Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Tuning Shims to Achieve Good Field Quality in Q2pF and Other EIC Magnets

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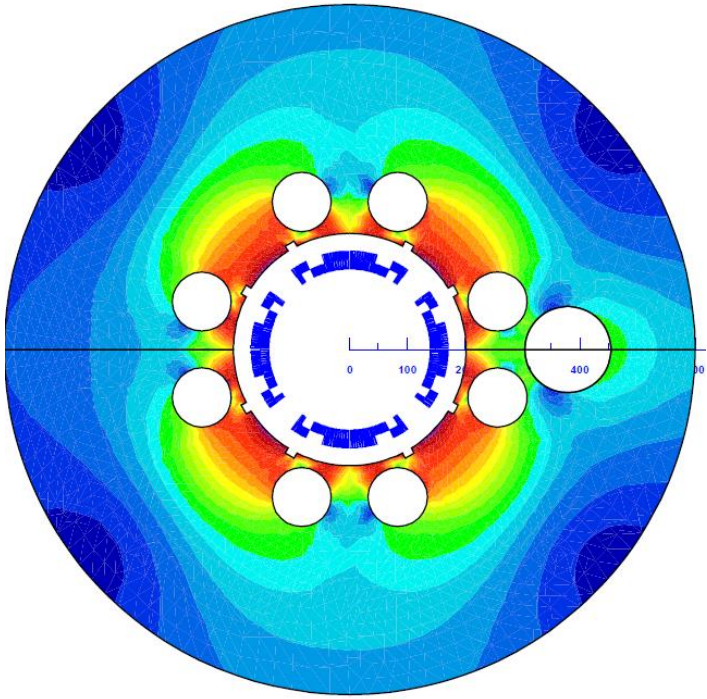
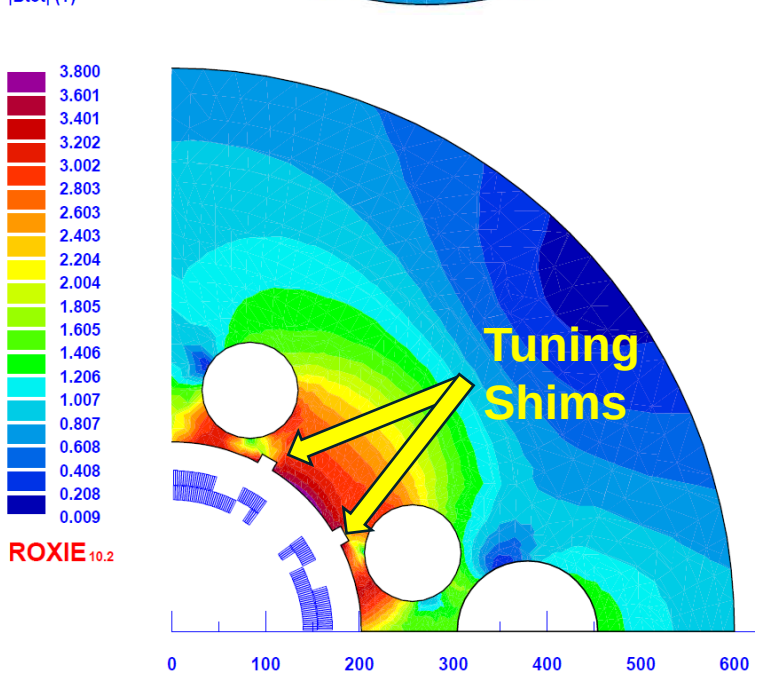
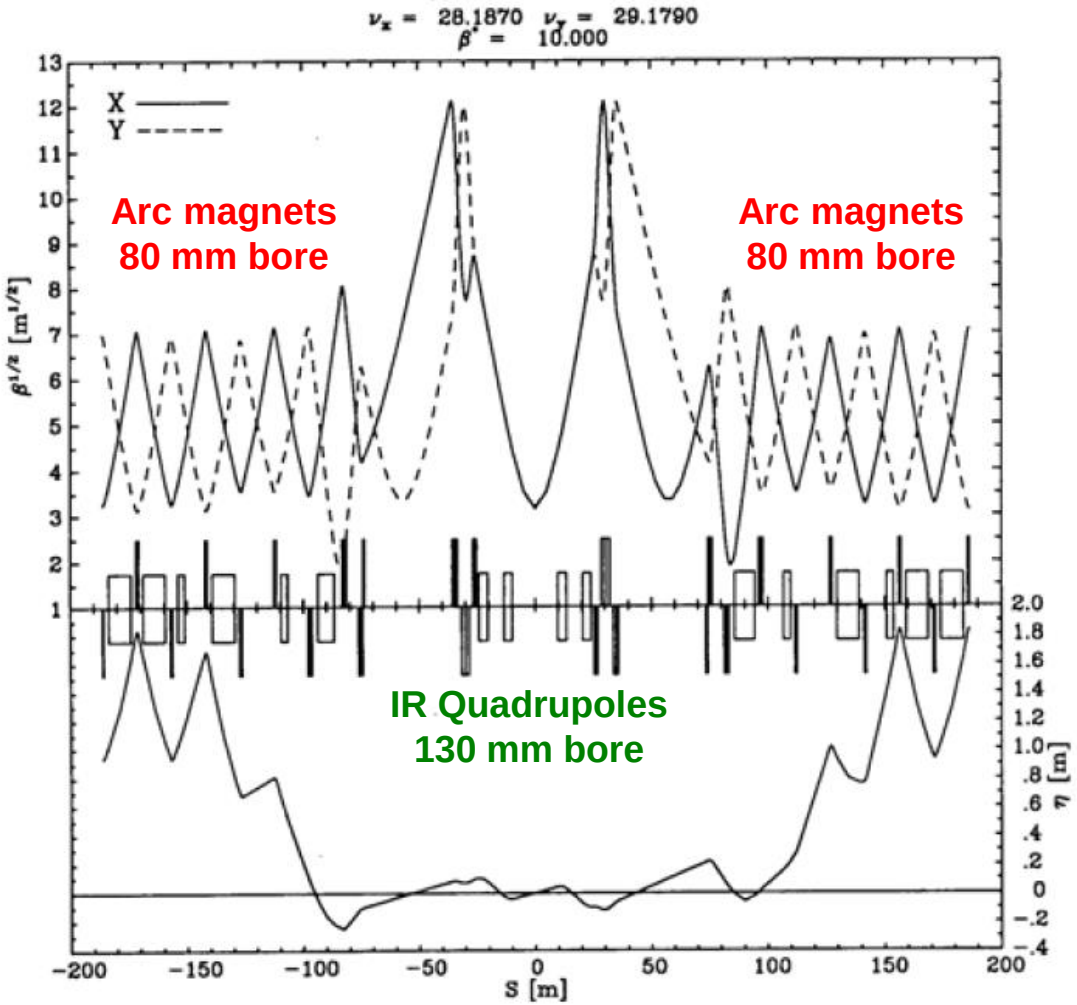
Field Harmonic Corrections with Tuning Shims after the construction

- Last presentation had the initial design of the tuning shims for the EIC quadrupole Q2pF.
- Since we are planning to apply it in several EIC magnets, a formal presentation, along with the steps needed to implement it, should be useful.
- Experience of RHIC IR quads, where the technique was first developed for accelerator magnets, will be presented.
- How good the field quality be with tuning shims?
  - *Experimental demonstration show that we nothing better can be done in such magnets*



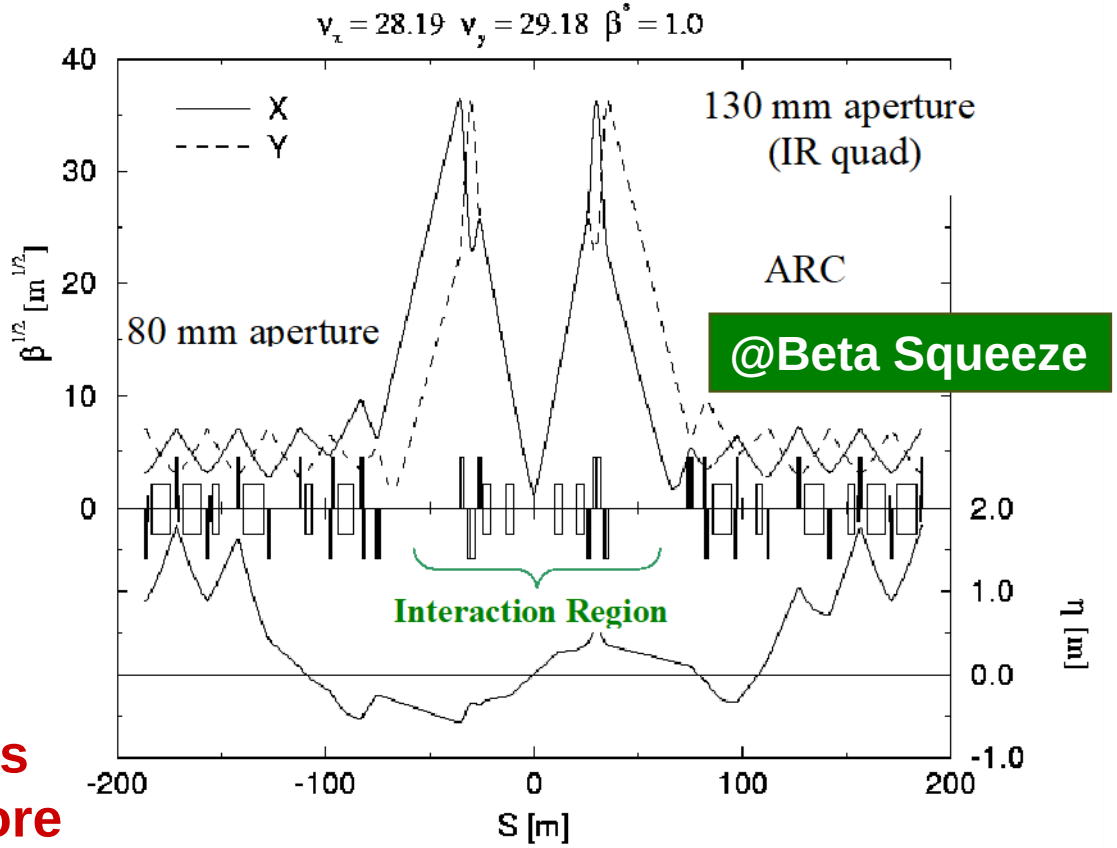


Field Quality Driver in RHIC Magnets



Beam size ∝ $(\beta^*)^{1/2}$

Compare the beam size versus magnet bore

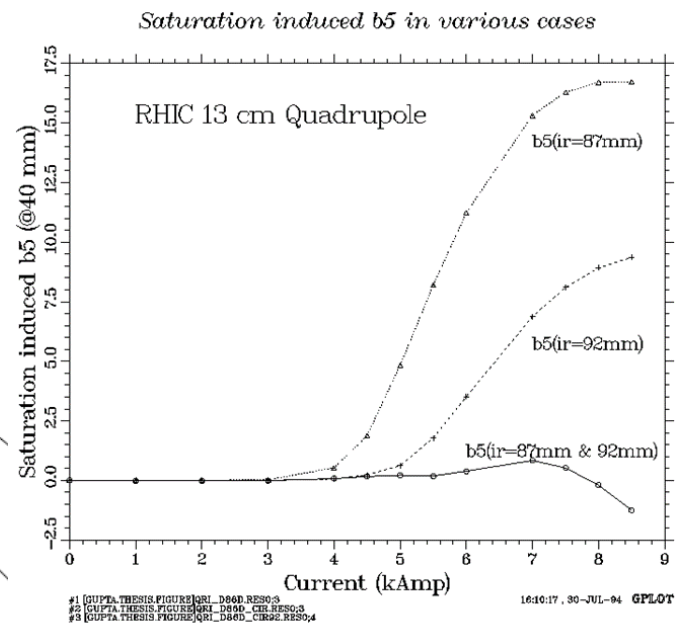


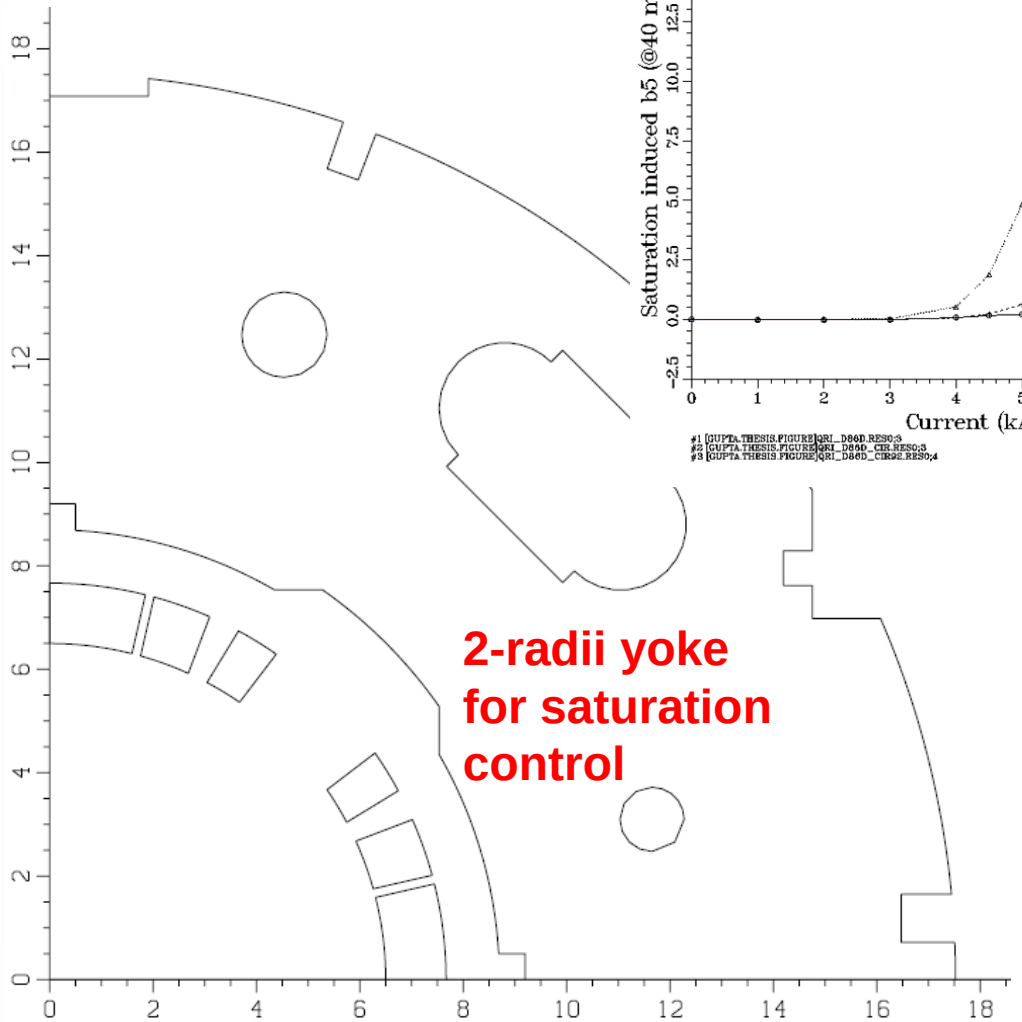
Ratio of Bore Size (IR/ARC) ~ 1.6
Ratio of Beam Size (IR/ARC) ~ 7

Good field quality is needed in arc magnets for injection & acceleration

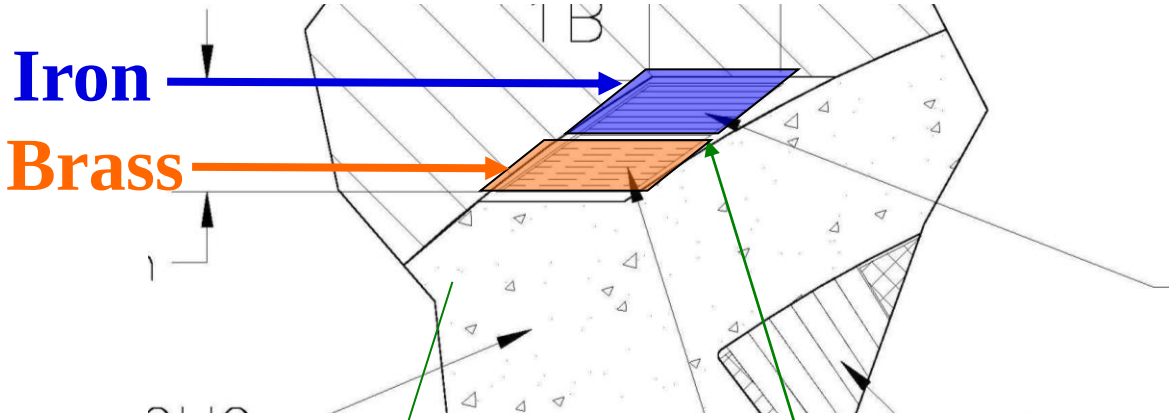
Ultimate luminosity performance of RHIC is, however, determined primarily by the field quality in "IR Quads"

Tuning Shims in RHIC IR Quadrupole

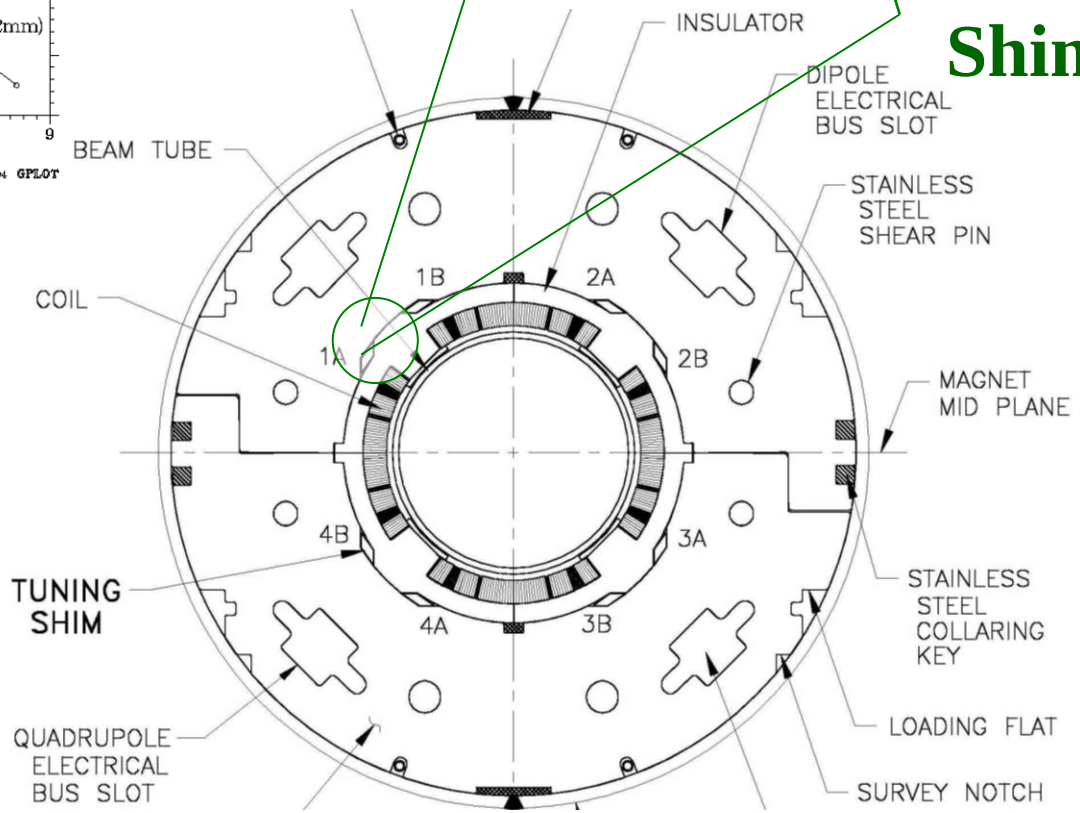




2-radii yoke for saturation control

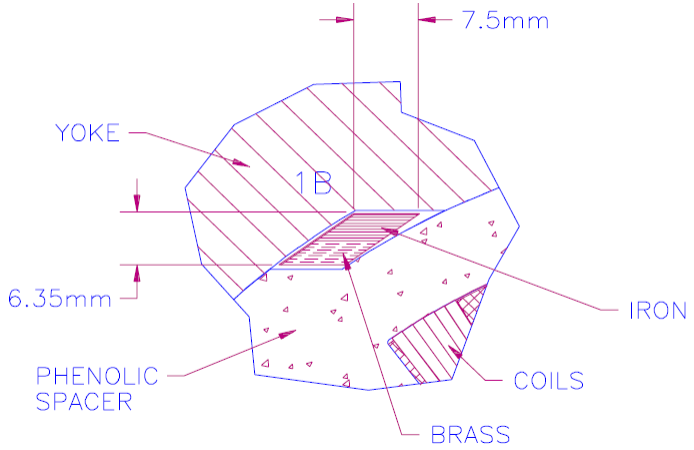


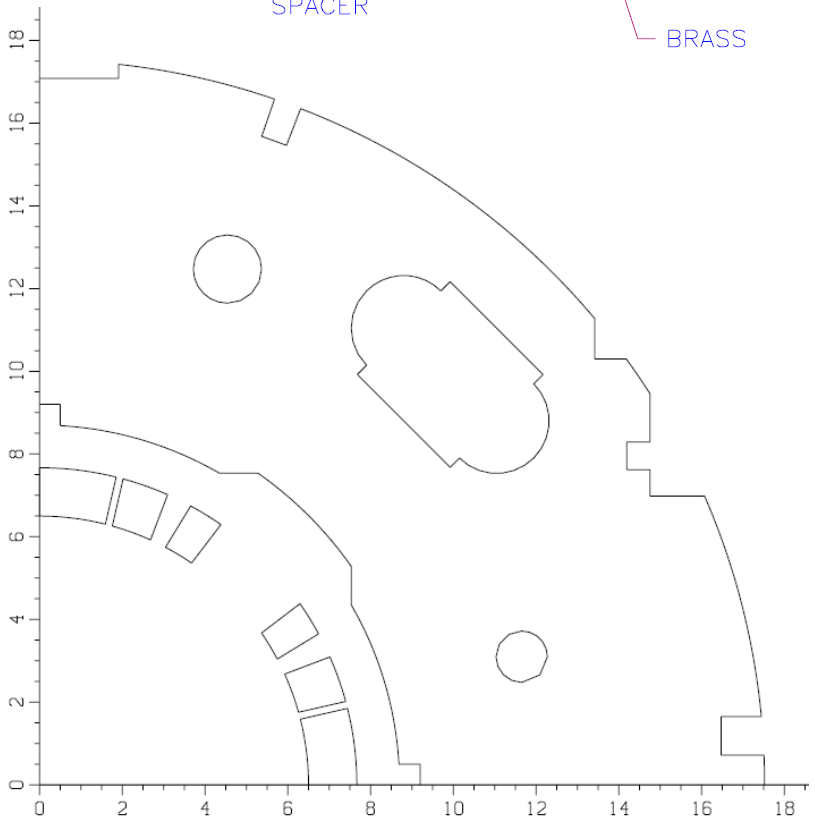
Tuning Shims



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 uniformity. The distortion from the nominal field can be expressed in terms of harmonic coefficients.
- Use these newly added 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.





On Implementing Tuning Shim Based Harmonic Correction

Basic Principle of Tuning Shims:

Addition of magnetized iron shims inside yoke iron modify the magnet harmonics.

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

Procedure used in RHIC IR for implement tuning shims:

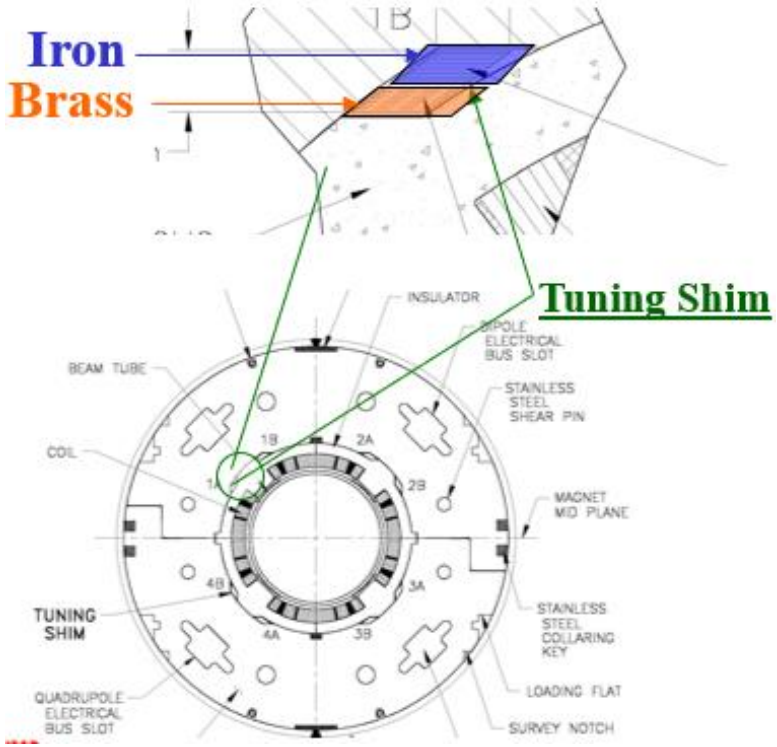
1. Measure field harmonics in a magnet (warm only for cost reasons).

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

➢ ***A separate set of programs are developed for harmonic correction (complicated since the correction is required cold at high fields)***

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 (warm and cold) after tuning shims for confirmation.



Program SHIMCAL for optimizing Tuning Shims

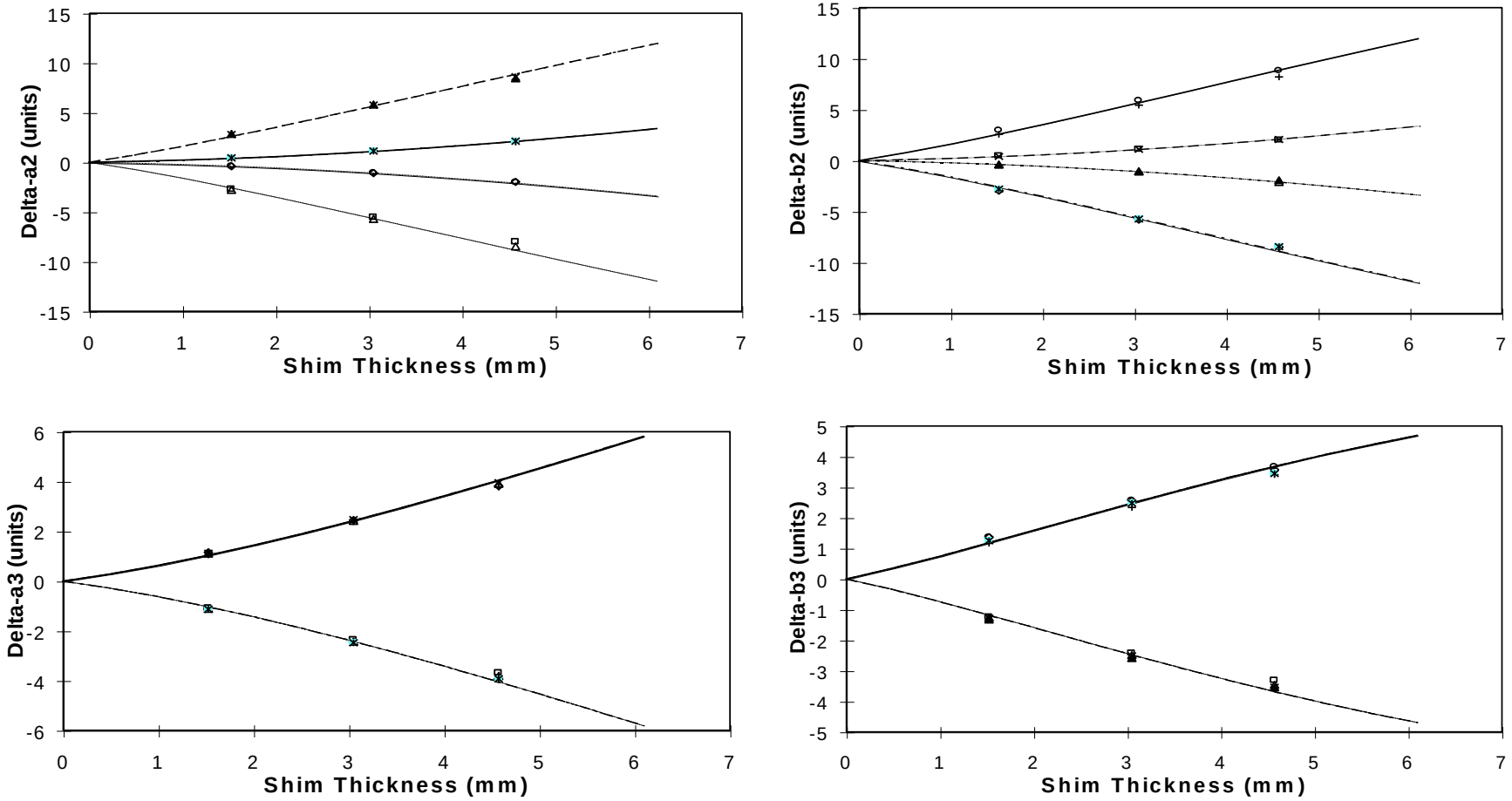
- **A program similar to PAR2dOPT (or ROXIE) to minimize 8 harmonics based on 8 constraints.**
- **Must include iron saturation as tuning shims iron at the yoke id gets highly saturated.**
- **Developed to run in auto-mode so that anyone can use it.**

A computer program SHIMCAL [8] has been written to compute the thickness of eight shims for compensating eight measured harmonics at 5 kA. At present it uses numerically computed coefficients based on POISSON calculations. Due to a large iron saturation at 5 kA and due to complexity of the problem, analytic formulae can not be derived. Thus after a series of magnetic measurements at 5 kA, experimentally determined coefficients will be used in the program.

Validation of Computer Models for Harmonic Correction with Tuning Shim

Changes in harmonics relative to the "no shim" or "zero iron thickness" case for each shim.

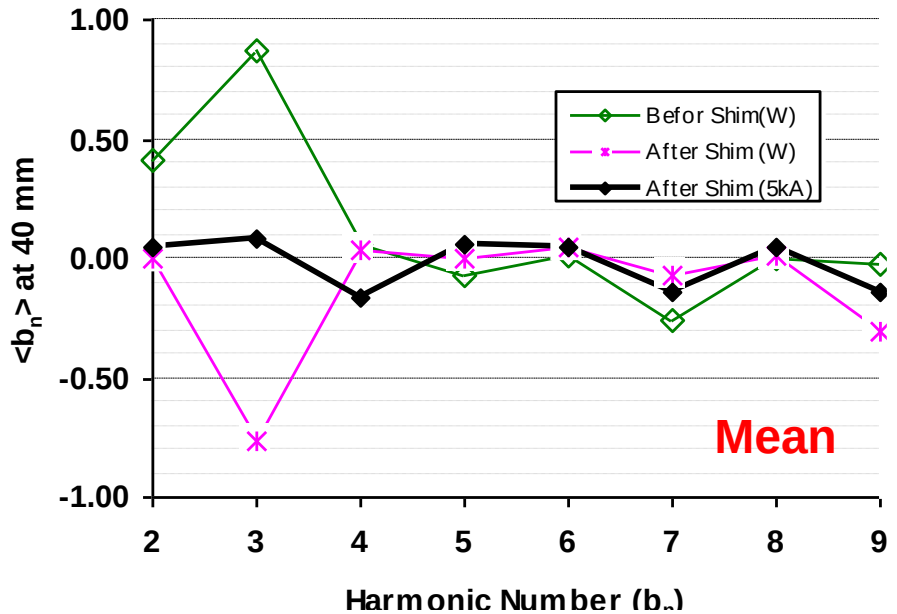
Eight symbols represent the measurements for the eight tuning shim locations and eight lines are the calculations for these locations.

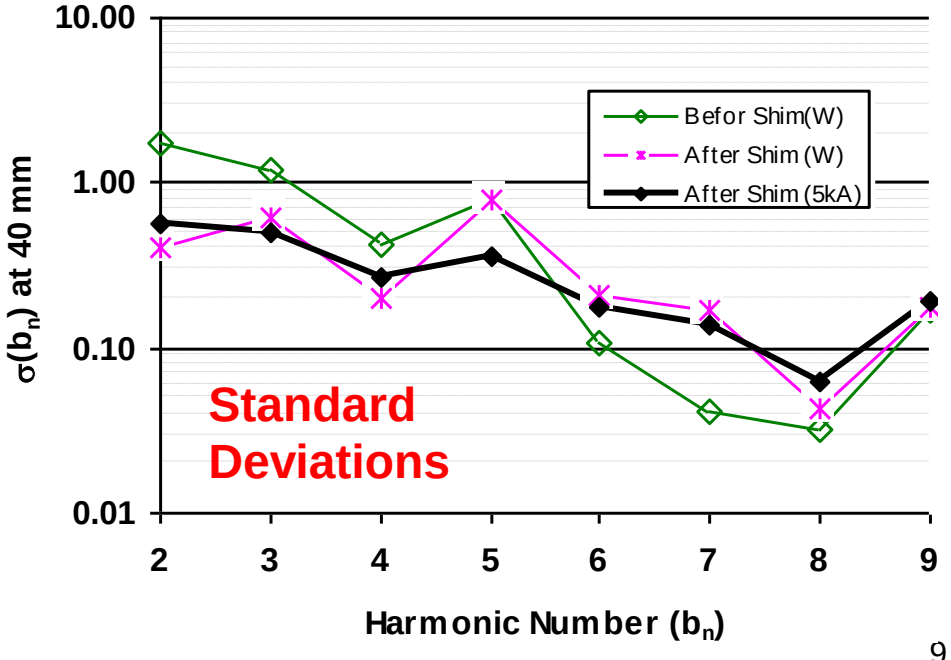


Field Quality Improvements with Tuning Shims (Normal Harmonics)

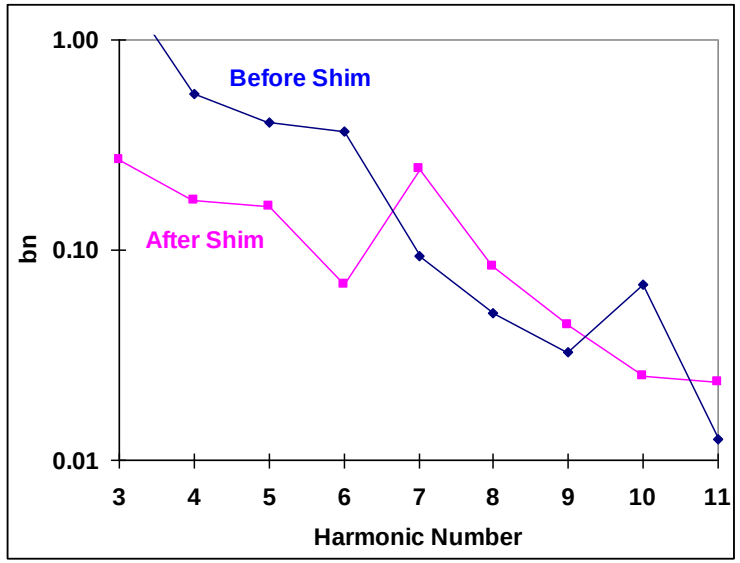
- Tuning shims brought major improvement in field quality (reduction in measured harmonics)
- Note: Improvements in standard deviation are plotted in log scale.
- Corrections are made magnet by magnet – very relevant to EIC.

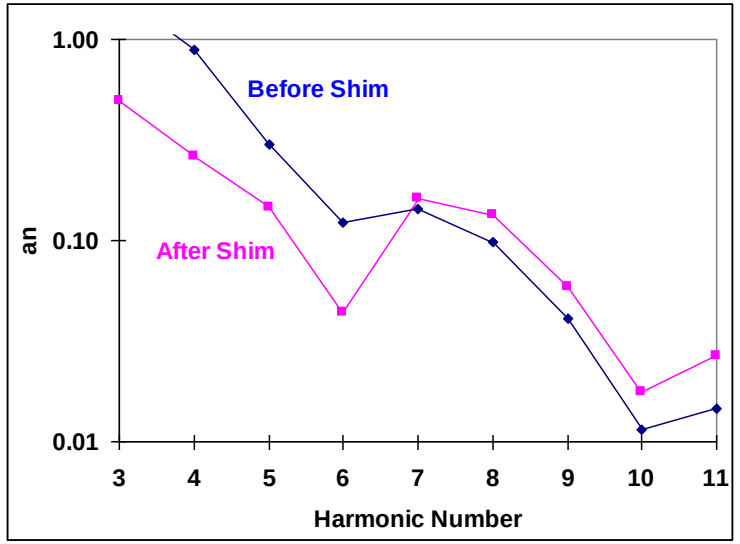
	$<b_n>$ (n=2 is sextupole)			$\sigma(b_n)$		
n	Befor Shim(W)	After Shim (W)	After Shim (5kA)	Befor Shim(W)	After Shim (W)	After Shim (5kA)
2	0.41	0.01	0.05	1.74	0.41	0.56
3	0.87	-0.76	0.08	1.19	0.60	0.49
4	0.06	0.03	-0.17	0.42	0.20	0.27
5	-0.07	0.00	0.05	0.78	0.78	0.36
6	0.01	0.05	0.05	0.11	0.21	0.18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





Improvement in Standard Deviation (log scale)





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)

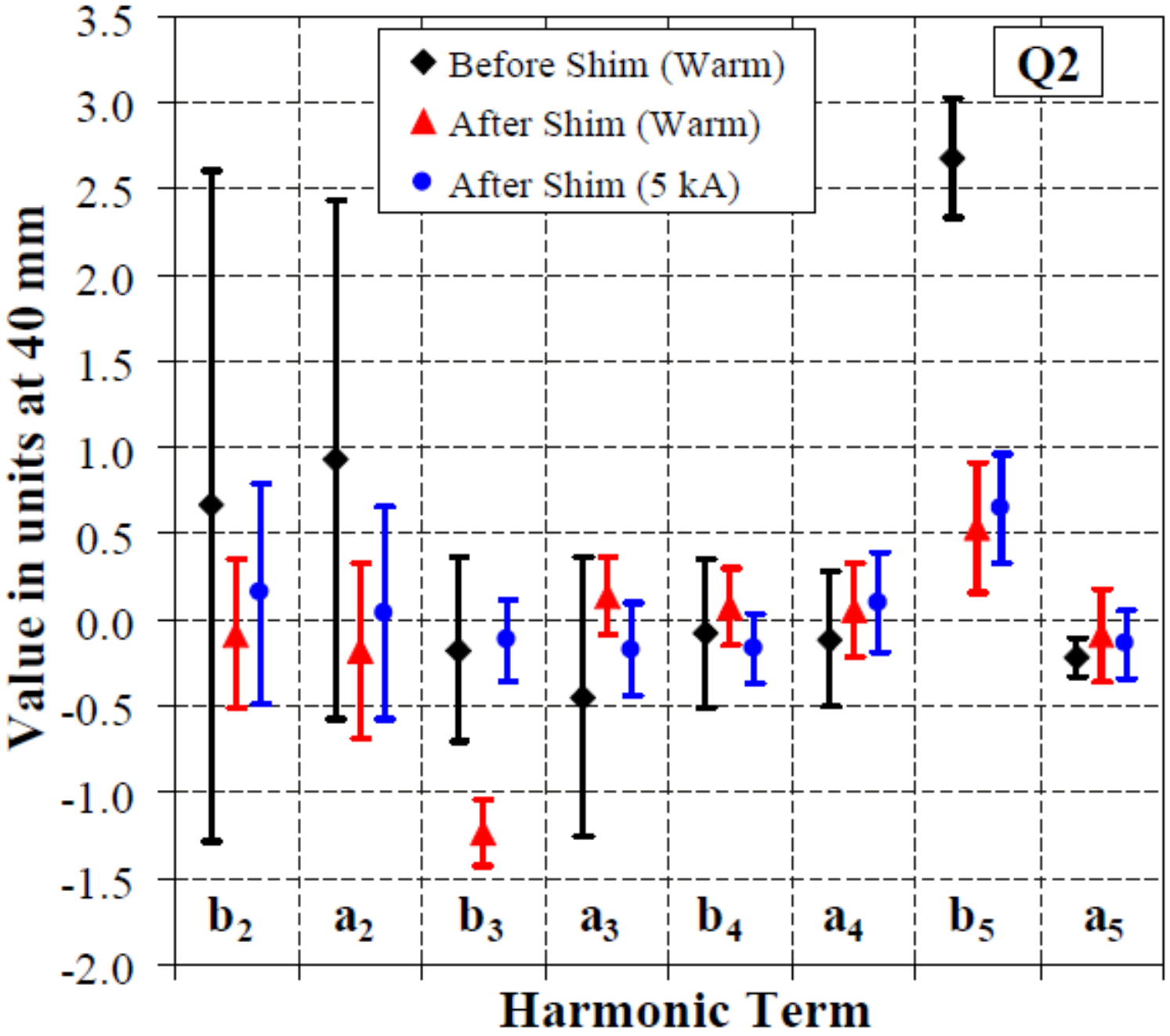
n	$\langle b_n \rangle$ (n=3:Sextupole)			σ (b_n)		
	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets	No Shims 17 Magnets	Shims (W) 10 Magnets	Shims (5kA) 8 Magnets
3	0.58	-0.17	0.30	1.87	0.47	0.27
4	-0.11	-1.21[(a)]	0.02	0.56	0.23	0.17
5	-0.18	0.05	-0.12	0.40	0.13	0.16
6	2.68	0.48[(b)]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

Specific Case 130 mm Q2

(other magnets Q1 and Q3)



Ultimate Field Quality in Superconducting 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).

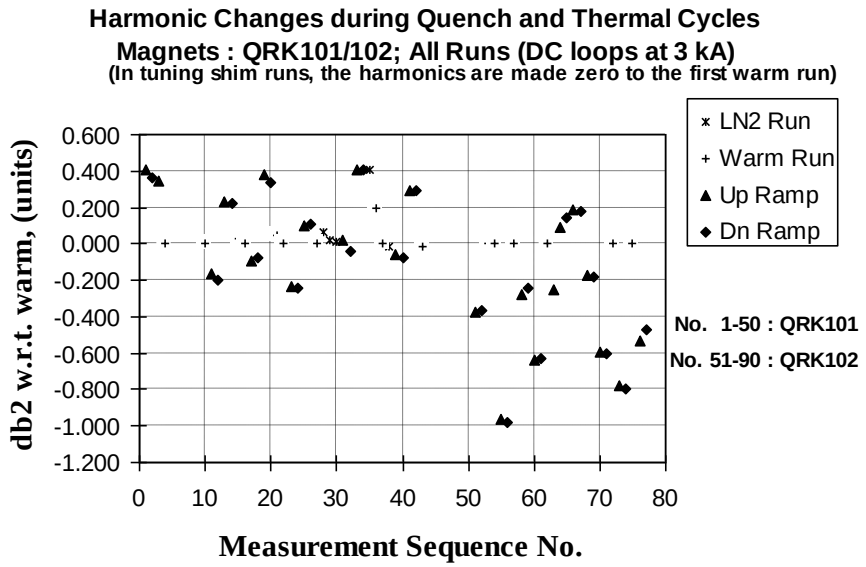
Animesh Jain at BNL found changes in harmonics between two runs in RHIC insertion quadrupoles.

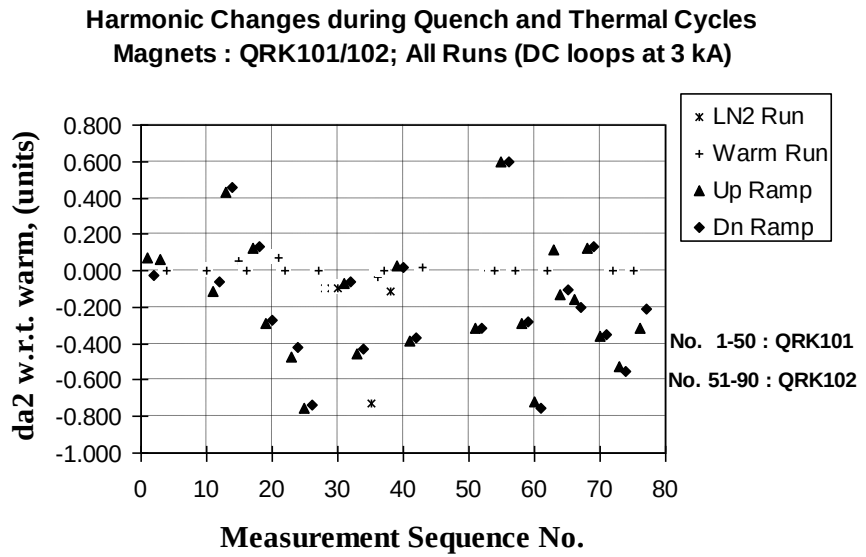
First thought that the changes were related to the tuning shims (argument didn't make a logical sense).

An experimental program was initiated (along with the analysis of previously measured data). It 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 the stainless collars.

Note: n=2 is sextupole





Ultimate Limit of Field Quality in SC Magnets (did we reach it?)

- When superconducting magnets are energized, individual turns in NbTi coils typically may move 25-100 μm
- When magnets go through a shock (quench or thermal cycle), turns may not return to the original place to a level better than 10 μm or so
- Mechanical changes of the order of 10 micron represent 10^{-5} change in field harmonics corresponds
- This puts a limit in field quality that can't be controlled even by tuning shims

CHANGE IN FIELD HARMONICS AFTER QUENCH AND THERMAL CYCLES IN SUPERCONDUCTING MAGNETS*

R. Gupta, A. Jain, J. Muratore, P. Wanderer, E.Willen, BNL, Upton, NY 11973 USA and C. Wyss, CERN, Geneva, Switzerland

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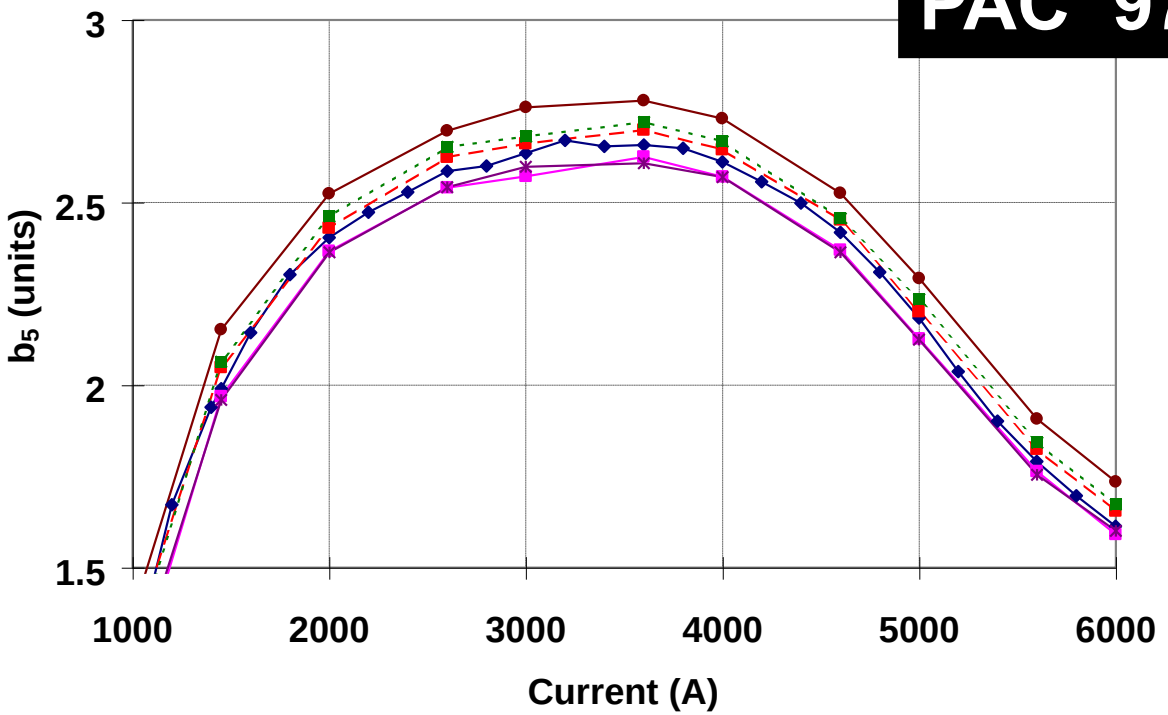
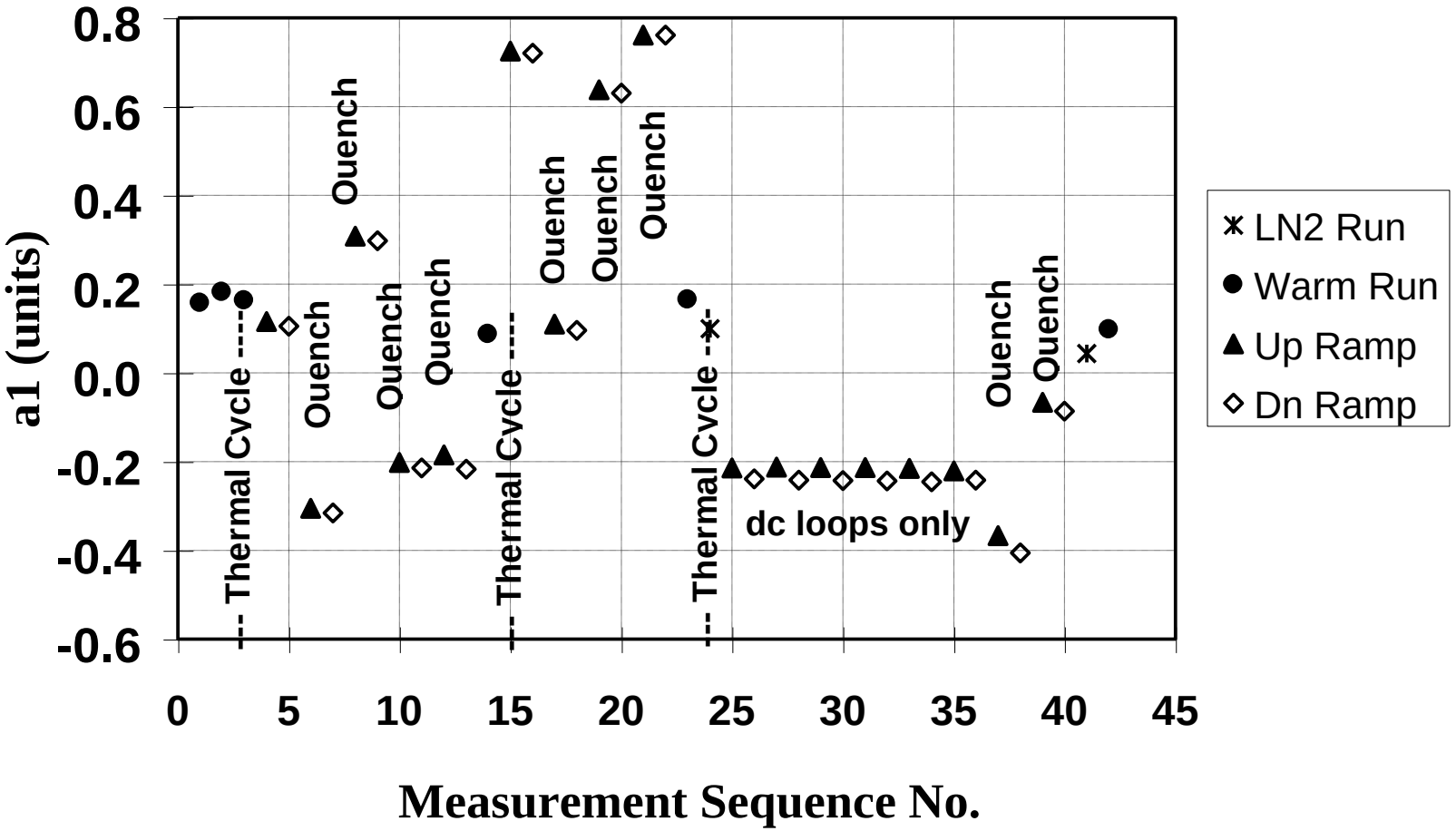


Current dependence in b_5 during six up ramps (separated by quench and/or thermal cycles) in 3.4 m long 130 mm aperture RHIC IR quadrupole QRK102.

What brings these micro-changes in harmonics and what don't

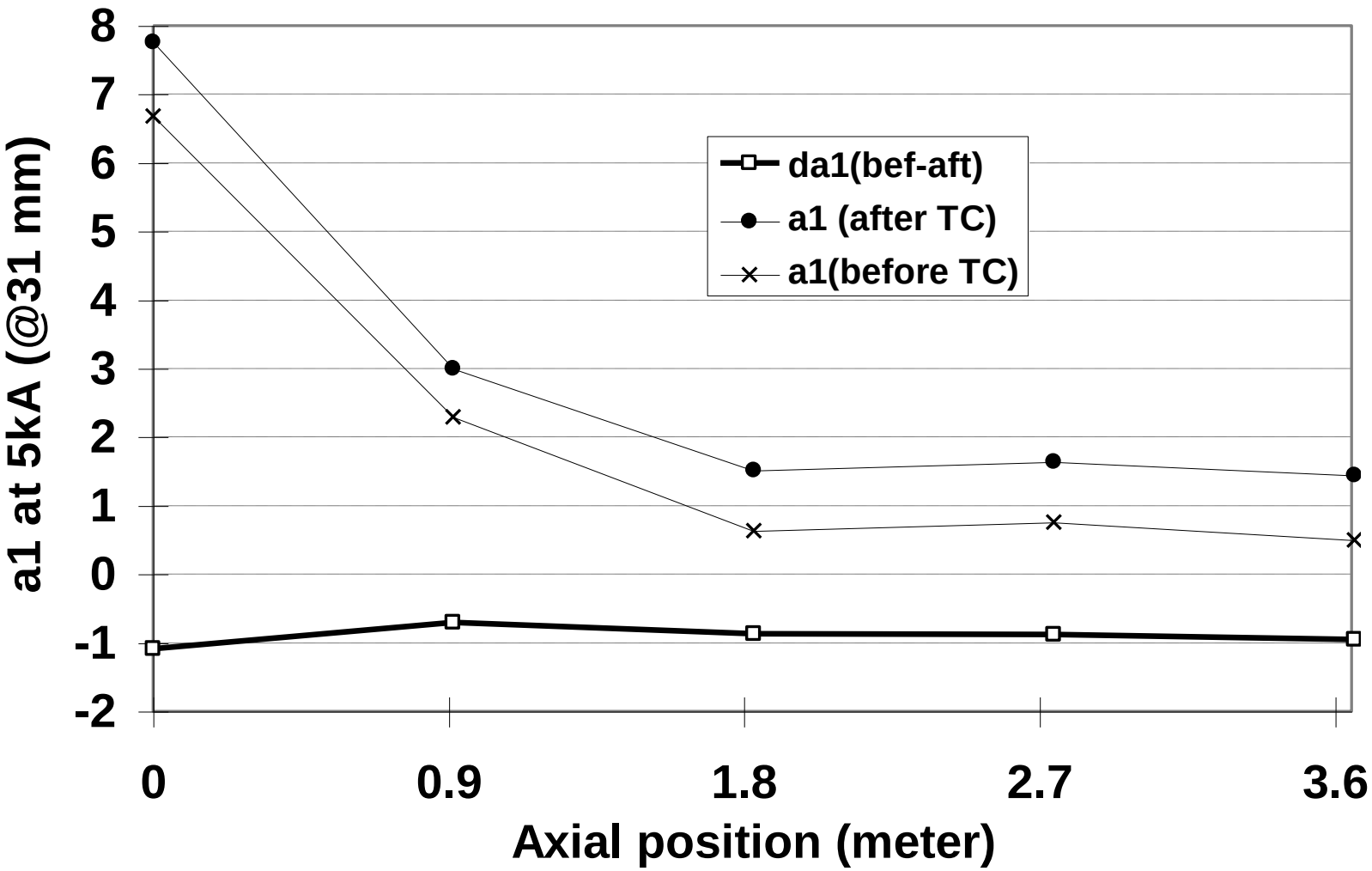
- Thermal shocks do
- Quench shocks do
- But ramp up-and-don't cycles don't. Turn movement must be smooth.



Variation in integral a_1 at 31 mm reference radius in RHIC 100 mm aperture dipole DRZ106 from quench and thermal cycles.

Axial Dependence of the Change in Harmonics

Relative change seems to be uniform along the axis.



Axial dependence of the change in a1(@31 mm) caused by a thermal cycle in DRZ106 (RHIC 100 mm dipole)

Small Change in Harmonics in 130 mm RHIC IR Quads due to Quench and Thermal Cycles

CHANGE IN FIELD HARMONICS AFTER QUENCH AND THERMAL CYCLES IN SUPERCONDUCTING MAGNETS*

R. Gupta, A. Jain, J. Muratore, P. Wanderer, E.Willen, BNL, Upton, NY 11973 USA and C. Wyss, CERN, Geneva, Switzerland

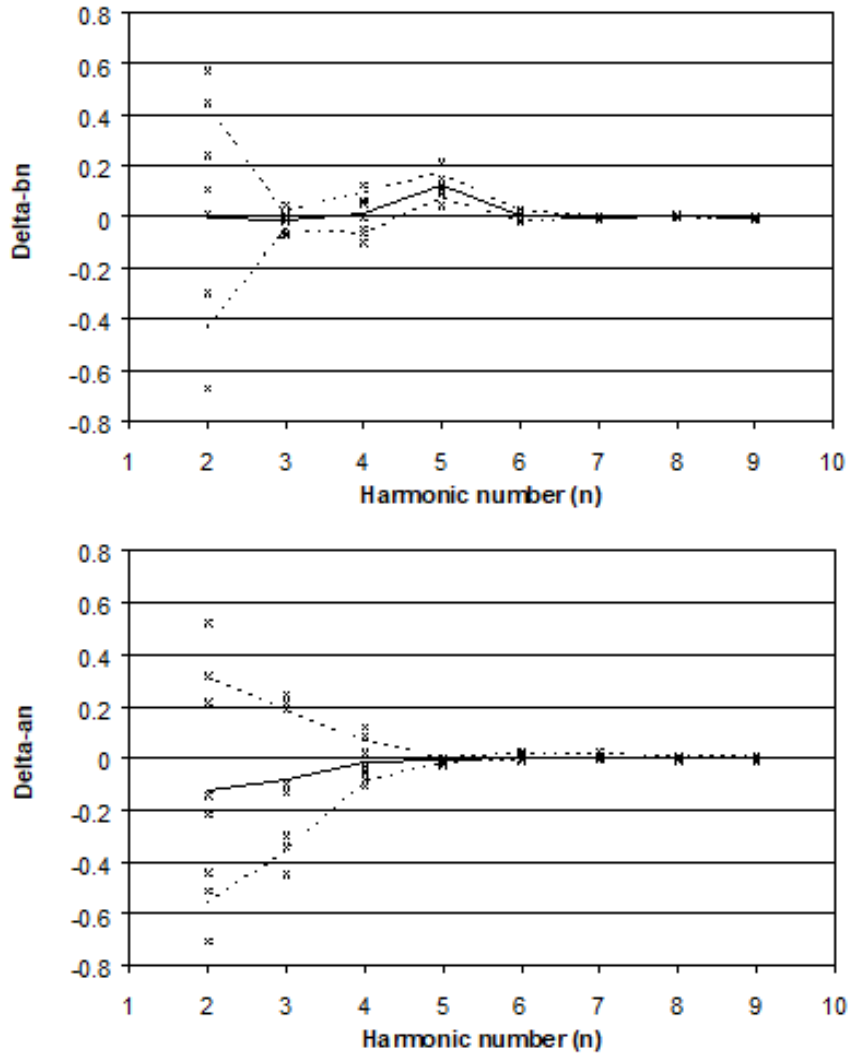


Fig. 4 : Change in harmonics in eight 130 mm aperture insertion quadrupoles caused by a quench.

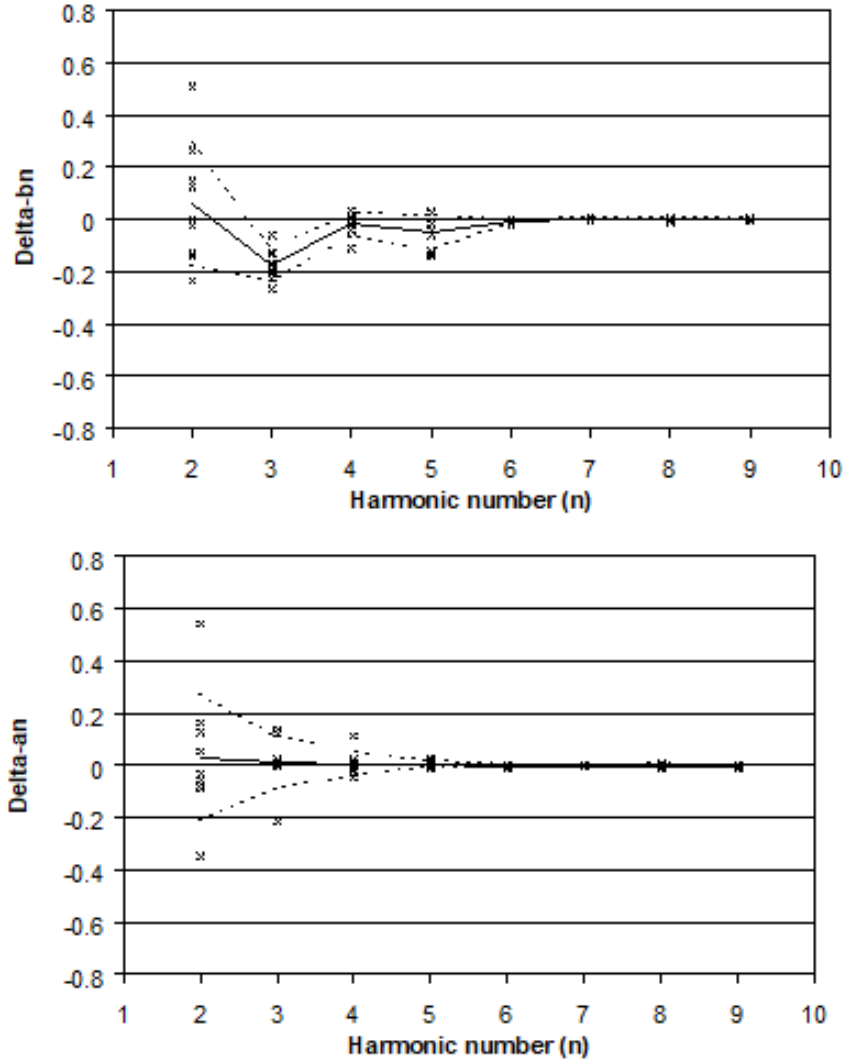
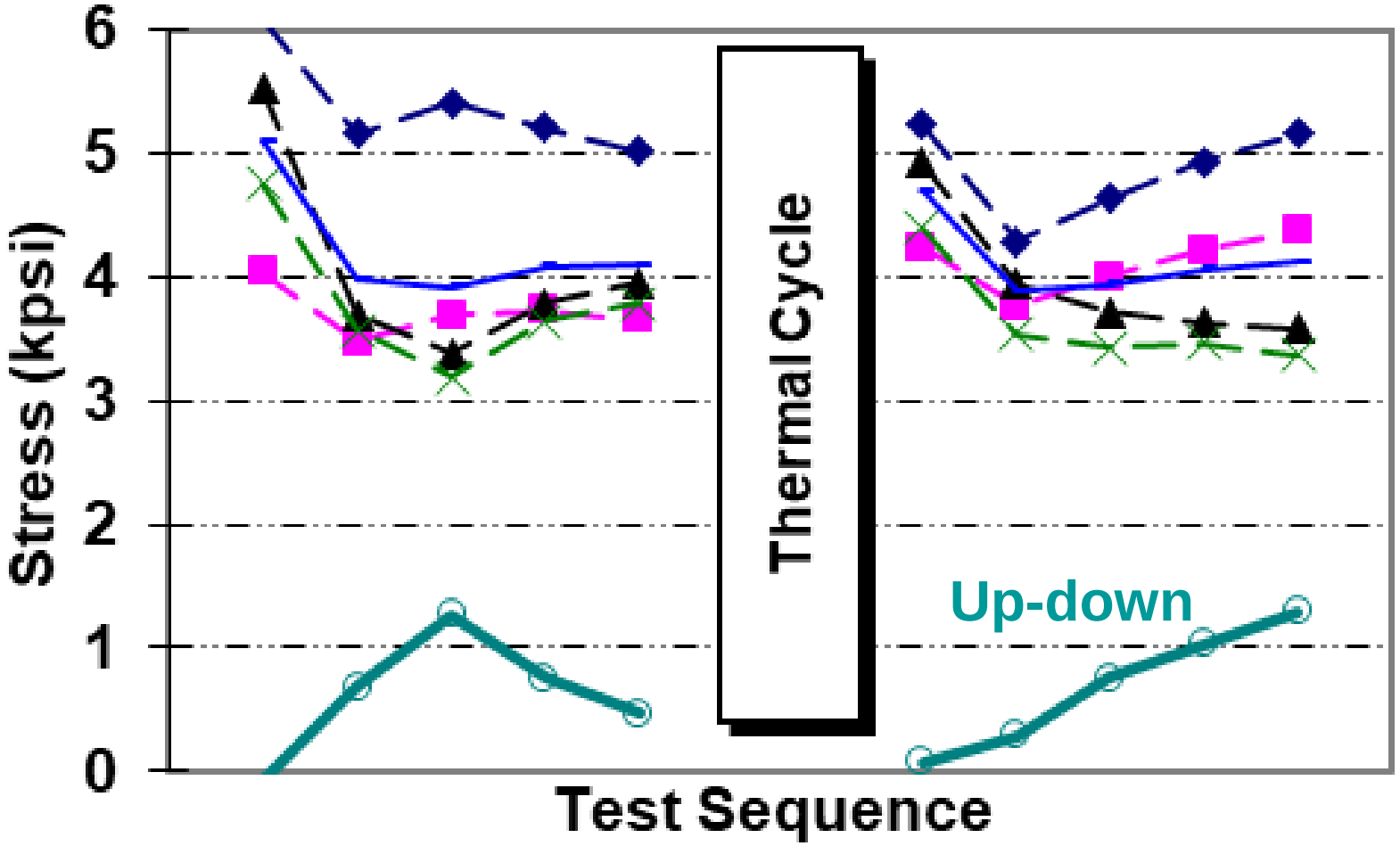


Fig. 5 : Change in harmonics in eight 130 mm aperture insertion quadrupoles caused by a thermal cycle.

Related Mechanical Signature of the Small Change

Hard to make a definitive correlation associated with the small changes in harmonics and prestress related to 10 micron. Possibility looks plausible.



The azimuthal stress on pole faces (dashed lines), average (solid) and difference between top and bottom (thick solid line) after successive quenches together with a thermal cycle in between in the magnet DRZ105.

SUMMARY

- Eight properly designed and placed tuning shims in the magnet can correct eight harmonics in the magnet.
- Tuning shims should be used for final adjustment. Other techniques (discussed elsewhere) should be used first.
- The technique corrects measured harmonics, one magnet at a time and is particularly suitable for EIC where we have several one of a kind magnets.
- We can benefit from RHIC IR magnet experience, still the program should be planned and developed thoughtfully for it to be successful.
- with tuning shims, we have been able demonstrate the best field quality magnet technically possible. Small changes due to thermal and quench cycles doesn’t make any further improvement possible.