	
n	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	**ssc < >**	**ssc σ**
1	0.0	0.04	0.2	0.04	0.5
2	0.0	0.2	0.4	0.8	1.15
3	0.0	0.002	0.03	0.026	0.16
4	0.0	0.02	0.05	0.08	0.22
5	0.0	0.001	0.002	0.016	0.02
6	0.0	0.002	0.005	0.013	0.02
7	0.0	0.0004	0.001	0.01	0.01
8	0.0	0.0005	0.001	0.02	0.0075
n	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$	**ssc < >**	**ssc σ**
1	0.0	0.04	0.5	0.04	1.25
2	0.0	0.02	0.15	0.032	0.35
3	0.0	0.01	0.07	0.026	0.32
4	0.0	0.002	0.02	0.02	0.05
5	0.0	0.002	0.008	0.016	0.05
6	0.0	0.001	0.005	0.013	0.01
7	0.0	0.0004	0.001	0.01	0.01
8	0.0	0.0004	0.001	0.008	0.0075
δL/L	--	0.0003	0.0004	--	0.0006

OTHER MAGNETS. (updating state of affairs)

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

~Same aperture and reference ra

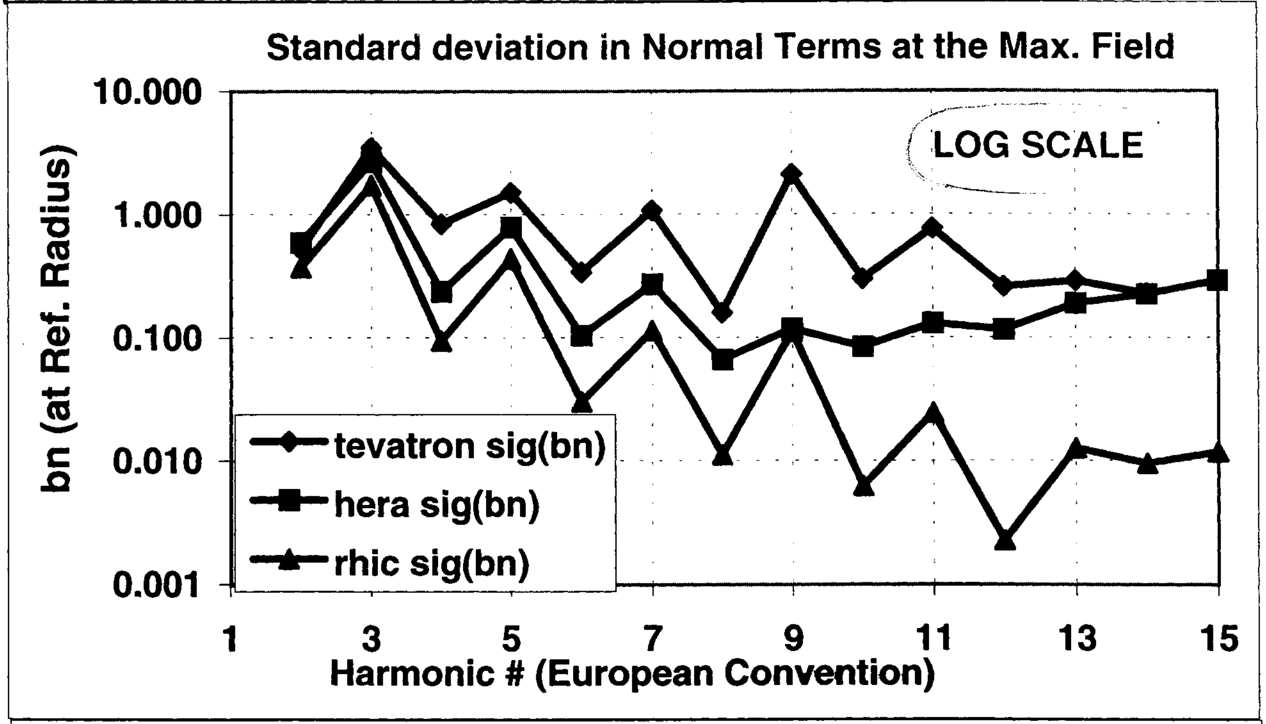


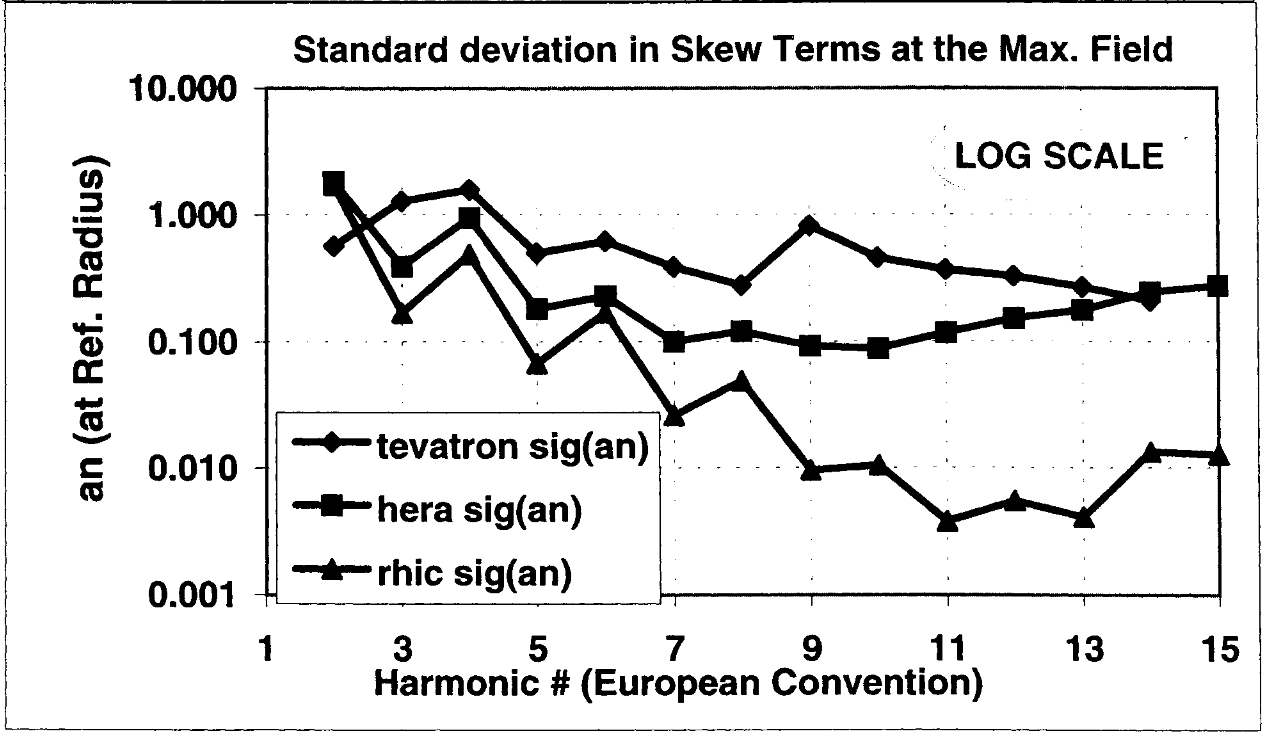


- RHIC has lower sigmas (except for a2 where tevatron used smart bolts)
- Lower Order Harmonics generally due to Construction Errors
- Higher Order Harmonics generally due to Measurement Errors

THER. MAGNETS (updating state of affairs)
(log scale to see improvements in higher order terms

	Tevatron	HERA	RHIC
Reference Radius (mm)	25.4	25	25
Coil Radius (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

Table 1: RMS errors in field harmonics at 25 mm reference radius in the magnets tested for various accelerators at the maximum design field. (US conventions – a_1 is skew quadrupole). Note that in RHIC only 8% of the magnets are being tested cold after first 30 magnets.

@ 25mm

Harmonic ↓	Tevatron (4kA) 788 magnets	HERA (5kA) 433 magnets	RHIC (5kA) 55 magnets
b_1	0.52	0.61	0.24
b_2	3.5	2.68	1.58
b_3	0.84	0.25	0.08
b_4	1.51	0.81	0.61
b_5	0.34	0.10	0.03
b_6	1.07	0.53	0.15
a_1	0.57[1]	1.81[2]	1.4
a_2	1.29	0.41	0.18
a_3	1.59	0.95	0.41
a_4	0.5	0.19	0.05
a_5	0.62	0.23	0.16
a_6	0.39	0.10	0.02

1. In Tevatron magnets, the smart bolts were used to reduce a_1.
2. In HERA magnets, coil pole shims were adjusted at times to reduce a_1.

In RHIC dipole no such individual magnet adjustment was made after the construction. As a global strategy, the size of the top and bottom coils were matched.

R. Gupta, 10/7/95

US convention
b_2 is normal sextupole

Recap on Sigma Estimates

Measurements and Analysis suggest that

(a) Model do not represent the real situation

(b) Improvements since Tevatron and HERA

- **Lower order harmonics by a large factor (~2-3)**
  especially non-allowed harmonics (quads have a lot of them)
- **Higher order harmonics by over order of magnitude**

Response to SSC Experience

old Model

Alternate Model

Examine how an error in a component or construction displaces conductors in the magnets.
This displacement would determine the actual field error.

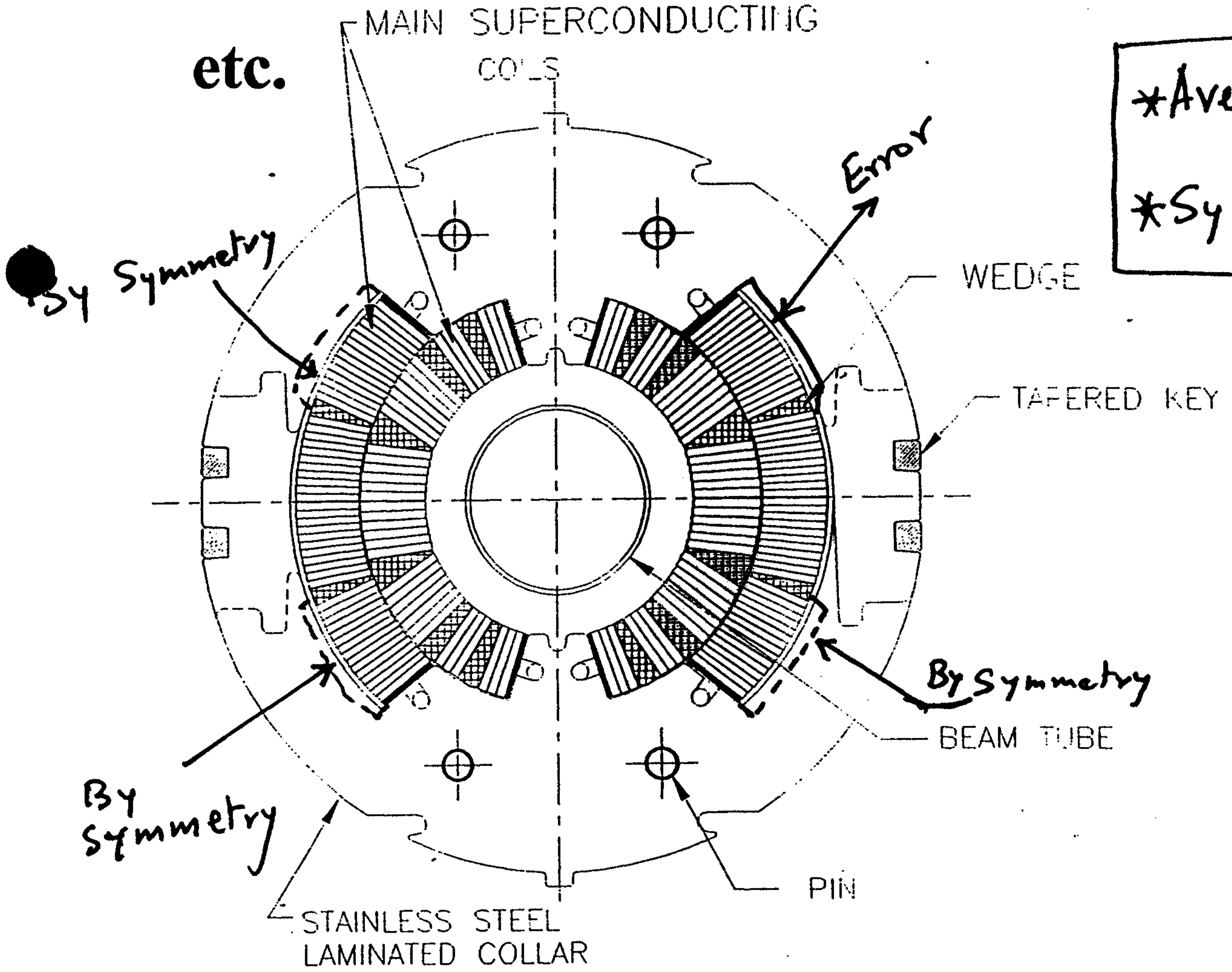
1. Averaging Effect.
2. Symmetry considerations for non-allowed harmonics.

Examples

- Error in collar geometry
- Error in wedges
- Error in insulated cable dimension
- Error in coil curing

etc.

*Averaging
*Symmetry



- overall coil geometry is primarily determined by collars

* Midplane is fought by the upper and lower coils

Lessons from SSC Experience

RMS errors are much smaller

Symmetry & Averaging helps
↓
Randomization

- ⟹ TRY TO USE THIS POWERFUL TOOL IN THE BASIC MAGNET DESIGN

- The same ~~should~~ also helps in the mean of non-allowed harmonics.

- Except if the tooling or if the magnet design has a bias.

⟹ FIND A WAY TO REMOVE/COMPENSAT

* ALLOWED HARMONICS DISCUSSED LATER

Relavance of SSC Experience to LHC magnets.

Similar Coil aperture

50 mm ⟷ 56 mm

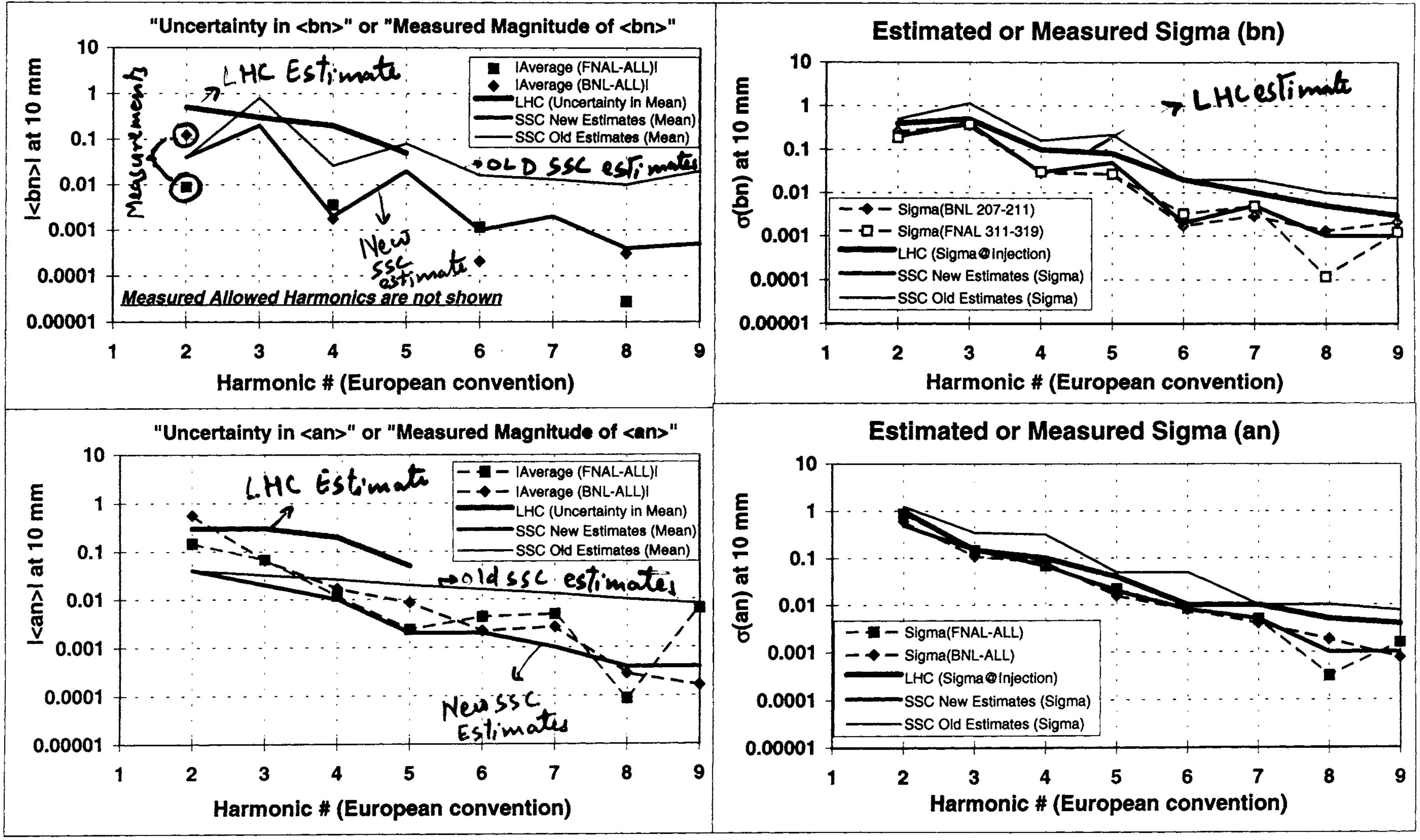
Therefore, in principle one should be able to get similar or better field quality!

(Except left-right assymetry)

↑ Try to minimize that; **both** in magnetic & mechanical design.

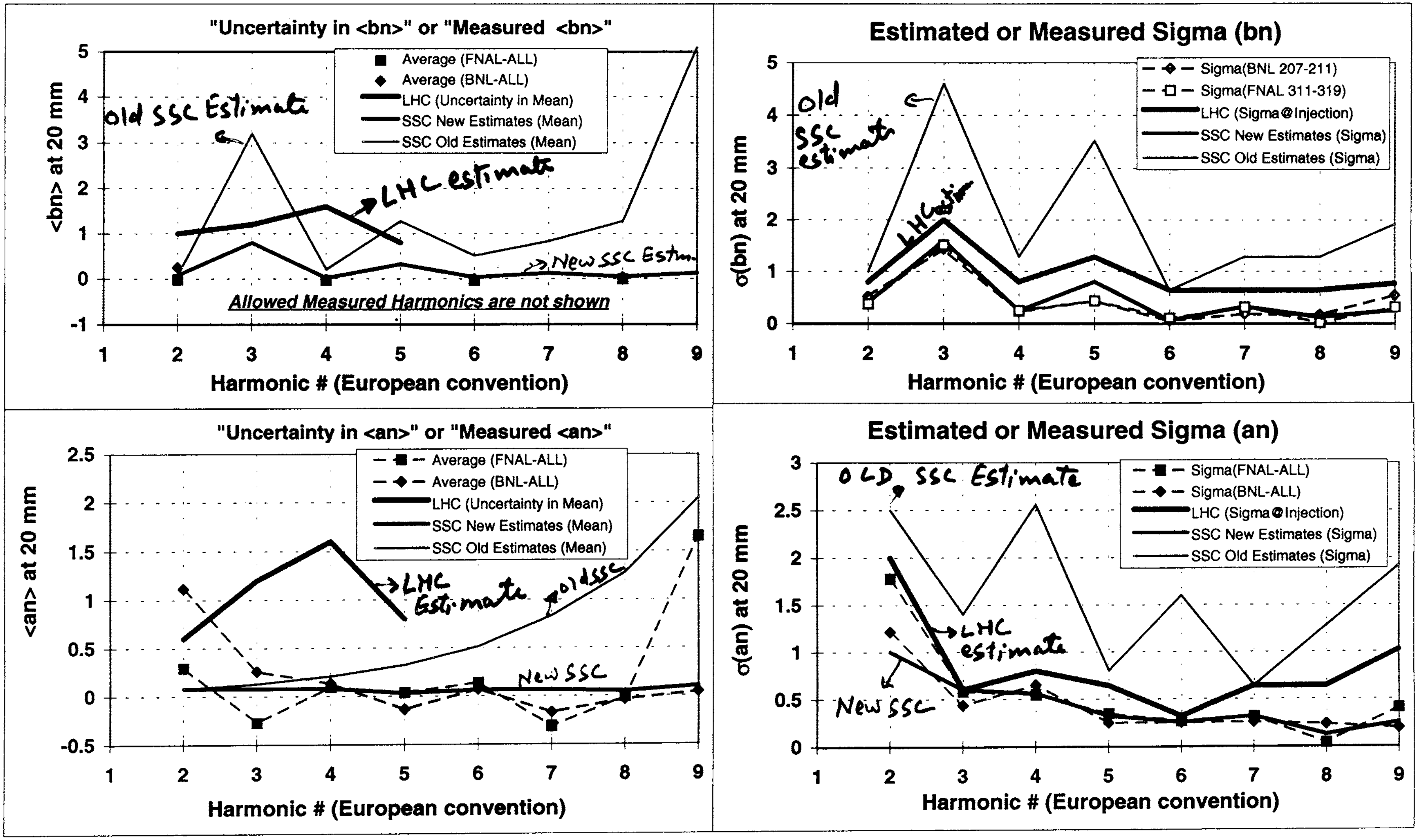
→ Compare SSC experience to LHC expected

Expected and Measured Harmonics at 2 T in SSC 50 mm Dipoles and Estimated Harmonics in LHC 56 mm Dipoles



Reference Radius = 20 mm
(Differences are more visible)

Expected and Measured Harmonics at 2 T in SSC 50 mm Dipoles and Estimated Harmonics in LHC 56 mm Dipoles



* No need of log scale (or counting number of zeros before actual number)

* Easier to conceptualize or caught a large value of harmonic

general Comments on developing a [illegible] algorithm for estimating "RMS" errors :

* Instead of moving block move coil as a whole within the boundary condition (collars) ? RMS [Experience SSC magnets ?

\+ Averaging would reduce error : 25 μm → 10 μm.

\+ Instead of "Random" motion of conductors/coil in four quadrant, used both coupled (mainly) and uncoupled movement.

This Symmetry condition would reduce σ in non-allowed harmonics

* skew quad, skew octupole are primarily determined by the mechanical differences in upper & lower coil

compare results of this new model with ~~[illegible]~~ measuremen,

⟹ Normalize coefficients

Intermediate Conclusion

since the coil shape in magnet is determined by the collar, the tolerances in curing can be significantly reduced.

Exception

Left & Right side must be matched (made similar)
as they determines the position of midplane.

skew sextupole (a_3) in dipoles

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Montreux '95

ESTIMATING AND ADJUSTING FIELD QUALITY IN SUPERCONDUCTING ACCELERATOR MAGNETS*

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The experience with estimating and adjusting field quality in RHIC (Relativistic Heavy Ion Collider) and SSC (Superconducting Super Collider) magnets is discussed. An alternate approach which makes a better estimate for systematic and random values of harmonics is presented.

Keywords: Superconducting magnets.

1 INTRODUCTION

An important task of magnet builders in the early phases of an accelerator project is to make a critical and a close estimate of expected field errors in a series (industrial) magnet production. The methods used in the past tend to overestimate these errors. This paper will examine the reasons behind those differences and present an alternate approach.

The following relation and convention is used in defining field harmonics:

$$B_y + iB_x = 10^{-4} B_{R0} \sum_{n=0}^{\infty} [b_n + ia_n][\cos(n\theta) + i\ \sin(n\theta)] \left(\frac{r}{R_0}\right)^n ,$$

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FIELD QUALITY IN SUPERCONDUCTING MAGNETS FOR LARGE PARTICLE ACCELERATORS*

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EPAC '96

Abstract

The expected field quality in superconducting magnets for large particle accelerators has improved over a period of time due to the development and application of a number of techniques. These design techniques will be described and as an example the expected harmonics in an improved design of the 50 mm aperture dipole magnets for the Superconducting Super Collider (SSC) will be presented. This field quality is based on experience with the Relativistic Heavy Ion Collider (RHIC) and SSC magnet programs. The initial results of a design approach will also be presented where the first design itself is adopted to produce good field quality in RHIC D0 insertion magnet.

1 INTRODUCTION

The purpose of this paper is *(a)* to give a brief outline of the concepts which either have been used or can be used in designing and then assuring good field quality in accelerator magnets, *(b)* to present a design concept which avoids the need of a normal magnetic design iteration which is both time consuming and expensive, *(c)* to present methods which can be used to control and match the field quality in the magnets built by several vendors, *(d)* to present techniques which overcome the influence of normal errors in parts and assembly and *(e)* to apply these concepts in a quantitative way to estimate field quality in a magnet which can be used as a reference for the next generation machines.

The field quality in accelerator magnets is characterized in terms of the normal and skew harmonics, b_n and a_n. They are defined in the following expression

$$B_y + iB_x = 10^{-4} \times B_{R0} \sum_{n=0}^{\infty} (b_n + ia_n)[(x+iy)/R]^n,$$

where B_x and B_y are the components of field at (x,y) and B_{R0} is the magnitude of the field due to fundamental harmonic at a "reference radius" R.

2 METHODS FOR CONTROLLING FIELD QUALITY

The methods for controlling field quality are only discussed briefly here (see references [1] to [9] for details).

2.1 Allowed Harmonics and Pre-stress on Coils

Two allowed harmonics can be adjusted by adjusting *(a)* the coil-to-midplane gaps (or midplane shims) and *(b)* the coil pole shims. This is an efficient technique for small adjustments in lower order harmonics (e.g., b_2 and b_4 in dipoles). It may be used either for normal cross-section iteration or to compensate for the differences in field quality of the magnets built by different vendors based on the same magnetic design.

The pre-stress on the collared coil, however, will change if there is a net change in the combined thickness of the pole and midplane shims. A small variation in pre-stress may be tolerated but if it is larger than a few kpsi, then to avoid it one should adjust the coil curing pressures to change the cured coil size. The first magnet of a series usually requires larger adjustment in field harmonics. This is further complicated by the experience that the desired pre-stress on the coils may also not be obtained by the nominal size pole shims. A change in pole shims in order to get the desired pre-stress also changes the field quality.

To deal with the above difficulties, an approach has been developed for the RHIC 100 mm aperture insertion dipole D0 [5] with the goal that the first design itself can be adopted for production by applying small adjustments which are part of the initial design. A third parameter to provide the desired pre-stress on the coils is obtained by increasing the effective thickness of one (or more) selected wedge(s) by changing the number of layers of insulation on it. This resulted in low field harmonics in the body of the magnet as good as those expected after a number of cross-section iterations. Also the magnet had the desired pre-stress on the coils. The first D0 magnet is being used in the RHIC machine. Based on measurements in the first magnet, small adjustments were made in the thickness of the midplane insulation caps and pole shims to compensate the end harmonics and 0.4 mm radius magnetic rods were inserted in the saturation control holes to reduce small values of saturation induced b_2 and b_4 harmonics.

A regular cross-section iteration generally requires a large mechanical change in several wedges and is associated with *(a)* a change in tooling and *(b)* a change in the end design. Both of these are time consuming and expensive and are avoided in the above approach. Moreover, this approach requires only small mechanical changes and therefore has a better chance of succeeding.

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*Work supported by the U.S. Department of Energy under contract No. DE-AC02-76CH00016.

Estimates of Error in the Mean

Details will not be discussed here
(more offline; however a flavor will be presented)

But

In the end story is similar to that of sigma

Sources of error in estimates are similar
+ the RHIC experience

* **Systematic errors in the critical harmonics can be fixed by small mechanical adjustments!**

- **A few examples to follow**

And

what can be done to remove systematic difference in LHC magnets supplied by different vendors ?

Control of Systematic Errors in Magnets

Philosophical discussion

① During initial (first) magnet development

Requires larger correction

② During series production < different vendor / drift in productio

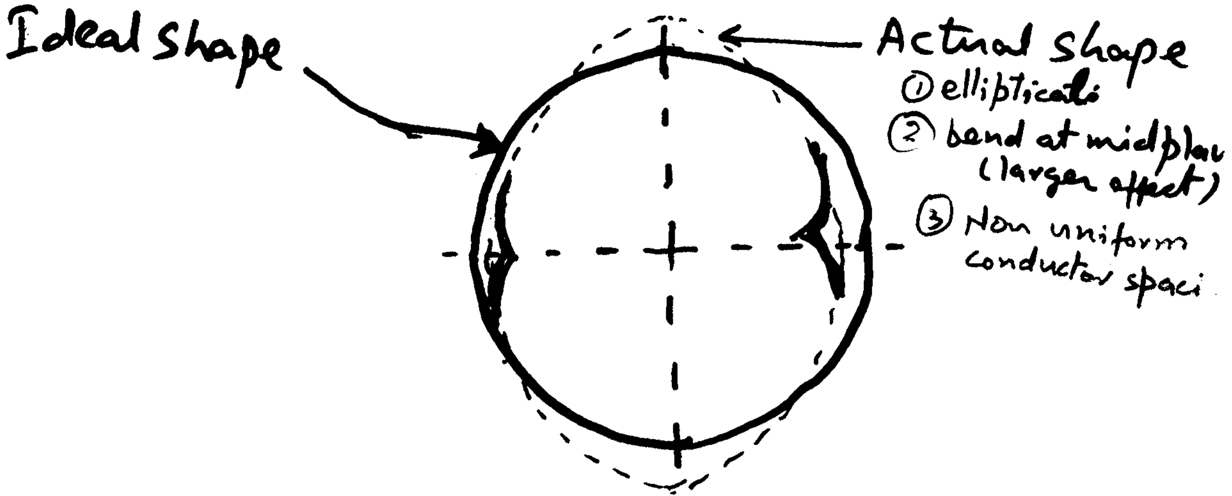
Requires smaller correction

→ but must be planned ahead!

Why the actual harmonics different from design?

① Error in parts

● Error / Differences between the shape used in design calculati and in the actual magnet



To model these deviation, the mechanical (ANSYS) analysis must give answer within 25 μm!

Can it?

Suggested approach

- → If you cannot compute it; find the net effect of it experimentally

→ Plan a way to accomodate it.

Typical Field Quality Requirements

$\frac{\Delta B}{B} = 10^{-4}$ at $\frac{2}{3}$ coil radius.

RHIC Arc Dipoles and Quadrupoles

Coil Aperture : 80 mm [Average ≈ 90 mm]

Circumference : 251 mm

Mechanical tolerances for 10^{-4} field quality :

$$251 \text{ mm} \times 10^{-4} = 0.0251 \text{ mm (1 mil)}$$

General argument; in detail, it depends on the location of error.

LHC

Coil id = 56 mm

Inner circumference ≃ 175 mm

Avg. coil ≃ 96 mm

Avg. circumference ≃ 300mm

Geometric
Saturation

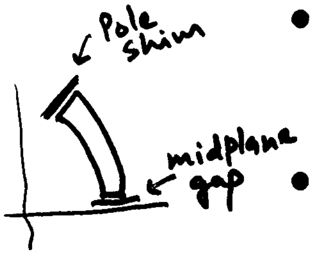
[persistant current
(above not valid)]

Experiences in Field Quality with Coil

1. Allowed harmonic not on target

(Usually first two; higher orders are ok)

This is typical in the first magnet.



- Impact : USUAL - Changes the wedges, etc.
- Suggestion : Use existing wedges/coils but change the midplane and pole shims.
- Result : 2 parameter 2 harmonics, measured change as computed.
- Advantage : Fast track approach, Results can be quickly verified. Time and money saved = ~ 1 year and $100,000.

NOTE : Some change in coil size can be accommodated during curing so that pre-compression on coil can be kept optimum.

~~And~~ + (in first magnet)

Pre-stress on coil is not right (either due to wrong coil size or wrong model based expectation)

Can be fixed by adding shims but then field quality is way off

DC Loop

Table 1: **The average and RMS values of field harmonics in various cross section designs for RHIC arc dipoles. The b2 harmonic is given at the maximum field (3.46 T) and the other harmonics at injection (0.4 Tesla). The measured warm cold correlation of 40 magnets is used to estimate harmonics in 130 magnets measured warm.**

Design	b_2	b_4	b_6	b_8
Prototype	**1.3±0.8**	**0.3 ±0.2**	**-0.1 ±0.05**	**0.40±0.03**
Phase 1	**0.4±1.6**	**-1.0 ±0.4**	**-0.38±0.09**	**0.20±0.06**
Phase 1A	**1.2±1.2**	**-0.4 ±0.30**	**-0.10±0.08**	**0.24± 0.03**
Phase 2	**-0.3±1.3**	**0.1 ±0.32**	**-.21±0.09**	**0.00 ±0.03**

Table 2: *The computed changes in the values of harmonics produced by a systematic azimuthal error of +25μm* (0.001") *in crucial parts in RHIC arc dipoles.*

Parameter	δb_2	δb_4	δb_6	δb_8
Wedge 1	**-0.98**	**-0.122**	**0.061**	**0.043**
Wedge 2	**0.69**	**0.423**	**0.022**	**-0.050**
Wedge 3	**1.42**	**-0.090**	**-0.068**	**0.041**
Pole Width	**-1.11**	**0.154**	**-0.039**	**0.014**
Midplane Gap	**-1.68**	**-0.557**	**-0.156**	**-0.050**

+ other parts (Yoke, insulator, etc).

→ Magnet harmonics are better than the tolerances in parts

→ This is the best one could expect from the industry 2 from the design

RHIC D0 INSERTION DIPOLE MAGNET

The First Magnet itself Goes to RHIC Machine *

Small Values of Low Field Harmonics in Body

Adjustments from

1. Midplane Cap
2. Pole Shim
3. Wedge Insulation
   [select the wedge(s)]

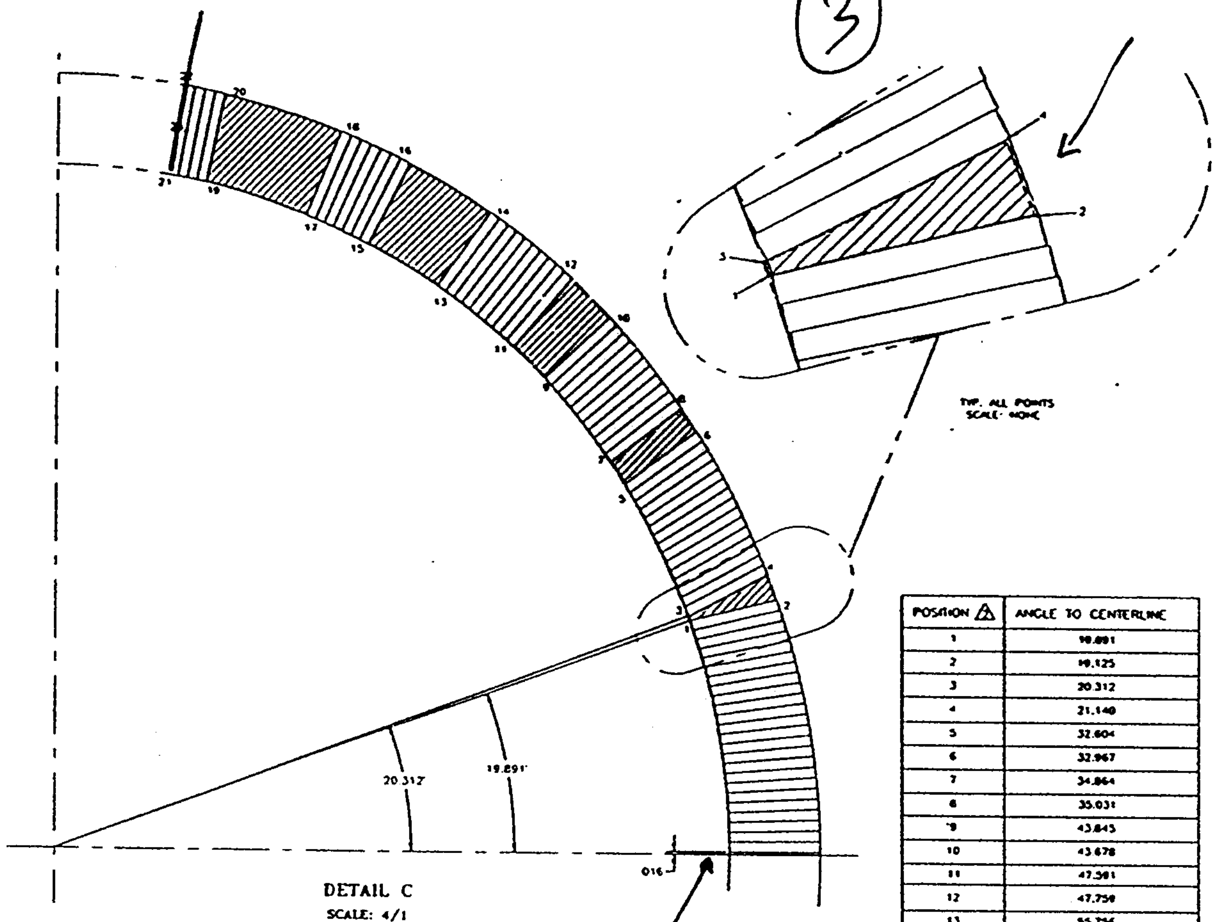
Adjustments for

1. b2
2. b4
3. Cable thickness or Pre-stress on Coil

Phillosophy

- We are almost there (10^{-3} if not 10^{-4})
- Small mechanical adjustment can fix the problem
  → (a few mil here and a few mill there)
- Don't start all over by big mechanical changes
  (if changes are bigger, you may not converge in ~~one~~ shot)
  SSC experience

Schematic of Adjustments in D0 Coil Cross-section:



DETAIL C
SCALE: 4/1

① Pole Shim

③ Small adjustment in Wedge

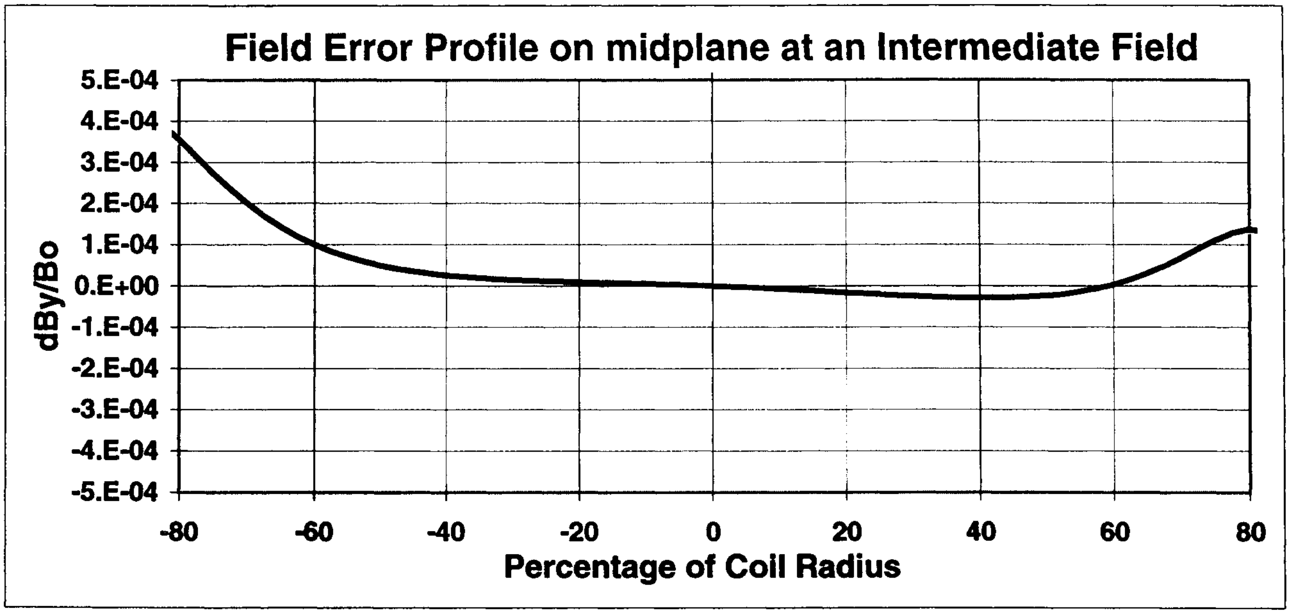
② Midplane Gap
16mil instead of usual 4mil

POSITION △	ANGLE TO CENTERLINE
1	19.891
2	19.125
3	20.312
4	21.140
5	32.604
6	32.967
7	34.864
8	35.031
9	43.845
10	43.678
11	47.391
12	47.759
13	55.756
14	55.619
15	62.493
16	62.630
17	68.208
18	68.131
19	77.307
20	77.474
21	79.847
22	79.831 –
23	79.839

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.

Harmonics at 2 kA (mostly geometric).
Measured in 0.23 m long section of 3.6 m long magnet.

Harmonics are given European convention (b2 is quadrupole).

Reference radius = 31 mm

b2	-0.39	a2	-1.06
b3	-0.39	a3	-0.19
b4	-0.07	a4	0.21
b5	0.78	a5	0.05
b6	-0.05	a6	-0.20
b7	0.13	a7	0.02
b8	-0.03	a8	-0.16
b9	0.14	a9	-0.01
b10	0.02	a10	0.01
b11	-0.04	a11	-0.06
b12	0.03	a12	-0.01
b13	0.16	a13	0.06
b14	-0.03	a14	0.03
b15	-0.10	a15	0.02

Reference radius = 10 mm

b2	-1.3E-01	a2	-3.4E-01
b3	-4.1E-02	a3	-2.0E-02
b4	-2.2E-03	a4	7.1E-03
b5	8.5E-03	a5	5.3E-04
b6	-1.8E-04	a6	-7.1E-04
b7	1.4E-04	a7	2.7E-05
b8	-1.3E-05	a8	-5.9E-05
b9	1.6E-05	a9	-1.1E-06
b10	7.5E-07	a10	2.3E-07
b11	-5.2E-07	a11	-6.9E-07
b12	1.3E-07	a12	-2.9E-08
b13	2.0E-07	a13	7.8E-08
b14	-1.2E-08	a14	1.1E-08
b15	-1.3E-08	a15	2.0E-09

Note: Harmonics in first D0 dipole are within or close to one sigma of RHIC production dipoles.

Intermediate conclusion

One can ~~po~~ perhaps make each R&D magnet a good magnet

- It would give beam physicst a bit more comfort
- It would give magnet builder more experience and more confidence

- Usually field quality issues are delayed to the end
- But it does not take much more to accomodate in initial magnets, if planned ahead.

Suggestion

Pl. try to test it in all magnets owit now onwards

How to accomodate different vendors?

Different vendors may have different systematic $\int B \cdot dl$ and different harmonics

(HERA experience)

A SIMPLE SOLUTION

- Leave room for a simple mechanical adjustment
- Measure ~10 magnets to determine $< >$, σ
- Apply the correction

correction may be required in

$\int B \cdot dl$, a_2, b_3, b_5

other higher order harmonics are usually OK.

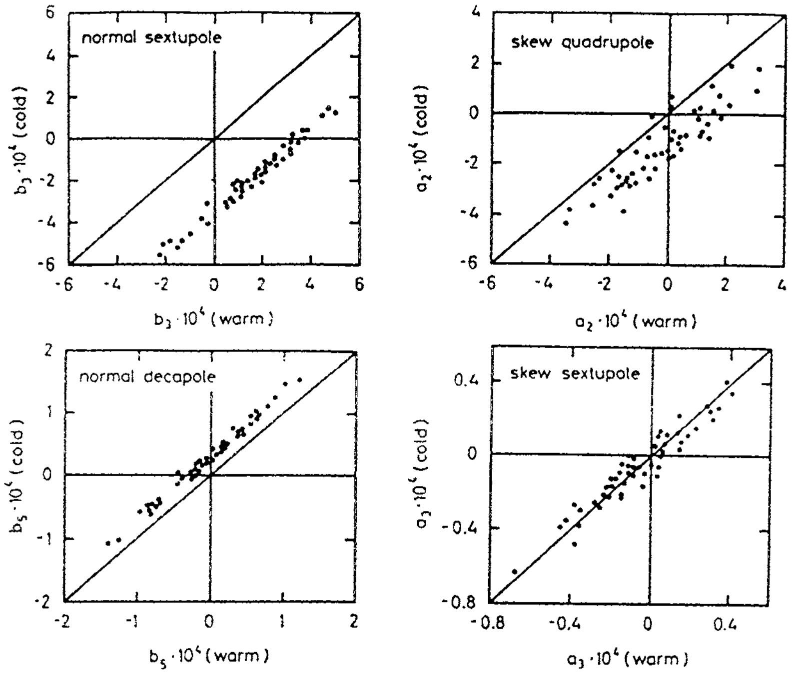


Figure 5.4: Correlation between room-temperature and cryogenic measurements of the multipole coefficients in the RHIC dipoles (R.C. Gupta, private communication). The systematic offset in the sextupole and decapole is caused by the fact that the cryogenic data were taken at high current where yoke saturation comes into play.

in these magnets is indeed rather good (Fig. 5.4) and allows to restrict cryogenic measurements to a 10% fraction of the magnets without sacrificing field quality.

The techniques for multipole measurements are described in Appendix A.

5.3 Field integral and field orientation

What counts for the deflection and focusing of a particle beam is the integral of dipole field and quadrupole gradient over the length of the magnet. An absolute determination of the integrated dipole field is possible by a longitudinal scan with a nuclear magnetic resonance (NMR) probe plus an additional Hall probe that covers the inhomogeneous end field (Preissner et al. 1990). For a quadrupole one can stretch a wire along the axis and move it perpendicular to the field by precision-tables, see Appendix B. The magnetic flux swept in the motion translates into a time integral of the induced voltage. Both methods permit accuracies in the 10^{-4} range. The field integral distribution of the HERA magnets is plotted in Fig. 5.5. The dipoles

from two production lines (Ansaldo/Zanon in Italy and Brown Bovery in Germany) turned out systematically different by $1.9 \cdot 10^{-3}$ although both were built according to the same drawings. Half of this difference is caused by different magnetic lengths (8825.7 ± 1.7 mm vs. 8833.5 ± 2.0 mm), the other half by different central fields ($B/I = 0.9328 \pm 0.0005$ T/kA resp. 0.9336 ± 0.0005 T/kA). In the HERA machine, correction magnets are used to compensate the systematic offset between the two sets of dipoles.

HERA Dipole

HERA Quad

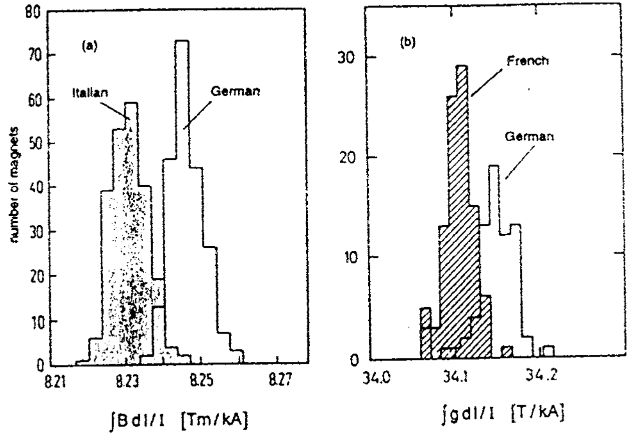


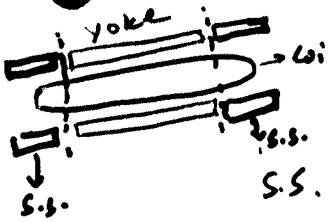
Figure 5.5: (a) Field integral of all HERA dipoles, normalized to coil current. (b) Integrated gradient of all quadrupoles, normalized to coil current (Brück et al. 1991).

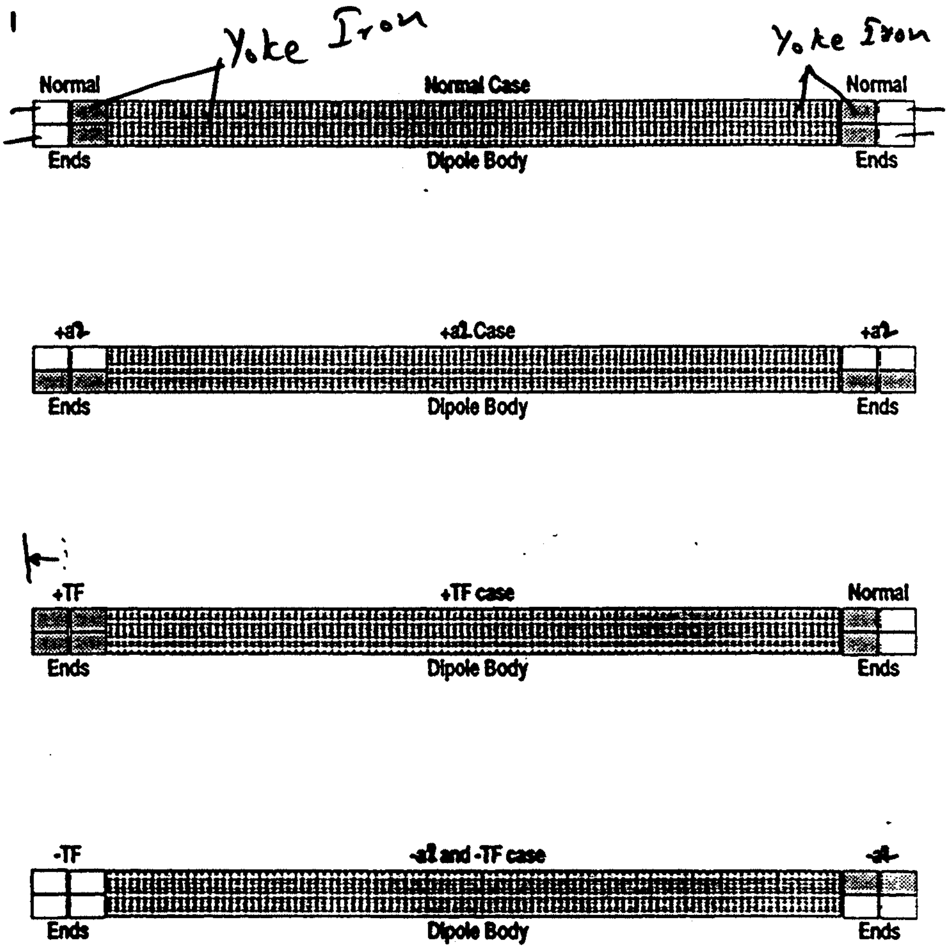
In order to keep the unavoidable closed-orbit distortions in the accelerator ring within tolerable limits (typically 1 mm rms in a large machine), the field orientation of the dipoles with respect to the ring plane has to be kept within a fraction of a milliradian and the axes of the quadrupoles must be aligned with an accuracy of better than 0.25 mm with respect to the nominal orbit. Contrary to conventional magnets with iron pole shoes, the centre axis and the field direction of superconducting magnets are not directly observable with theodolites and leveling instruments when the cryostat is closed. A tedious procedure is needed to transfer the data from magnetic measurements to optical reference targets which are mounted on the outer cryostat vessel and which can later be utilized for surveying the magnets in the accelerator tunnel.

The dipole field direction can be determined with a device that combines two orthogonal Hall probes and a gravitational sensor with electronic readout. The precision is a fraction of a milliradian. The collared dipole coil by itself is not a stiff structure and may be bent or twisted along its length. The mechanical stability is provided by a stainless-steel cylinder welded around the iron yoke. The average twist of the HERA dipoles is 0.06 ± 0.2 mrad/m. An interesting method is applied

Adjustment in Skew quad & Transfer functions in Dipole

(Tuning)





a_2 adjustment

Increase TF

Adjustment in a_2 & TF

Figure 5.3.1: A conceptual diagram for correcting the integral a_2 harmonic and integral transfer function in a superconducting dipole magnet. The proposed adjustment is applied in the end region of the magnet. The actual starting point would be somewhere in the dipole body where the field is still high. In the normal case (top figure) the change between the magnetic, low carbon steel laminations [dark or filled] and non-magnetic stainless steel laminations [light or empty] occurs at a nominal location. Interchanging the stainless steel and low carbon steel laminations between top and bottom halves (second figure) creates an a_2 which can be used to compensate the measured a_2 in a magnet. Increasing the number of low carbon steel magnetic laminations increases the integral transfer function (third figure). An adjustment (decrease) in both a_2 and integral transfer function can be obtained together by mixing the two schemes in the same magnet (bottom figure).

b_3 & b_5 adjustment

- → Use midplane cap & pole shim

  Must leave room in the initial design

- This has been used effectively in all RHIC magnets (several time in each)
  - 80 mm aperture main dipole
  - 80 mm aperture main quadrupole (b_6 & b_4 also)
  - 100 mm insertion dipole
  - 130 mm insertion quadrupole
  - 180 mm insertion dipole (planned)

  All had midplane gap increased from 0.1 mm to over 0.2 mm.

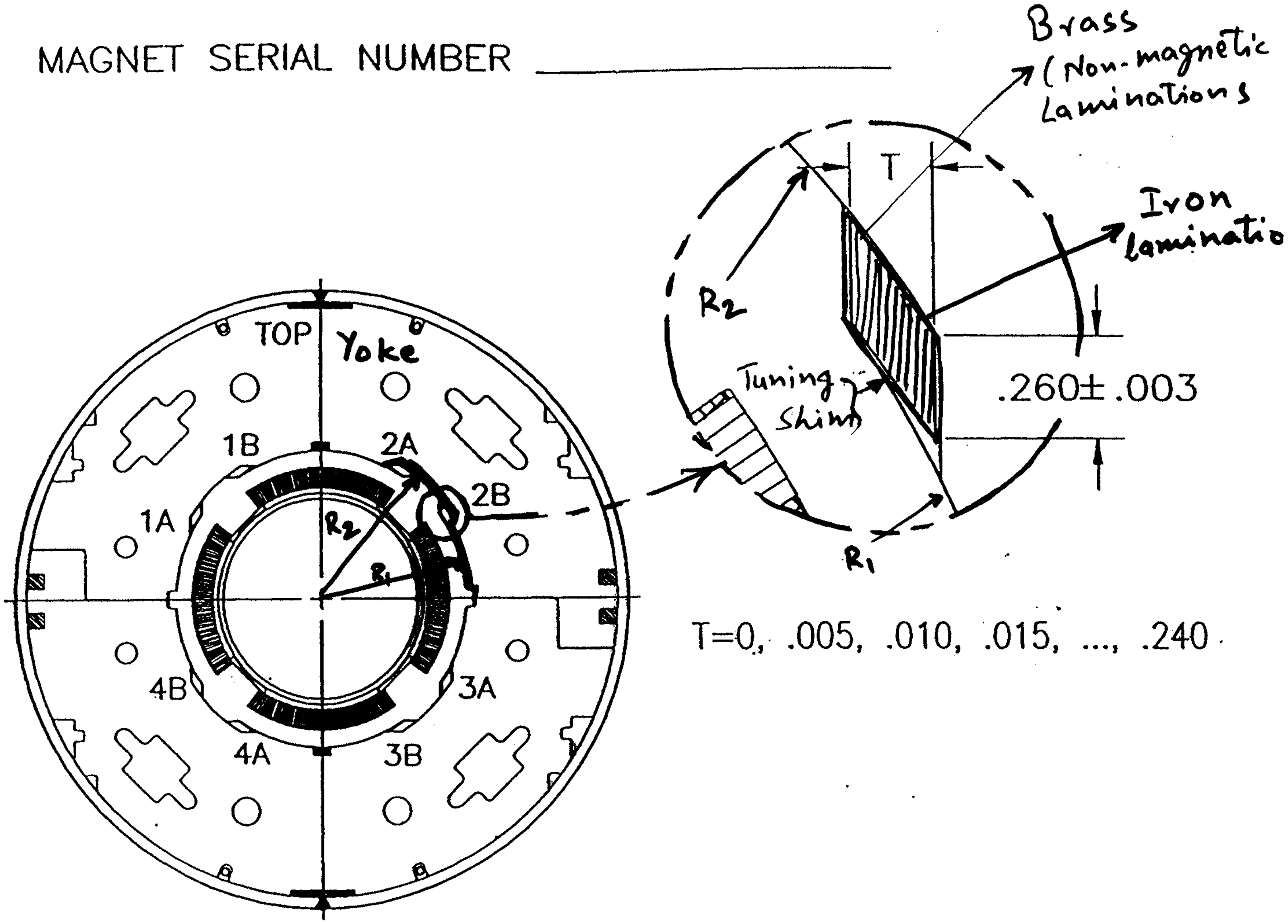
- Situation should be better in LHC magnets.

  → Better adjustment because of 2 layers

Method to obtain 10^{-5} field errors at 2/3 radius

TUNING SHIM MATERIAL WORKSHEET A
RHIC 13cm QUADRUPOLE

MAGNET SERIAL NUMBER ____________



T=0, .005, .010, .015, ..., .240

Harmonics due to iron saturation

Approaches to reduce it

① Remove the iron which saturates

- increase yoke i.d.
→ elliptical aperture

~~etc~~

this is a popul~~ar~~ approach

(2) Make yoke saturation more uniform

→ holes

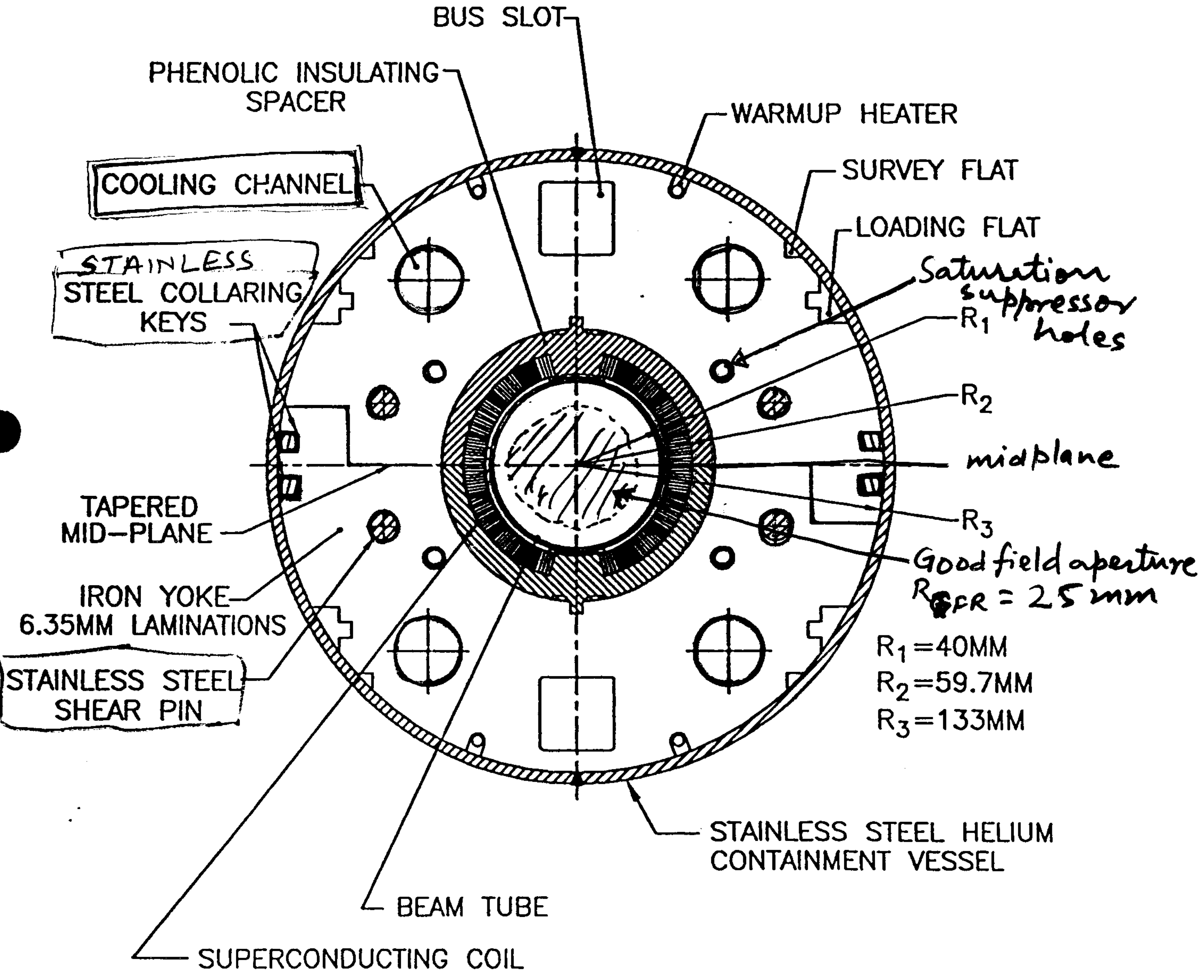
→ 2-rad. aperture

used effectively in various RHIC magnets

- Increases iron contribution to ~~the~~ total field

- May make magnet cheaper by reducing the collar thickness (magnet mechanics involv

RHIC ARC DIPOLE COLDMASS



$R_{GFR} = 25$ mm

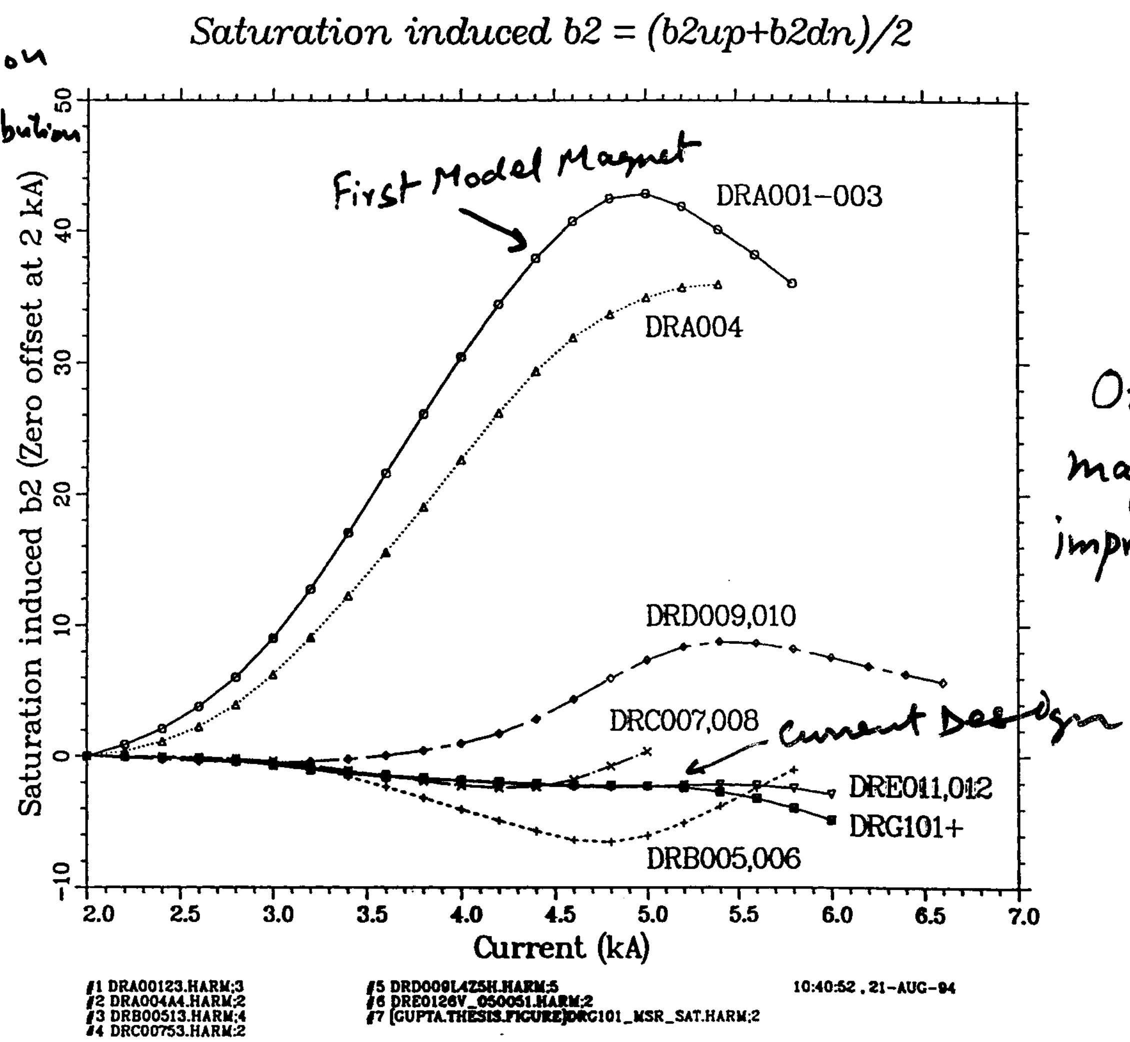
R_1=40MM
R_2=59.7MM
R_3=133MM

mr/8cm–arcdip

Experience

RHIC Dipoles

- Close-in-Iron
- Large contribution from Yoke
- Expect large Saturation



Order magnitude improvement

Figure 3.3.2: Measured saturation induced sextupole harmonic (b_2) as a function of current. The b_2 harmonic shown here is the average of b_2 measured during an up and down ramp. This removes the persistent current b_2 to first order in the operating range. Moreover, in order to make an easy relative comparison between various designs, the value of b_2 in each magnet is biased so that each curve starts from a zero value at 2 kA.

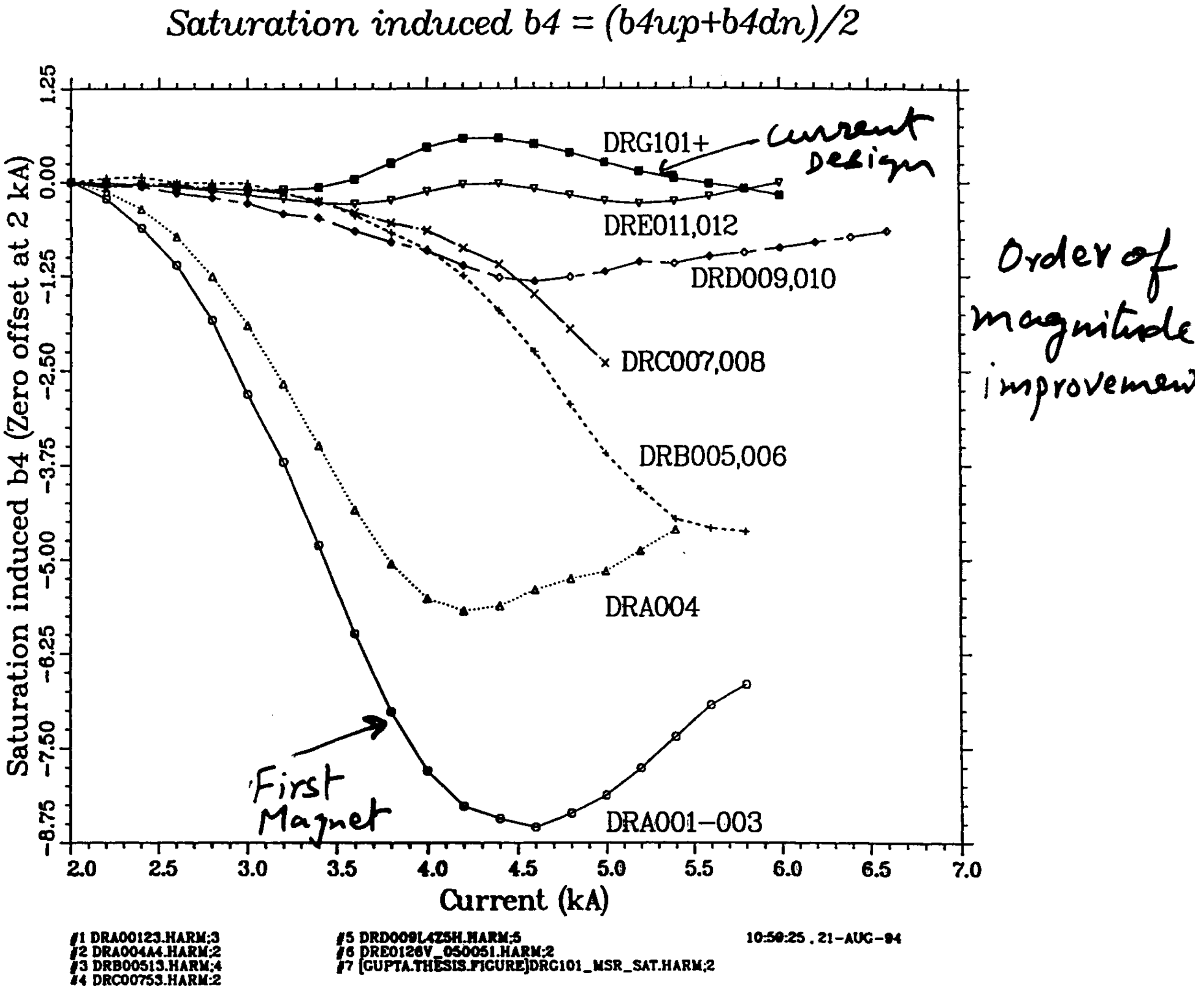
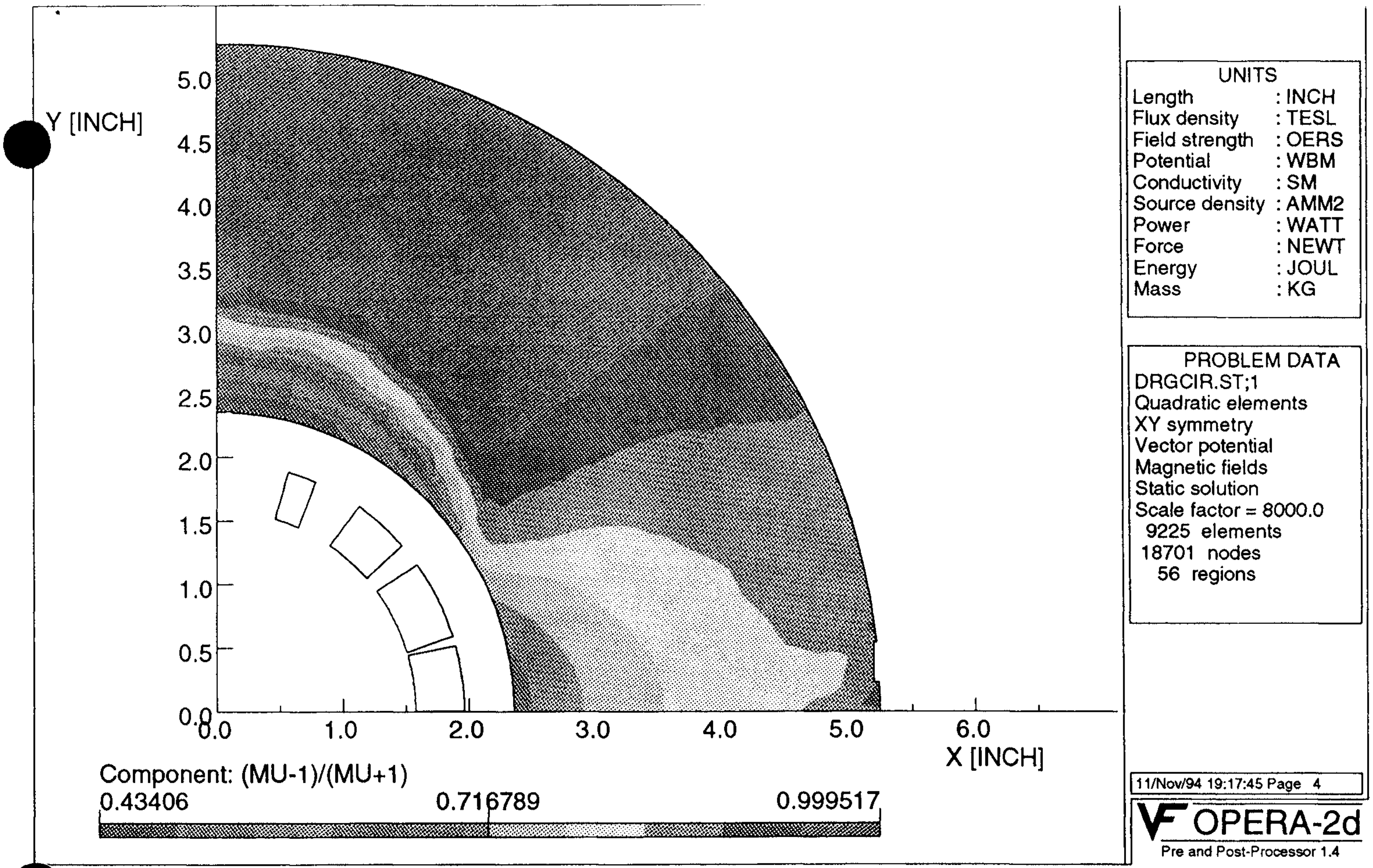


Figure 3.3.3: Measured saturation induced decapole harmonic (b_4) as a function of current. The b_4 harmonic shown here is the average of b_4 measured during an up and down ramp. This removes the persistent current b_4 to first order in the operating range. Moreover, in order to make an easy relative comparison between various designs, the value of b_4 in each magnet is biased so that each curve starts from a zero value at 2 kA.

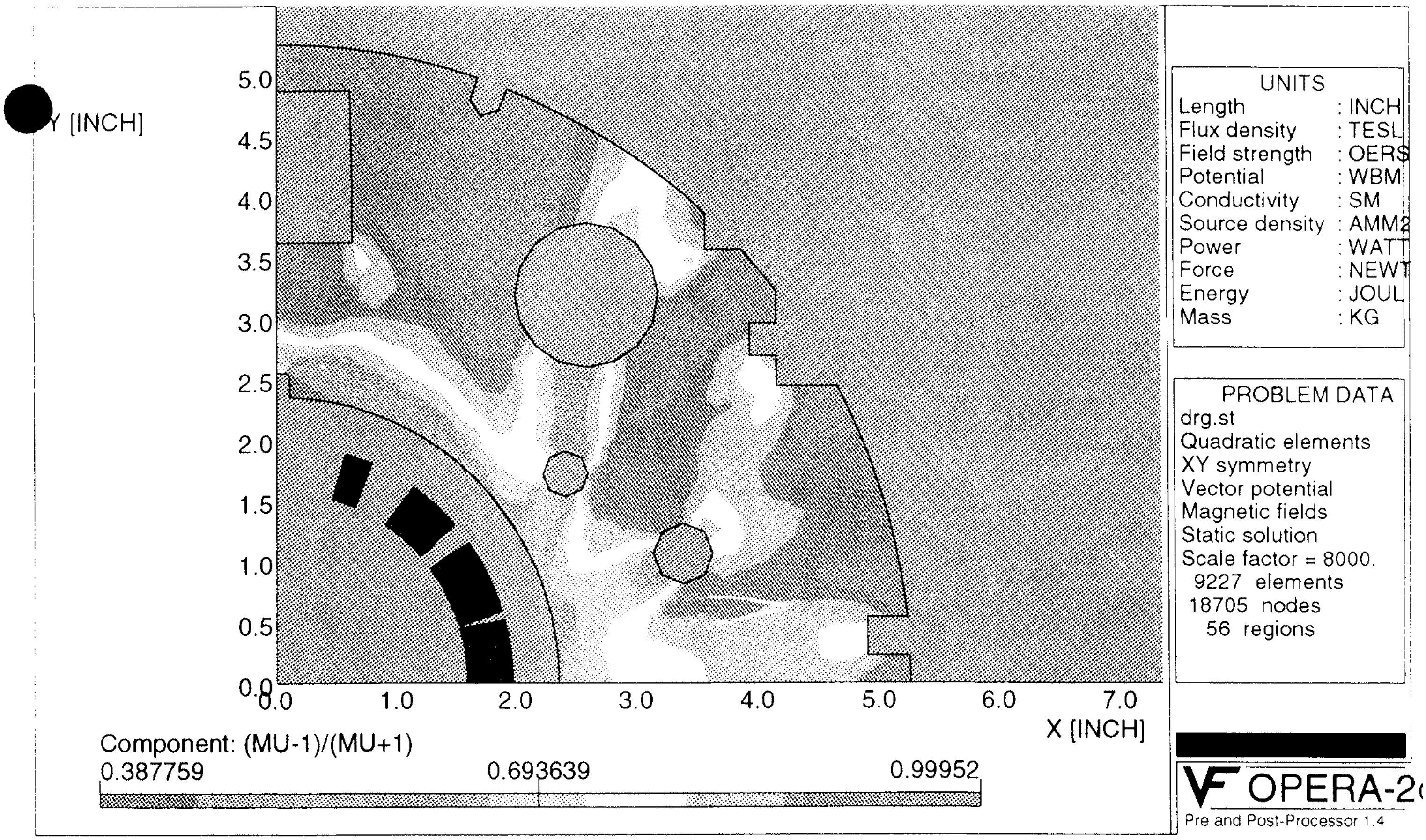


$\frac{\mu-1}{\mu+1}$ in Yoke with no structure (at 8kA)

See a large change in $\frac{\mu-1}{\mu+1}$ near the yoke aperture.

0'43 → ~ 0·8 (about a factor of 2)

This means that iron contribution is now a function of ~~any~~ and field shape gets ~~deformd~~ deformed.



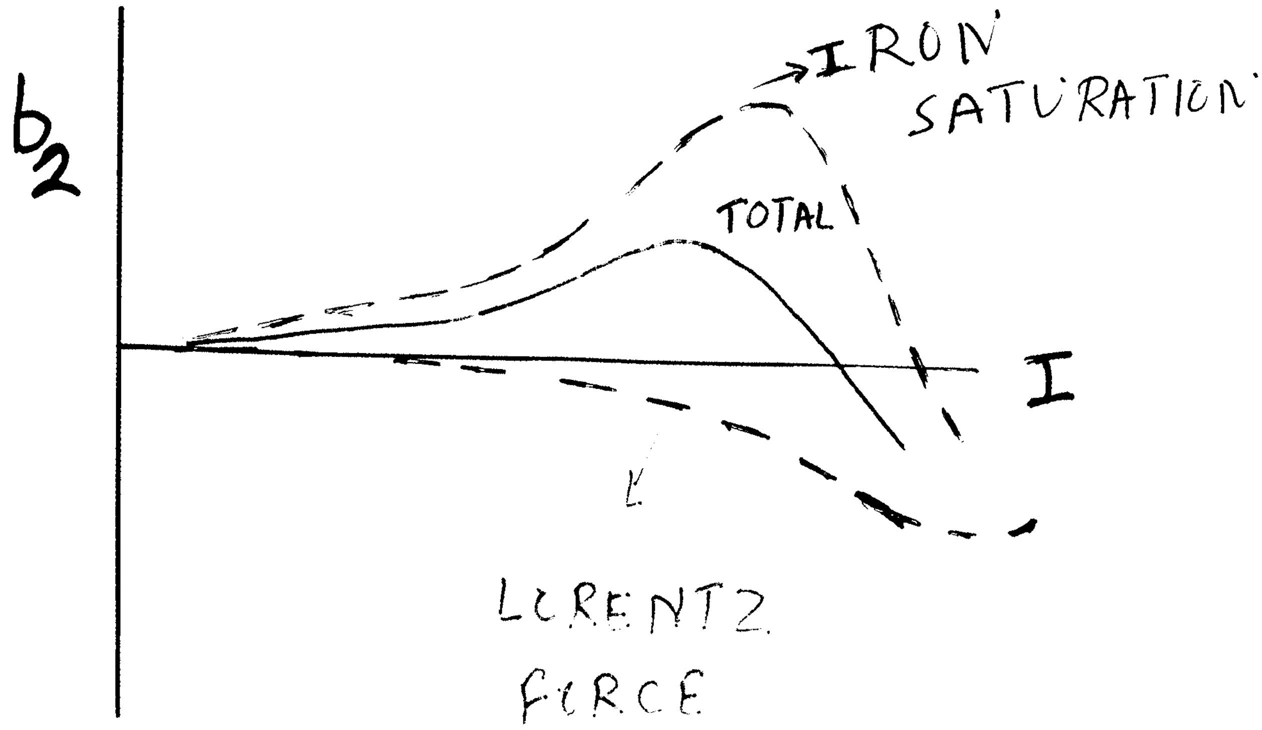
UNITS
Length : INCH
Flux density : TESL
Field strength : OERS
Potential : WBM
Conductivity : SM
Source density : AMM2
Power : WATT
Force : NEWT
Energy : JOUL
Mass : KG

PROBLEM DATA
drg.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 8000.
9227 elements
18705 nodes
56 regions

-rupole harmonic

---

b_2 Vs I



b_2 (Measured) = b_2 (IRON) + b_2 (COIL)

+ some due to Persistent currents

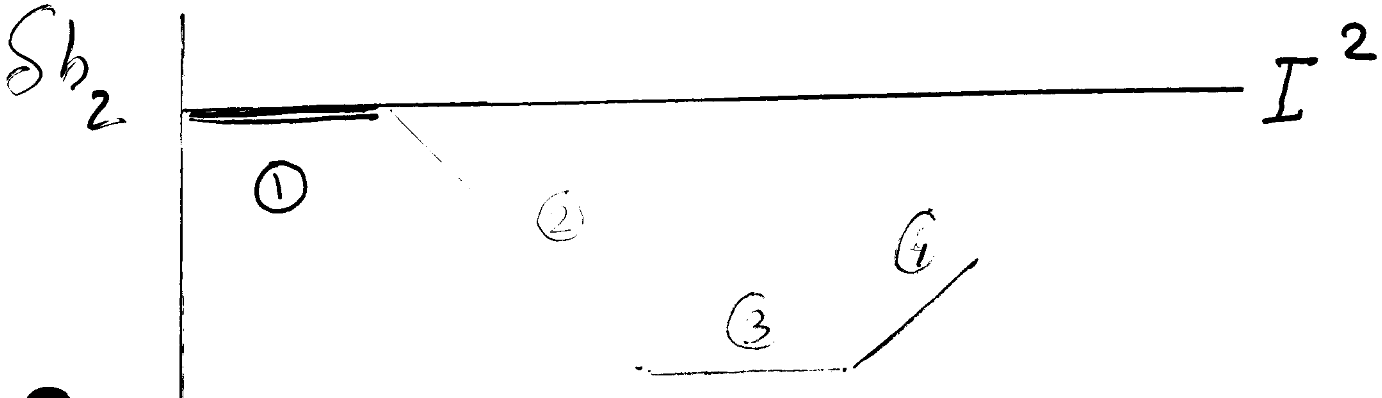
---

b_2 (Measured) $= \frac{1}{2} \{ b_2$ (up ramp) $+ b_2$ (down ramp)$\}$

→ Make zero at 2 kAmp to take out Geometric multipole

Change in b_2 due to Lorentz Force

I^2 effect



① LOW LORENTZ FORCE REGION
No change in b_2.

② RADIAL COMPONENT OF LORENTZ FORCE
Negative change in b_2

③ CONTACT IS MADE BEWEEN COLLAR & IRON
No change in b_2

④ AZIMUTHAL COMPONENT OF LORENTZ FORCE
Pole turns move; Positive change in b_2.

→ Above are combined

SSC Experience

- Two group of magnets, based on similar yoke design, had very different current dependence of sextupole. ~~to~~

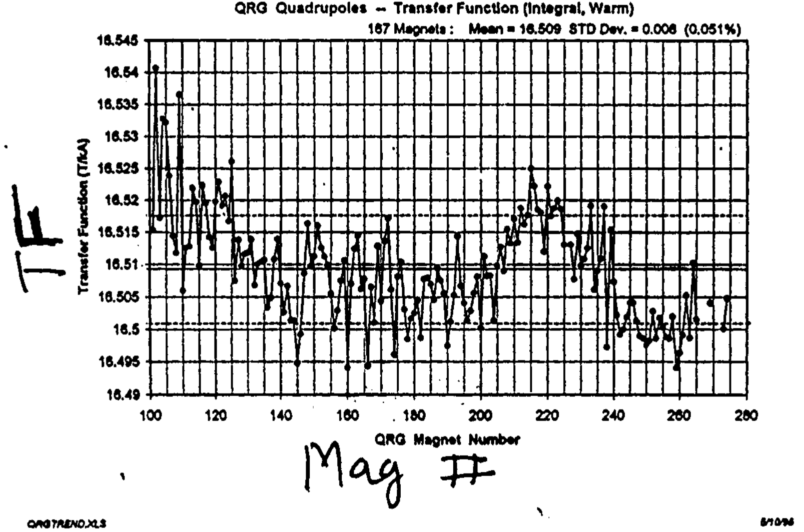
- It was traced to a change in yoke die, which increased the gap between collar & yoke; and hence allowed collar and coil to deform more until it made a contact to yoke i.d.
(verified with stress measurements)

Ref. see pac paper

Field Quality as a tool to monitor production

some stories from RHIC magnet production

⊗ RHIC Quad QRG

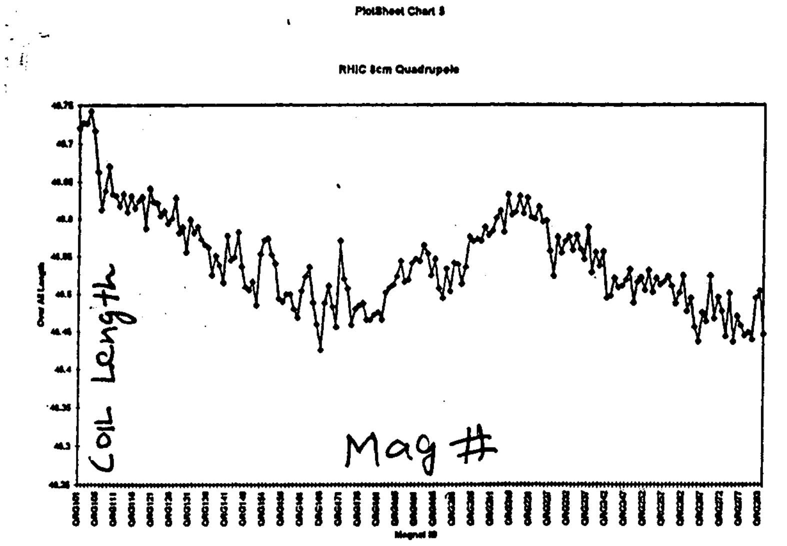


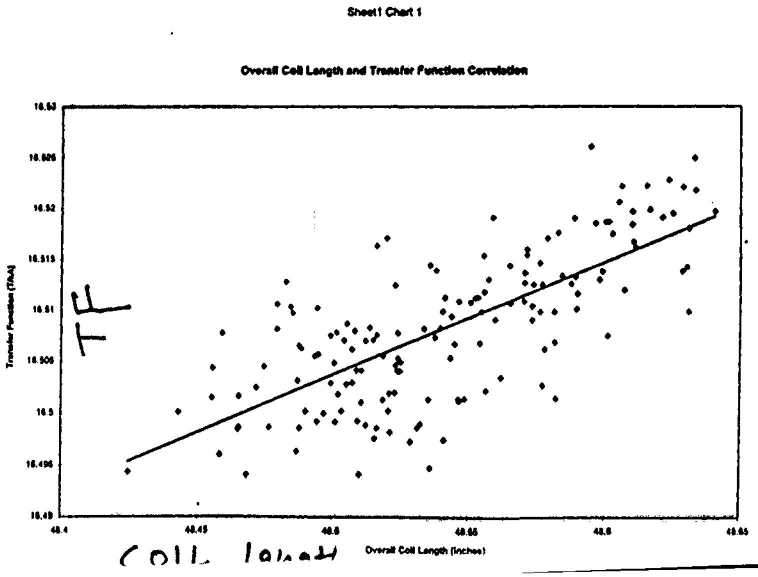
QRGTREND.XLS

5/10/95

R. Gupta
5/10/95

The Variation in Quad Integral Transfer Function is found to be related to the coil length (averaged over 4 coils).





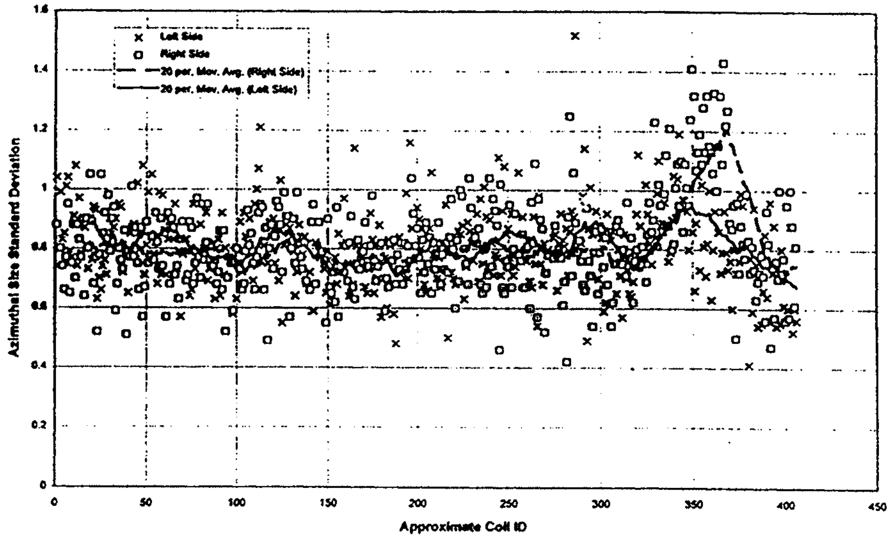
Ramesh Gupta
Aug. 21, 1995

Axial Variation in Coil Sizes

As shown by Animesh in the last acceptance committee meeting, a large axial variation in field harmonic has been observed in DRG magnets. The possible sources for that were discussed and an axial variation in coil size is one of them. I checked the standard deviation in coil sizes with David and found that indeed this is the case. The plots are made for the standard deviation together with the moving averages of 10 magnet worth of coils in dipole and quadrupole magnets. The following observations can be made. In dipoles, there was an increase in standard deviations (particularly on the right side of the coil) which could be responsible for the harmonics like b1, b3 and a2 and a4, etc. It appears that the things are getting back to normal now. In quadrupoles, the right side always had larger standard deviation then left side. This gives terms like a3, a5, etc.

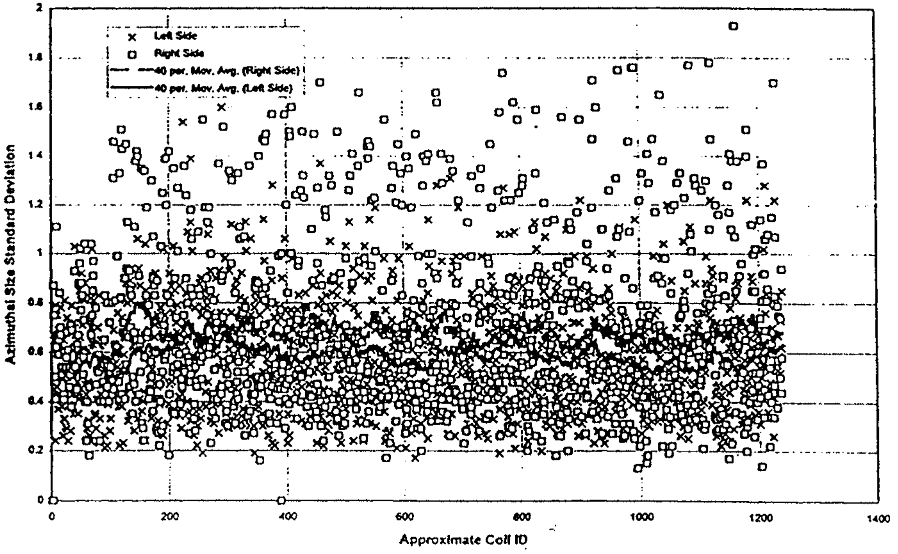
DRG

Standard Deviation of Left and Right Dipole Coil Azimuthal Sizes
with 20 Point Moving Average

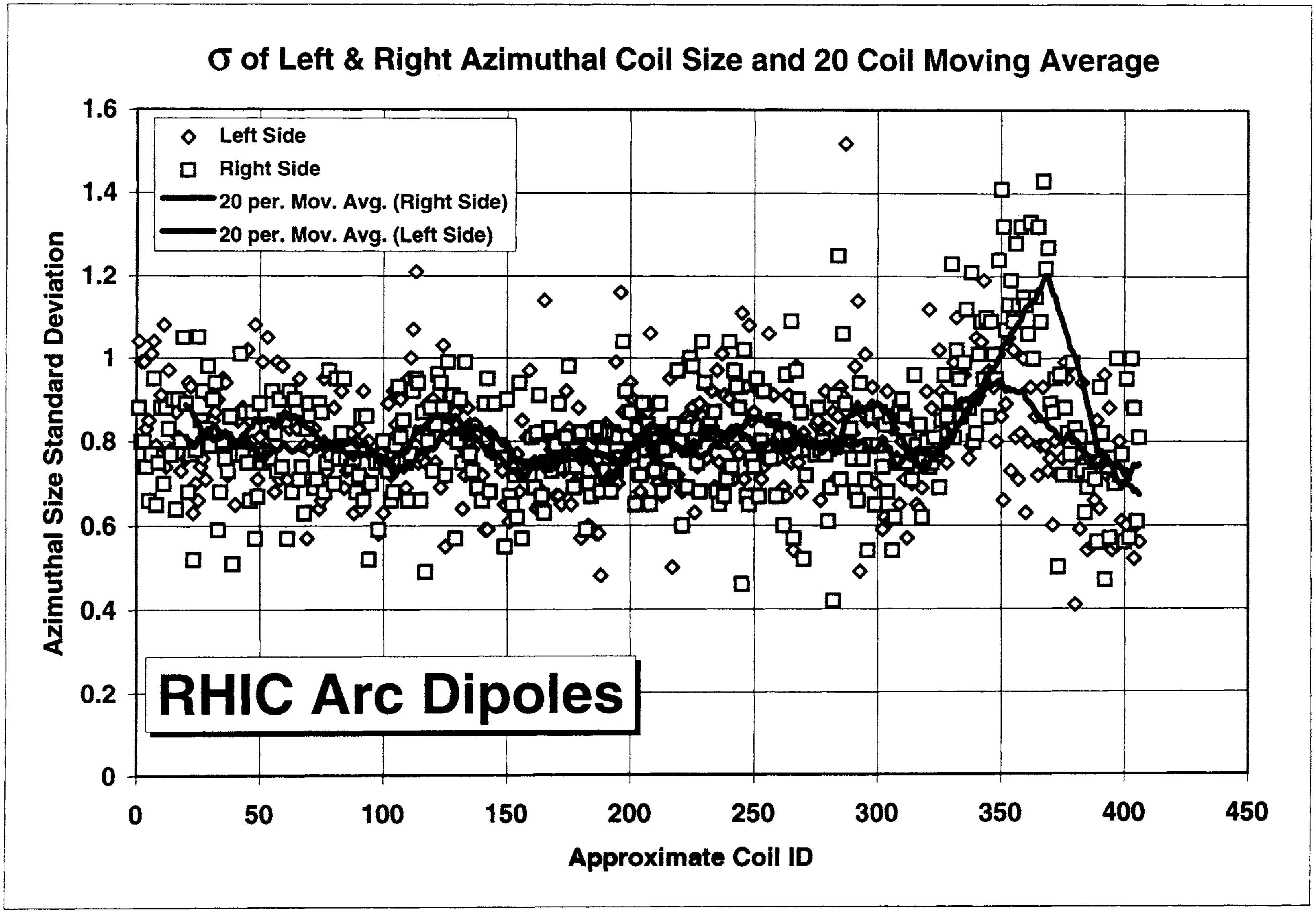


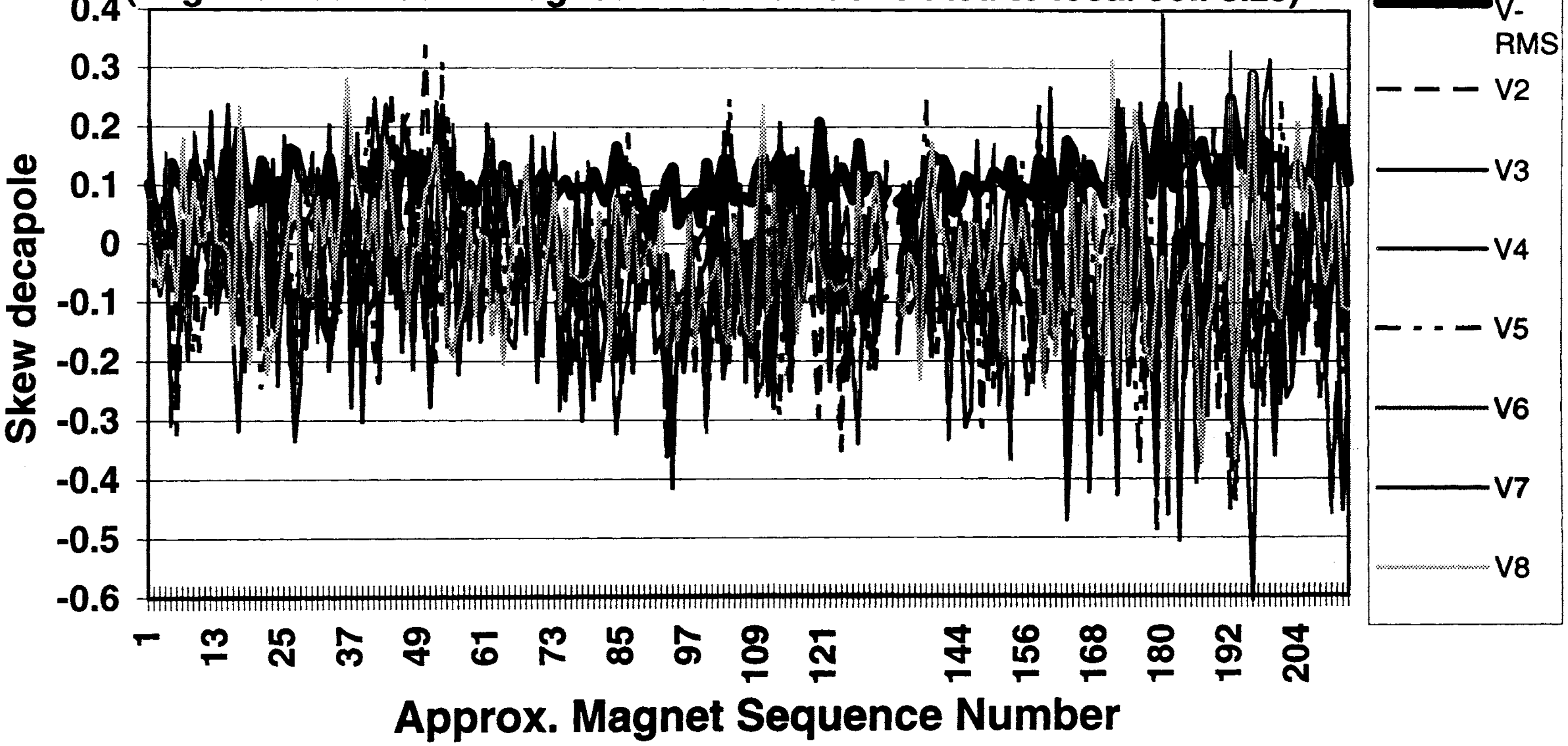
QRG

Standard Deviation of Left and Right Quadrupole Coil Azimuthal Sizes
with 40 Point Moving Average



David McChesney c:\qrg\qudazstd.xls 8/21/95

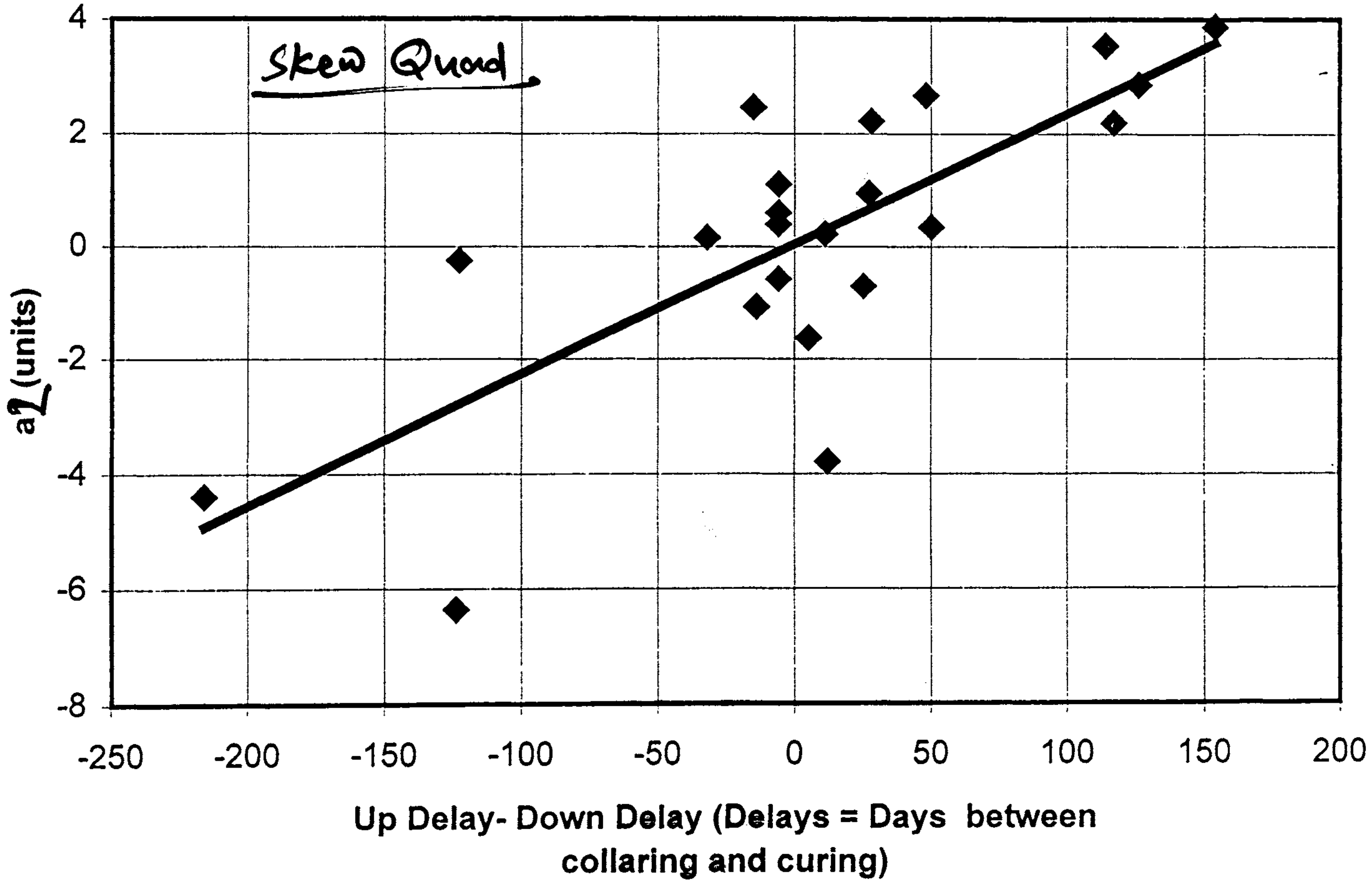

σ of Left & Right Azimuthal Coil Size and 20 Coil Moving Average
Left Side
Right Side
20 per. Mov. Avg. (Right Side)
20 per. Mov. Avg. (Left Side)
RHIC Arc Dipoles
Azimuthal Size Standard Deviation
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
Approximate Coil ID



Skew decapole at various locations with magnet No. in RHIC dipoles
(large values around magnet #170-210 was related to local coil size)

- Coils sizes were [illegible] when they were made (cured)
- Coil size tend to grow when left for sometime
- * Coil sizes between upper and lower were based on measurements made when they we

Possible source of a2 in D0 Magnets



Note : Coil size grows with time. However, in magnets it is matched based on the size when it was measured (cured).
a2 also comes from other sources

CONCLUSIONS

Magnet construction, measurements, design & analysis techniques have significantly improved since HERA

SSC & RHIC magnet production demonstrates that

Hence, one should expect a better field quality than generally thought.

But one must plan ahead and demonstrate it

* * *

A flow chart which I used for feedback