Estimating Field Errors in Real Magnets and Managing Low Harmonics in EIC IR Magnets

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August 21, 2026

OVERVIEW (1)

NOTE: Estimating field errors (not just writing specs) was a major topic in SSC and RHIC as that has an impact on the performance of machine.

There are several steps to estimating field harmonics in real magnets

- Step 1: Design: Geometric+saturation-induced (can't do better than that)
  - ➢Also compute from persistent current (nothing fancy is being done to reduce them)
- Step 2: Compare ideal geometry Vs. real geometry
  - ➢Individual turns don't go where assumed in ROXIE and that creates field errors
  - ➢Deformation in geometry due to Lorentz forces + properties of iron
- Step 3: Compute errors from tolerances in parts and construction
  - ➢ Errors from parts may be estimated but estimating from construction is tricky.
- Step 4: Review past production
  - ➢GianLuca Sabbi discussed them in a previous presentation

OVERVIEW (2)

As interesting as reviewing the harmonics in past magnet production is, that may only be indicative for what to expect in EIC IR magnets since:

- Those were usually results of several iterations (not the case in EIC)
- Harmonic are expressed via mean and sigma. Not helpful for a single magnet (as the case in EIC) as that can be many sigma off.

In addition, to the computed errors from parts, construction and statistics, schedule pressure may force us to accept out-of-spec parts – more errors.

➢ Also, there are surprises in production, adding further to field errors.

- **Above consideration makes potential field errors in real magnet rather lareg.**
- **This could, however, be mitigated by developing initial designs (not an after thought) which anticipate them and deliver good field quality despite that.**
- **First some positives with real examples, and then what should we be doing.**

Field Quality in the 1st RHIC 100 mm Dipole - NO Prior R&D Magnet
Relevant to EIC (a few things were done to get the harmonics right)

FIRST MAGNET

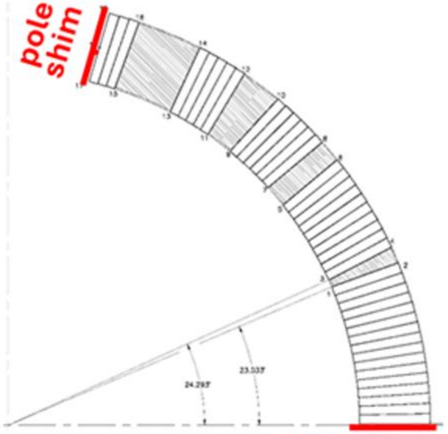
Harmonics at 2 kA (mostly geometric).

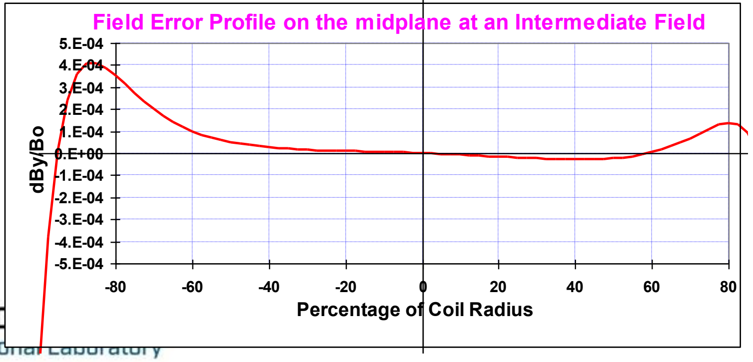
Measured in 0.23 m long straigth section.

(all harmonics within ~1 unit at 62% of coil radius)

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



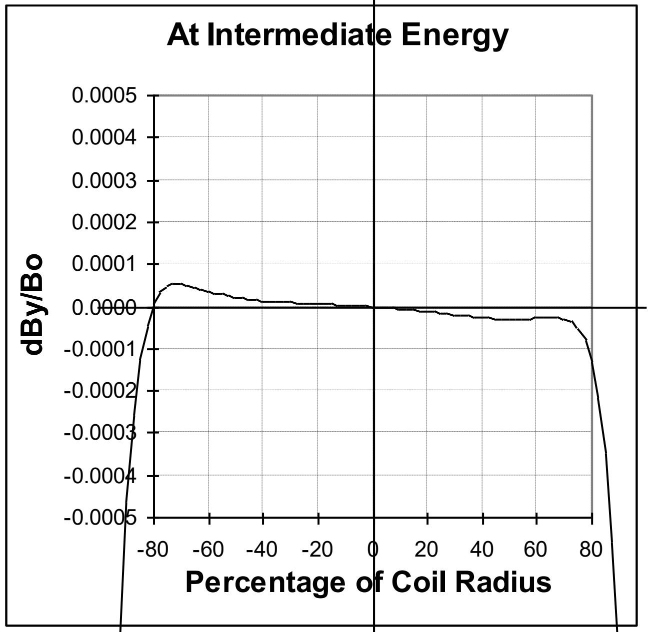


SHORT PRODUCTION (adjustments during production)

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*

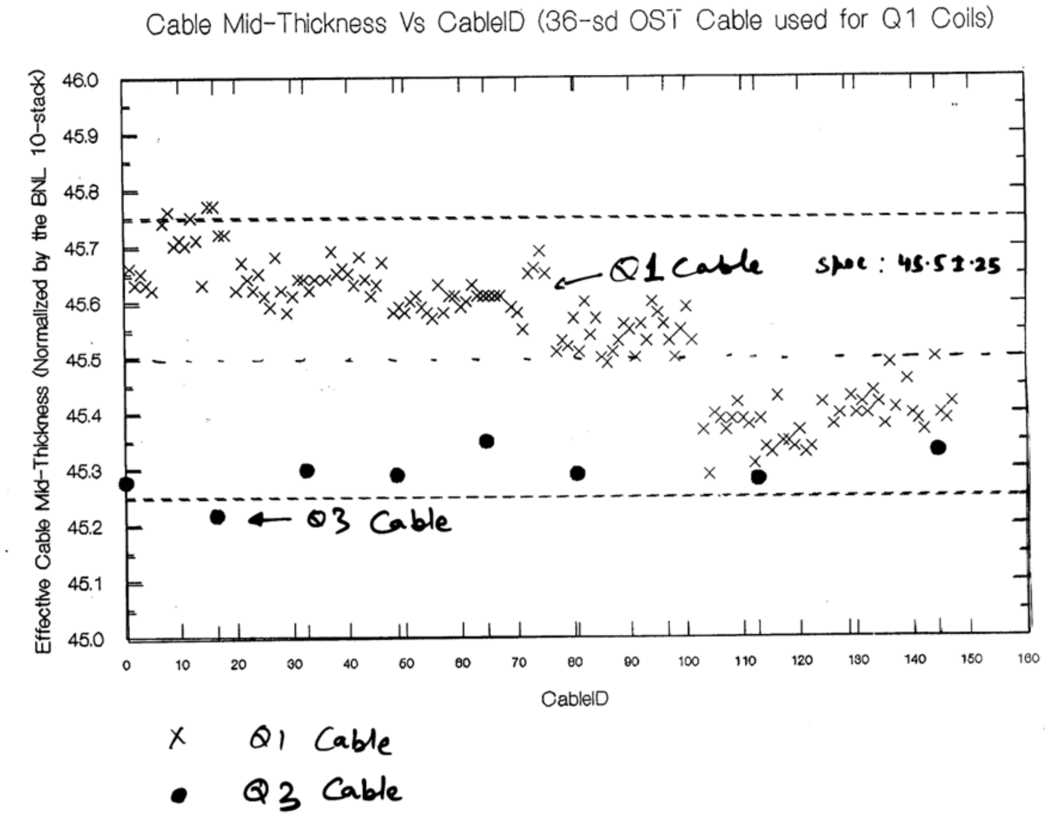
Field errors are 10^{-4} to 80% of the aperture at midplane.

(Extrapolation used in going from 34 mm to 40 mm; reliability decreases)

Updated the initial design to allow large midplane gaps and pole shims. Measured harmonics warm and adjusted the values.

Real World Challenges: Even When Things Are Within Spec

Cable Spec: +/- 0.25 mil (6.5 micron)



RHIC IR Quad (27 turns)

Error build-up=> 240 micron
➢ **much larger than acceptable.**

A flexible design approach accommodated it!

In addition to coil pole shims and midplane caps, a rectangular wedge in coil absorbed such large variations without compromising the field quality.

- Feedback to EIC: Design magnets with that in mind, right from the beginning.

We used to examine 100's coil design to choose one which has such flexibility, etc.. Is it being done now?

A real-life case: We were way off in RHIC DX magnet. We added one turn and yet managed good field quality!

➢ **Point to emphasize don't get lost in paper studies. Plan for beyond when no prototypes.**

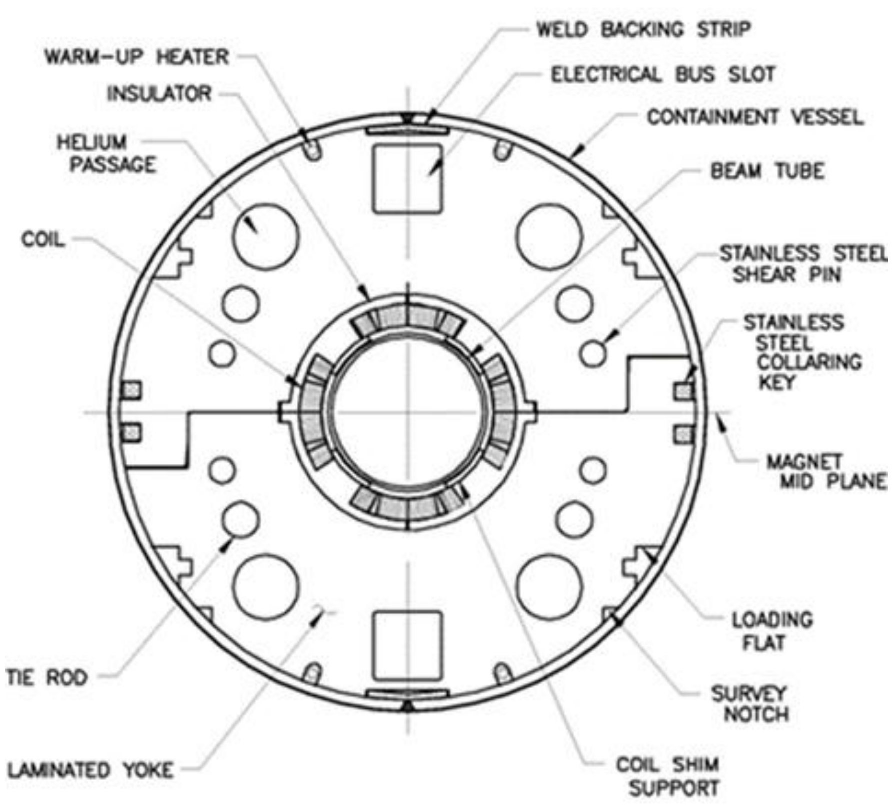
Wider Use of Pole Shims and Midplane Gaps to Correct Measured Errors

Pole shims and midplane gap can be used to correct non-allowed harmonics also (a simple, yet a powerful tool).

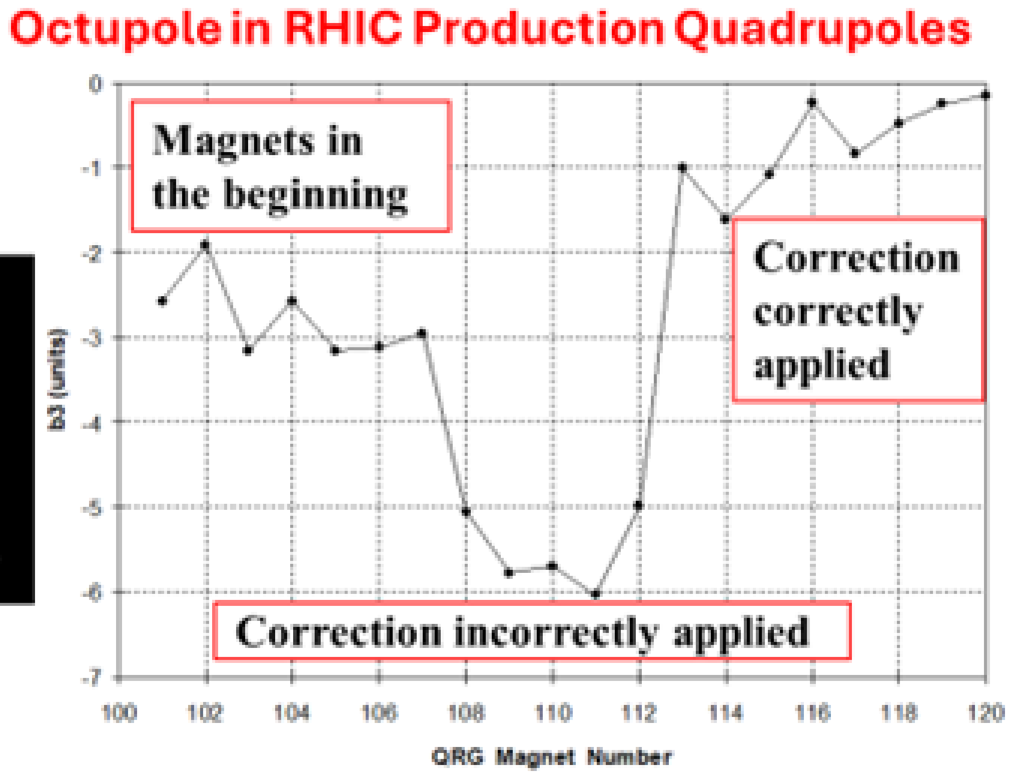
- Procedure: First measure harmonics warm in collared magnet. Then de-collar and re-assemble coils with adjusted midplane gap and pole shim values to correct both allowed and non-allowed harmonics.

➢ **Example: RHIC Quads where a large error (7 units) was removed by non-equal use of midplane caps.**

RHIC ARC QUADRUPOLE



b_3 was over +7 units in twelve R&D quadrupoles

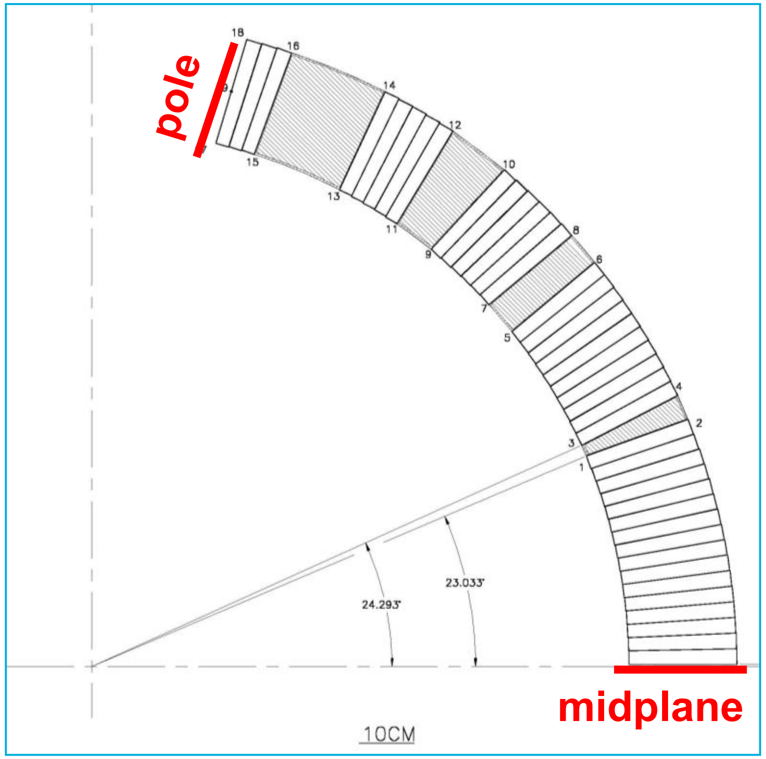


Note: RHIC quads were assembled like dipoles to save cost. That created octupole errors.

Design Strategy: Find a Flexible and Adjustable Design
(this is how the SSC dipole and RHIC magnets were designed)

First SCAN thousands of cases to find islands of good solutions

- BNL had a host of pre- and post-processor to aid the process




```
        1 N1         19.00000    0.         1.         30.
 enter min,max number of turns for blk [and increament in FOR017]
13 21 2
        3 N2         16.00000    0.         1.         30.
 enter min,max number of turns for blk [and increament in FOR017]
12 18 3
        5 N3         13.00000    0.         1.         4.
 enter min,max number of turns for blk [and increament in FOR017]
10 14 1
        7 N4          10.0       0.0        0.         4.
 enter min,max number of turns for blk [and increament in FOR017]
8 12 1
        9 N5          6.00000    0.         1.         4.
 enter min,max number of turns for blk [and increament in FOR017]
3 8 1
       11 N5          4.0        0.0        0.         4.
 enter min,max number of turns for blk [and increament in FOR017]
2 6 1
 -------------------------------------------------------
 YOU HAVE SPECIFED # cases=       47250
  Enter start cycle, end cycle [<cr> for all]
10001 20000
 Base design has total turns =           68
 ENTER min,max number of total turns
67 69
 Do you wish a constraint on a subtotal?
 eg total number of turns for inner layer-- (yes/[NO])
y
 Enter First, Last blocks to be included in sum
1 3
 ENTER lower,upper limits of sum
20 40
```

Then find ~100 to examine in more detail

Select ~10 for final check to select one

```
BNLADA>ty LANL-73TX1D.PARSLCT;
 LANL quad ***SELECT CASES***          10-DEC-01 11:18:39    BNLADA$DKA200:[GUPTA.LANL]LANL-73TX1D.D04;1
# WMP    BLOCKS    RIN      ROUT     Current  Thickness  KEYSTONE  AzInsul    <-----   Cable Information
1 4.0    11.     18.2165  19.3845   1.       53.0       3.2       3.45
Turns  Chisq  T.F.   Pole    b2     b4     b6     b8     b10    b12    W1     W2     W3     W4     W5    CASE  BNHin   BssInf
JKDA56 0.720 0.337 43.00 -0.05  0.03  -0.85  0.00  0.00  0.00  0.469  2.185  0.764  9.297  0.303  301  26.598  24.93
JKDC45 0.951 0.341 43.00 -0.06 -0.13  -0.96  0.00  0.00  0.00  0.399  1.368  2.439  8.276  0.533  305  25.430  25.78
JKDC54 0.451 0.342 42.99 -0.13 -0.12  -0.65  0.00  0.00  0.00  0.309  1.542  2.103  8.304  0.755  306  24.999  26.10
JKDC63 0.579 0.342 42.97 -0.07 -0.17  -0.74  0.00  0.00  0.00  0.300  1.514  2.084  8.372  0.721  307  24.740  26.28
JOAA46 0.447 0.339 43.00  0.08 -0.03  -0.66  0.00  0.00  0.00  0.493  2.666  0.324  8.964  0.572  346  25.952  25.40
JOAA55 0.570 0.339 42.99  0.00  0.09  -0.75  0.00  0.00  0.00  0.499  2.622  0.413  9.046  0.429  347  25.924  25.42
JOAA73 0.641 0.339 43.00  0.05  0.04  -0.80  0.00  0.00  0.00  0.476  2.623  0.325  9.126  0.468  349  25.554  25.67
JOAC44 0.698 0.343 42.92  0.01  0.02  -0.83  0.00  0.00  0.00  0.387  1.691  2.273  8.287  0.303  350  24.896  26.20
 100 cases examined.   8 cases selected for: CHISQ< 5.0000 TF> 0.300 POLE<85.00; |bn|< 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
A=10 B=11 C=12 D=13 E=14 F=15 G=16 H=17 I=18 J=19 K=20 L=21 M=22 N=23 O=24 P=25 Q=26 R=27 S=28 T=29 U=30 V=31 W=32 X=33 Y=34 Z=35
FILEname =         BNLADA$DKA200:[GUPTA.LANL]LANL-73TX1D.D04;1
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Dealing with Current Dependence in Harmonics that doesn't Match Calculations

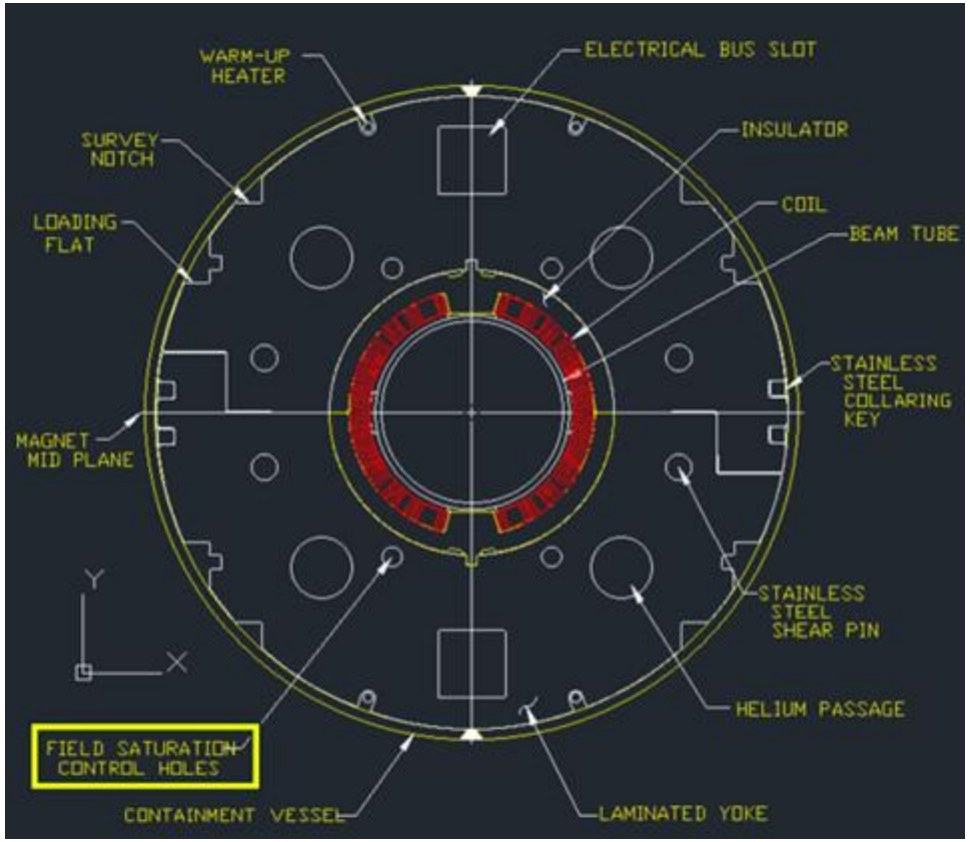
Calculations are performed for iron saturation only assuming certain properties of iron.

- However, yoke may be different than one assumed.
- Lorentz forces may change the geometry (overall shape and intra-turn spacing)
- Clerance between collar o.d. and yoke i.d. may impact the coil shape under Lorentz forces and hence the harmonics (we saw that in SSC dipoles).

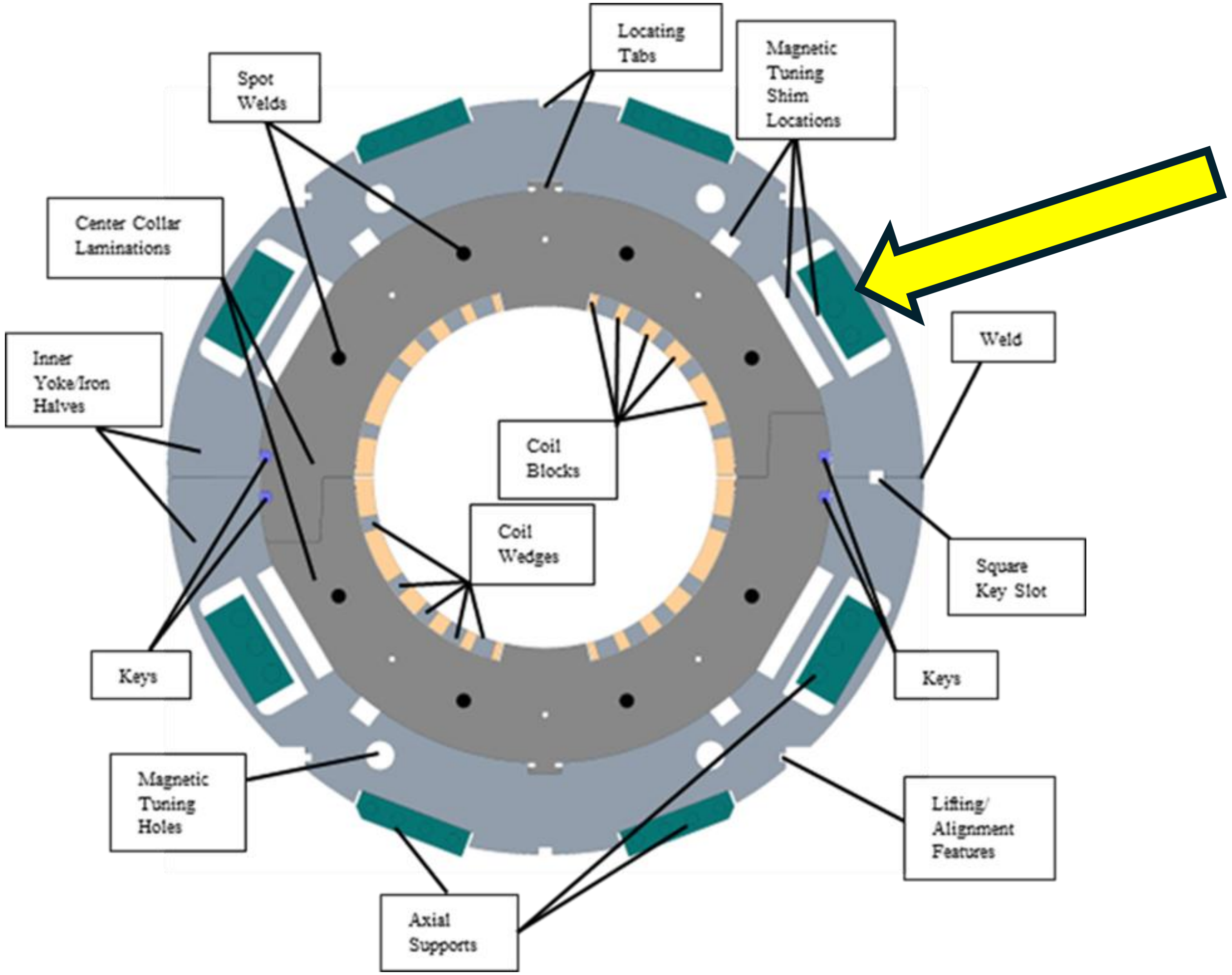
Initial design can have in-built tools to adjust change in harmonics with current

Example: RHIC 100 mm dipole (no R&D)

Saturation control holes filled with Fe rods to reduce Sextupole Vs. Current



Example: EIC - B1pF Prototype Design (Febin Kurian)



Adjustable filling of the cutout with iron shims to change "Sextupole Vs. Current"

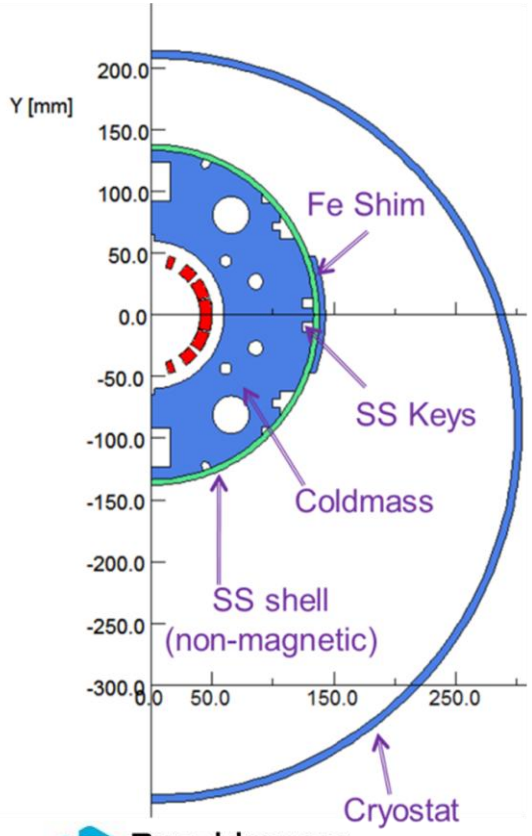
(tune after cold measurements)

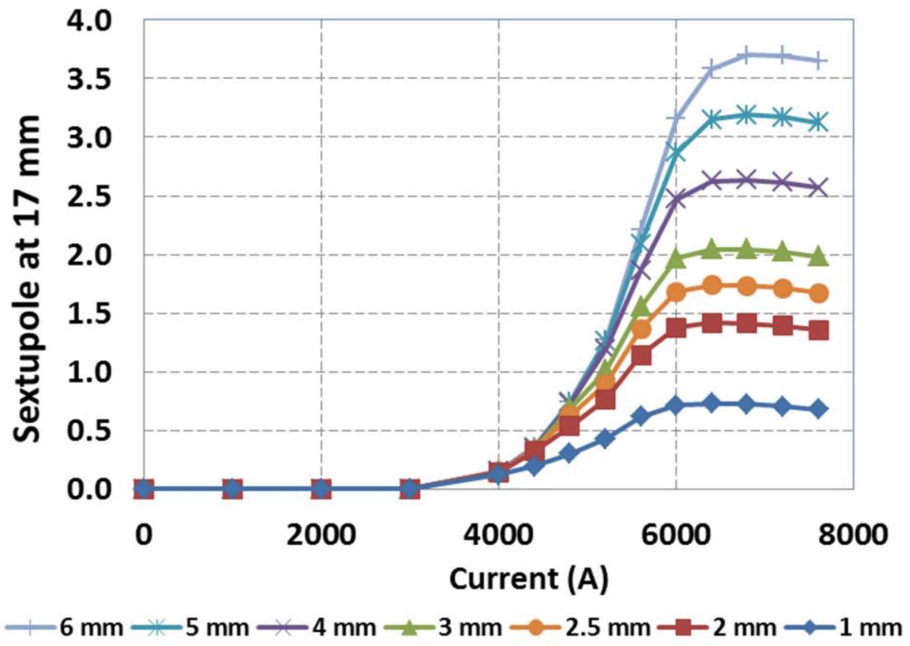
[Strategies to Assure/Tune Field Quality in EIC IR Cable Magnets (with B1pF as an example)]

https://wpw.bnl.gov/rgupta/eic-work-in-progress/

Adjusting Current Dependence in Magnets after Horizontal Test in Cryostat

- **Relevant to EIC.** Magnet has shell and structure fully sealed. Inserting iron rods (as done in RHIC D0 after vertical test) will be too much work.
- A unique solution was found and successfully implemented in LHC D1
- Tuning shim moved outside the shell (easier) to change sextupole Vs I





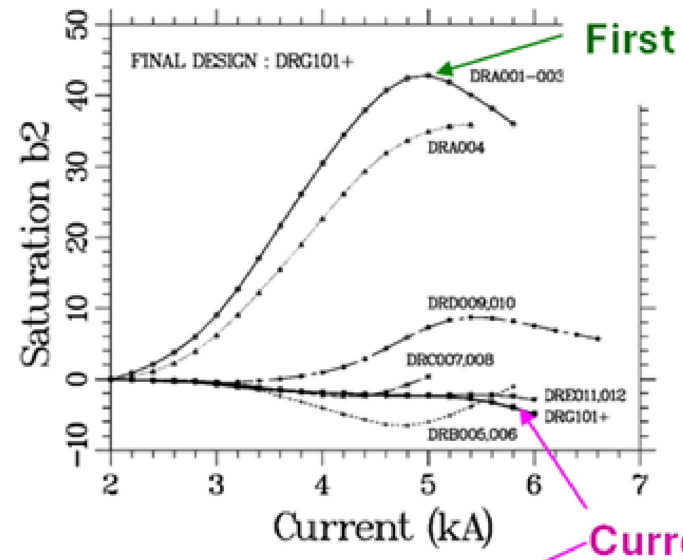
Relative change in Sextupole Vs Current for various thickness of outside Fe Shims

Harmonics Due to Yoke Saturation in SC Magnets

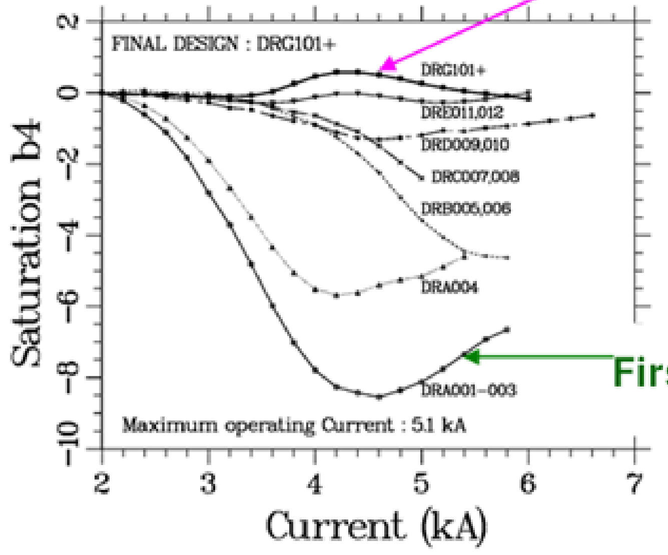
(change in field harmonics w.r.t. current made negligible)

- In RHIC dipoles, yoke is close-in and contributes 50% of the coil field.
- A large saturation was present in early design. It was made negligible.
- Iron is non-linear. So, there will be a change in transfer function. However, the field quality or field harmonics will not change much, if the yoke is made (forced) to saturate uniformly near the aperture.
- Techniques developed to reduce current dependence in harmonics.

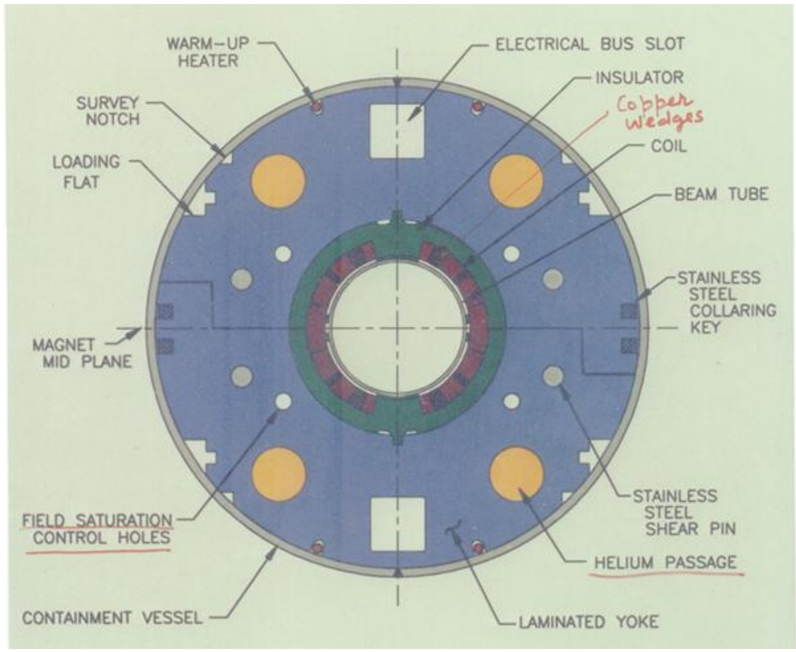
First Design

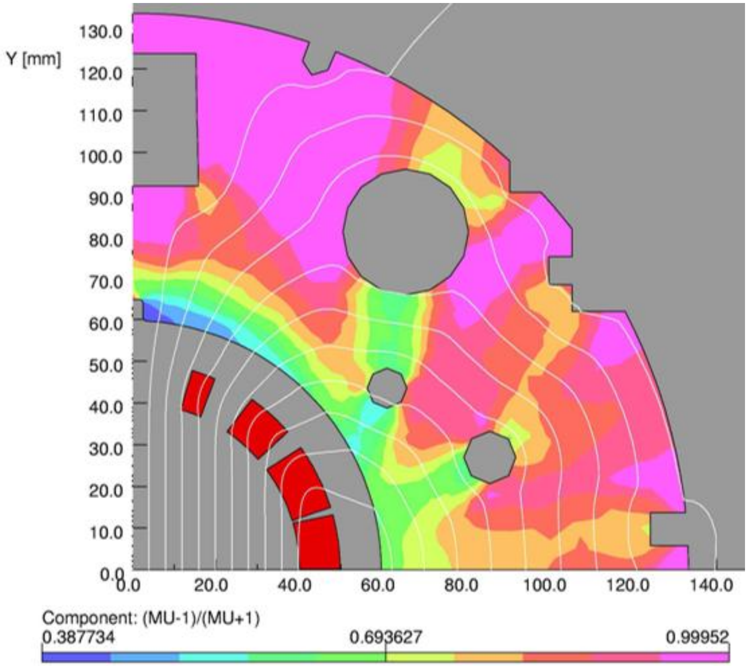


Current Design



First Design



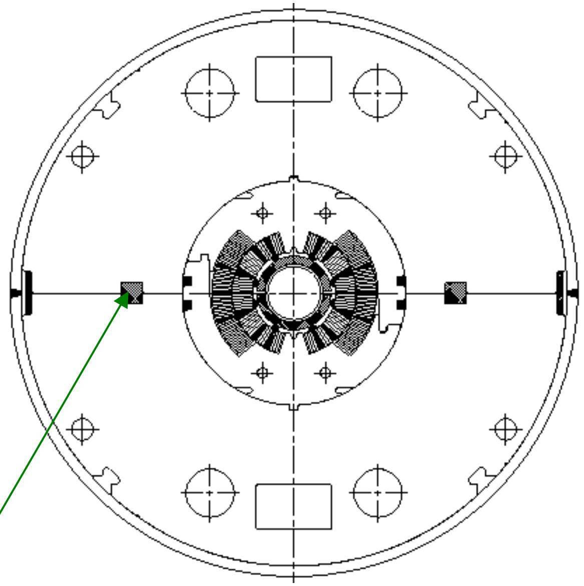


Current Dependence in Sextupole in SSC Dipoles

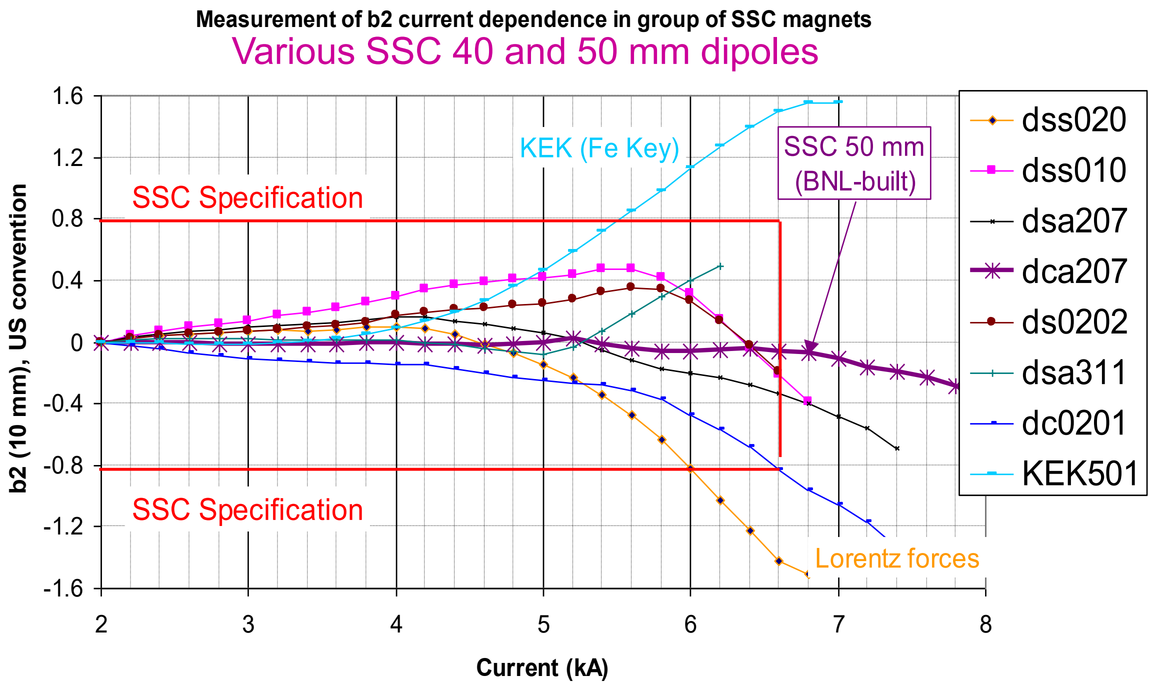
Same coil and similar yoke design for both BNL-built SSC 50 mm Dipole

- Made negligible in the final design (see SSC 50 mm)

Cross section of SSC 50 mm Dipole
Yoke optimized for low saturation



Non-magnetic key to force uniform saturation

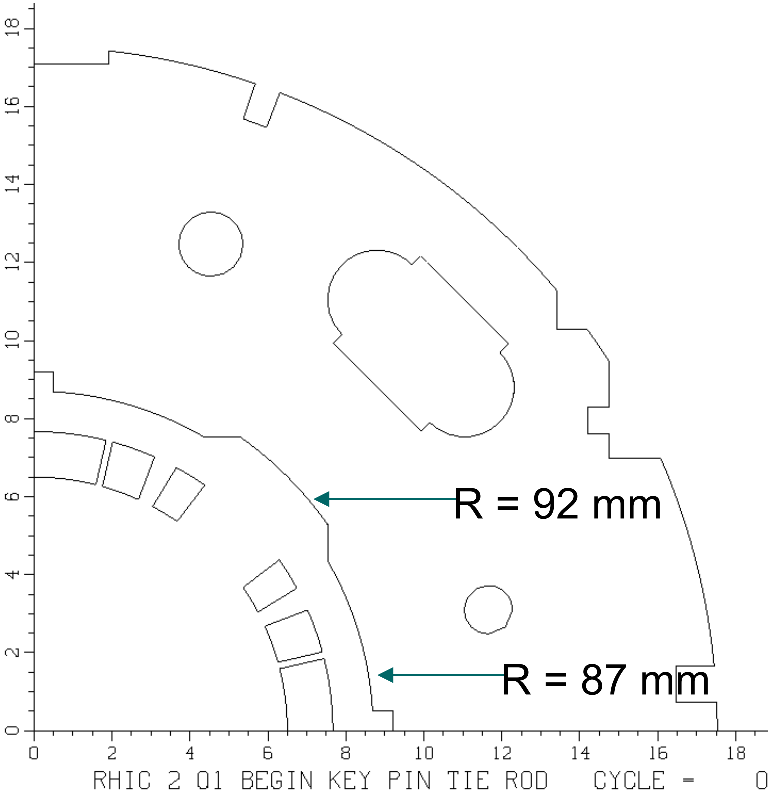


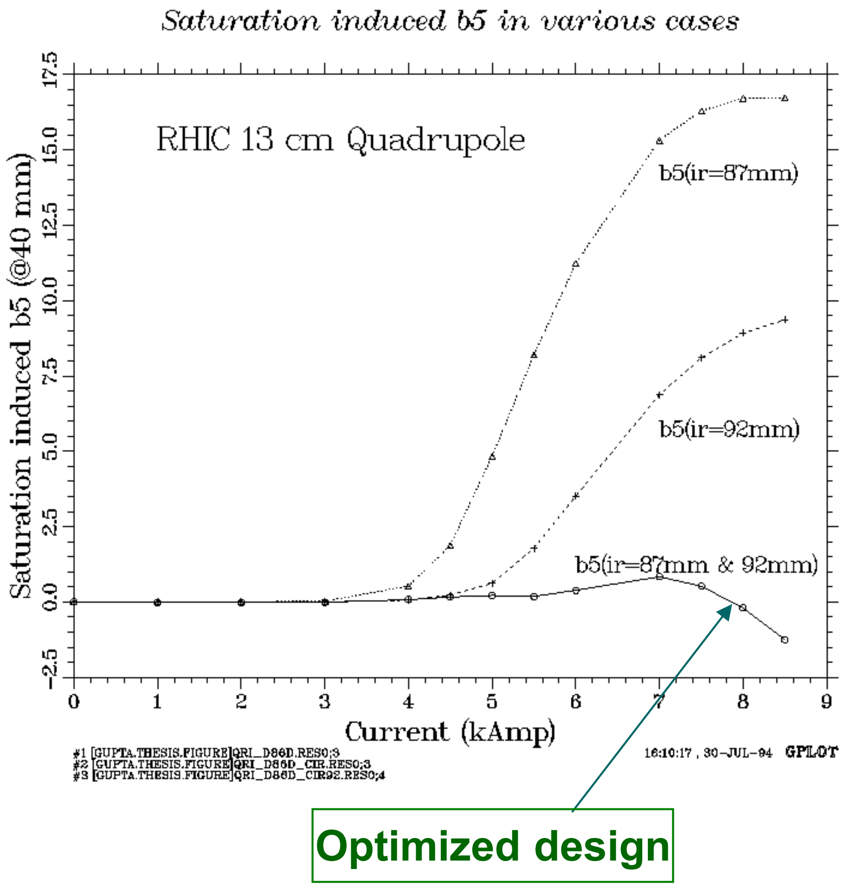
Note: the impact of Lorentz-forces due to a little gap between the collar and yoke (within spec?)

➢ **Need to be prepared for "real world" EIC magnets.**

Controlling Yoke Saturation in Quadrupole Magnets

- ➢ **Quads are a bit different since the amount of flux to force uniform saturation is much lower**
- ➢ **Since holes were less effective in controlling saturation, a 2-radius method was developed**



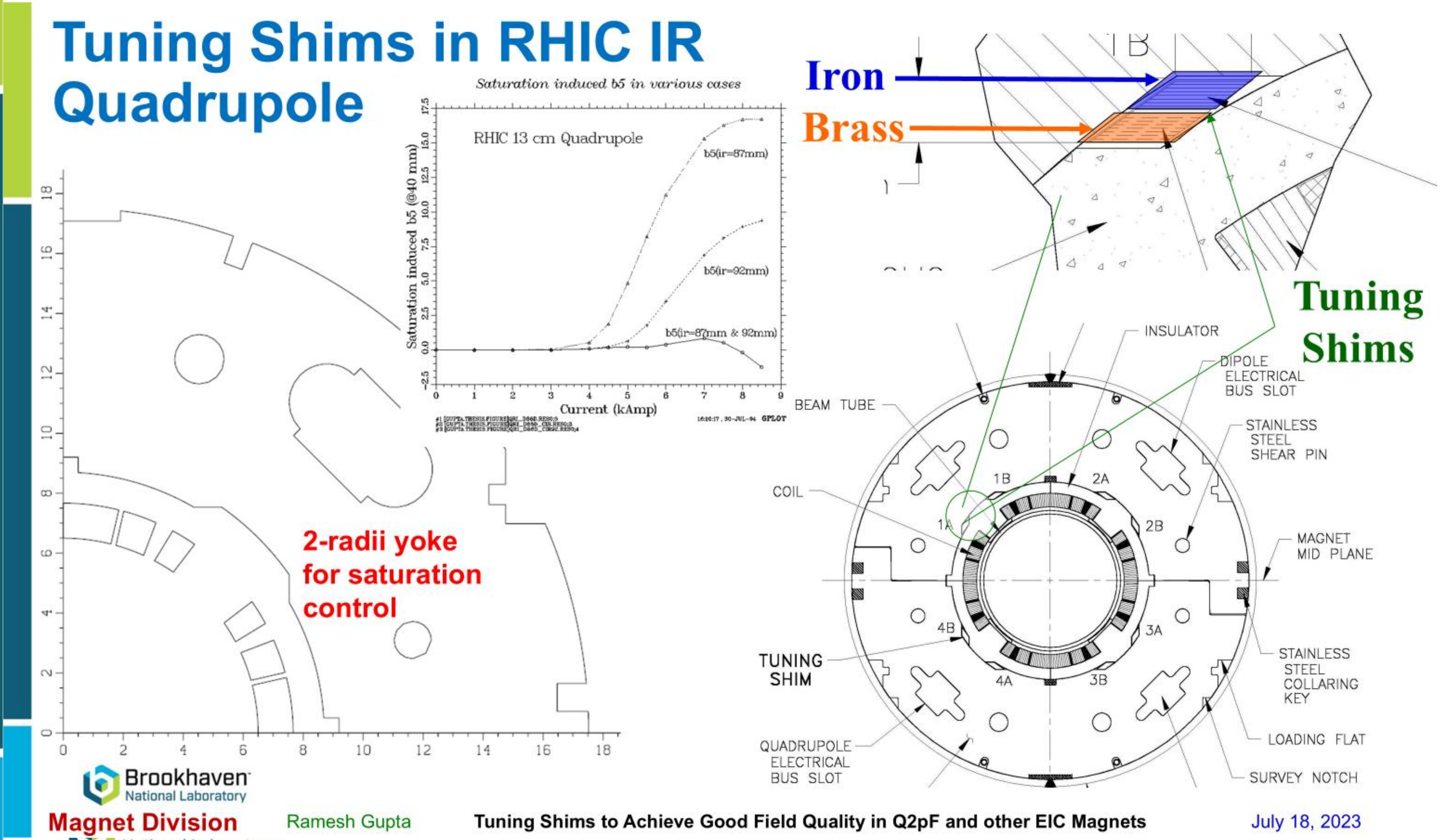


Should be effective in EIC Q2pF also in reducing saturation-induced b_6

➢ **No hole at yoke midplane to adversely impact cross-talk**

Tuning Shim For Ultimate Field Quality

(correct after measurement to make harmonics nearly zero)



Choosing a proper location for tuning shim is imoprtant.

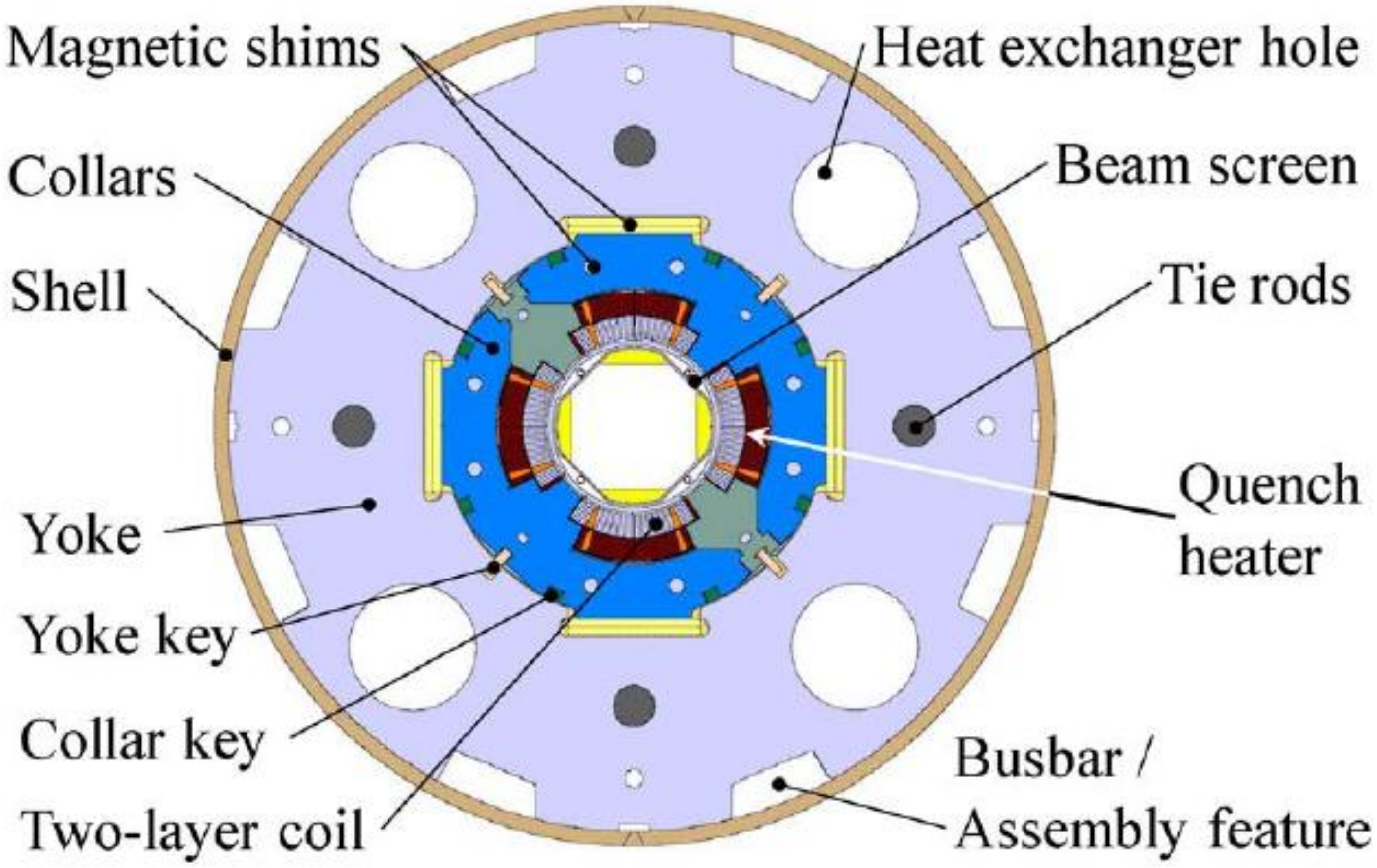
Quad provides eight locations.

A proper choice of angular location would give a good liver arm to zero-out eight harmonics.

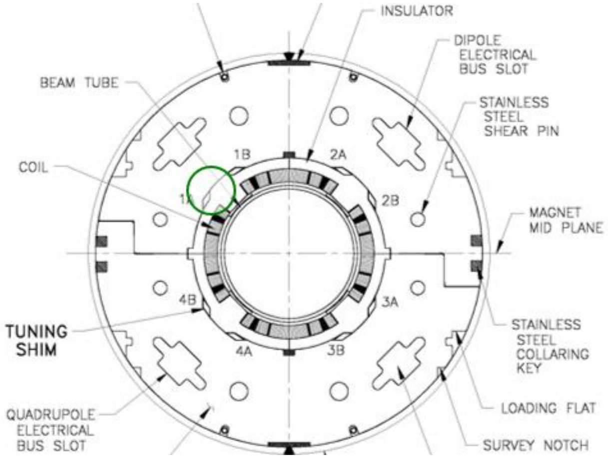
A proper choice will also minimize loss due to saturation.

It turns out that the natural location in RHIC IR was just fine.

Why We Should be More upbeat on Tuning Shims from MQXC



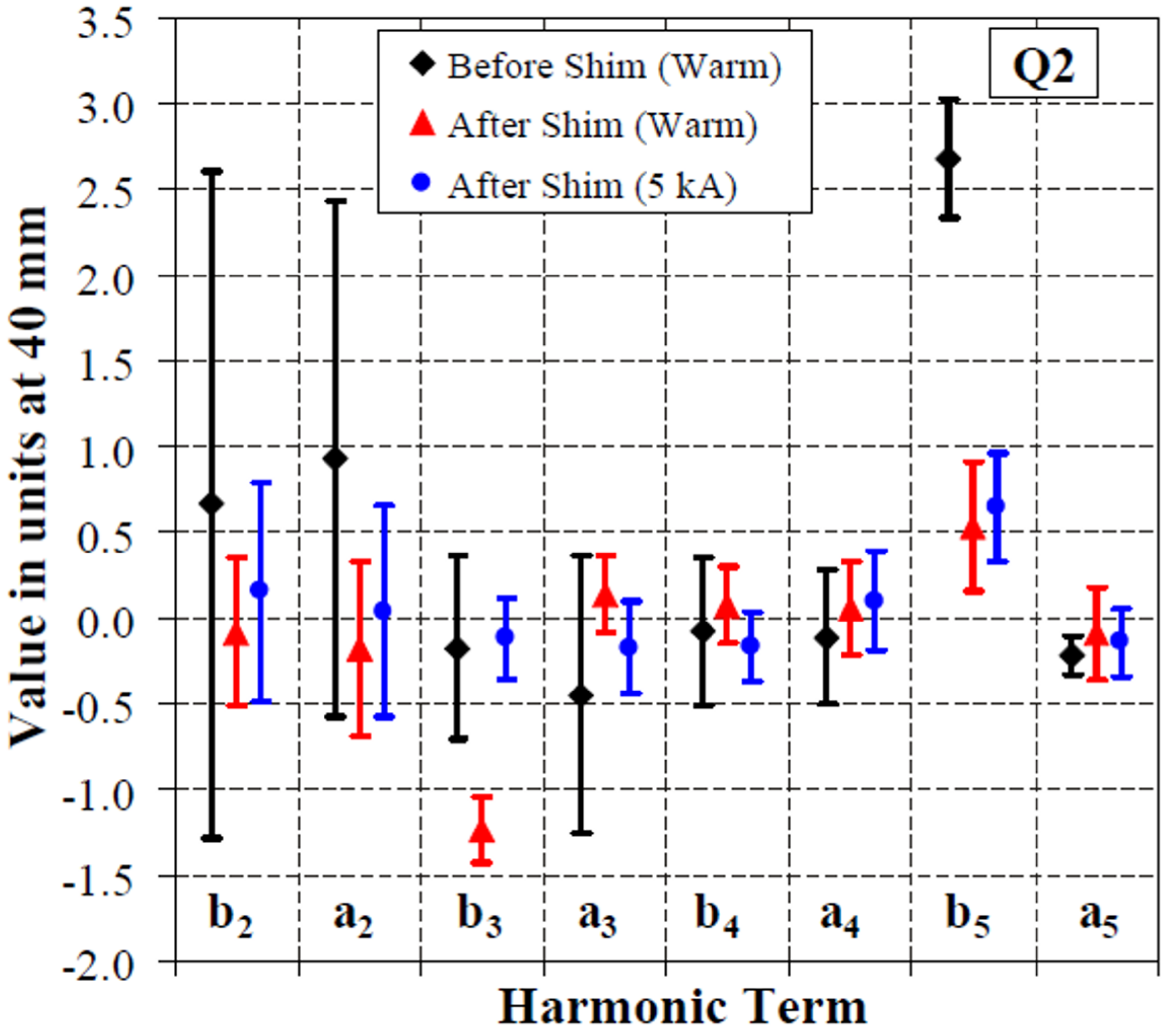
- Location of tuning shims must have been chosen on practical reasons.
- They are at the location (pole) where the saturation will be worst.
- They are at location where the liver arm to remove eight harmonics is not best.

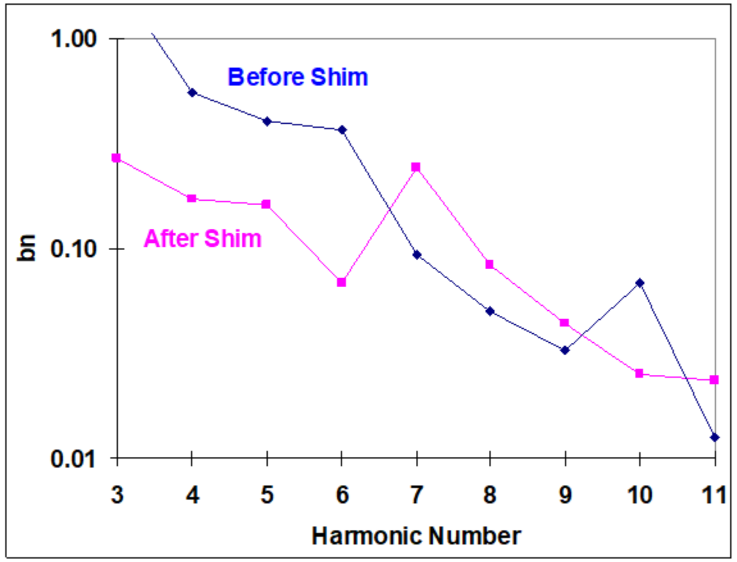


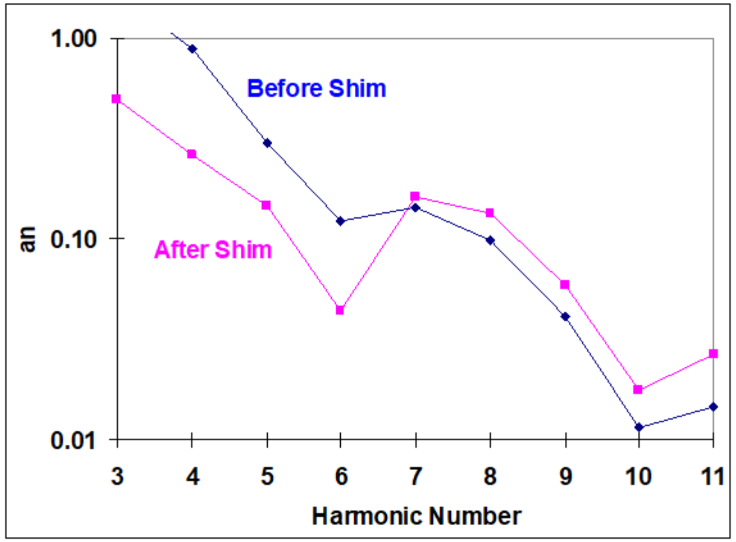
Expect different outcome from a different location in RHIC IR

- ➢ Suggest similar for EIC Q2pF

Harmonic Correction in RHIC IR Quad with Tuning Shims



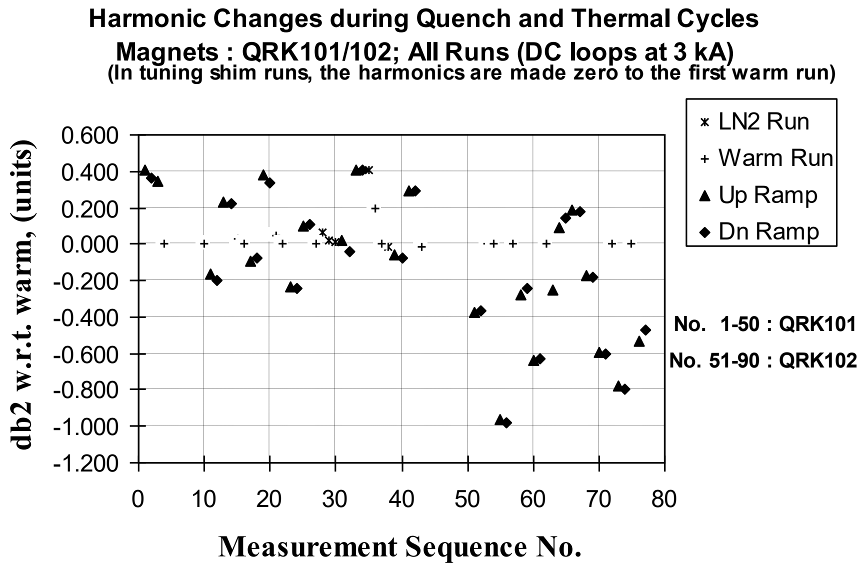


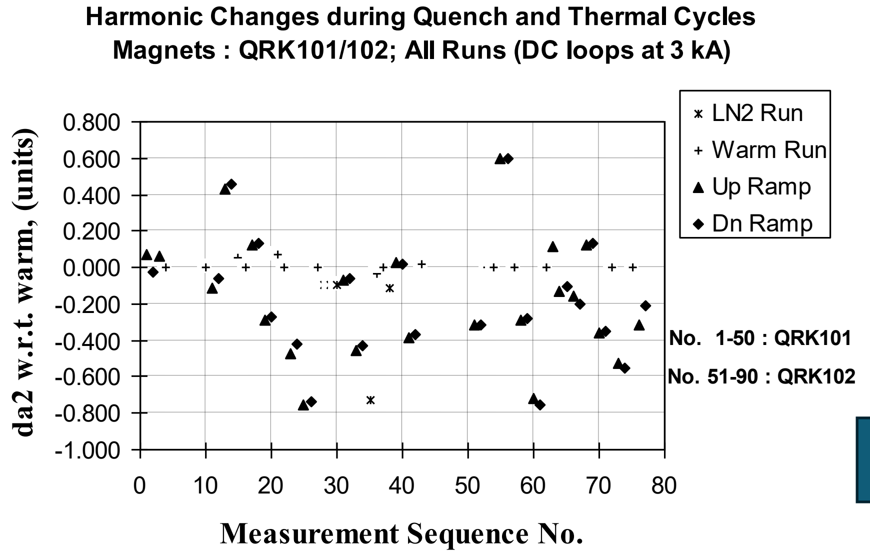


<u>**Key Observations**</u>:

- 8 harmonics made nearly zero.
- Harmonics are minimized at the maximum field.
- But the current dependence is small.
- Only 1/3 needed to be very good (golden), so we chose not to go crazy for all (sorting)

Ultimate Field Quality in Superconducting Magnets





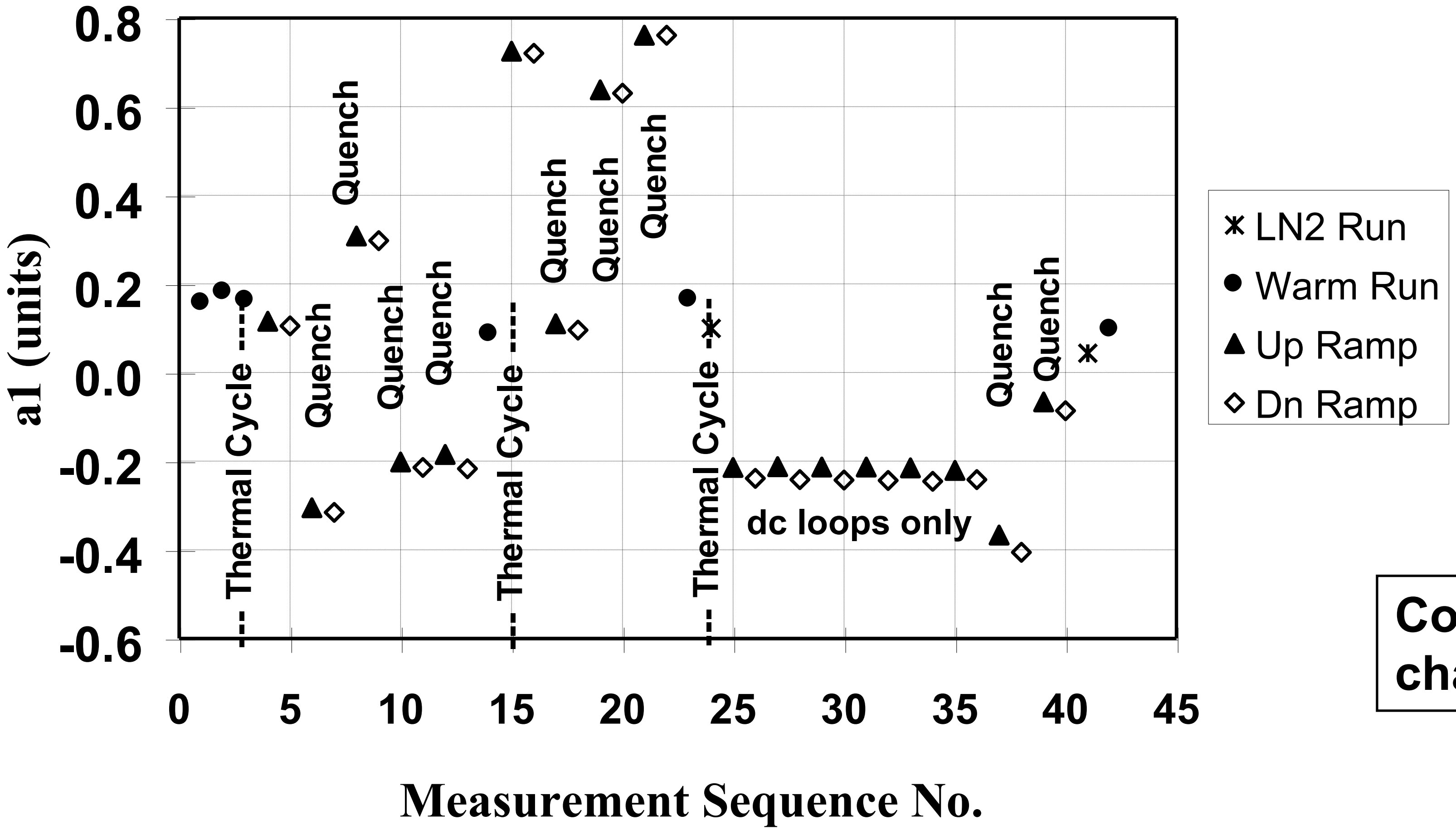
Note: n=2 is sextupole

- 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).
- We found changes in harmonics between two runs in RHIC insertion quadrupoles. An extensive experimental program initiated.
- It was found in other magnets also. These changes put an ultimate limit on field quality.
- Changes were smaller in collared magnets.

Corresponding dimension changes ~10 micron or less!

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

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



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

Corresponding dimension changes ~10 micron or less!

Not Discussed in Details: Cross-talk

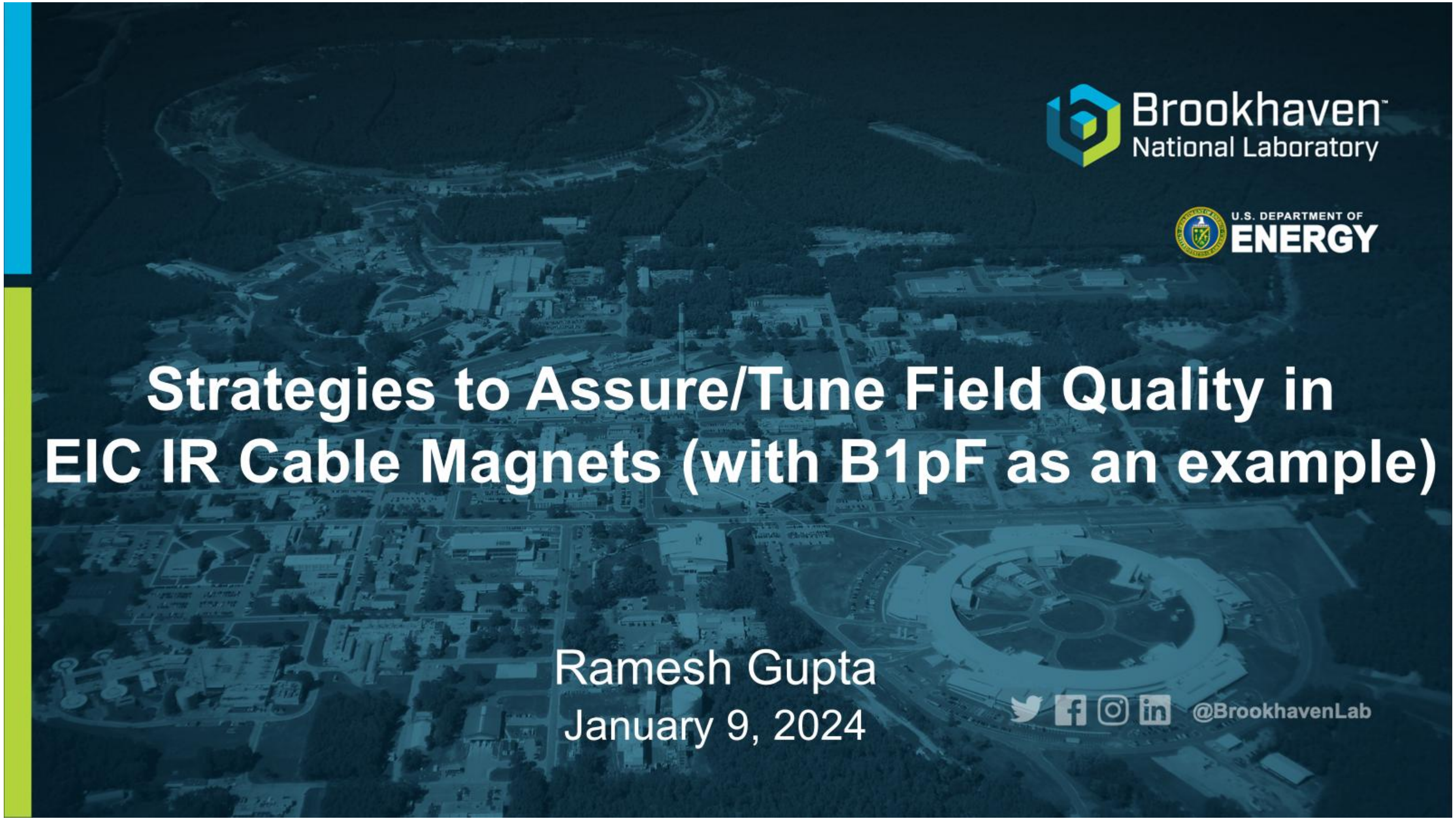
- We have not covered on what additional techniques be used (in addition to what is already being done) to control cross-talk harmonics.
- One can try thin high permeability material sheet over beam tube.
- One can also try small a high saturation filler in an area cut between the hadron beam and electron beam.
- Above two techniques have not yet experimentally examined.
- It is recommended that initial inexpensive test is performed in room temperature magnets.
- Superconducting shield has been tested and shown to work.
- Above listing is in the order of my personal preference.

Summary

- In discussing harmonic specifications and to bring realism, we should go by "real word" magnet experience, not just by paper design studies. GianLuca discussed this at length during his last presentation.
- Experience from previous magnet program is useful but can't be directly applied to EIC where we have one off magnet. On one side, there is no planned iteration (bad), but on the other side they can be hand crafted (good).
- One must go magnet by magnet and see what can be done before we discuss with larger audience.
- This was a major topic of discussion in EIC between accelerator psychists, magnet builder and management.
- We had ongoing discussion and kept track of how specifications were arrived, what could be done to make them better or what made them worse (two examples will be emailed).

Extra Slides

From a Previous Presentation

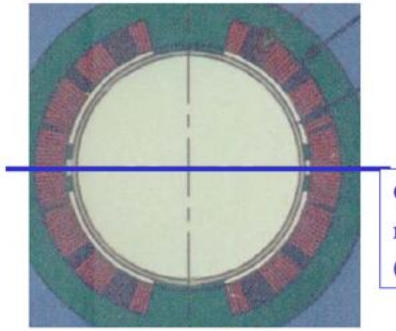


Adjustments in midplane gaps and pole shims to correct both allowed and non-allowed harmonics

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Change in Midplane Gap to Adjust Harmonics

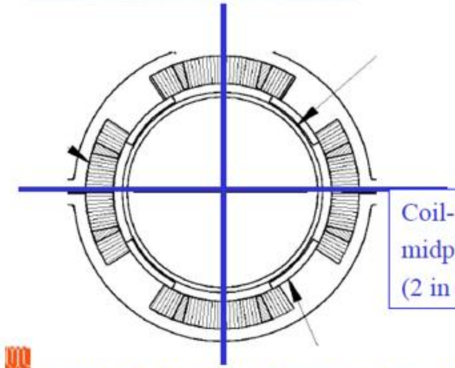
(can be easily done by changing the size of the ground-plane insulation cap)



Coil-to-coil midplane gap (1 in dipole)

Table 4.4.1: The computed and measured change in field harmonics at 25 mm reference radius due to a change in the coil midplane gap. The midplane gap was increased from 0.114 mm to 0.16 mm in the rebuilt 80 mm aperture RHIC model dipole magnet DRS009. In the production magnets, the midplane gap was changed back to 0.114 mm from 0.16 mm to adjust the b_4 harmonic.

	Δb_2	Δb_4	Δb_6	Δb_8
Computed	-3.0	-1.0	-0.28	-0.09
Measured	-3.0	-1.0	-0.29	-0.12



Coil-to-coil midplane gap (2 in quads)

Table 4.5.1: The measured and computed change in field harmonics caused by an asymmetric increase in the coil-to-midplane gap in the prototype 130 mm aperture RHIC interaction quadrupole QRI002. The gap was increased by 0.1 mm in the horizontal plane only. The harmonics are given at a reference radius of 40 mm.

	Δb_3	Δb_5	Δb_7	Δb_9
Computed	-6.8	-1.3	-0.45	-0.16
Measured	-6.5	-1.2	-0.30	-0.17

January 16-20, 2006, Superconducting Accelerator Magnets   Slide No. 17 of Lecture 4 (Coil Optimization)   Ramesh Gupta, BNL

- An example of correction in non-allowed harmonics
- Also, an example of correction implemented wrong (trust but verify)

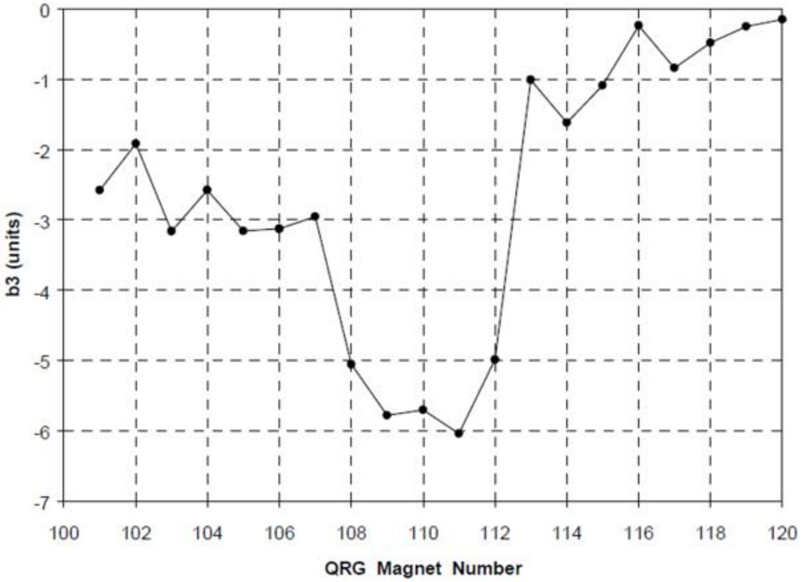


Figure 3: The measured octupole harmonic with the magnet number (first magnet named QRG101) in RHIC 80 mm aperture quadrupoles.

Brookhaven National Laboratory
Magnet Division   Ramesh Gupta   Strategies to Assure/Tune Field Quality in EIC IR Cable Magnets   January 9, 2024   8

Actual shape of coil in most collared magnets going through collaring & excitation is not what is modelled:

- ➢ Change in overall coil shape
- ➢ Change in internal turn spacing

This has impact on field harmonics

BASIC Problem

(a) Trying to assemble quad like dipole

or

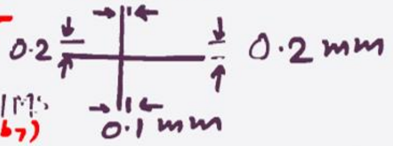
(b) Starting Yoke i.d. is circular (which becomes non-circular after assembly)

FIX

1. Start out-of-round yoke; so that when assembled, it is round

→ Too late for that (and too expensive to change)

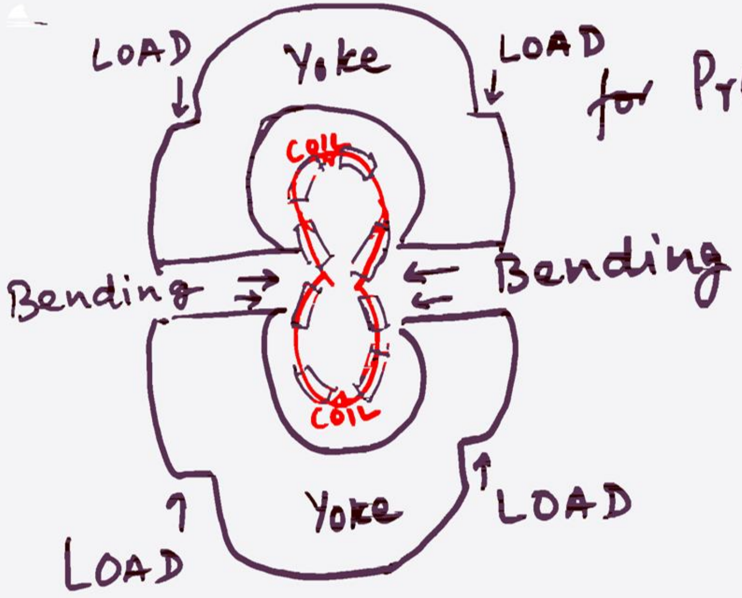
2. Create deliberate asymmetry in coil to compensate for that



→ Easy, Tested and Worked

AND/OR USE MAGNETIC TUNING SHIMS (b_3 & b_7)

Measured b_3 (octupole) ≠ 0)



for Pre-compression

Also seen in 80 mm Arc Quad (7 unit in both magnets)

Strategy to Assure Good Field Quality in the 1st Magnet (1)

- Let me put more meat on the magnetic measurements and how our initial thinking is on assuring field quality. We recognize that it is not a standard practice to assure accelerator grade field quality in the first magnet without building one or more prototype(s).

- However, we have done this sort of things before, and our present strategy is the extension of those strategies. They have been mostly published earlier.

- Please see the details of this thinking in the subsequent slides.

Strategy to Assure Good Field Quality in the 1st Magnet (2)

- The target is not only fixing field quality but pre-stress in the coil. For example, in RHIC IR quadrupole we had superconductor from two vendors, and both provided them with the geometric tolerances. However, they were almost at the two ends of the tolerances and therefore we had to accept it. The total difference accumulated over all turns was over 200 microns, which means if we maintain the field quality, we will lose the pre-stress or we make the pre-stress we lose the field quality.
- Since it was known we accommodated by simply changing the wedge thickness. There was only one wedge, but it was at the right place.
- The problem was even bigger in DX dipole magnet which had many more turns. We accommodated by adding extra turn. We know the technique, but we need to evaluate the present designs and need to demonstrate that such large non-conformance can be accommodated without a wholesale redesign which was the case in early SSC and RHIC R&D magnets.

Strategy to Assure Good Field Quality in the 1st Magnet (3)

- Once the above 0th order fix is in place before winding the coil, the design is developed to accommodate three more adjustments. First adjustment will be made after the warm measurements. B1pF already has a thin yoke which provides sufficient yoke for warm measurements. B1ApF is likely to have a small ring around it which may or may not be present during the cold measurements in vertical dewar.
- The correction strategy will depend on the measured values of harmonics. Let's take B1pF as example as this is more developed. If the non-zero harmonics can be adjusted (both allowed and non-allowed) by adjusting iron tuning shims on the inner radius of the iron, it will be done with that only. If that is not sufficient, we will uncollar the magnet and adjust pole and midplane shims.

Strategy to Assure Good Field Quality in the 1st Magnet (4)

- These two shims are not independent parameters, and we have to mindful of the change in pre-stress. On the other side of the coin, this adjustment can be used to get right pre-stress on the coil as well, if needed.
- Please note that these pole and midplane shims can be used to correct non-allowed harmonics also. We have used this to move non-allowed harmonics in RHIC arc quadrupoles. We will readjust the iron tuning shims, if needed, after the second warm measurements to verify the change. No coil midplane and pole shims will be adjusted.

Strategy to Assure Good Field Quality in the 1st Magnet (5)

- The tuning shims mentioned above are very powerful technique and we have demonstrated that to deliver harmonics to deliver first eight harmonics (both allowed and non-allowed) to 10^-5 level, corresponding to the geometric errors of about 10 microns.

- Then the magnet will be tested in vertical dewar. At low current, we will get warm-cold correlation and use that to further correct tuning shims at the yoke id if needed.

Strategy to Assure Good Field Quality in the 1st Magnet (6)

- Then the magnet will be measured in the horizontal stand with full iron. This will not change the harmonics at a low current. However, they will first time provide the measurements at high current.
- If the harmonic changes (created either by iron saturation or the deformation in coil geometry due to Lorentz forces) are beyond the acceptable amount, we will change the iron shim in the rectangular slot.
- No magnetic measurements are planned, and we are planning to rely on calculations only. The error in this adjustment is likely to be much smaller than the specified tolerances.