A few slides from PAC99 Presentation on

RHIC IR Quadrupoles and Field Quality State of the Art in Superconducting Accelerator Magnets

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The RHIC IR Quadrupoles
(An Inherently Low Cost Design)

Low Cost Features:

At first glance a very unlikely magnet for making the best field quality magnets. But ...

Iron Yoke Used as Collars

(common to practically all RHIC Magnets)

- Close-in iron (large saturation-induced b_5)

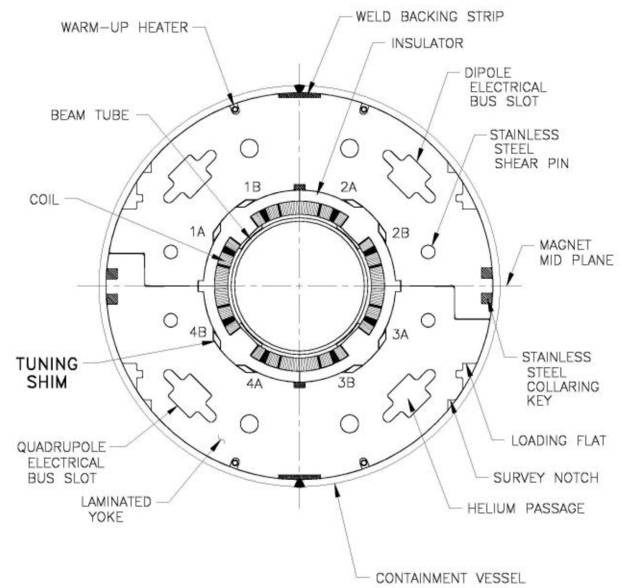
Uses Dipole Collaring Press

- Doesn't have the basic 4-fold quadrupole symmetry (large non-allowed b_3 harmonics)

Uses RX630 Spacers

- Large errors in parts ⇨ large harmonics.

  Randomization and Tuning Shims



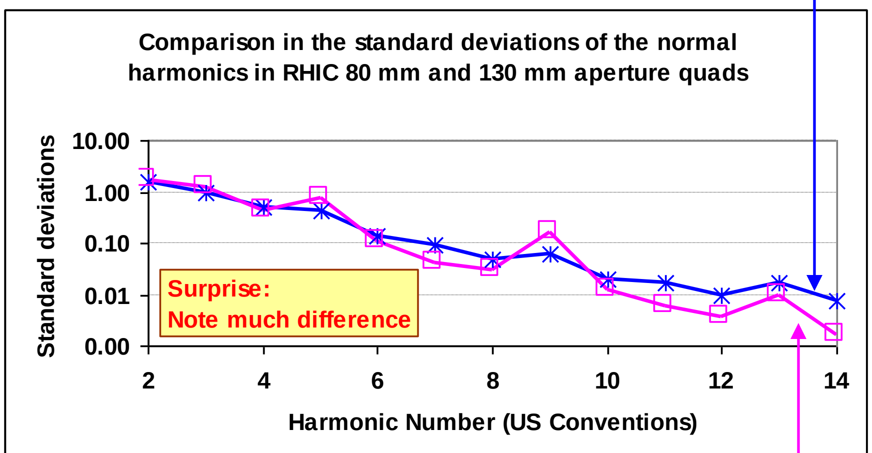
Cross section of the 130 mm aperture RHIC insertion quadrupole

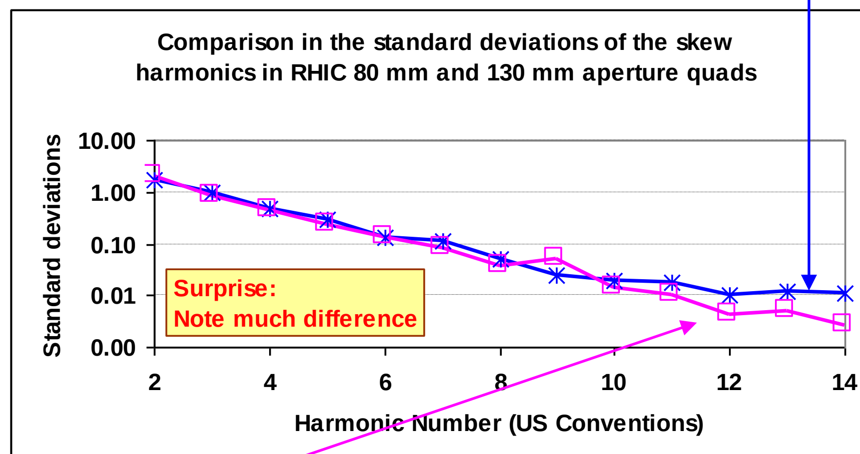
Conventional Wisdom: Increasing Aperture Reduces Standard Deviation at 2/3 of the Coil Radius.

Ouch! Reality Hurts !!!

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

80 mm aperture ARC Quads (25 mm reference radius)





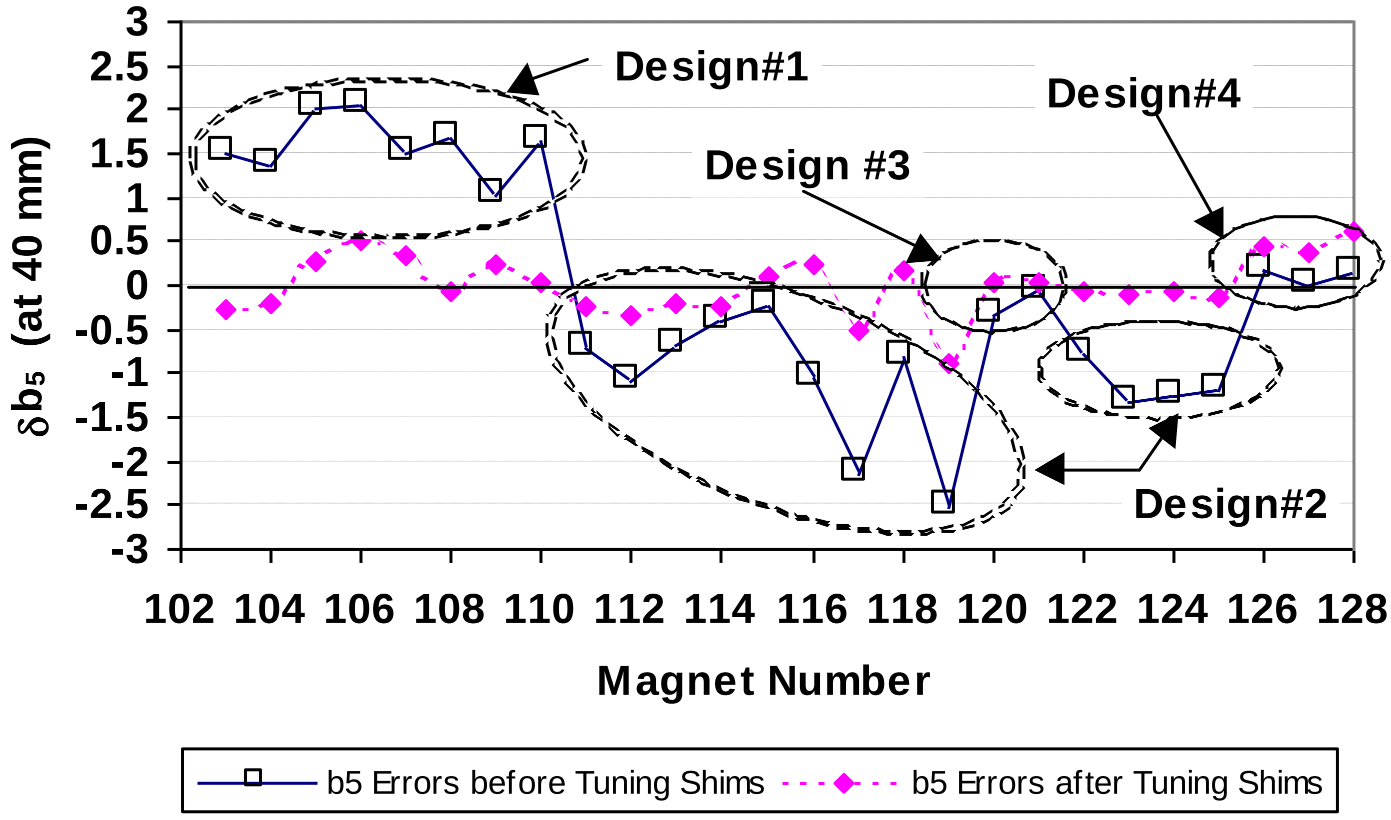
Normal Harmonics

Skew Harmonics

130 mm aperture IR Quads (40 mm reference radius)

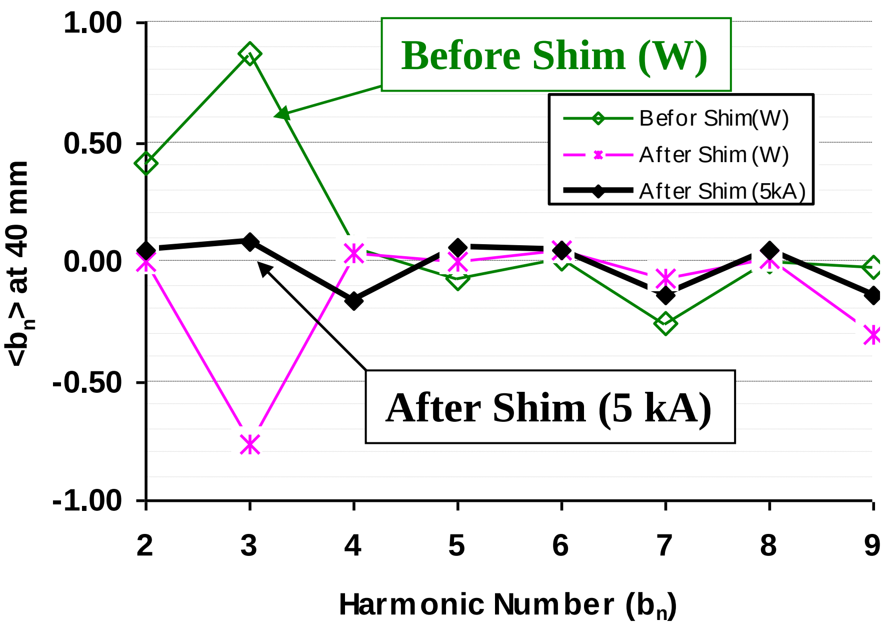
Flexible Design
(Adjustment in b_5 During Production in Q1)

1. Design Changes (large) During Production
2. The Magic of Tuning Shims

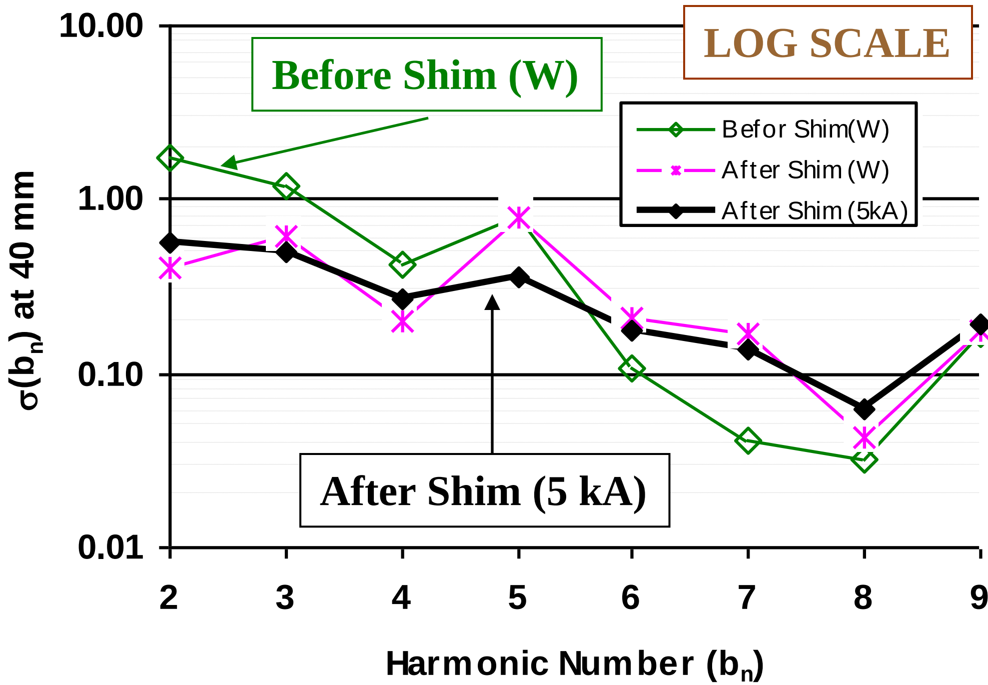


Field Quality Improvements with Tuning Shims (Normal Harmonics)

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

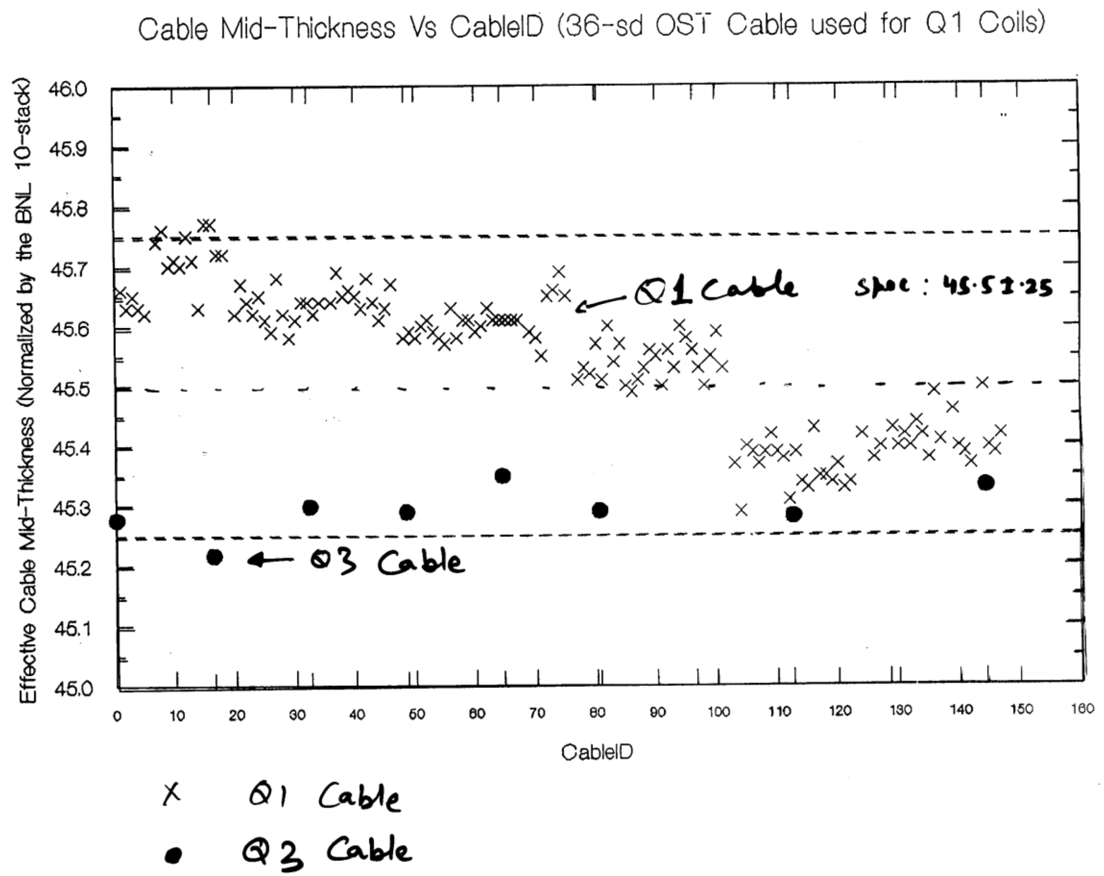
Different Size Cable (within spec) from Two Different Vendors

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.

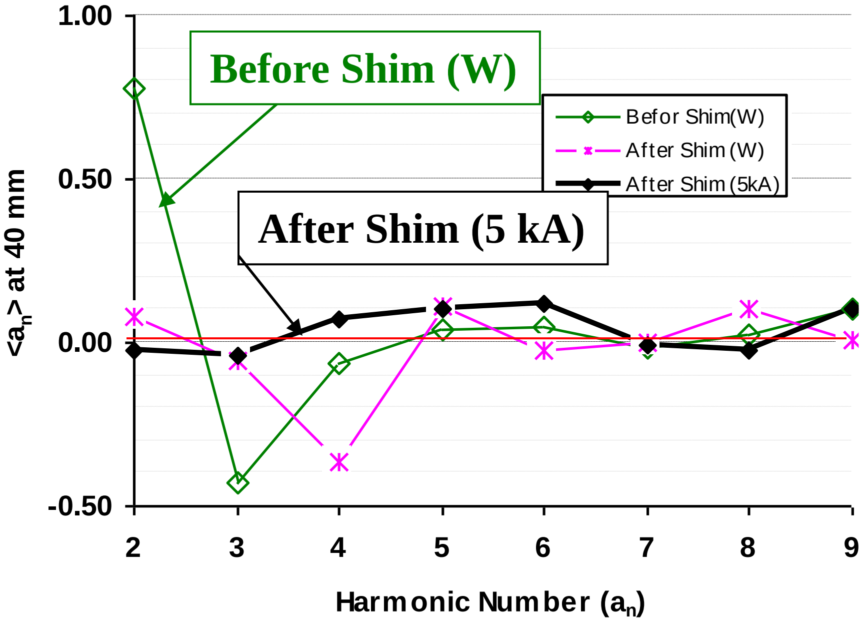
A flexible design accommodate it!



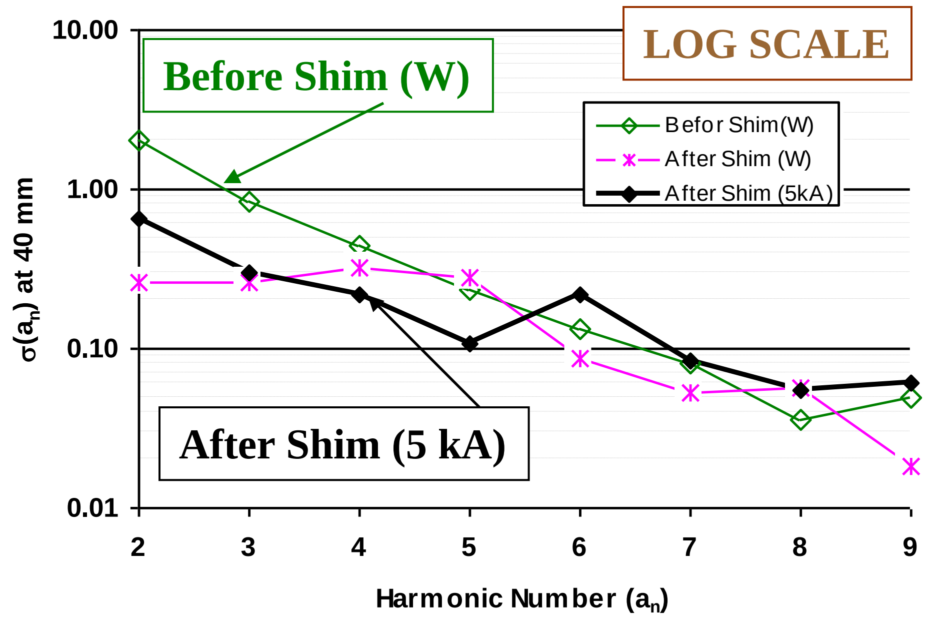
This may be relevant to LHC.

Field Quality Improvements with Tuning Shims (Skew Harmonics)

Mean



Standard Deviations



	$\langle a_n \rangle$ (n=2 is sextupole)			$\sigma(a_n)$		
n	Befor Shim(W)	After Shim (W)	After Shim (5kA)	Befor Shim(W)	After Shim (W)	After Shim (5kA)
2	0.77	0.08	-0.02	2.04	0.26	0.65
3	-0.43	-0.05	-0.04	0.84	0.26	0.30
4	-0.07	-0.36	0.07	0.45	0.33	0.22
5	0.04	0.11	0.10	0.24	0.28	0.11
6	0.05	-0.03	0.12	0.14	0.09	0.22
7	-0.02	0.00	-0.01	0.08	0.05	0.08
8	0.02	0.11	-0.03	0.04	0.06	0.05
9	0.10	0.01	0.11	0.05	0.02	0.06

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

More Challenges:

Started out with ~ 1 mil (25 µm) 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.
- Challenge:

  Dare a field quality coil design that can absorb such large differences.

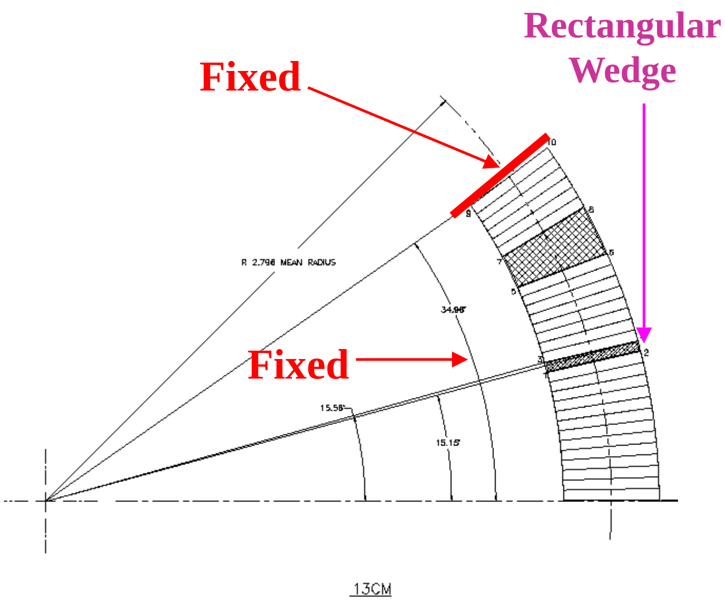
  ⇒ Developed a design in which all of the difference was absorbed in a rectangular wedge!

  ⇒ No change in pole angle means:

  ⊗ No change in coil curing press

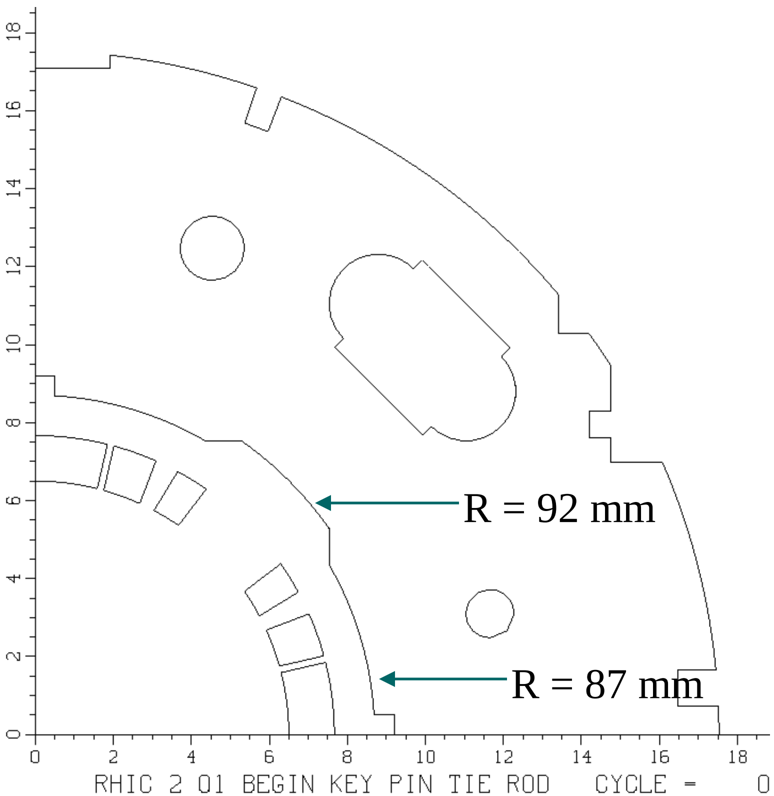
  ⊗ No change in collar/spacer

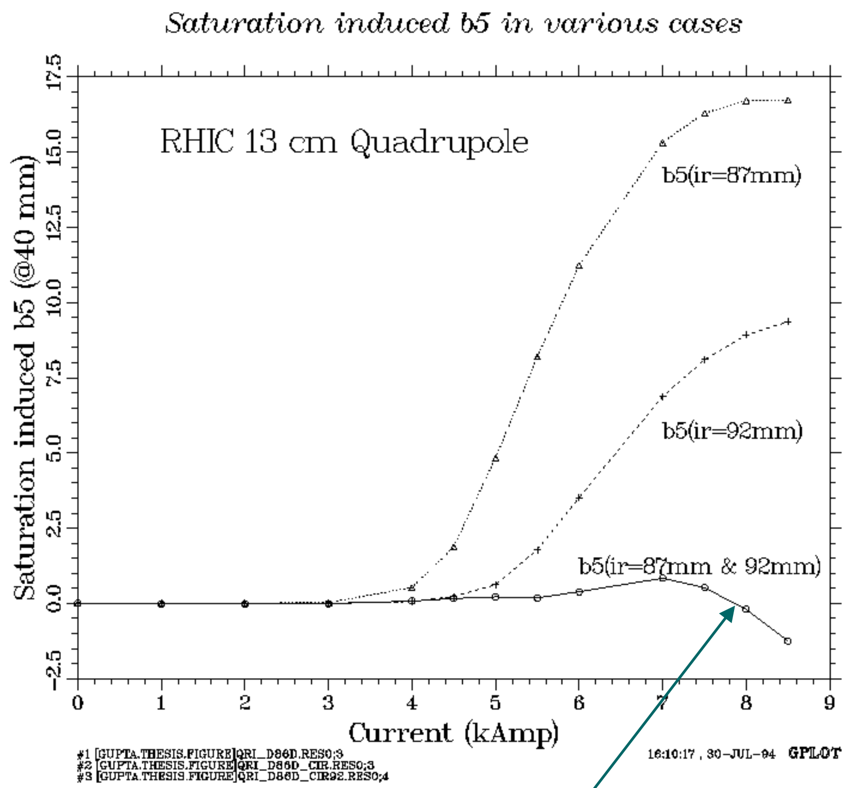
  ⊗ No change in first allowed harmonic (b_5)



Coil Cross section of the 130 mm aperture RHIC insertion quadrupole

Saturation Control in RHIC IR Quads





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 quadrupoles, a 2-radius method was used.

PAC '99

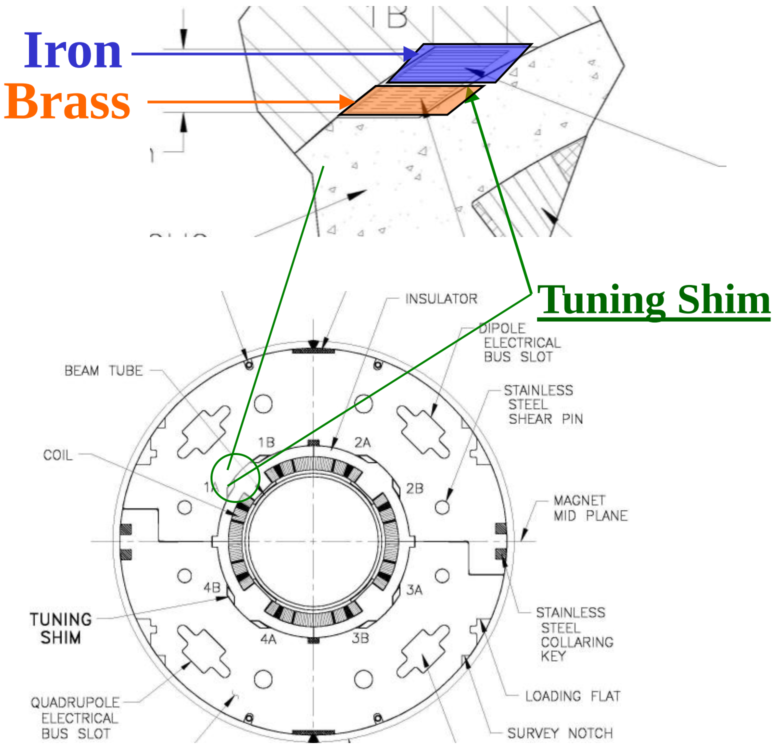
Tuning Shims for 10^{-5} Field Quality at 2/3 of coil radius

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).

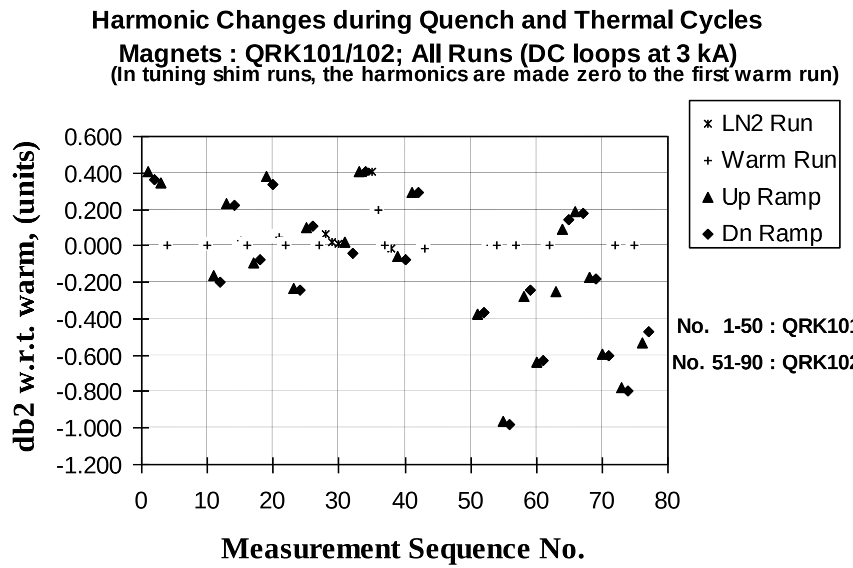
Animesh Jain at BNL found changes in harmonics between two runs in RHIC insertion quadrupoles.

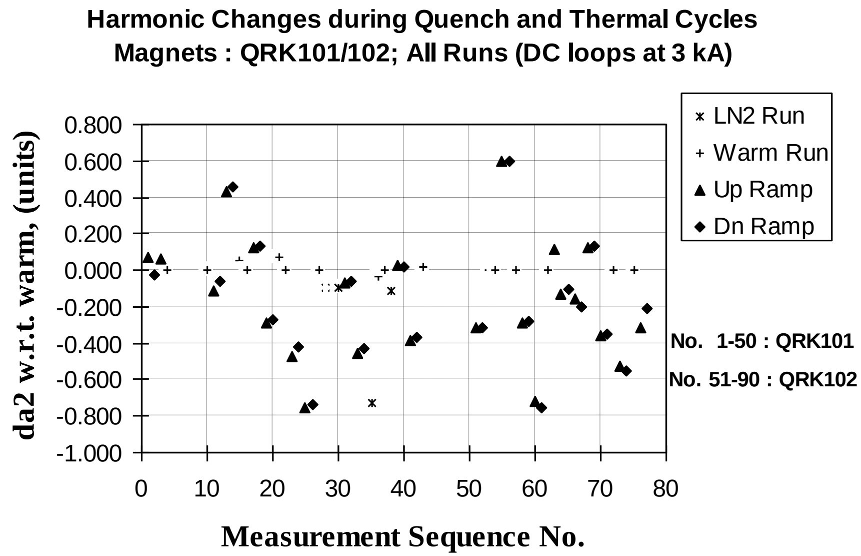
First thought that the changes were related to the tuning shims.

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.

Note: n=2 is sextupole





See Paper THP108 : Scandale et al., for a detailed report on a similar observation in LHC magnets.

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

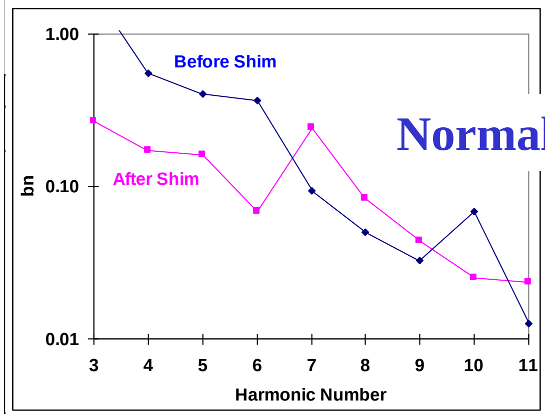
Field Quality in RHIC Insertion Quadrupoles
Improvements in field errors with tuning shims:

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)

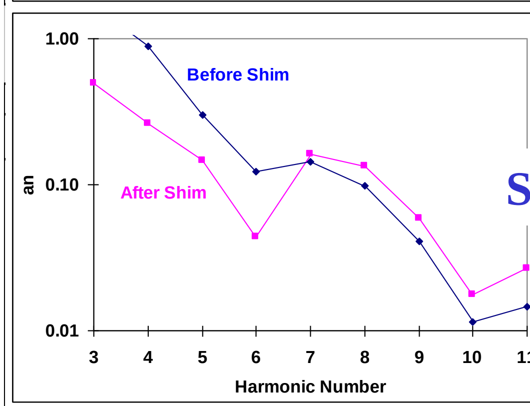
n	$\langle b_n \rangle$ (n=3:Sextupole)			$\sigma(b_n)$		
	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets
3	0.58	-0.17	0.30	1.87	0.47	0.27
4	-0.11	-1.21[(a)]	0.02	0.56	0.23	0.17
5	-0.18	0.05	-0.12	0.40	0.13	0.16
6	2.68	0.48[(b)]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