Lecture VI

Magnetic Design

Field Quality Adjustment After Initial Design

(Even after the start of the production run)

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A Flexible Design Approach

Conventional Approach:

- **Fix design parameters as soon as possible.**

Alternate Approach:

- **Develop a flexible design that can accommodate variations in parts, etc.**
- **It also allows variations in design (for example, as requested by accelerator physicists)**
- **It assures good field quality during the production while maintaining the schedule and cost.**

Adjustment After Construction

Another Related Subject

- Some times, it is more efficient to find ways to make small adjustments, than iterate the original design to achieve the desired field quality.

- Moreover, in magnets that require very high field quality, some adjustments or tuning may be essential to overcome the limitations due to tolerances in parts and manufacturing.

- Developing a magnet design that allows such adjustments is more likely to achieve the desired field quality and may also be more cost-effective, in an overall sense.

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

Note: Integral B.dl

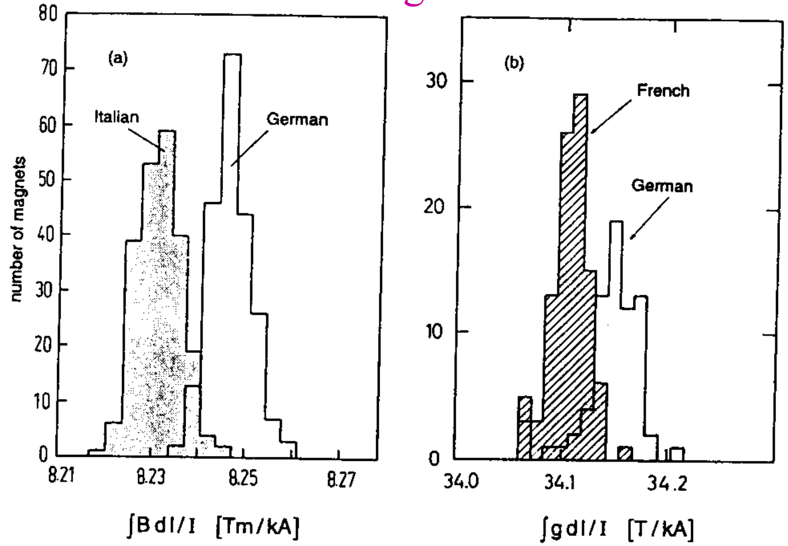
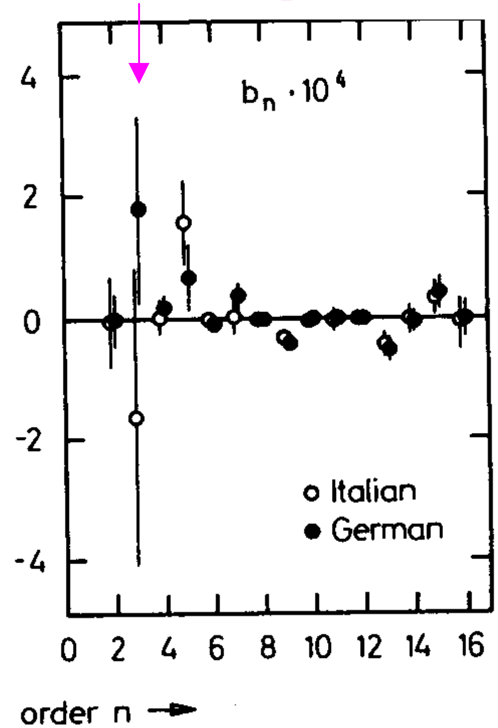


Figure 5.5: (a) Field integral of all HERA dipoles, normalized to coil current. (b) Integrated gradient of all quadrupoles, normalized to coil current (Brück et al. 1991).

Note: Sextupole



- Parameters do deviate from nominal value.
- It takes time to locate the cause of the problem and then fix it (conventionally that meant a cross section iteration). Takes too long and the magnet production cannot stop.
- *An alternate method to accommodate such variations is to develop a flexible design that assures good field quality despite such deviations.*

Feedback in design from HERA experience

A Method to Adjust Integral Field and Skew Quad

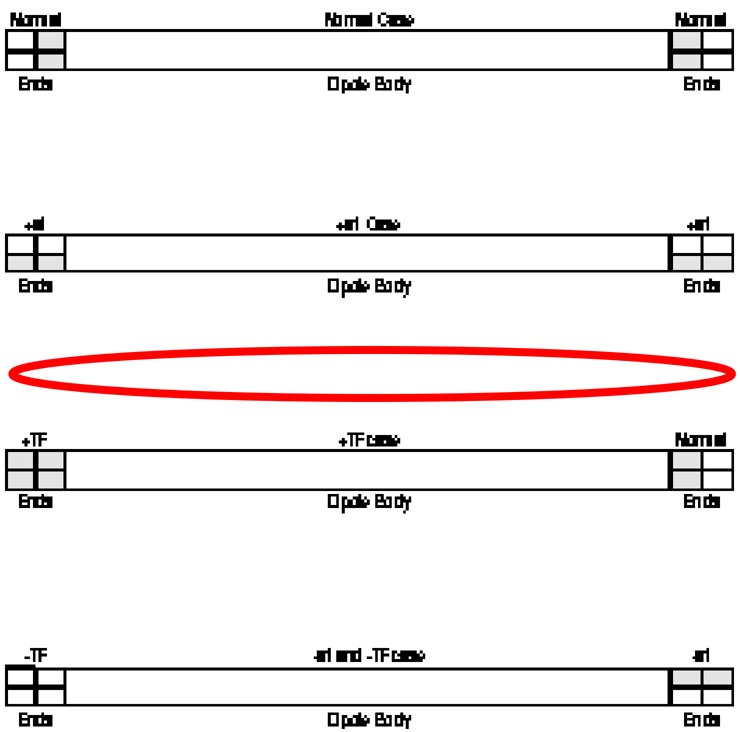


Figure 6.3.1: A conceptual diagram for correcting the integral a_1 harmonic and integral transfer function in a superconducting dipole magnet. The proposed adjustment is applied in the end region of the magnet. The actual starting point would be somewhere in the dipole body where the field is still high. 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_1 which can be used to compensate the measured a_1 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_1 and integral transfer function can be obtained together by mixing the two schemes in the same magnet (bottom figure).

Iron laminations were successfully used in RHIC to adjust transfer function saturation in different length magnets and to control skew quad in main 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 correct compression messes up field quality.

2. Higher order harmonics are OK but lower order are not (generally first two).

- *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.

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

➢ Fixed in the first magnet assembly itself and obtained 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) harmonics.

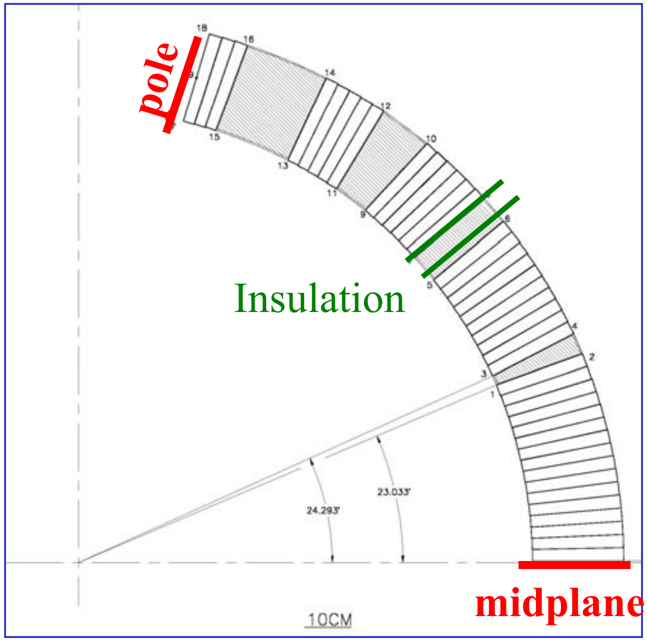
➢ The above adjustments are faster and cheaper than normal cross-section iterations. The coil cross-section was specified before the first magnet was tested and was never changed during production.

A Flexible Design from the Beginning

Design Philosophy:

• Start out with a design that allows significant adjustability for field harmonics and mechanical parameters (cable thickness, wedges, etc.).

• A flexible design is generally economical, efficient and produces magnets with better performance. I think it's a prudent approach.



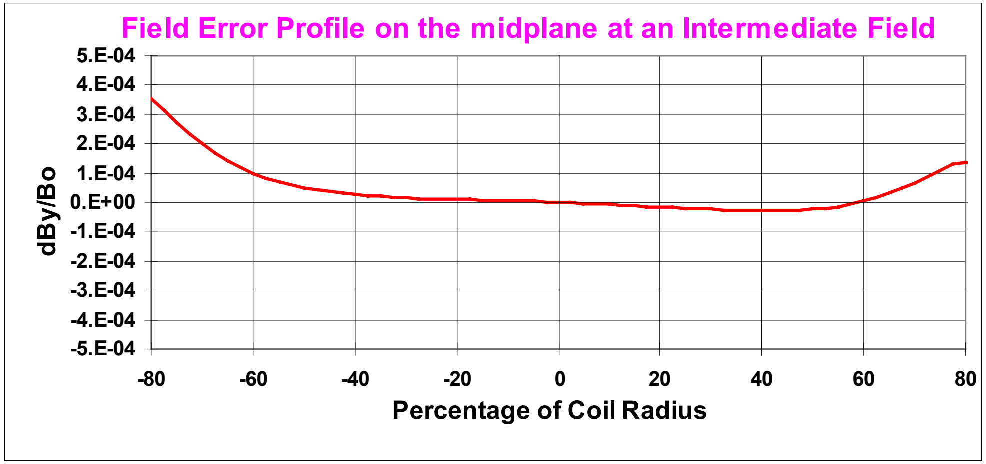
Geometric: Start with a larger than required shim and midplane cap. Then adjust it, as required without changing the cross-section of the cured coil. One can also adjust the layers of wedge/cable insulation, if needed. These three parameters can adjust the first two allowed harmonics and pre-stress or cable insulation. This approach was used extensively in various RHIC magnets.

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.

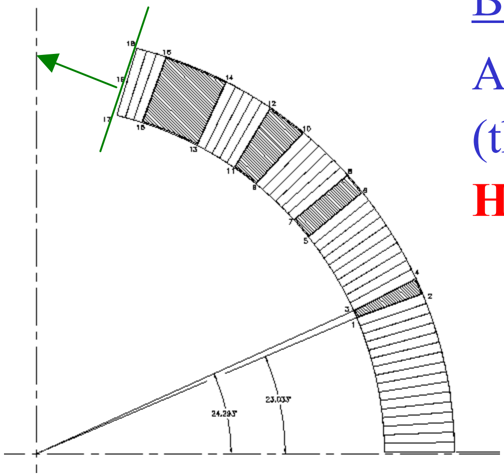
Harmonics at 2 kA (mostly geometric).
Measured in 0.23 m long straigth section.

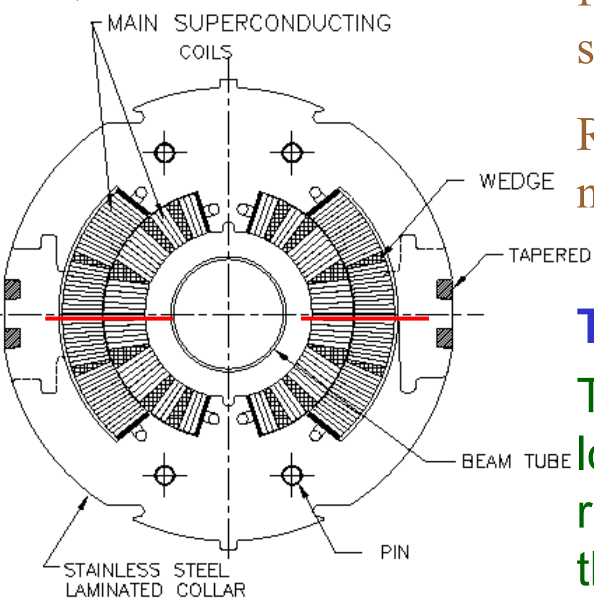
Reference radius = 31 mm

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.

Impact of Cable Thickness on Field Quality





Basic Analysis:

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

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

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

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

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

The location of the midplane determines skew harmonics.

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

The RHIC IR Quadrupoles
(A Flexible Design from the Beginning)

Practical Challenges:

Started out with ~ 1 mil (25 μm) uncertainty in insulated cable thickness.

- Total ~27 mils (order of magnitude more than the typical 2 mil) in overall coil dimensions for 27 turns.
- Conventional Approach : Fix cable first.
- Alternate Approach :

A field quality design that can absorb this.

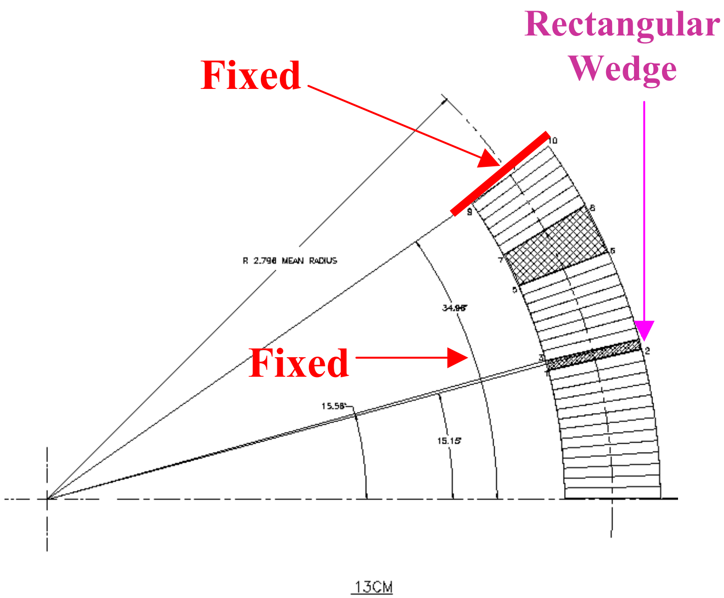
⇒ Developed a design in which all of the difference was absorbed in a rectangular wedge!

⇒ No change in pole angle means:

⊗ No change in coil curing press

⊗ No change in collar/spacer

⊗ No change in first allowed harmonic (b_5)



Coil Cross section of the 130 mm aperture RHIC insertion quadrupole

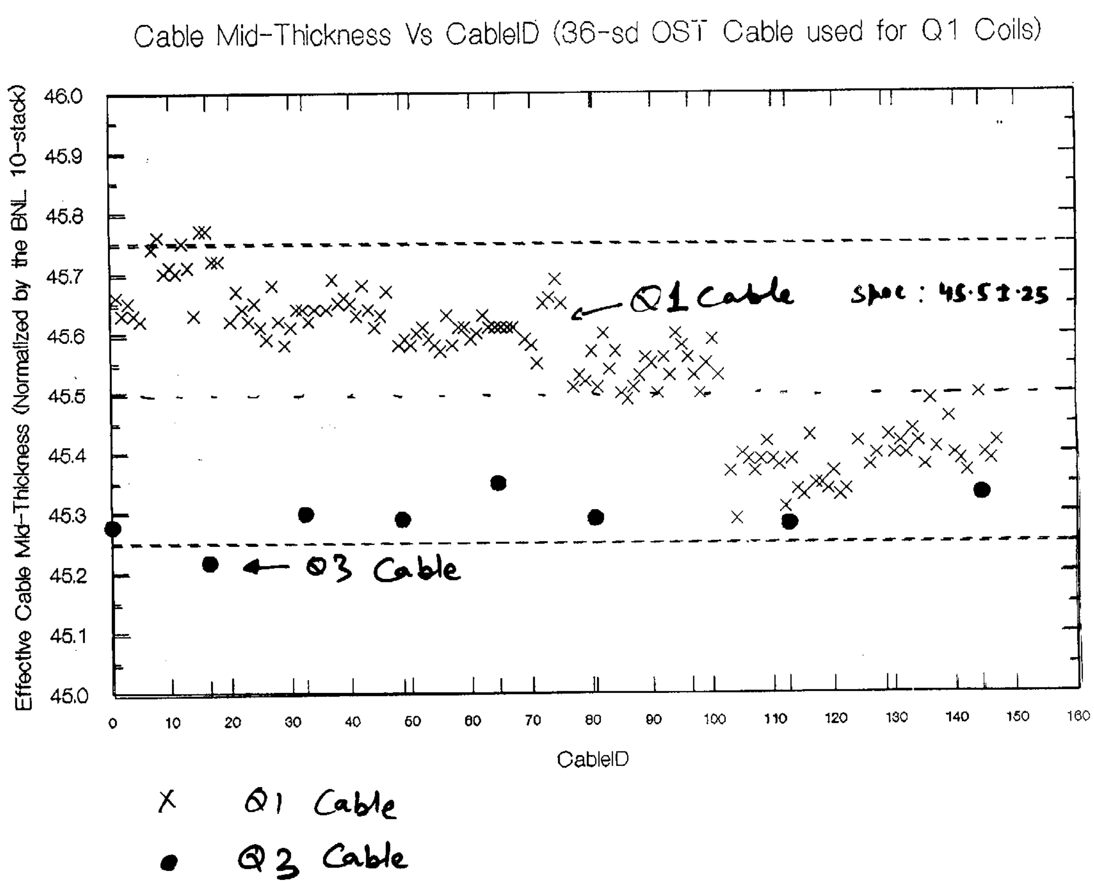
Different Size Cable (within spec) from Two Different Vendors

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

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

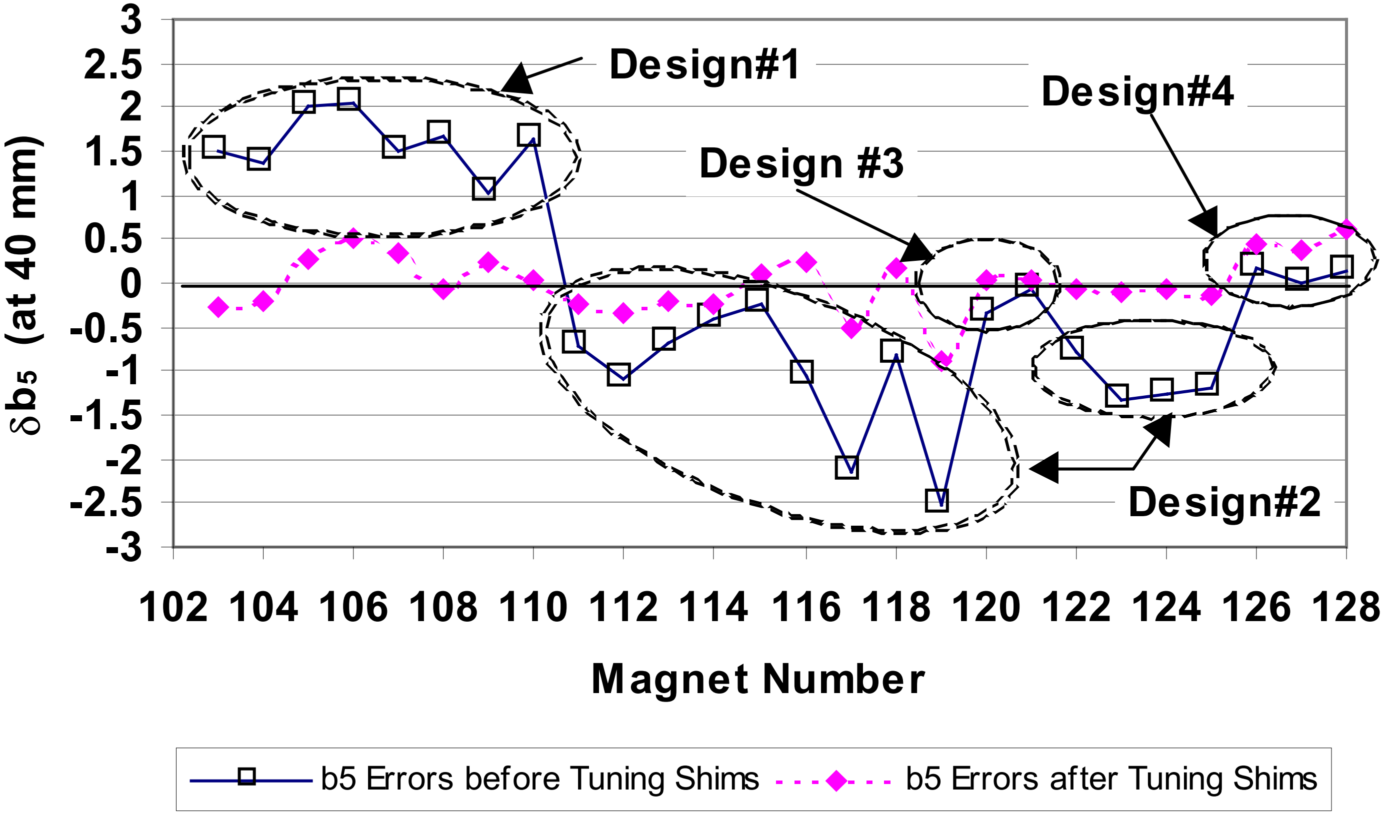
27 turns => 9 mil (0.24 mm) much larger than desired.

A flexible design accommodated it!



Flexible Design
(Adjustment in b_5 During Production in Q1)

Design Changes/Adjustments During Production

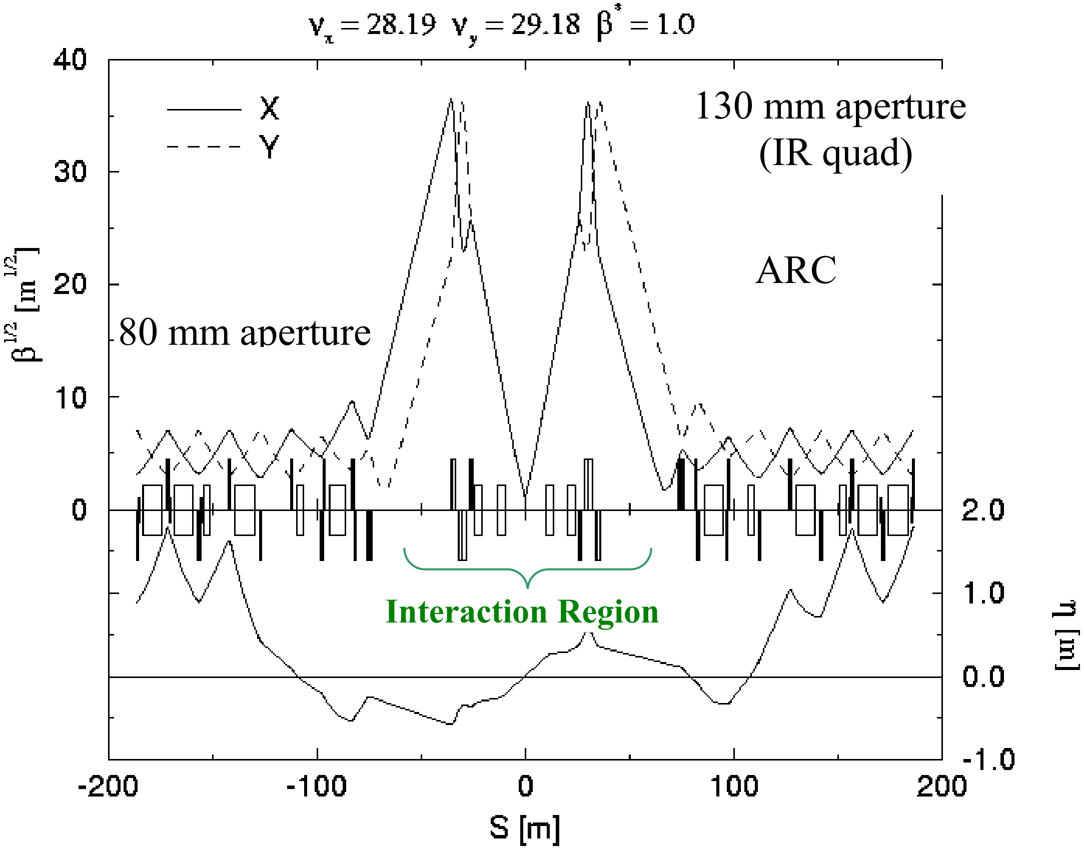


Importance of Field Quality in RHIC Interaction Region Quad

Good field quality is needed in arc dipoles for injection & acceleration.

However, the ultimate RHIC luminosity performance is determined primarily by the field quality in “IR Quads” !

Beam size $\propto (\beta^*)^{1/2}$



Compare the beam size versus magnet aperture in RHIC :

Ratio of Aperture Size (IR/ARC) ~ 1.6

Ratio of Beam Size (IR/ARC) ~ 7

Expected Field Quality in Superconducting Magnets

The field quality in interaction region magnets may significantly influence the ultimate luminosity performance of modern high energy colliders such as RHIC.

The field quality in any magnet depends on:

- The design
- The errors in parts used (practical tolerances)
- The Manufacturing process

In most magnet, they produce a cumulative errors of 25-50 micron

These mechanical errors translate to a relative field errors of 10^{-4}.

❖ **To overcome, these basic magnet manufacturing errors, one must apply correction after construction.**

❖ **The RHIC Tuning shim method reduces the field errors to a few parts in 10^{-5}.**

Basic Principle of Harmonic Correction by Tuning Shim

- **If a magnetic material (shim) is placed in the aperture of the magnet, it will get magnetized.**
- **This will distort the field. The distortion from the nominal field can be expressed in terms of harmonic coefficients.**
- **Use these harmonics to cancel out the measured harmonics.**
- **Properly chosen <u>sizes</u> and <u>locations</u> of "*n*" magnetic shims can compensate "*n*" non-zero measured harmonic coefficients.**

Advantage of Tuning Shims

- The tuning shims achieve field quality in superconducting magnets significantly better than what is expected from normal manufacturing errors.

- They are relatively easy to implement.

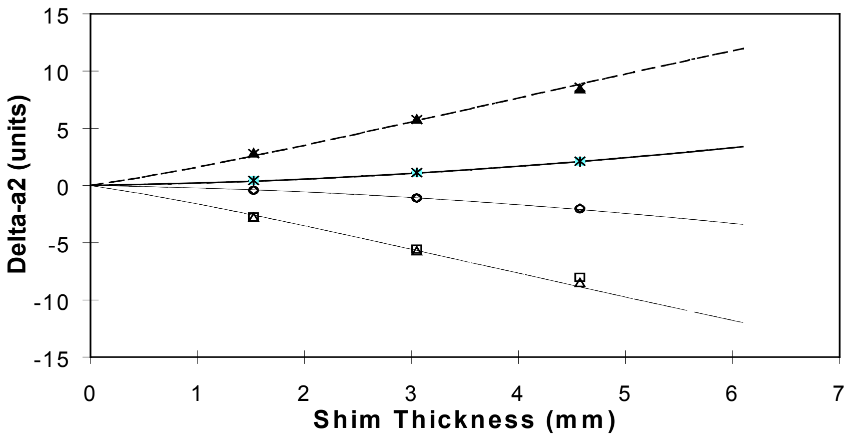
- They correct the field errors in the magnets, where it is and therefore may be more efficient than the global and lumped correctors. This difference is important in low beta optics where the beam size changes rapidly in the interaction region.

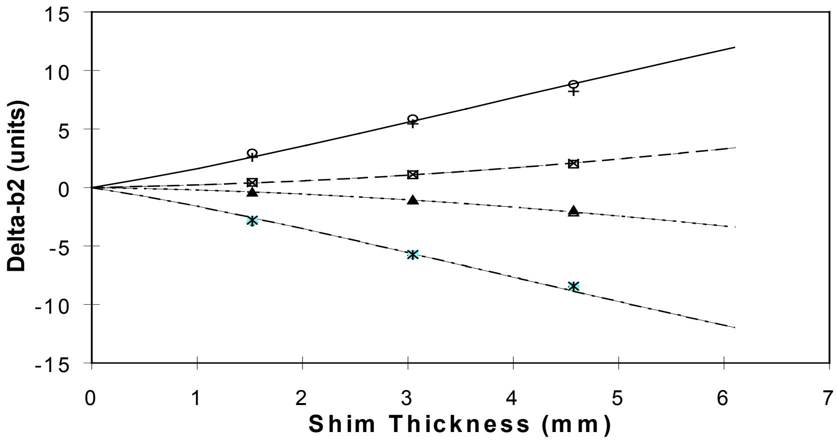
- Lower field errors may allow the coil aperture to be reduced, which in turn may increase the field gradient for a given maximum field in the coil.

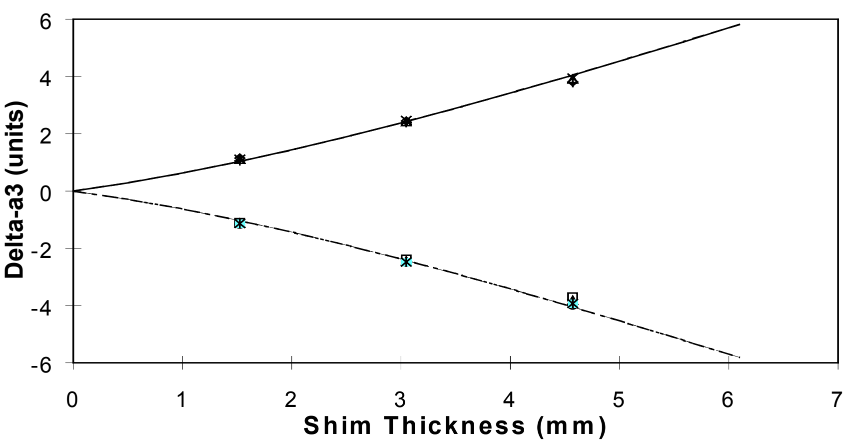
- For best efficiency, the tuning shim should be considered as an integral part of the design and should be incorporated from the beginning. Since the maximum luminosity is desired at the top energy, the shim should be tuned at that field.

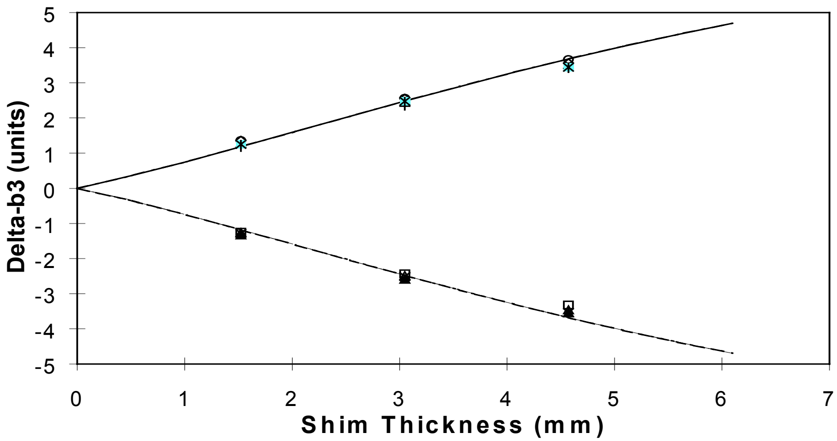
Harmonic Correction As A Function Of Tuning Shim Thickness

These are the changes in harmonics relative to the "no shim" or "zero iron thickness" case for each shim. The eight symbols represent the measurements for the eight tuning shim locations and eight lines are the calculations for these locations.









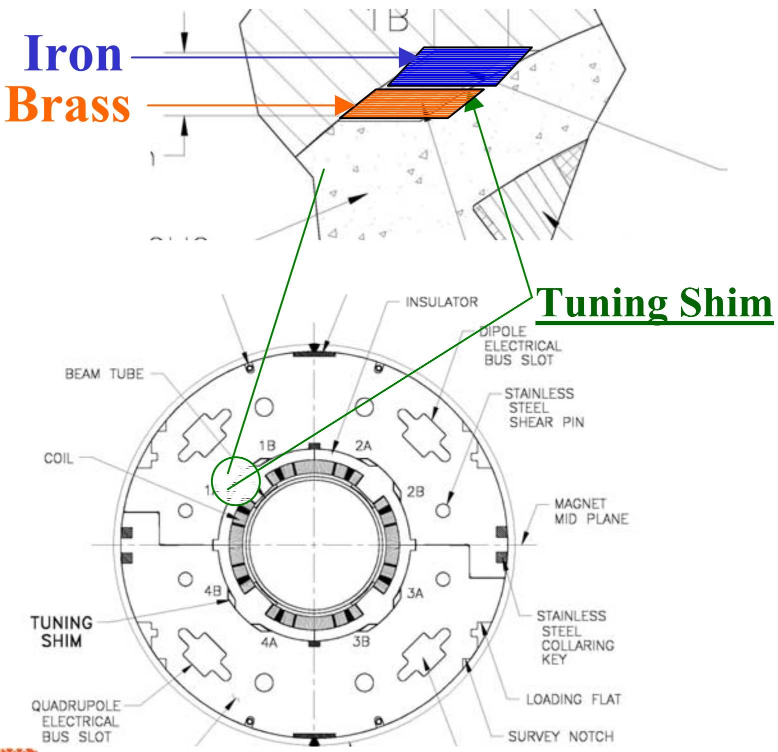
Tuning Shims for 10^{-5} Field Quality at 2/3 of coil radius

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 will 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 change by a small but a significant amount).

4. For confirmation, measure field harmonics after tuning shims are installed.

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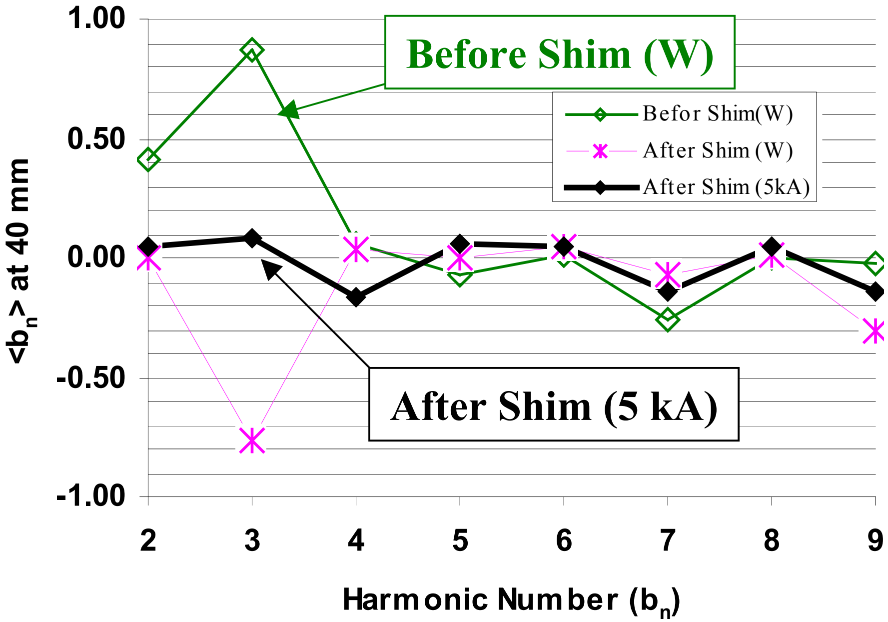
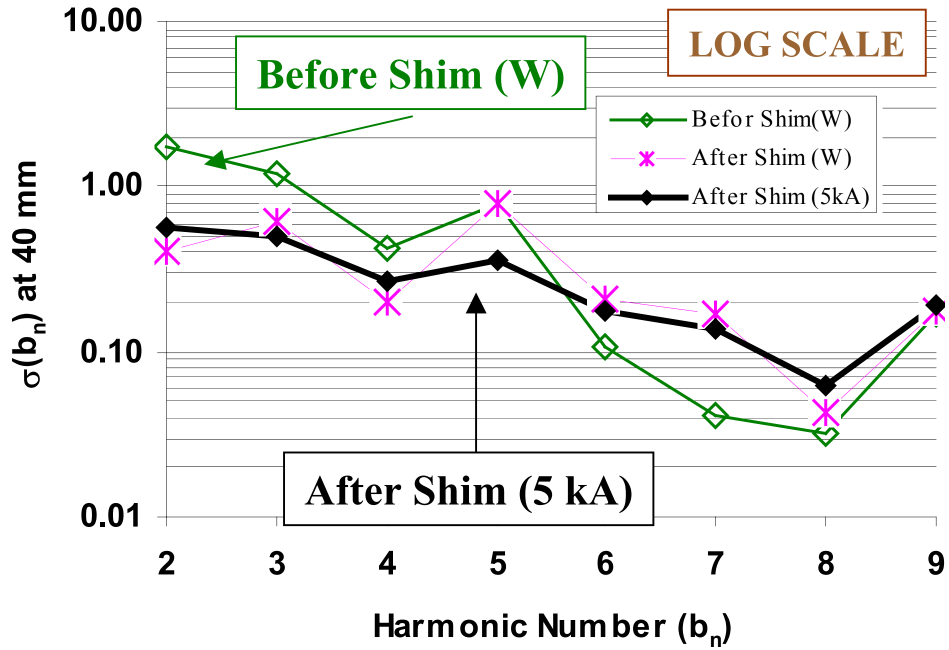
Field Quality Improvements with Tuning Shims (Normal Harmonics)

Mean



Standard Deviations



	$<b_n>$ (n=2 is sextupole)			$\sigma(b_n)$		
n	Befor Shim(W)	After Shim (W)	After Shim (5kA)	Befor Shim(W)	After Shim (W)	After Shim (5kA)
2	0.41	0.01	0.05	1.74	0.41	0.56
3	0.87	-0.76	0.08	1.19	0.60	0.49
4	0.06	0.03	-0.17	0.42	0.20	0.27
5	-0.07	0.00	0.05	0.78	0.78	0.36
6	0.01	0.05	0.05	0.11	0.21	0.18
7	-0.26	-0.07	-0.14	0.04	0.17	0.14
8	0.00	0.01	0.04	0.03	0.04	0.06
9	-0.03	-0.30	-0.14	0.17	0.18	0.19

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

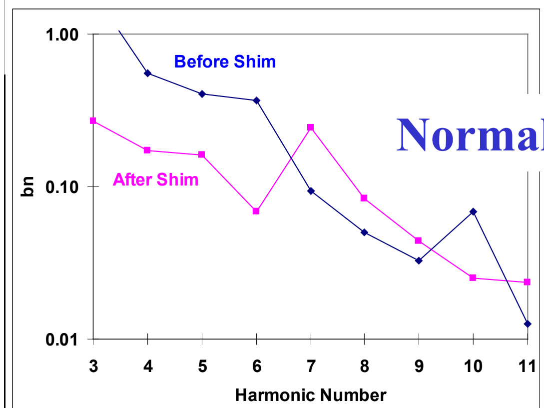
Field Quality in RHIC Insertion Quadrupoles
Improvements in field errors with tuning shims:

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)

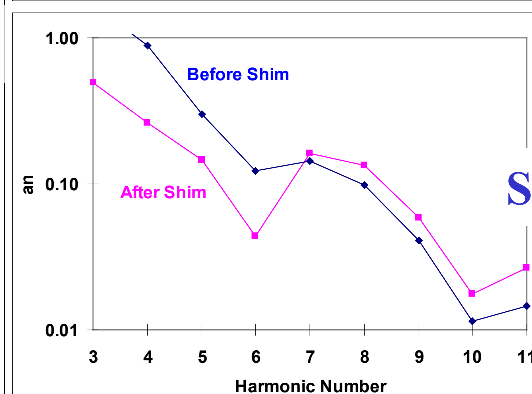
n	$\langle b_n \rangle$ (n=3:Sextupole)			$\sigma(b_n)$		
	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets
3	0.58	-0.17	0.30	1.87	0.47	0.27
4	-0.11	-1.21[a]	0.02	0.56	0.23	0.17
5	-0.18	0.05	-0.12	0.40	0.13	0.16
6	2.68	0.48[b]	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^{-5}.

SUMMARY

A flexible design approach allows efficient adjustments in the design.

This also permits a strong interaction between accelerator physicists and magnet scientists during the course of magnet manufacturing.

- Reasonable variations in parts accommodated
- Tolerances in parts reduced
- Good field quality in the magnet assured

Tuning shim allows significant improvement in field quality in accelerator magnets over what can be typically expected from normal tolerances in parts and manufacturing. Tuning shims may improve the ultimate luminosity performance of the machine.