Q2pF Electromagnetic Design

Ramesh Gupta

Magnet Steering Group Meeting

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Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

Overview

- Q2pF is one of the most challenging cable magnet in EIC. This is the largest aperture quadrupole with a high gradient. B1pF and B1ApF dipoles have larger aperture, but they have a lower design field.
- Since this magnet has been under consideration for Fermilab to build, the design work has been limited lately. Electromagnetic (EM), kept getting updated, since that requires a relatively smaller effort.
- A significant work on the EM design has already been carried out. It is well documented with 37 presentations to benefit from, if desired.

  https://wpw.bnl.gov/rgupta/eic-q2pf-em/

- Development of the Q2pF design benefited from the SSC and RHIC magnet experience, which are incorporated in other magnets as well.

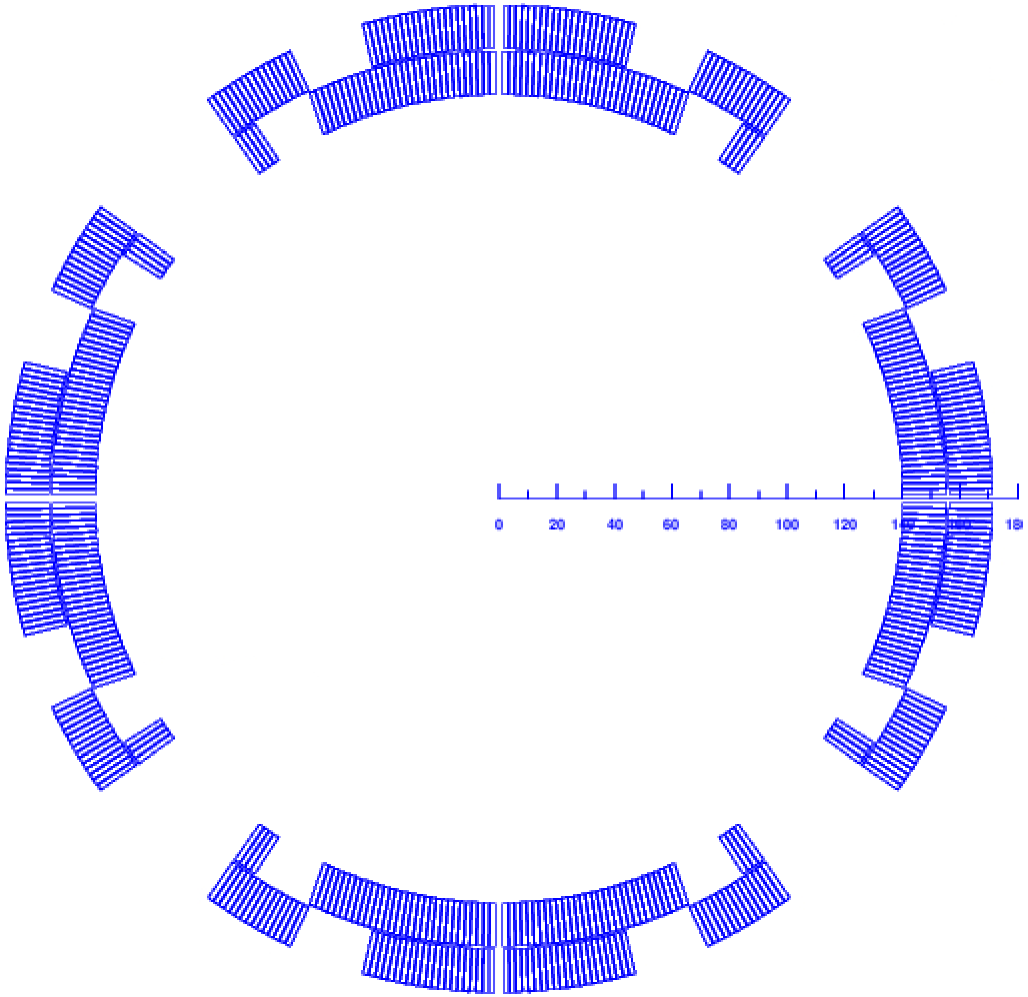
Q2pF Magnet Design Parameters

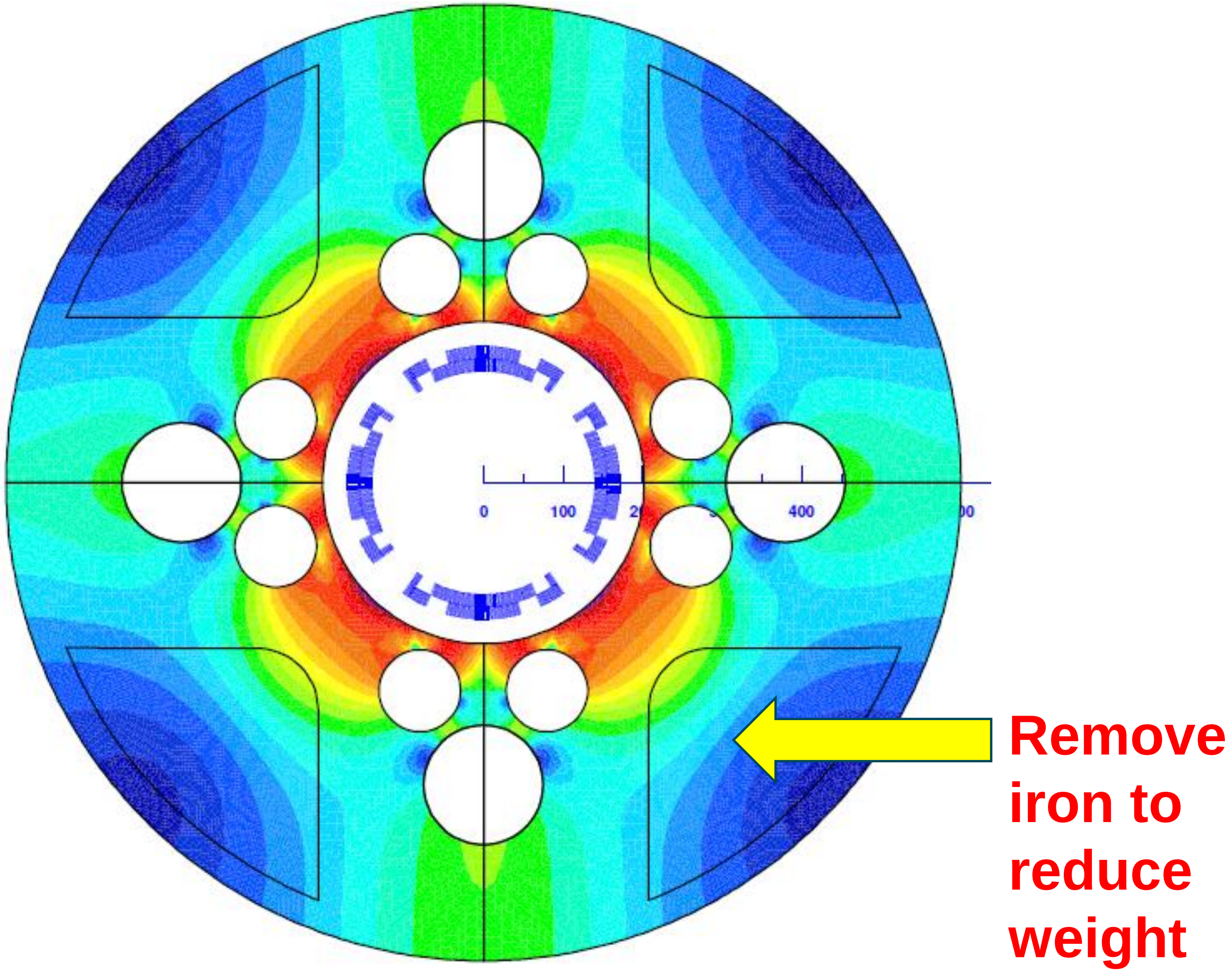
Date	3/28/2025	
Magnet Name	Q2pF	
Magnet type	Quadrupole	
Coil inner diameter	**280**	**mm**
Coil outer diameter	342.8	mm
Number of layers	Two	
Integrated gradient @design	**133.55**	**T**
Design gradient (@center)	**38.22**	**T/m**
Operating current @ design	**8536**	**A**
Magnetic length	3.494	meter
Coil length (last turn to last turn)	3.64	meter
Yoke length	3.72	meter
Total number of turns per coil	69	per octant
Number of turns in inner layer	35	per octant
Number of turns in outer layer	34	per octant
Cable required (whole magnet)	~2	km

Coil temperature (for calculation)	2	K
Stored energy @design gradient	2.7	MJ
Inductance	75	mH
Quench current	14440	A
Gradient @Quench	60.5	T/m
Peak field @design	**6.4**	**T**
Peak field @quench	10.2	T
Loadline Margin	**38**	**%**
Temperature Margin	**3.4**	**K**

Superconductor	NbTi	
Cu/Sc Ratio (nominal)	1.6	
Strand diameter (mm)	1.065	
Number of strands in cable	28	
Cable width, bare (mm)	15.1	mm
Cable mid-thickness, bare (mm)	1.9	mm
Cable insulation radial	0.15	mm
Cable insulation azimuthal	0.965	mm
Cable width, insulated	15.4	mm
Cable mid-thickness, insulated	2.14	mm

Overall Cross-section (coil and yoke)

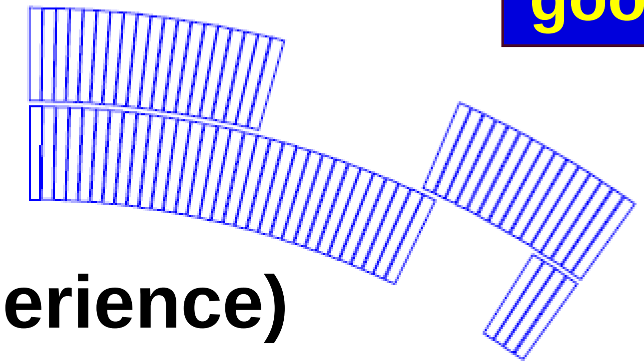


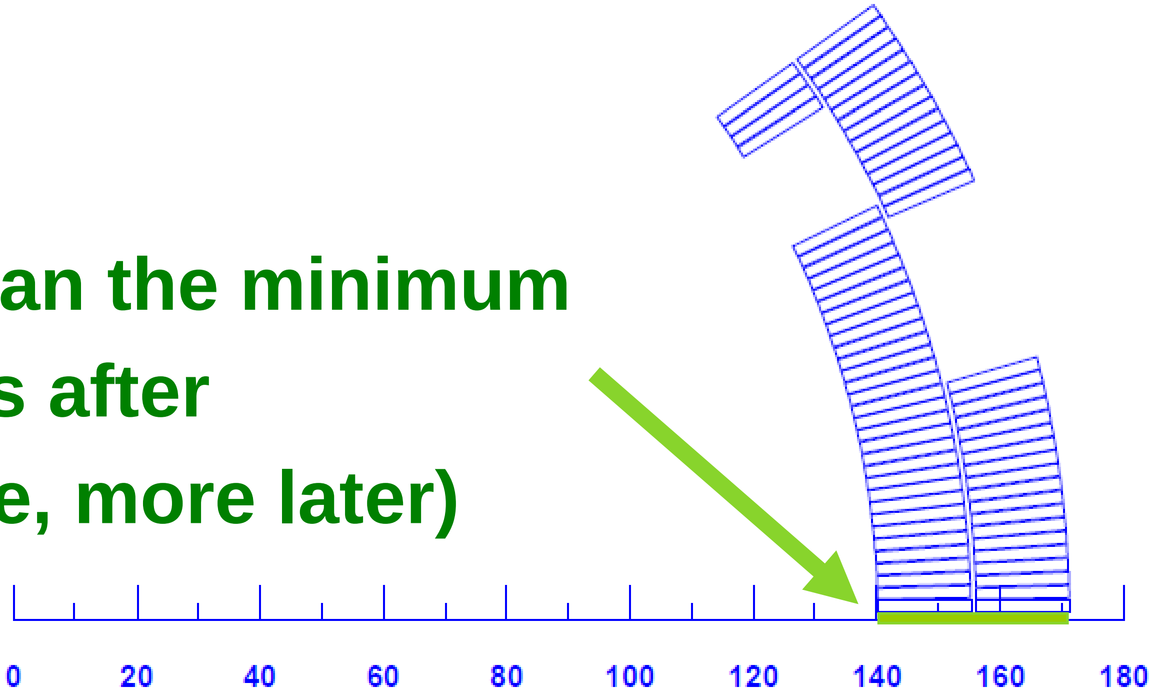


Coil Cross-section

Visually looks good mechanically

- **Uses EIC Quad cable**
- **Two layers, 69 turns (35+34)**
- **Symmetric wedges (RHIC/SSC experience)**
- **Poles of outer and inner layers aligned**
- **Peak field optimized**
- **Field quality optimized**
- **Midplane gap made much larger than the minimum required for tunability of harmonics after construction (RHIC/SSC experience, more later)**





Computed Harmonics (from ROXIE)

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	-0.00000	b 2:	10000.00000	b 3:	-0.00000
b 4:	0.01392	b 5:	-0.00000	b 6:	0.15609
b 7:	0.00000	b 8:	0.00209	b 9:	0.00000
b10:	-0.00012	b11:	-0.00000	b12:	0.00003
b13:	0.00000	b14:	-0.57806	b15:	0.00000
b16:	0.00000	b17:	-0.00000	b18:	0.01598

All harmonics <1 unit (spec: 2 units)

Reference radius: 83 mm

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	-0.05666	b 2:	10000.00000	b 3:	-0.00299
b 4:	0.00103	b 5:	-0.00052	b 6:	-0.00162
b 7:	0.00000	b 8:	-0.00001	b 9:	-0.00000
b10:	0.00001	b11:	0.00000	b12:	-0.00000
b13:	-0.00000	b14:	-0.00034	b15:	0.00000
b16:	0.00000	b17:	0.00000	b18:	0.00000

Reference radius: 45 mm

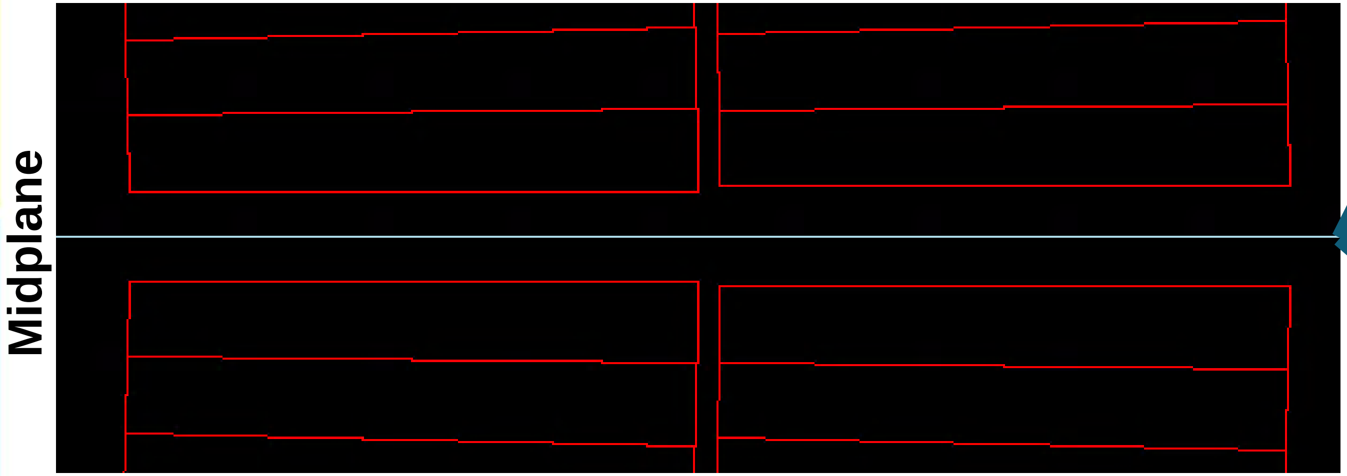
All harmonics <0.1 unit (impact of ref. radius, larger on higher order)

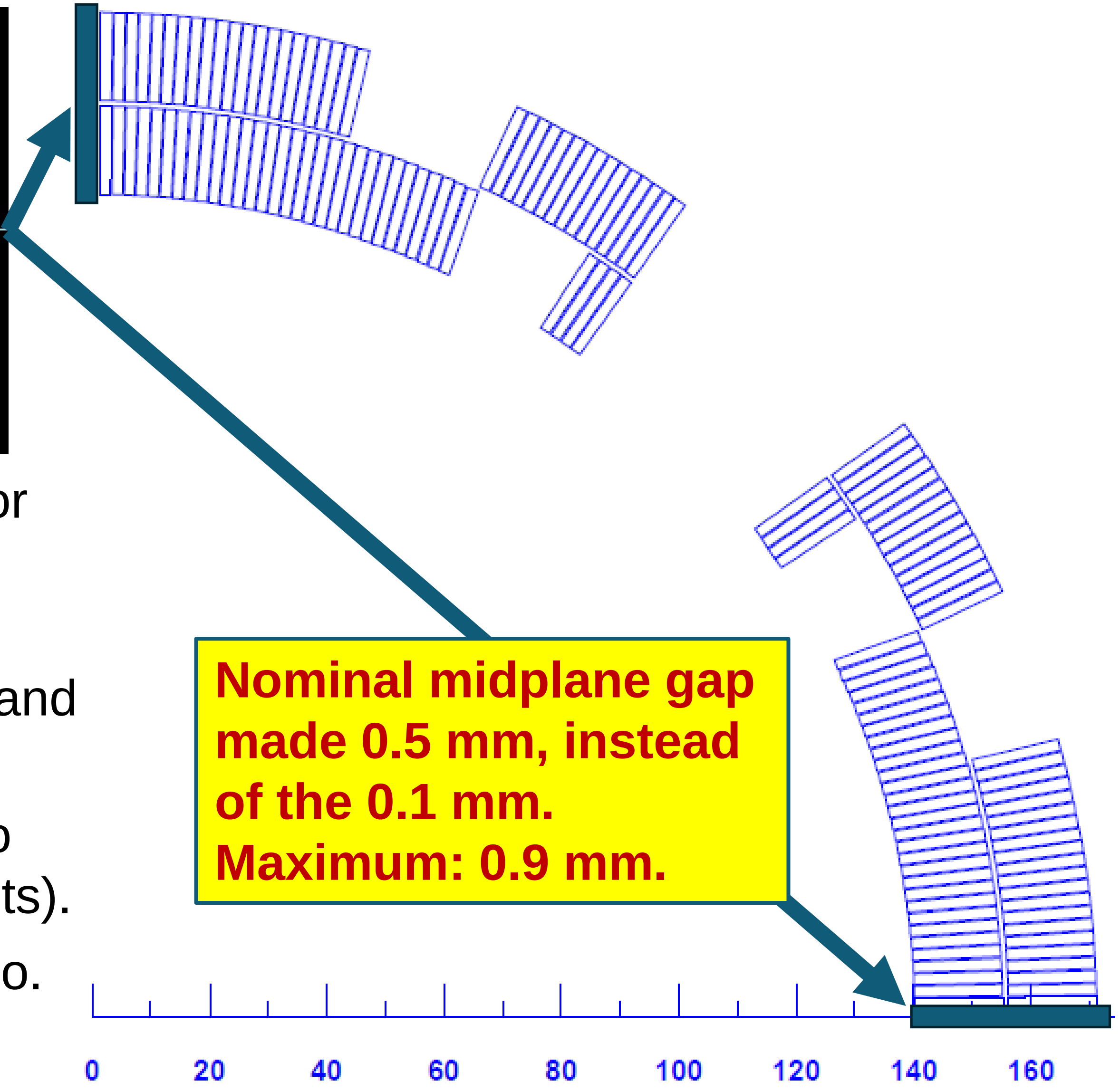
Harmonics in the first magnet depends on the error in parts, real construction and other deviations from the paper design

Field Quality Consideration Specific to EIC IR Magnets
(which are different from magnets for other accelerators)

- **Good news:** Larger aperture (Q2pF 280 mm Vs. SSC 40/50 mm and RHIC 80 mm dipole/quad) means that same error in parts will have smaller impact on harmonics.
- **Now challenges:** Small differences in cable thickness (even if they are in spec) has a major impact. The impact is larger in larger aperture magnets.
- EM code assume ideal and same cable thickness (turn-to-turn spacing) going from midplane to pole in a circular aperture. This is not true in a real magnets.
- Magnet tooling may produce a coil geometry different from what was assumed in the design which may have impact on field quality.
- To assure success, we need to plan ahead as going back to fix is time consuming.
- Make design flexible by augmenting the techniques developed during SSC and RHIC programs. A significant part of this presentation is to assure a good field quality despite anticipated and unanticipated deviations from the paper design.

Flexible Coil Design from the Start (midplane gap)



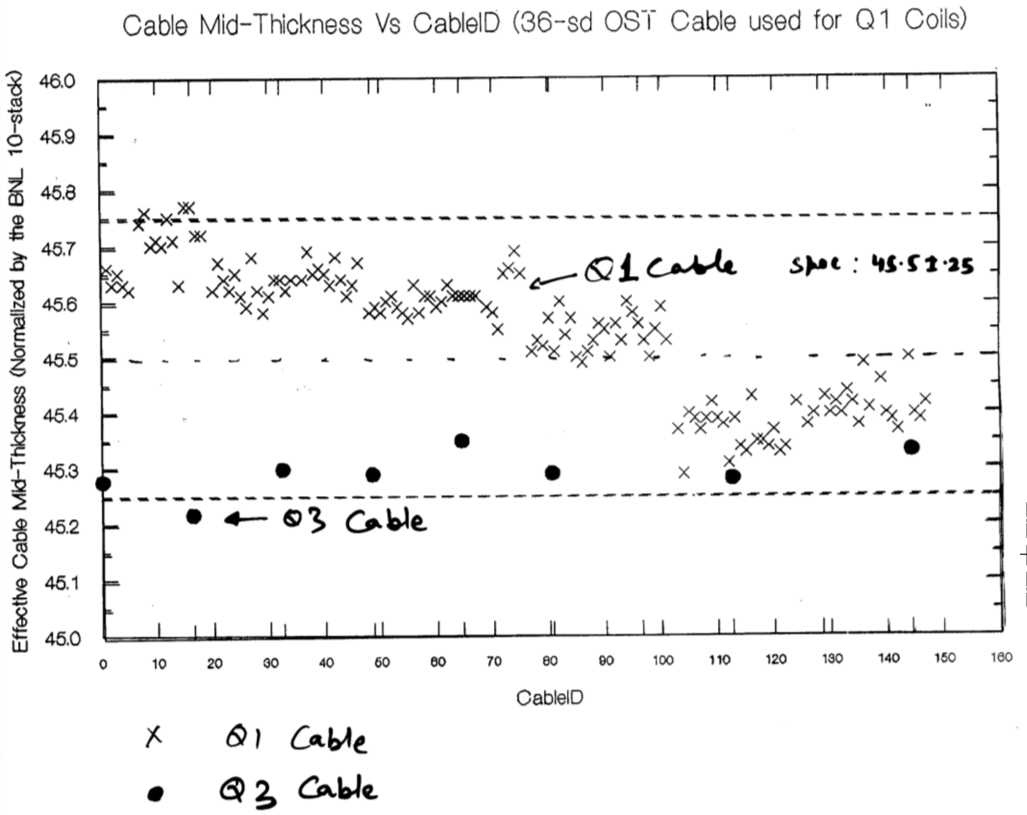


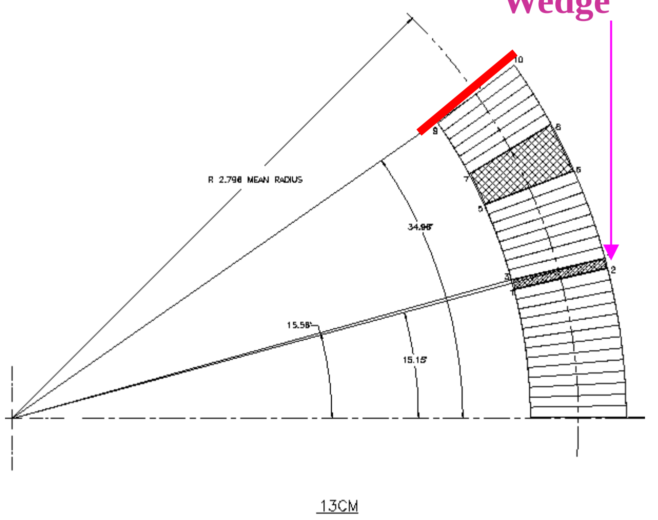
- This simple tool offers +/- 7.2 units adjustment in b_6 for <0.1 units change in b_{10}, while using the same coils.
- A powerful tool (along with the pole shims), used extensively in RHIC magnets, both in small in-house and in large industrial production at Northrop Gruman.
- Difference between horizonal and vertical midplane to adjust non-allowed b_4 (used in RHIC quads for ~7 units).
- Can use this tool for other non-allowed harmonics also.
- These tools were also be used for accommodating deviation in cable sizes and for adjusting the pre-stress.

Example of Accommodating Cable of Non-ideal Thickness (RHIC IR Quad)

Two vendors gave cable which differ systematically, but within specs
(+/- 0.25 mil or 6.5 micron)

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





Coil Cross section
of the 130 mm aperture
RHIC insertion quadrupole

A flexible design accommodated this and produced good field quality

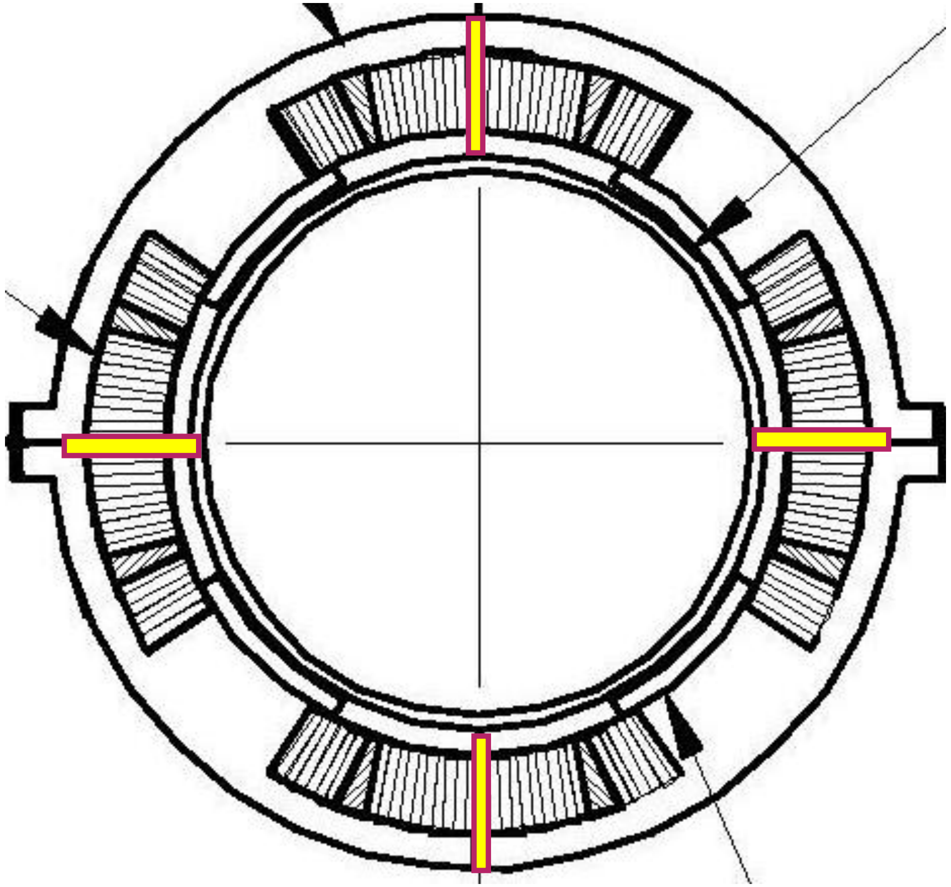
- ⊗ No change in pole angle
- ⊗ No change in coil curing press
- ⊗ No change in collar/spacer
- ⊗ No change in harmonic (b_6)

In RHIC DX dipole, we had to add extra turn. Be prepared for such situations in EIC also !!!

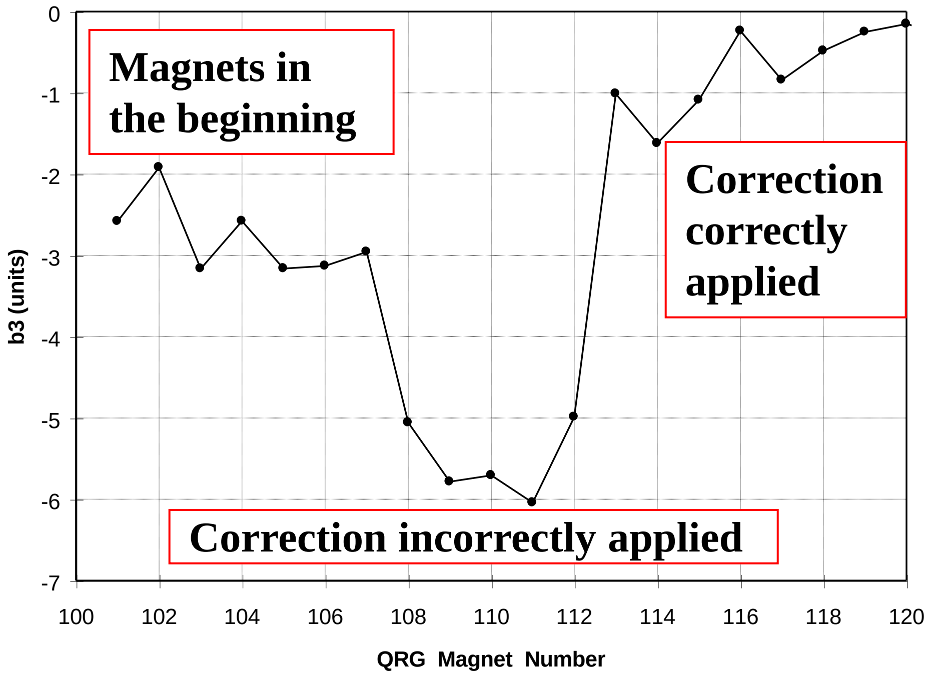
Example of adjusting a Non-Allowed Harmonic
(during the production of RHIC 80 mm Arc Quad)

RHIC quadrupoles are assembled like dipoles. They had a large octupole (b_4 ~ +7 units)

Another deliberate asymmetry to cancel this term
<u>Difference</u> between the horizontal and vertical coil to midplane gap



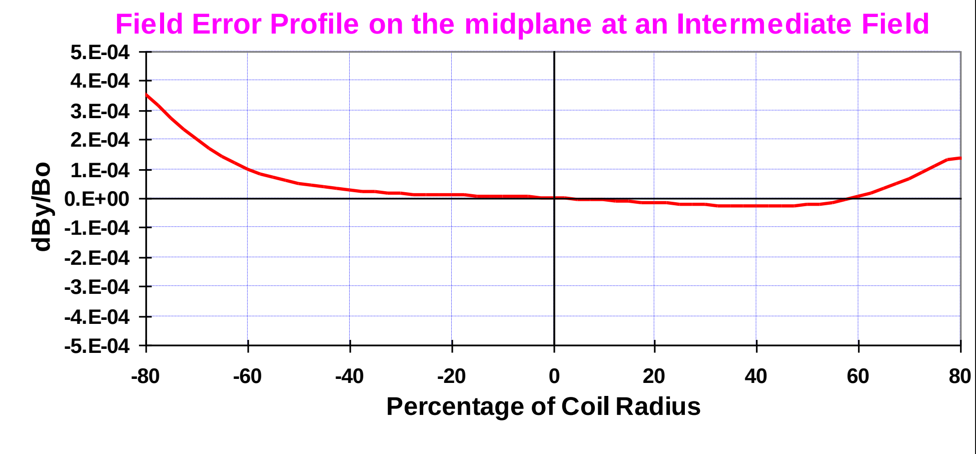
Got overcompensated in the beginning



Bottom line. Were we able to make the 1st magnet, a field quality magnet?

Yes. And we are using these proven strategies in EIC IR magnets, as well!

RHIC 100 mm Aperture Insertion Dipole DRZ101:
>The first magnet itself gets the body harmonics right !!!



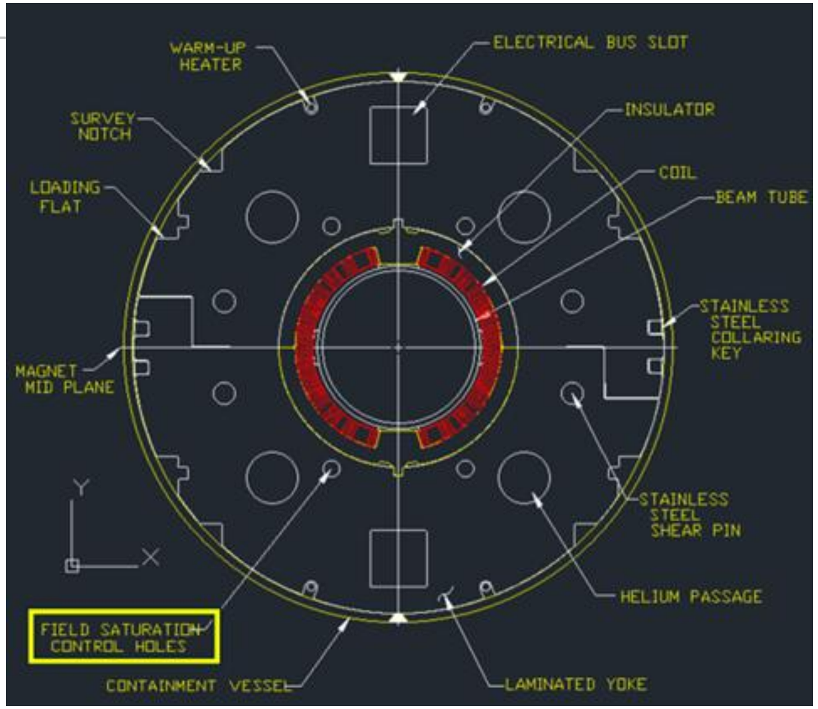
Field errors within 10^{-4} at 60% of coil radius, and ~4* 10^{-4} at 80% in the first magnet itself

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



Later magnets had adjustments for integral field and saturation control. The coil cross-section never changed.

Harmonic Corrections after Measurements

- First adjustment should be made with the coil shims at midplane and poles, as mentioned in previous slides.
- Tuning shims (next), as developed for RHIC IR quads, can be used for the next level of harmonic correction.

➢ *These corrections may be considered as value engineering (in terms of schedule and cost, in addition to producing high field quality magnets) as they allow accepting out of tolerance parts, and correct resultant errors irrespective of the source (design, construction, or just lack of understanding).*

[Tuning Shims to Achieve Good Field Quality in Q2pF and Other EIC Magnets, July 18, 2023](https://wpw.bnl.gov/rgupta/wp-content/uploads/sites/9/2023/07/EIC-gupta-tuning-shims-07-18-2023.pdf)

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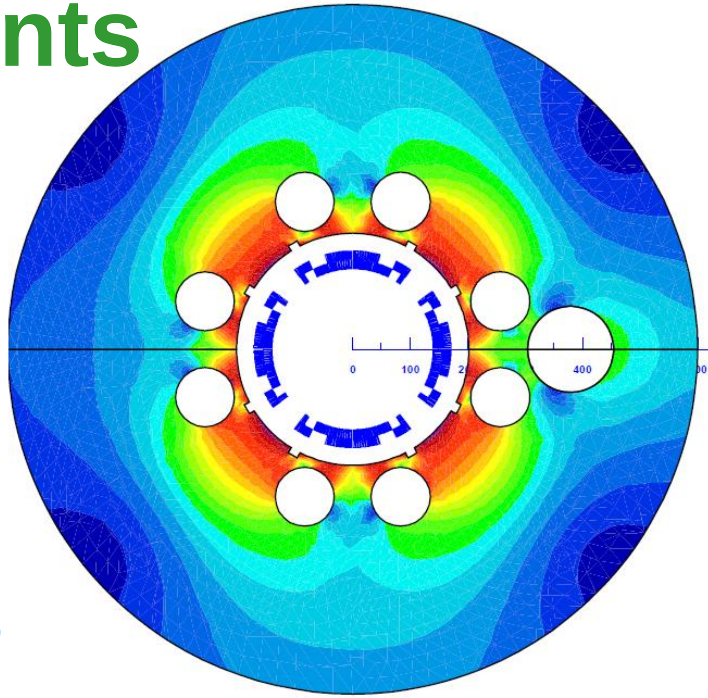
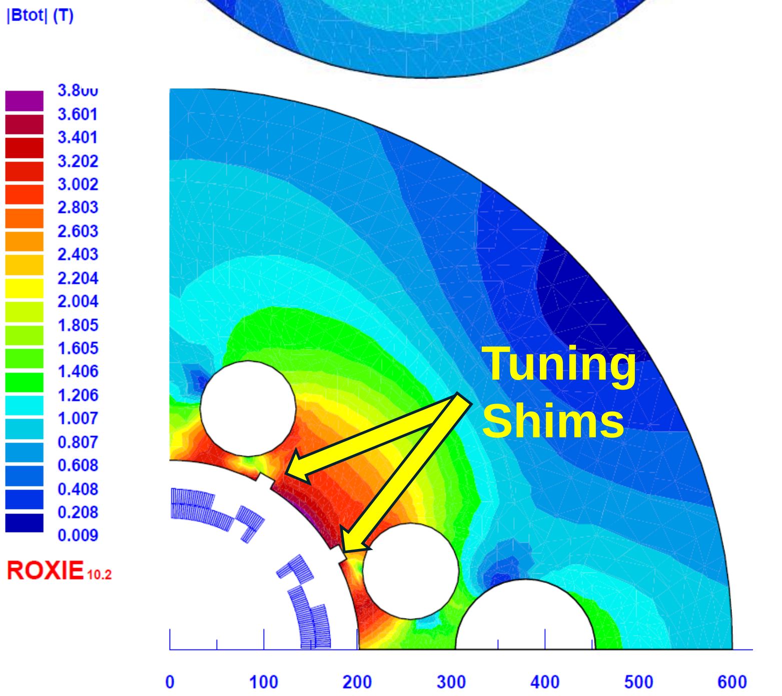




Tuning Shim Based Harmonic Correction in RHIC IR Quad

Basic Principle of Tuning Shims:

- Addition of magnetized iron shims inside yoke modify the magnet harmonics.
- Eight harmonics can be corrected by adjusting the amount of iron(magnetic)/brass (non-magnetic) content in eight "Tuning Shims", if placed in at appropriate locations.

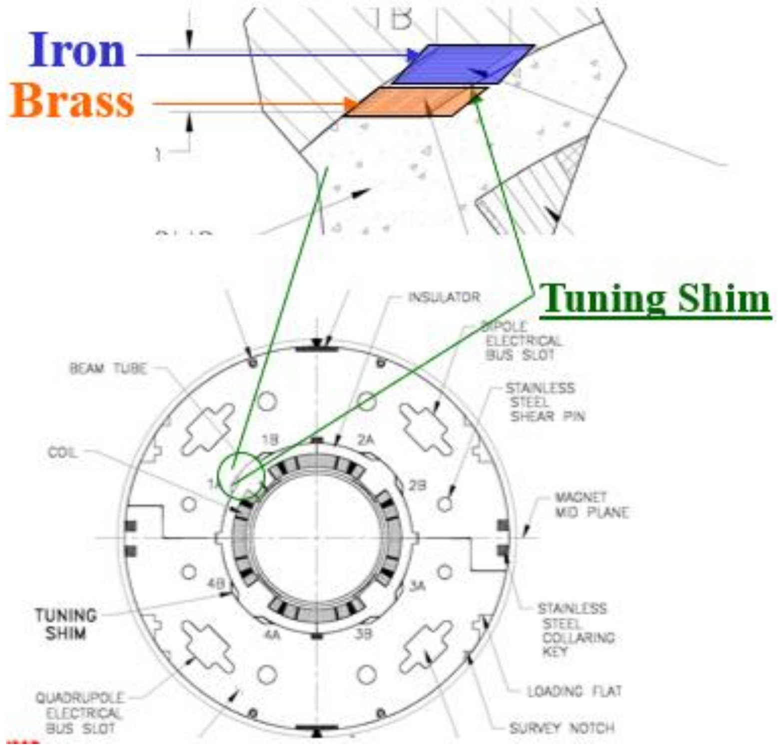
Procedure used in RHIC IR for implement tuning shims:

1. Measure field harmonics with nominal shims.

2. Compute the Iron/Brass content for each of eight tuning shim to compensate up to eight measured harmonics.

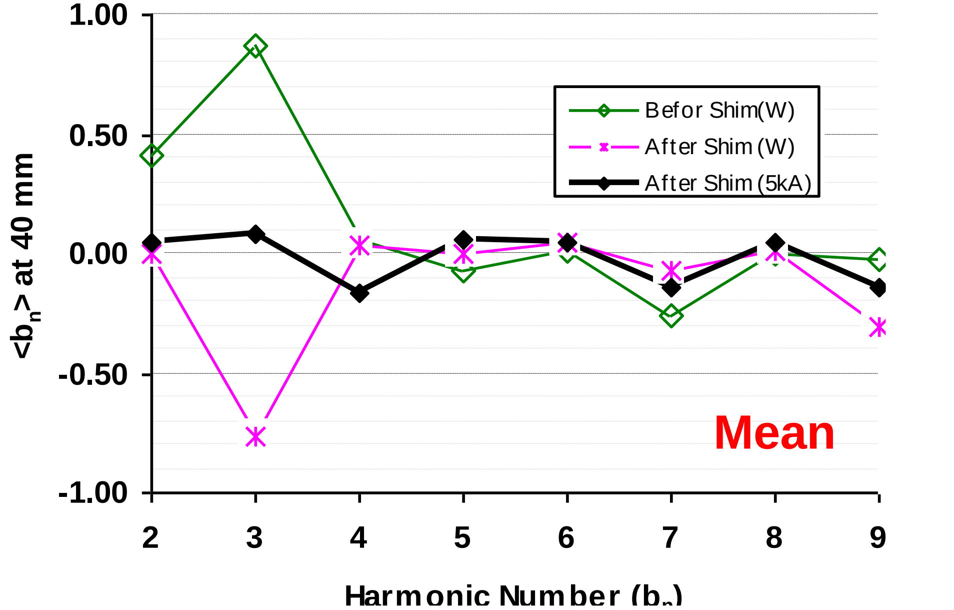
3. Insert optimized tuning shims without opening the magnet.

4. Measure harmonics to validate the corrections.

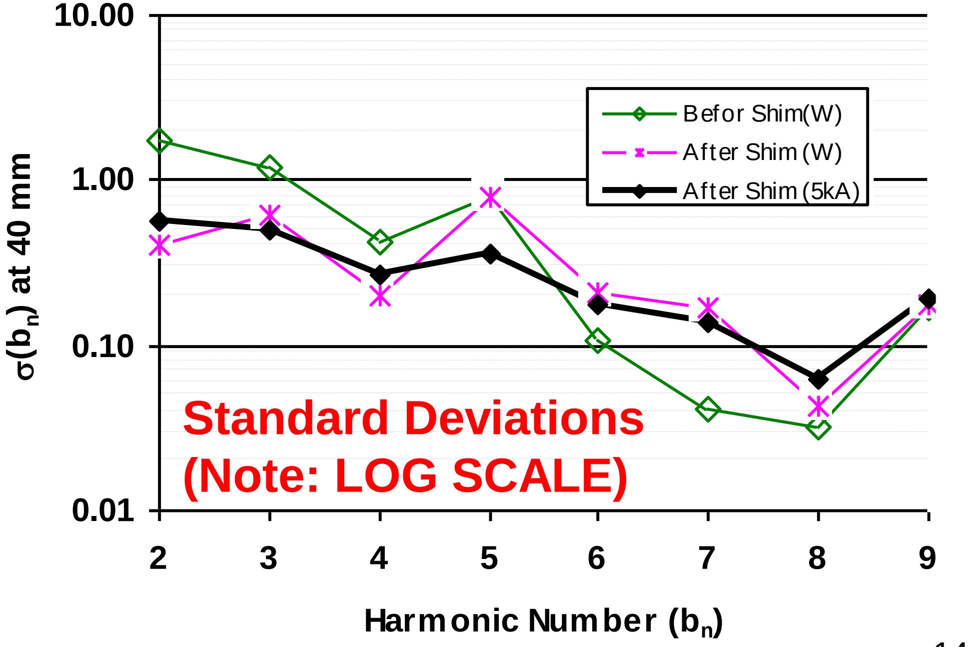


Field Quality with Tuning Shims (a few parts in 10^{-5} at ~2/3 coil radius)

- Tuning shims made RHIC IR quads, very high field quality magnets (a few parts in 10^{-5}, see plots).
- Nothing like this has ever been achieved in accelerator magnets – either in a series production of magnets or in an individual magnet.
- The ultimate field quality in a magnet will be what it can maintain during the machine operation.
- Next slide shoes that we did achieve the ultimate!



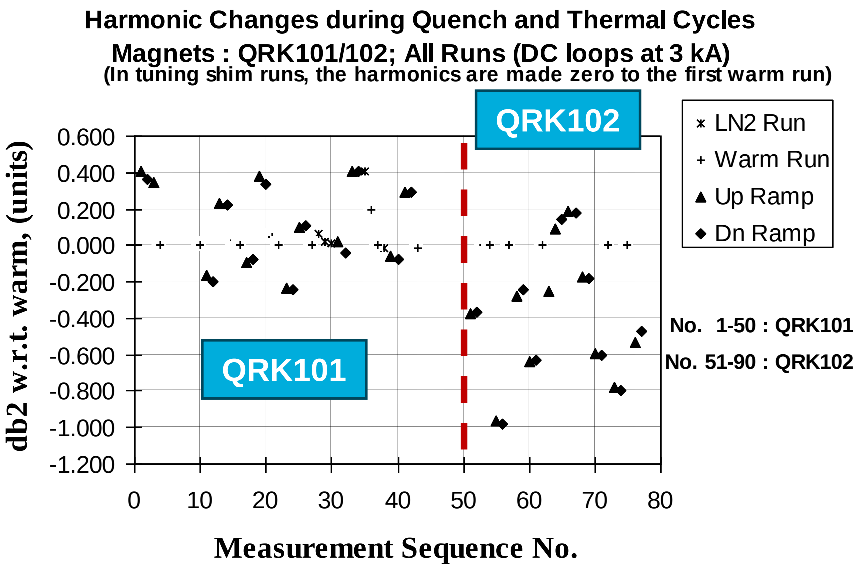
	$<b_n>$ (n=2 is sextupole)			$\sigma(b_n)$		
n	Befor Shim(W)	After Shim (W)	After Shim (5kA)	Befor Shim(W)	After Shim (W)	After Shim (5kA)
2	0.41	0.01	0.05	1.74	0.41	0.56
3	0.87	-0.76	0.08	1.19	0.60	0.49
4	0.06	0.03	-0.17	0.42	0.20	0.27
5	-0.07	0.00	0.05	0.78	0.78	0.36
6	0.01	0.05	0.05	0.11	0.21	0.18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

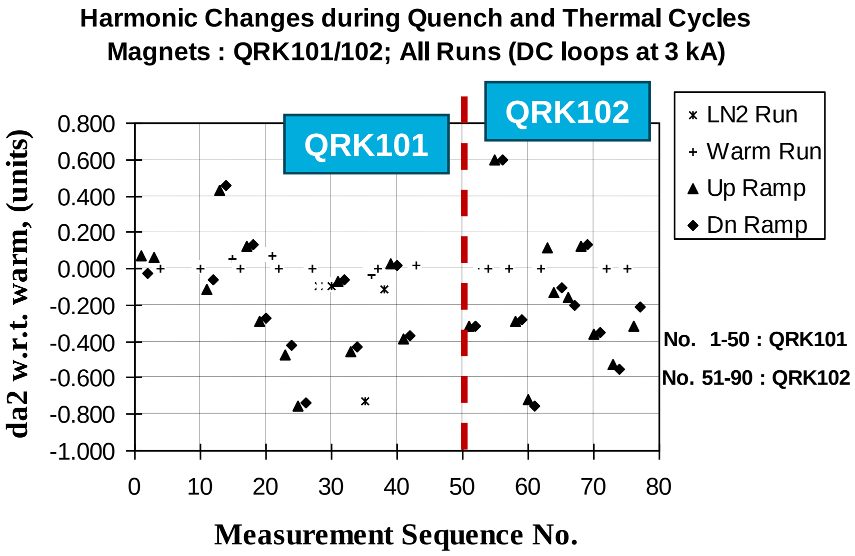


Ultimate Field Quality in SC Magnets (did we achieve that?)

- We observed that field harmonics changed after quench or thermal cycle by a few parts in 10^{-5} (typically people don't notice such small changes – see extra slide for other magnets).
- The theory is that when magnets go through a shock (quench or thermal cycle, but not smooth powering), individual 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 produce 10^{-5} change in harmonics (see extra slide for mechanical signature in pre-stress).
- These micro changes put an ultimate limit on the field quality. We achieved that in RHIC IR quads since the final harmonics were within that limit.

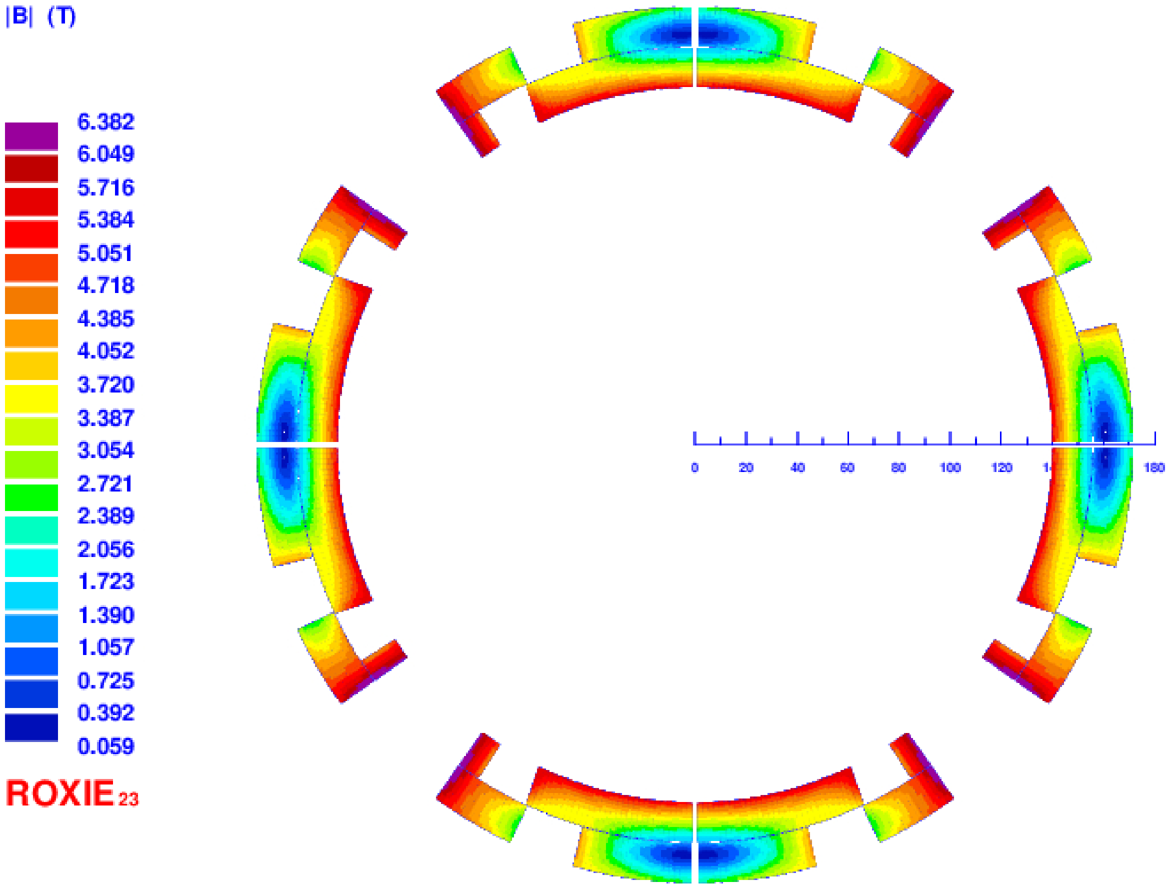
Note: n=2 is sextupole

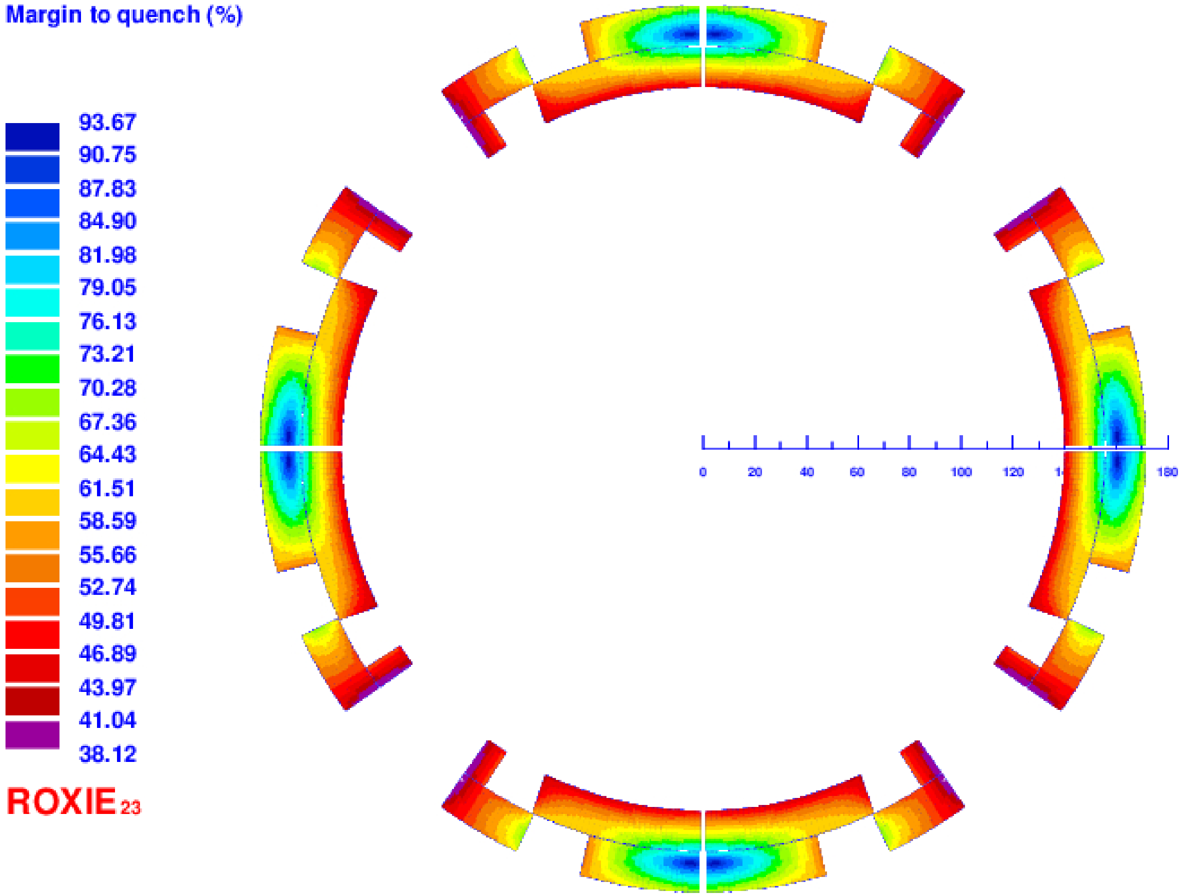




Optimized Q2pF Coil Design

Peak Field and Operating Margin

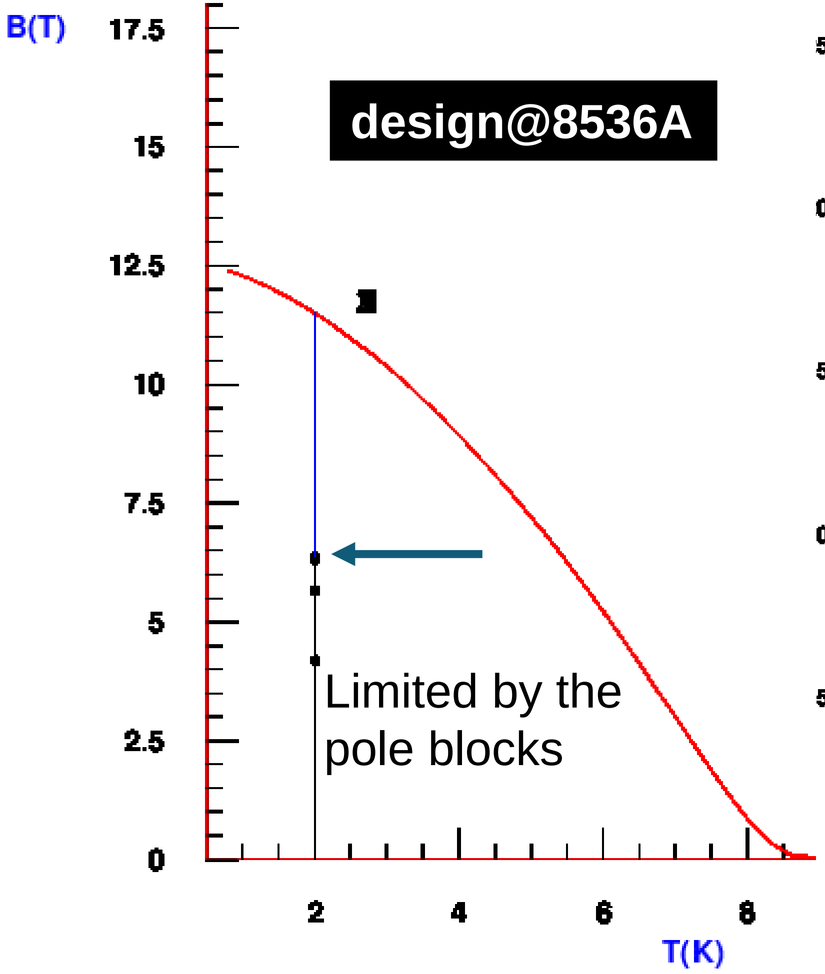


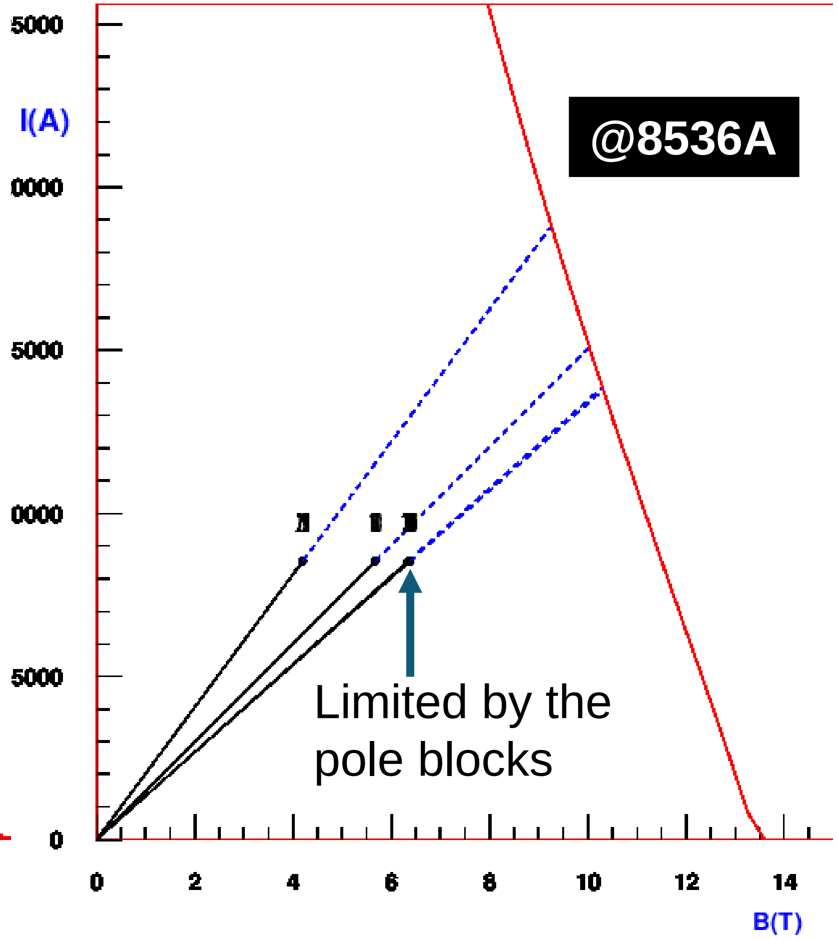


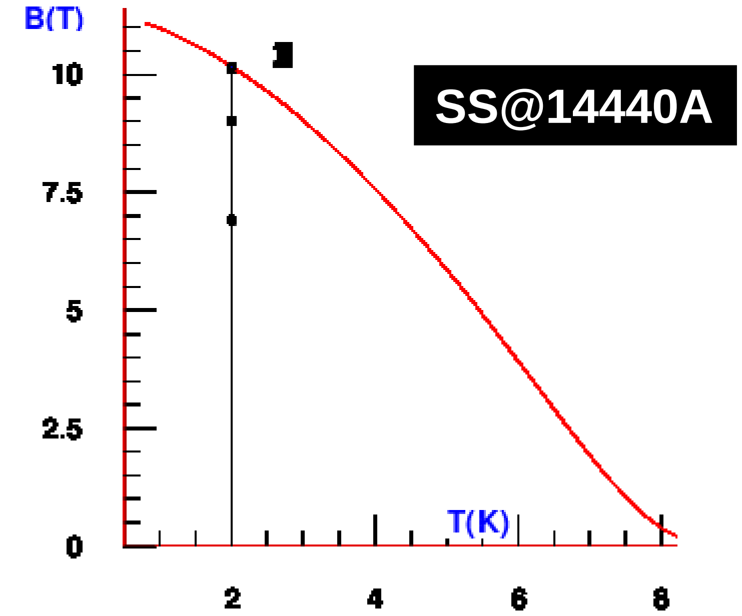
Design optimized to reduce peak field enhancement (max field on the cable over the field at midplane) to ~18%

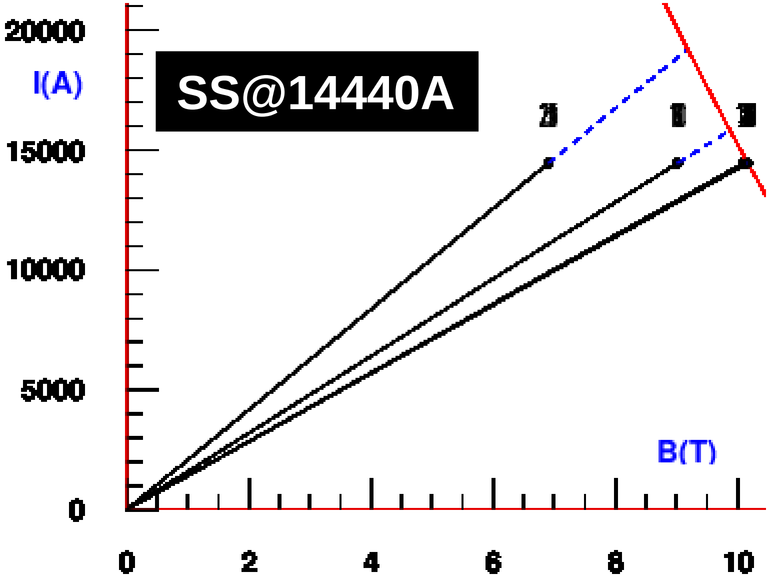
Margin on Load-line: 38%
Conventional definition
(short sample over design): 56%

Field and Temperature Margins in the Body of the Magnet
(in individual blocks)









Temperature margin: 3.4 K

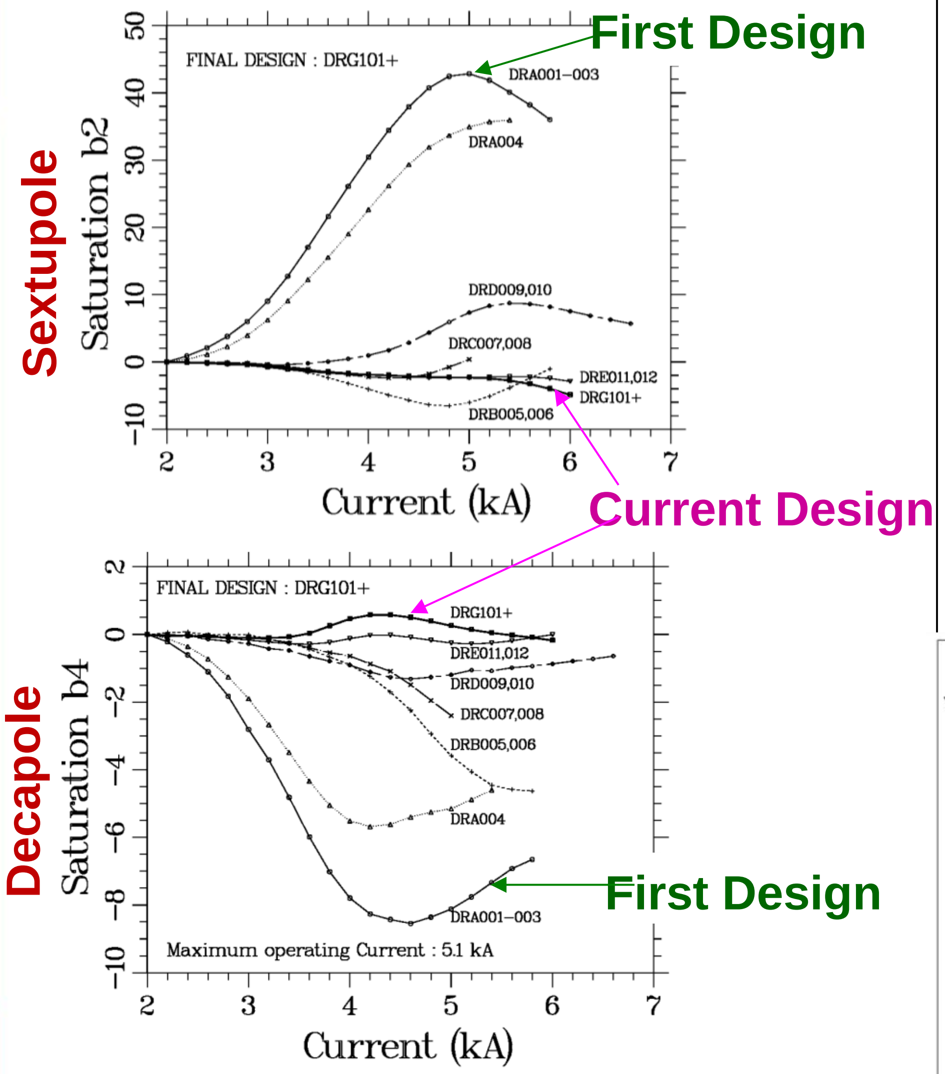
Load line margin: 38%

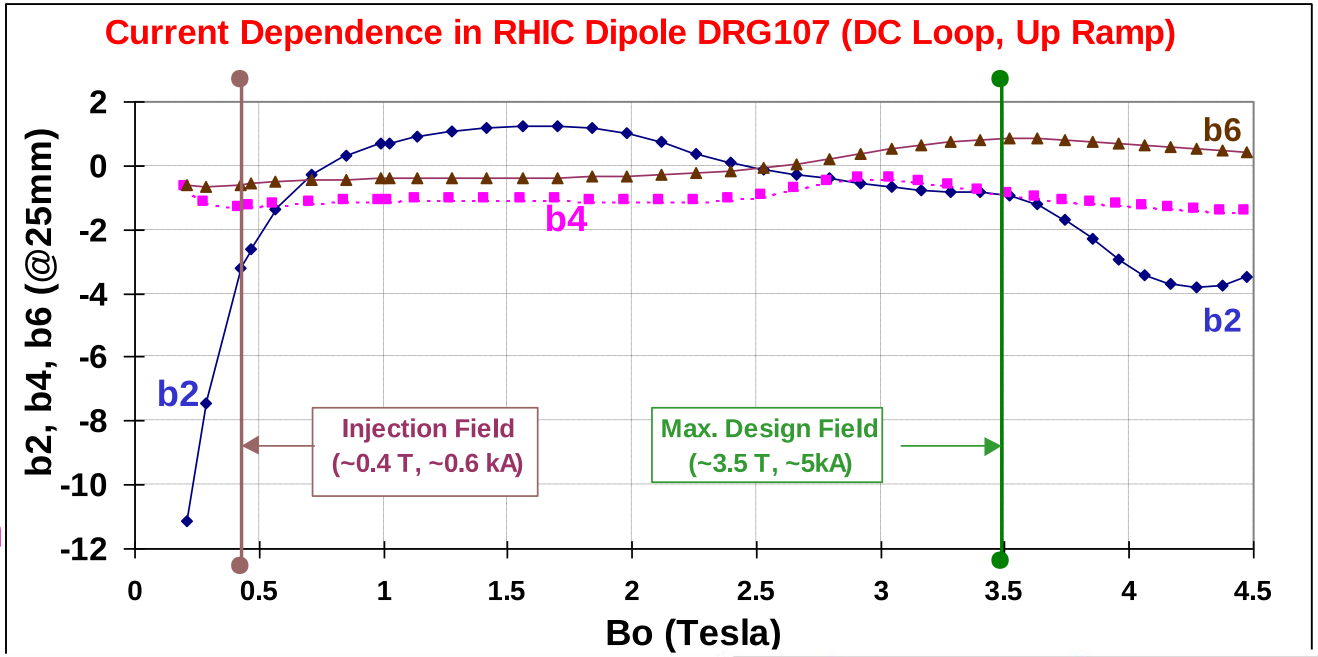
Yoke Optimization for EIC Magnets

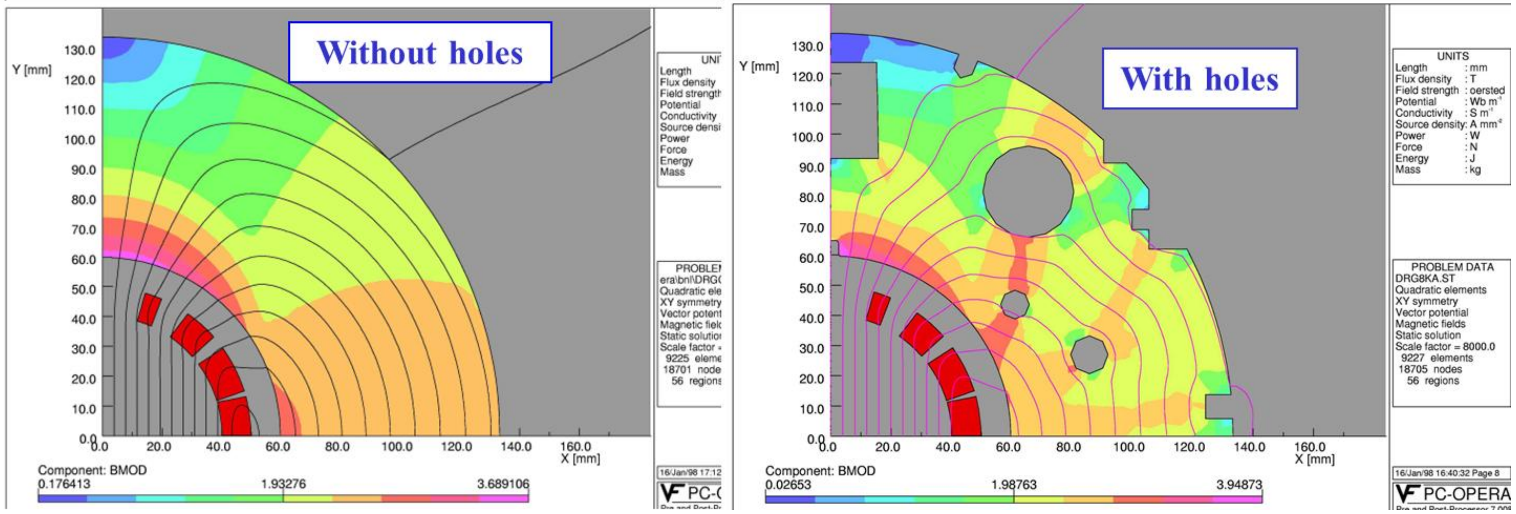
- Yoke must be optimized to make sure that the field harmonics due to iron saturation (and Lorentz forces on coils) remain within specifications through-out the range of operation. Persistent current harmonics primarily depend on the cable.
- Field in the hole (where electron beam traverses), must stay within acceptable limit. This is not a consideration in the most accelerators/colliders but is critical for EIC.
- We took advantage of our experience with SSC and RHIC magnets in the yoke optimization of Q2pF and EIC magnets.

RHIC Experience (order of magnitude improvement)

- **Good field quality beyond RHIC design helps in higher field operation in EIC**

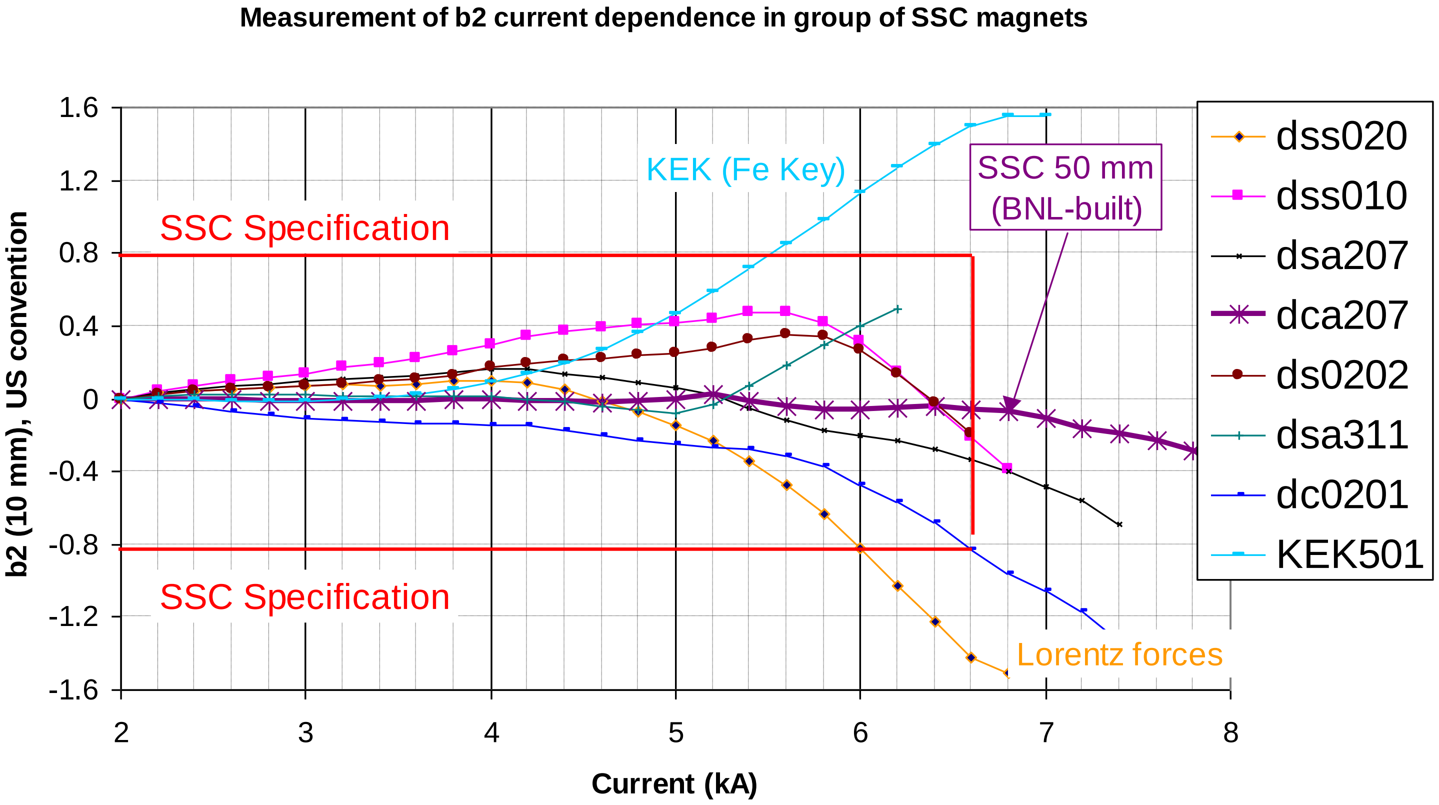




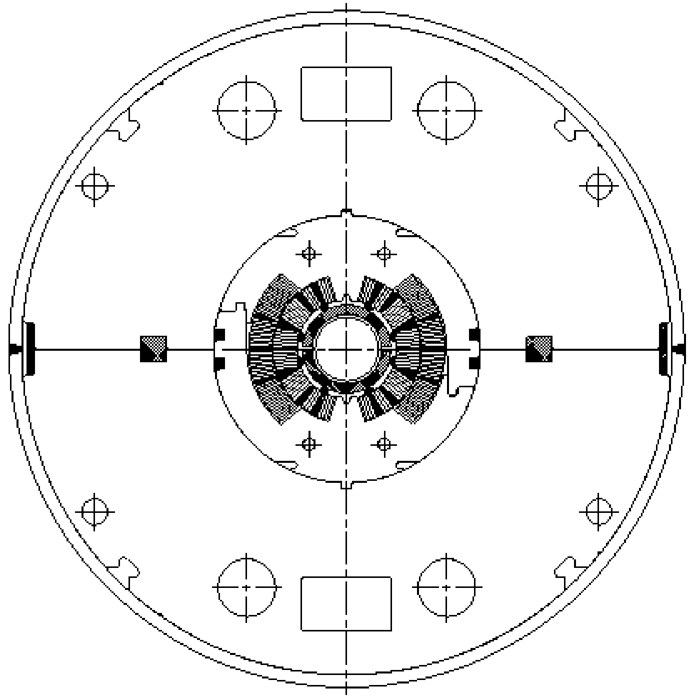


Experience from SSC Dipole

We did magnetic design of both BNL-built and Fermilab-built SSC 50 mm dipoles

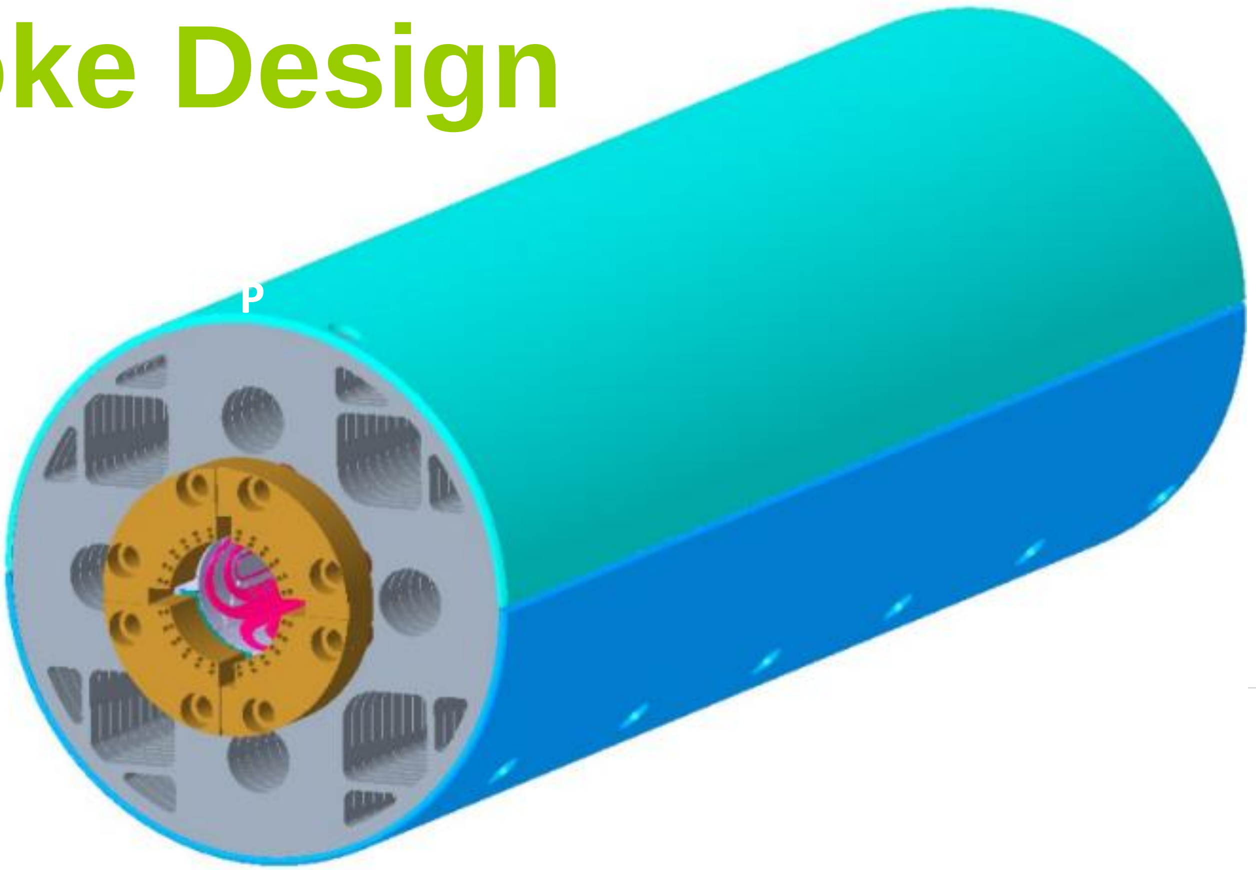


Cross section of SSC 50 mm Dipole
Yoke optimized for low saturation

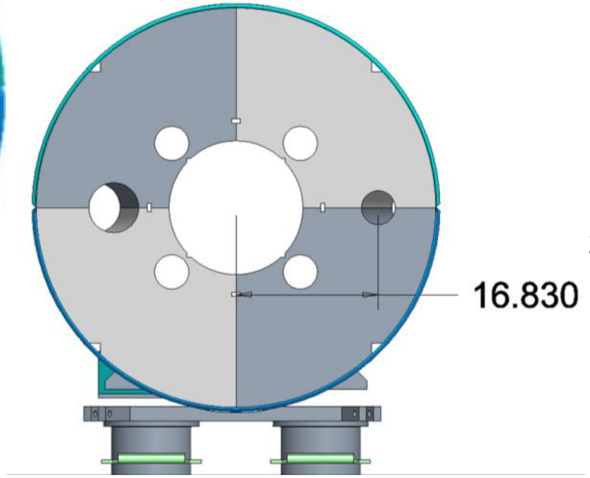


Technology and strategies developed during SSC directly benefitted RHIC magnets and now being applied to EIC magnets and being transferred to the next generation

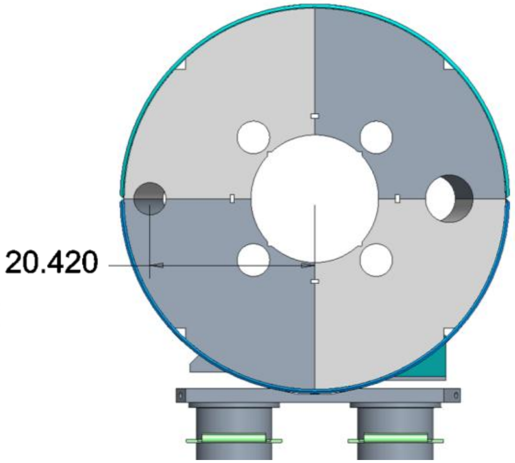
Yoke Design

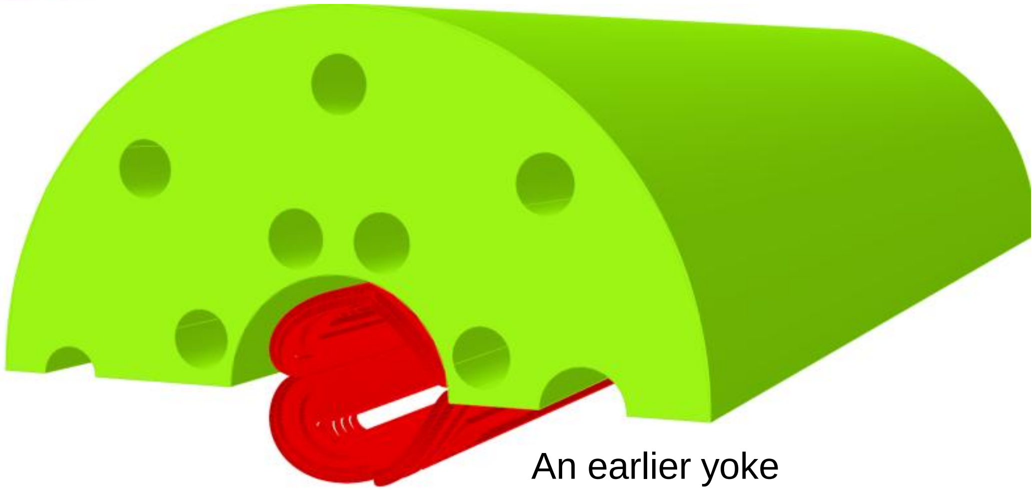


IP end



Non-IP end





An earlier yoke

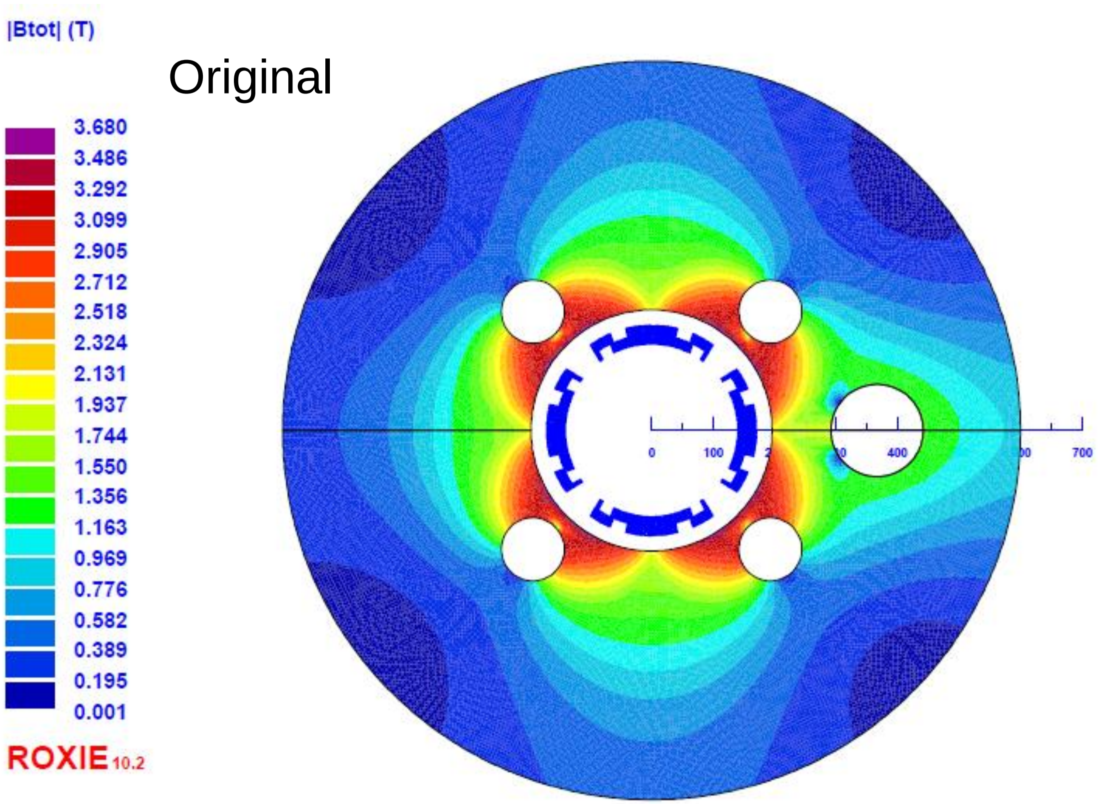
Yoke is first optimized in 2-d for IP end and for non-IP end.

Yoke design is then confirmed with the 3-d simulation for diverging cutouts and ends.

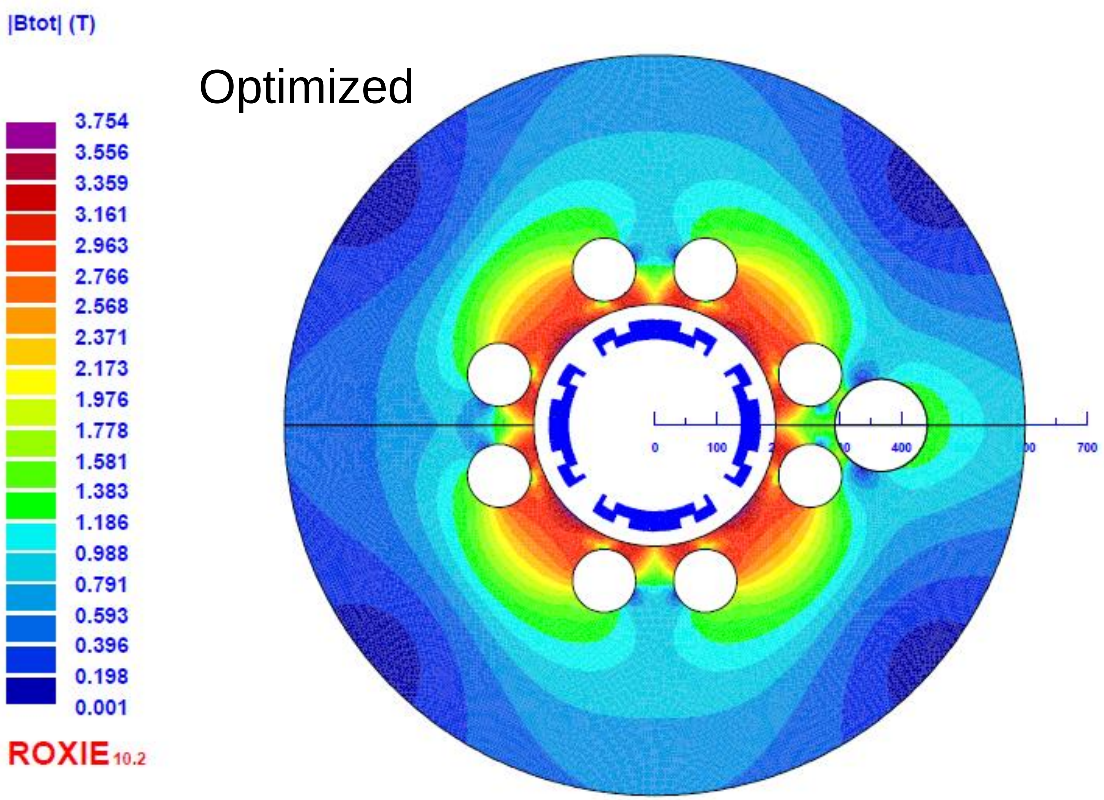
Yoke Optimization – Use the Position and No. of Tie Rods Holes

- Tie rods near the collars are needed for restraining the end forces. Initial location of the holes for them in yoke had a large adverse impact on the yoke saturation.
- Strategy: Let's try to make use of those large holes as a tool of opportunity!

Original



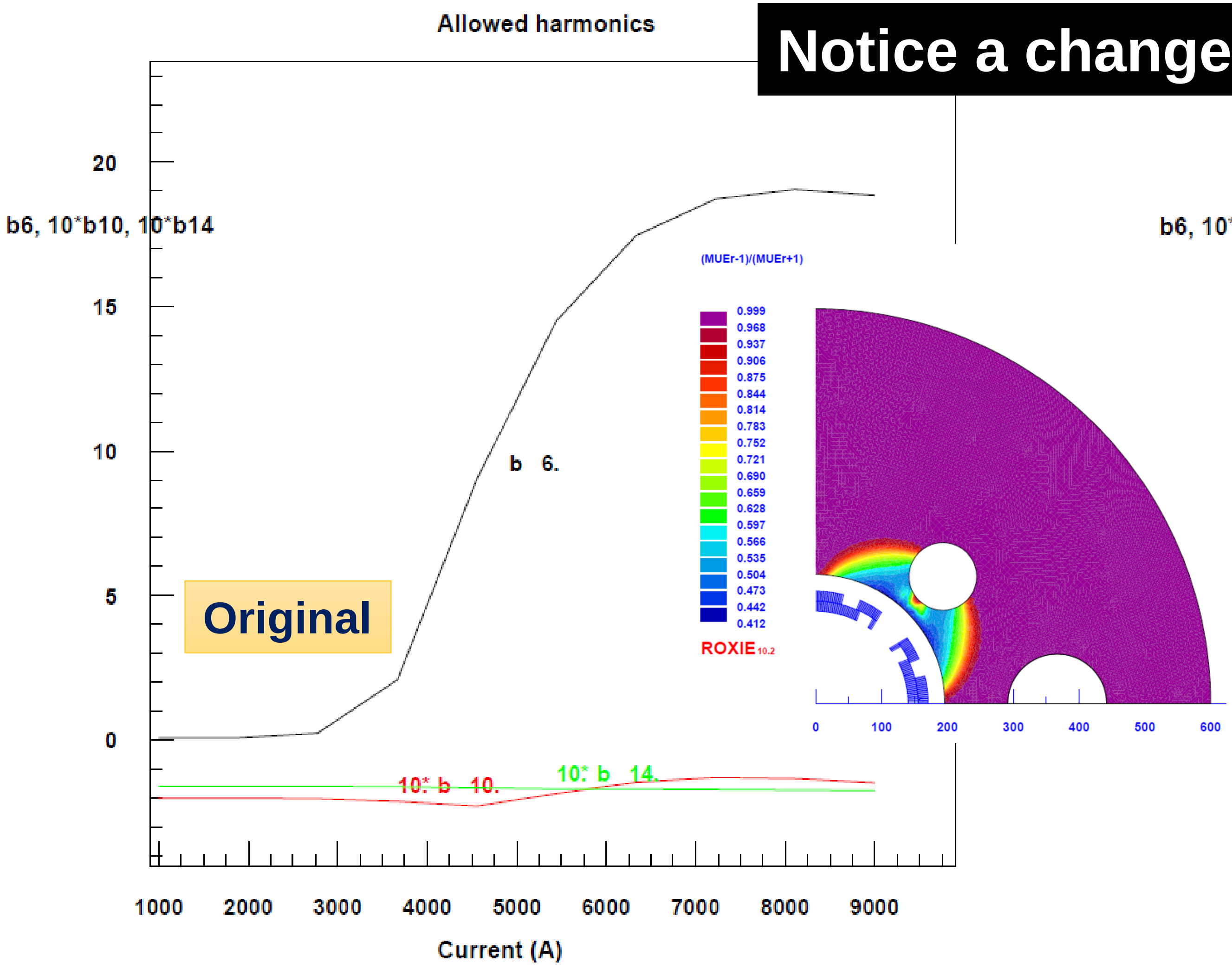
Optimized

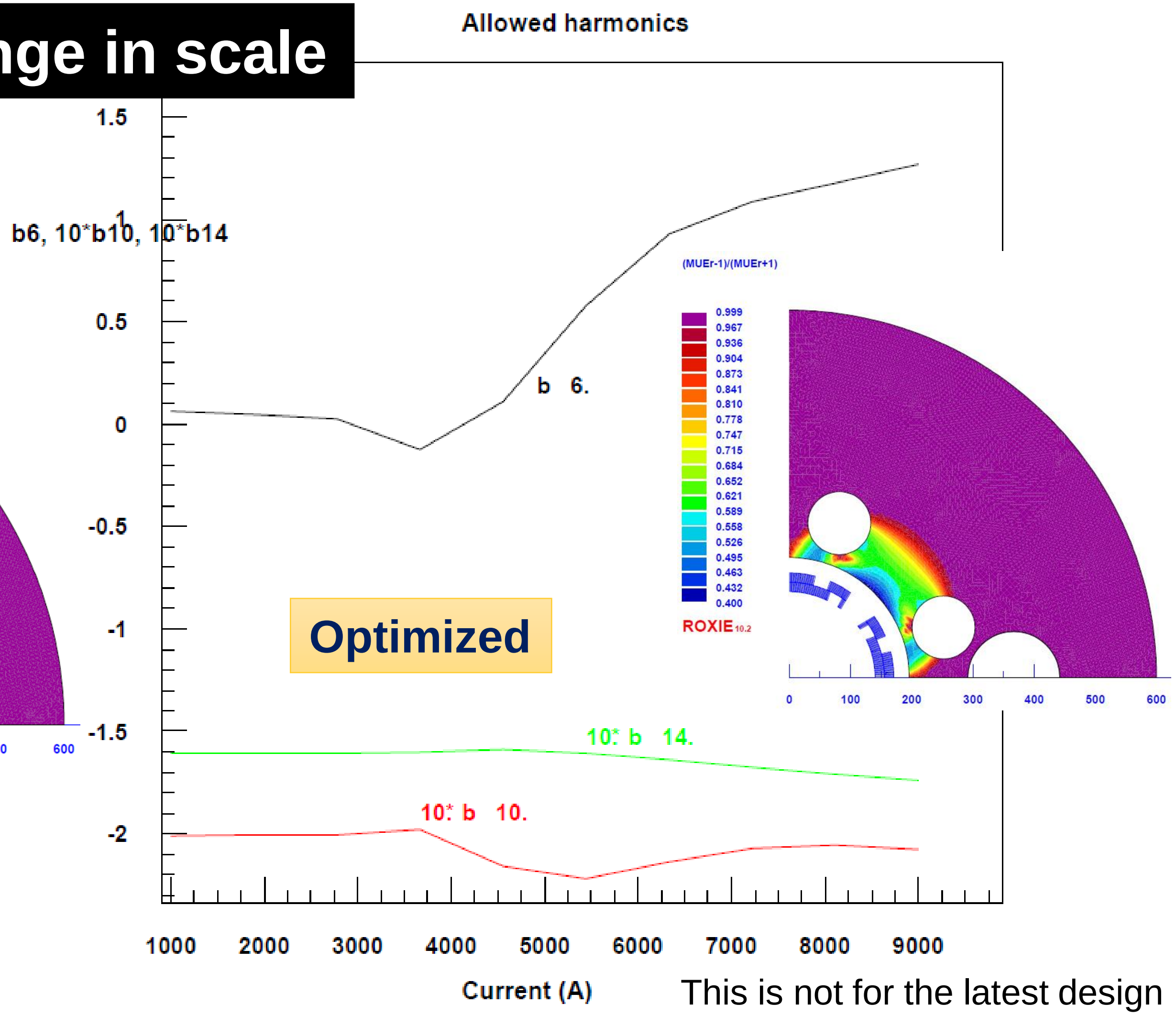


Note: Field in yoke iron at the aperture – it has become higher all around (more uniform)

Tie Rods to Reduce Saturation-induced Harmonics

Notice a change in scale



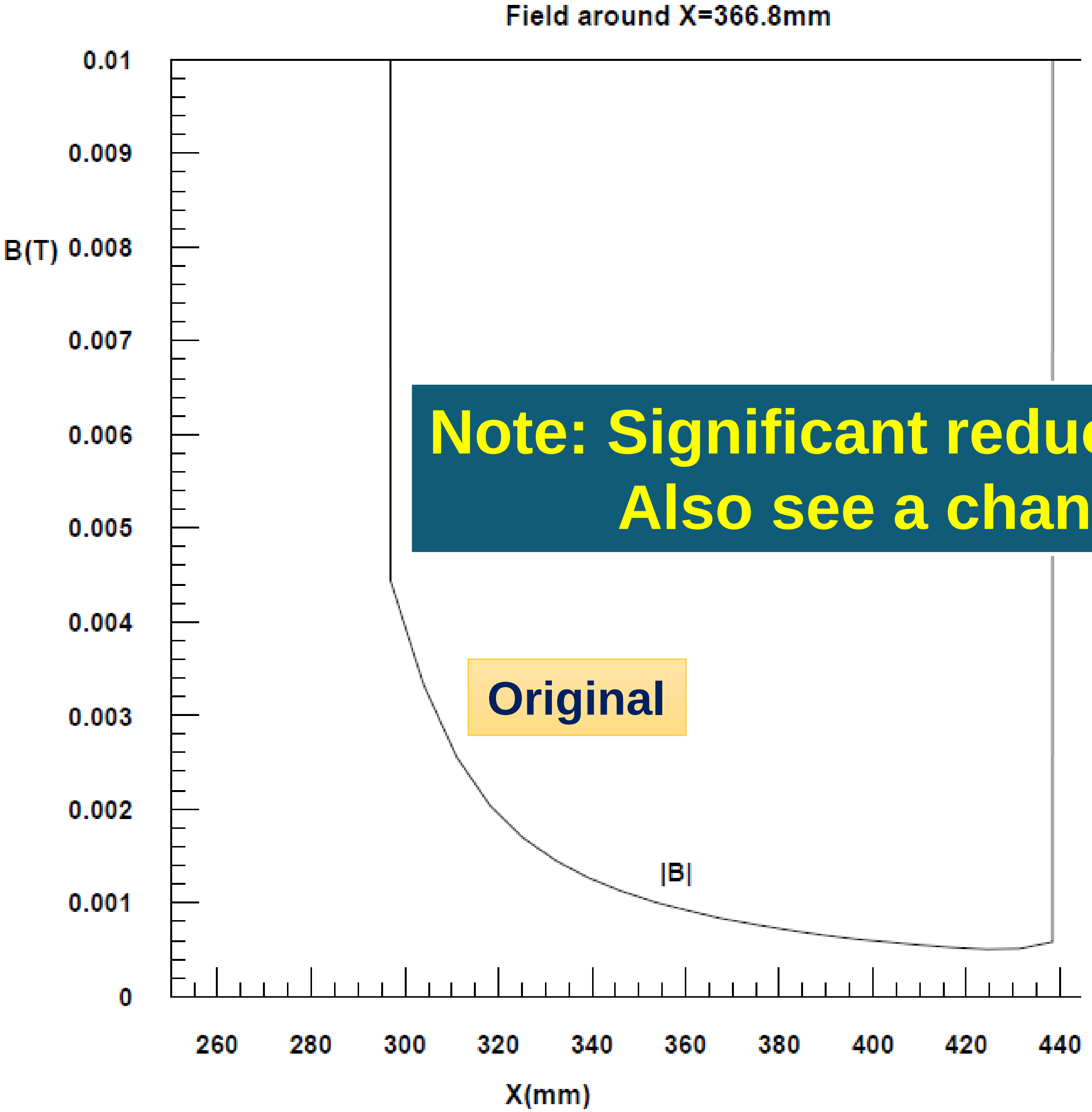


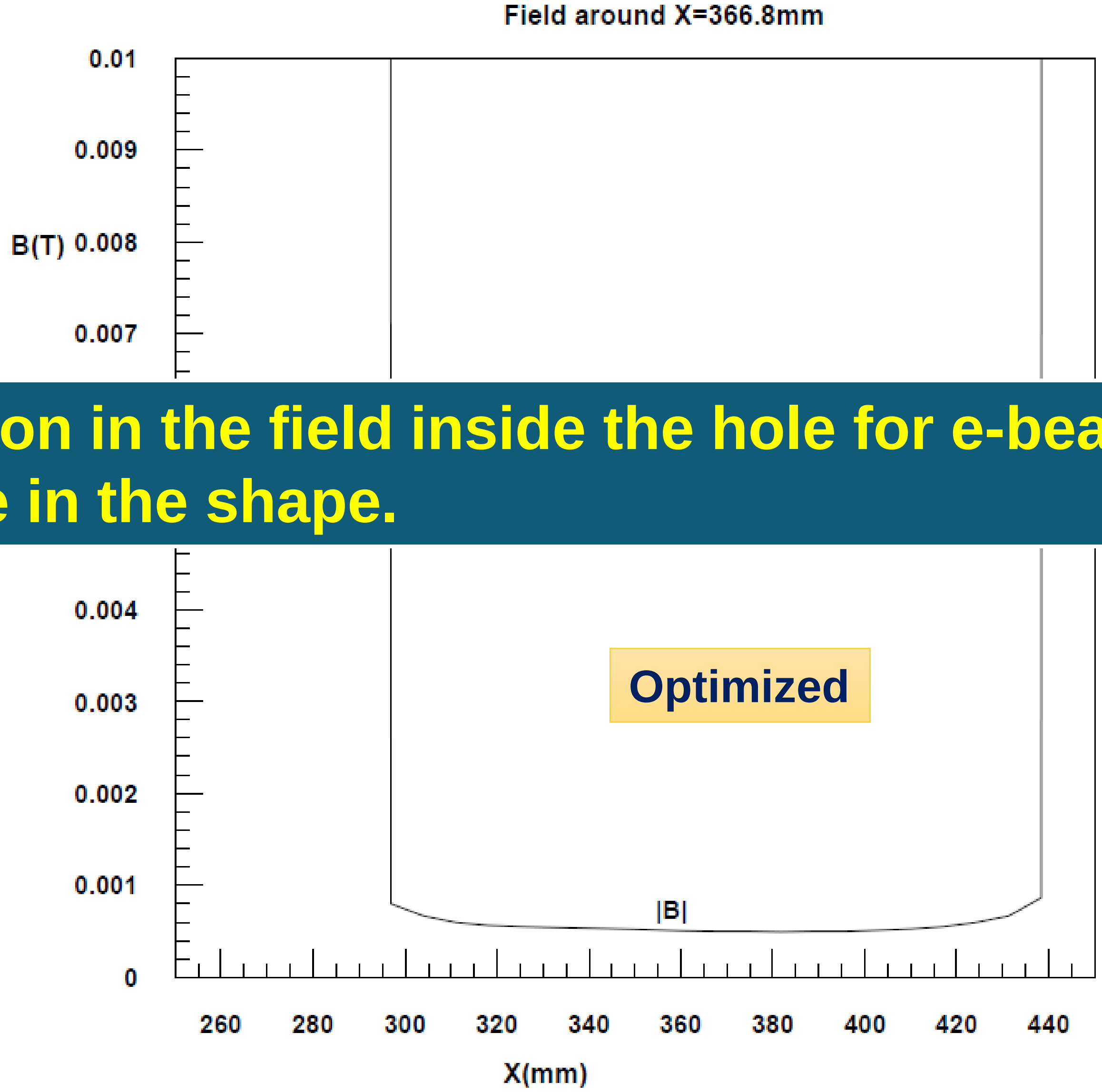
This is not for the latest design

Optimized Iron: Major reduction in saturation induced allowed harmonics (order of magnitude)

Field Gradient @7.7 kA goes down from 36.2 T/m to 35.7 T/m for 2X holes (controlled saturation)

Tie Rods also used to reduce field in the hole for e-beam

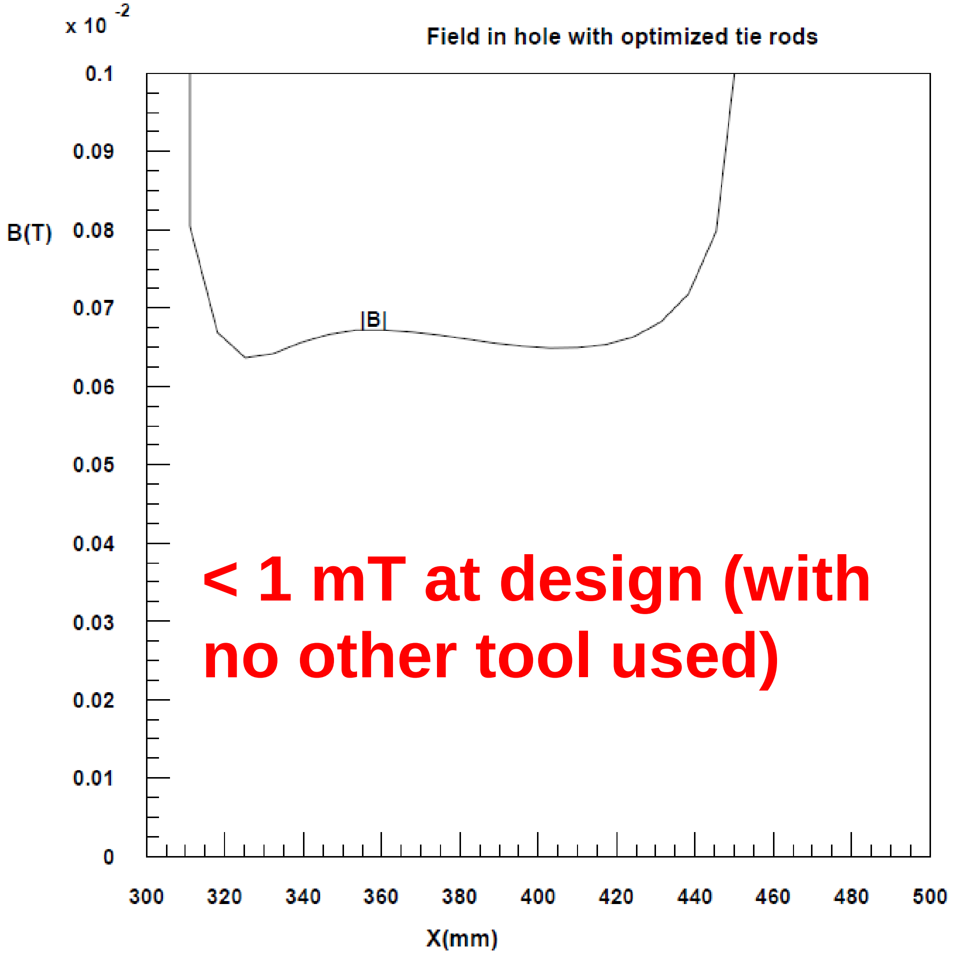




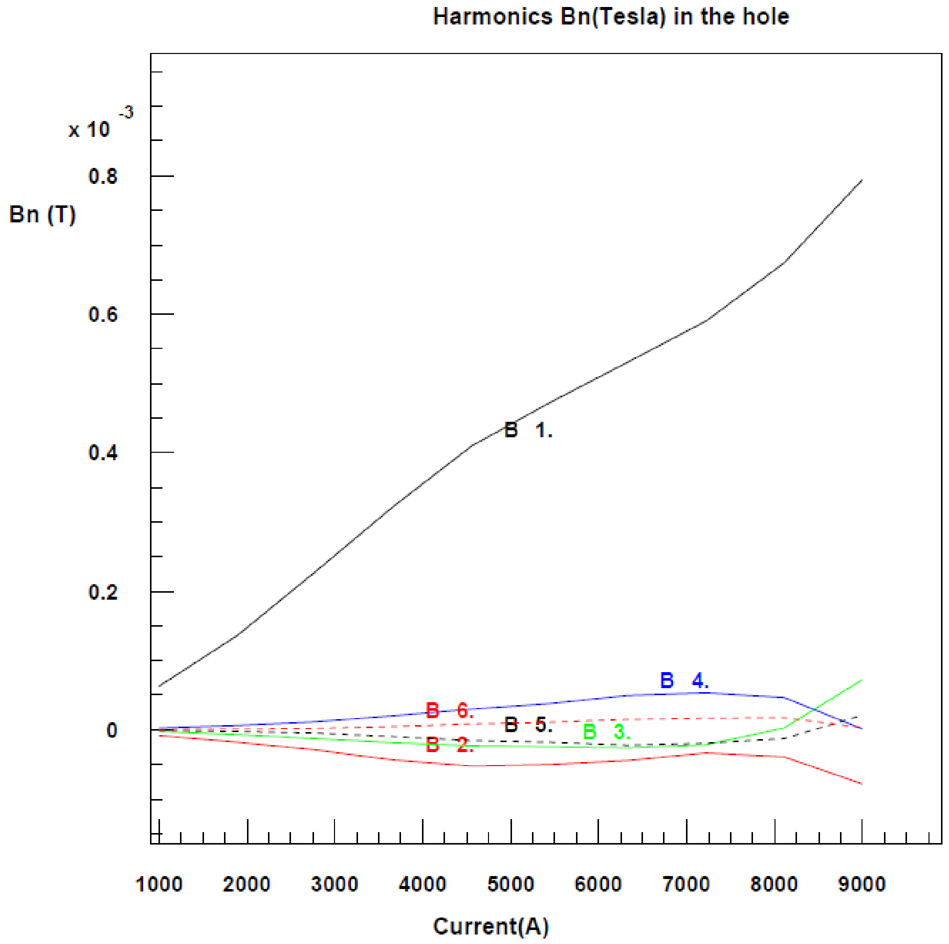
Note: Significant reduction in the field inside the hole for e-beam
Also see a change in the shape.

Note: This is not for the latest design, but the general argument is still valid

Field in the 75 mm Hole for e-beam (IP End @379.2 mm) (tie rod holes in yokes are used to reduce field inside)



< 1 mT at design (with no other tool used)



Harmonics B_n in Tesla remain $<10^{-4}$ units at 50 mm radius.

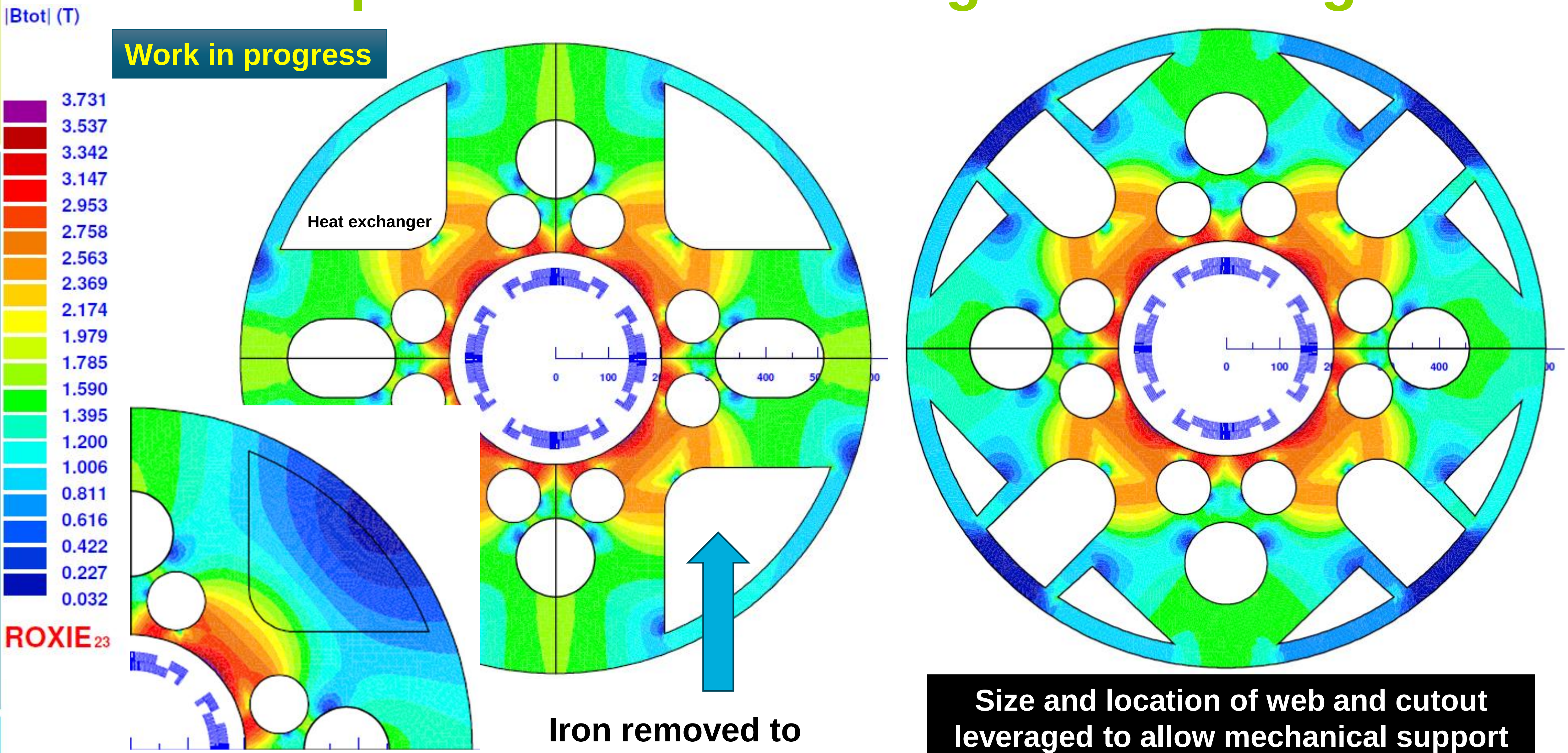
B_1 and B_2 should be less critical

Uniform field brings a larger reduction in B_n's

Measure the merit of a solution by |B| and/or by B_n's

Attempt to Reduce the Weight of the Magnet

Work in progress

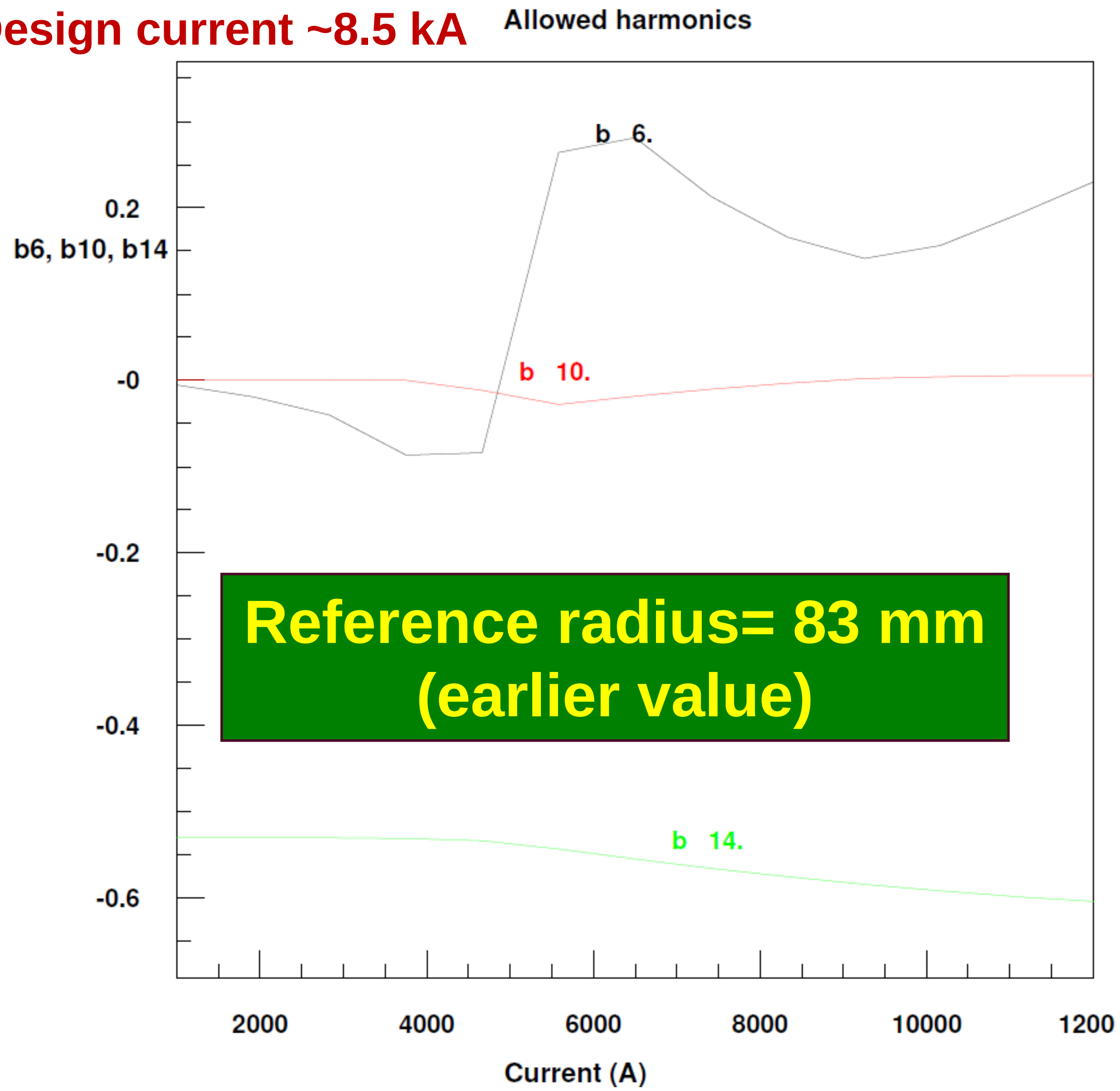


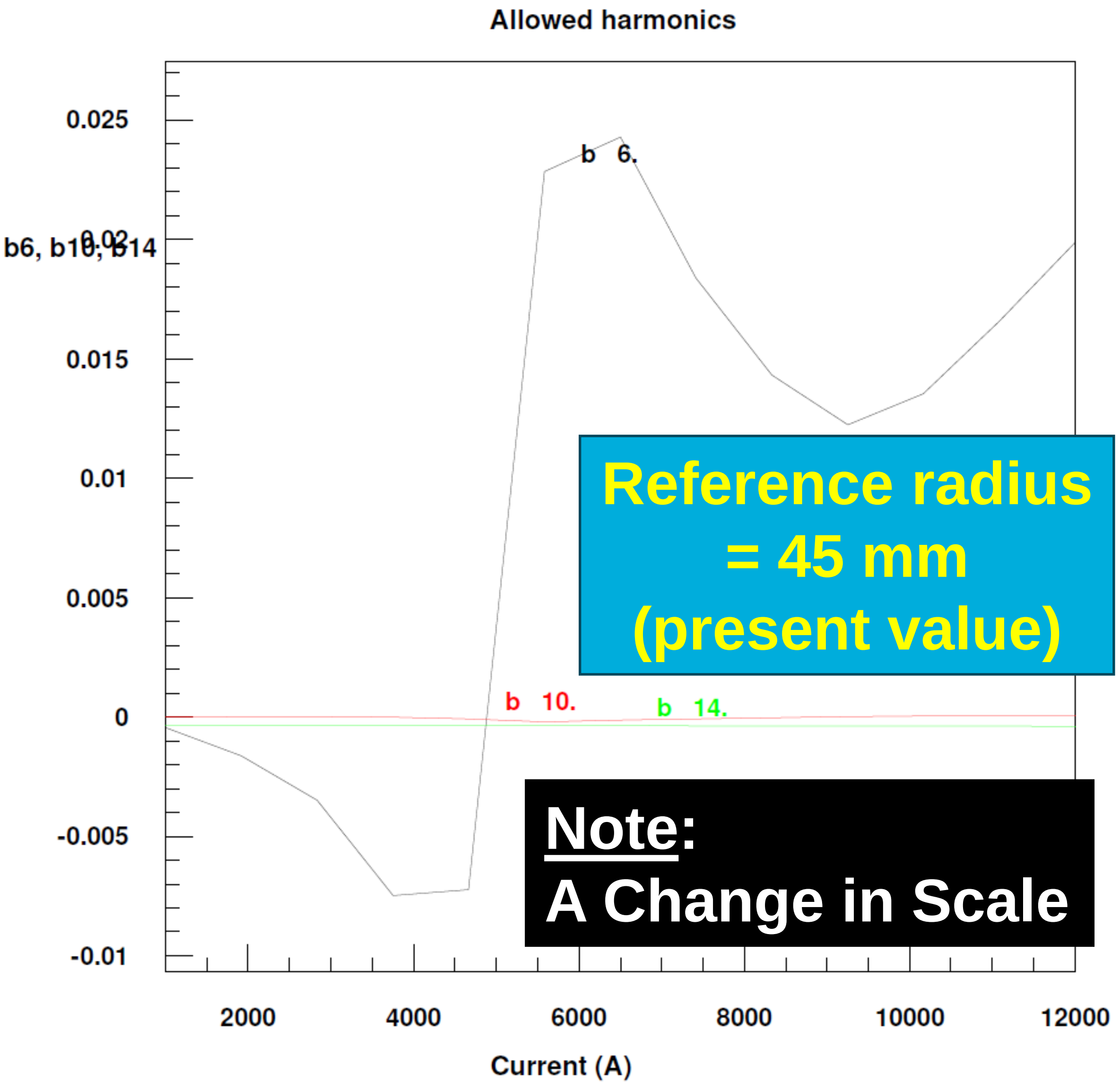
Iron removed to make yoke lighter

Size and location of web and cutout leveraged to allow mechanical support and reduce field in the electron hole

Harmonics as a Function of Current Remain Small

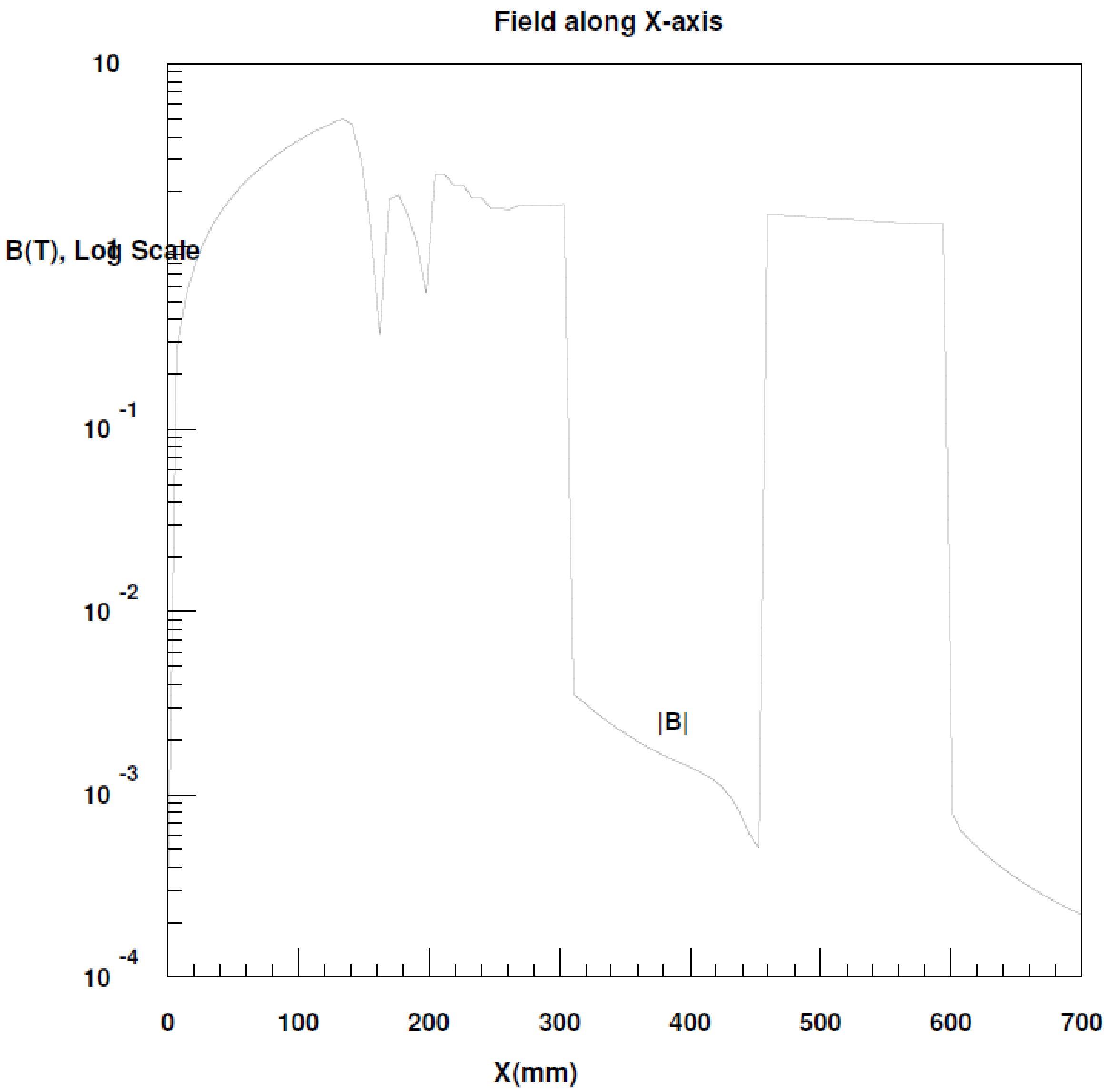
Design current ~8.5 kA

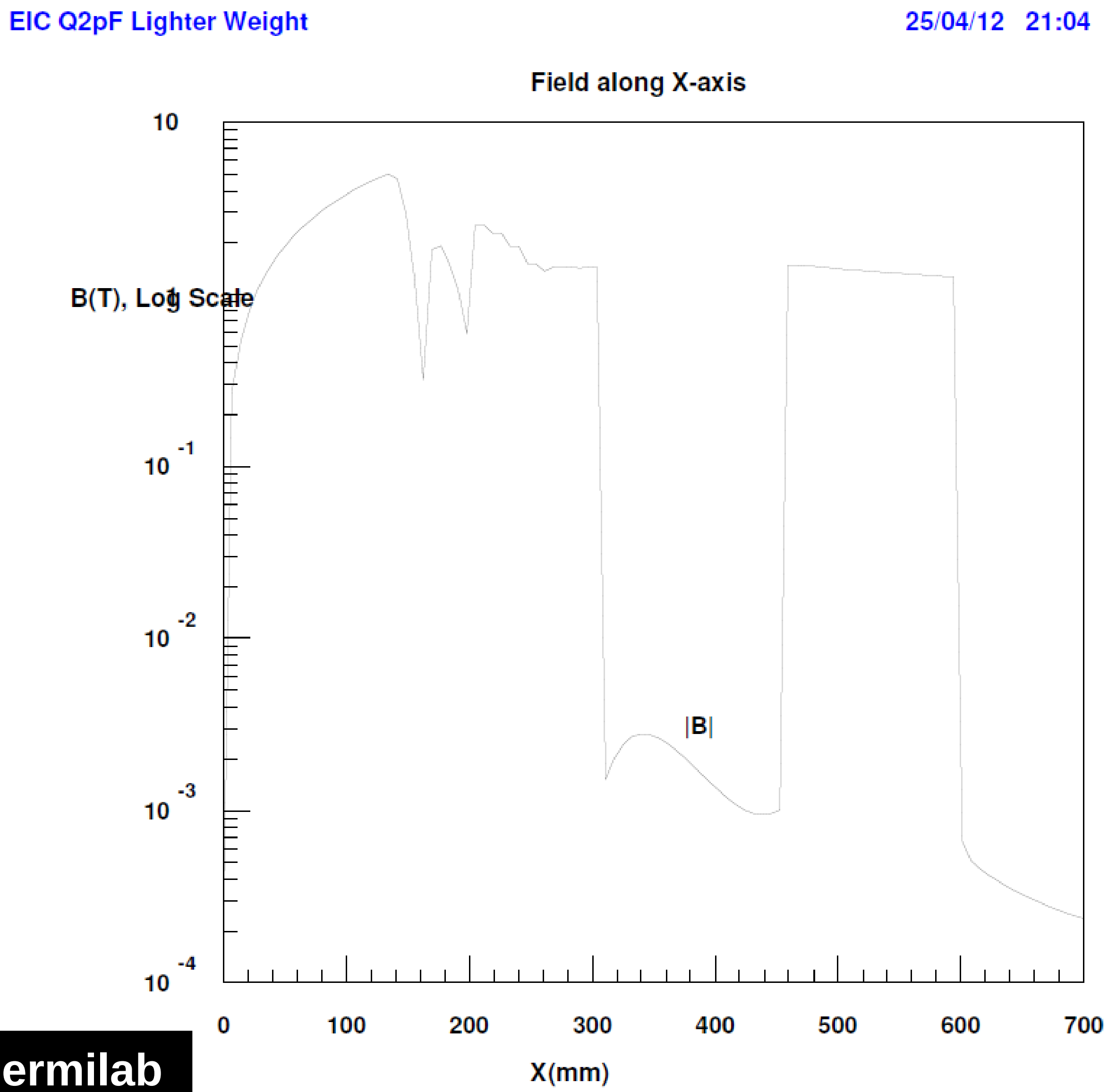




Leveraging Holes and Cutouts to Reduce Field in the Electron Hole

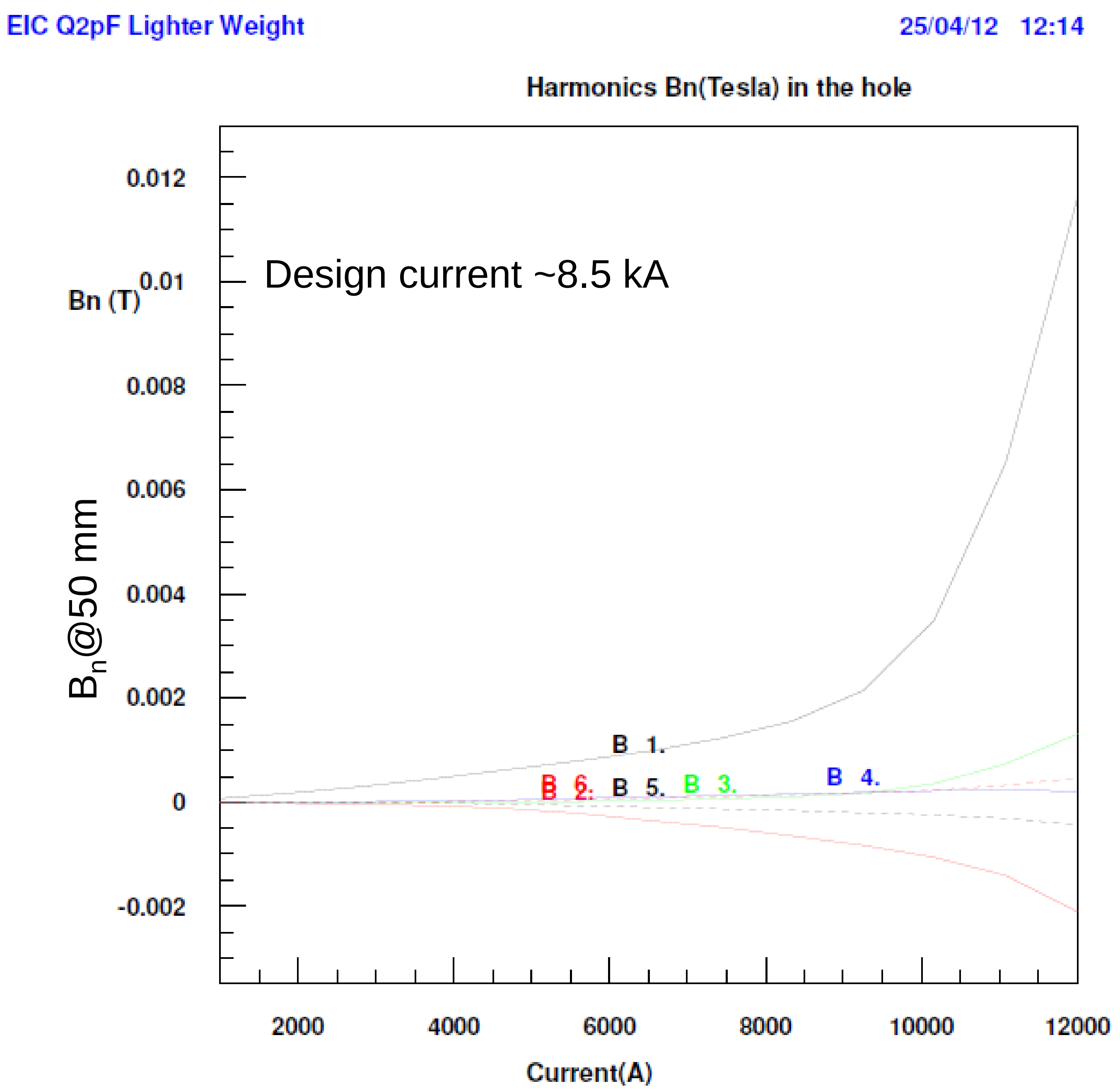
(<1 mT should be possible with more iterations)





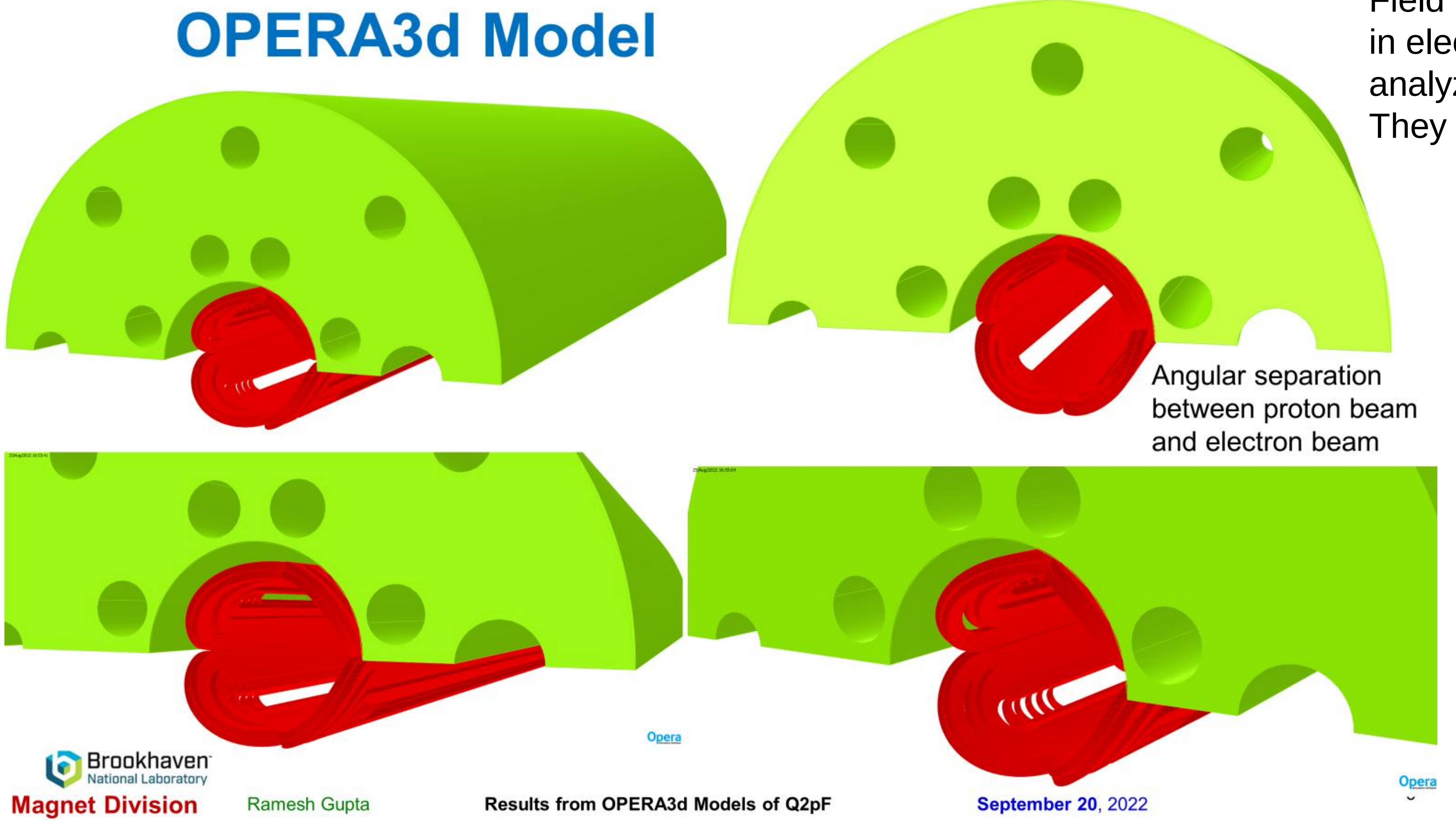
Not fully optimized as it moves to Fermilab

Harmonics in electron hole need further evaluation/ optimization



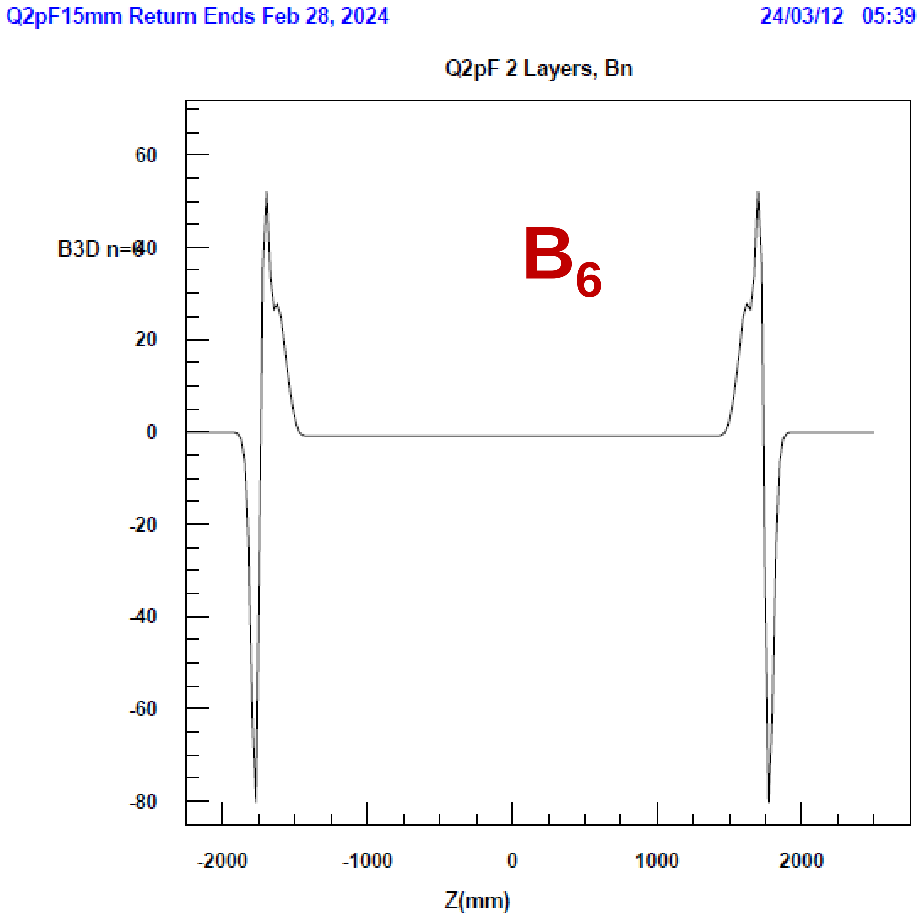
EM 3-d yoke

Field and field harmonics in electron hole are analyzed along the axis. They remain low.

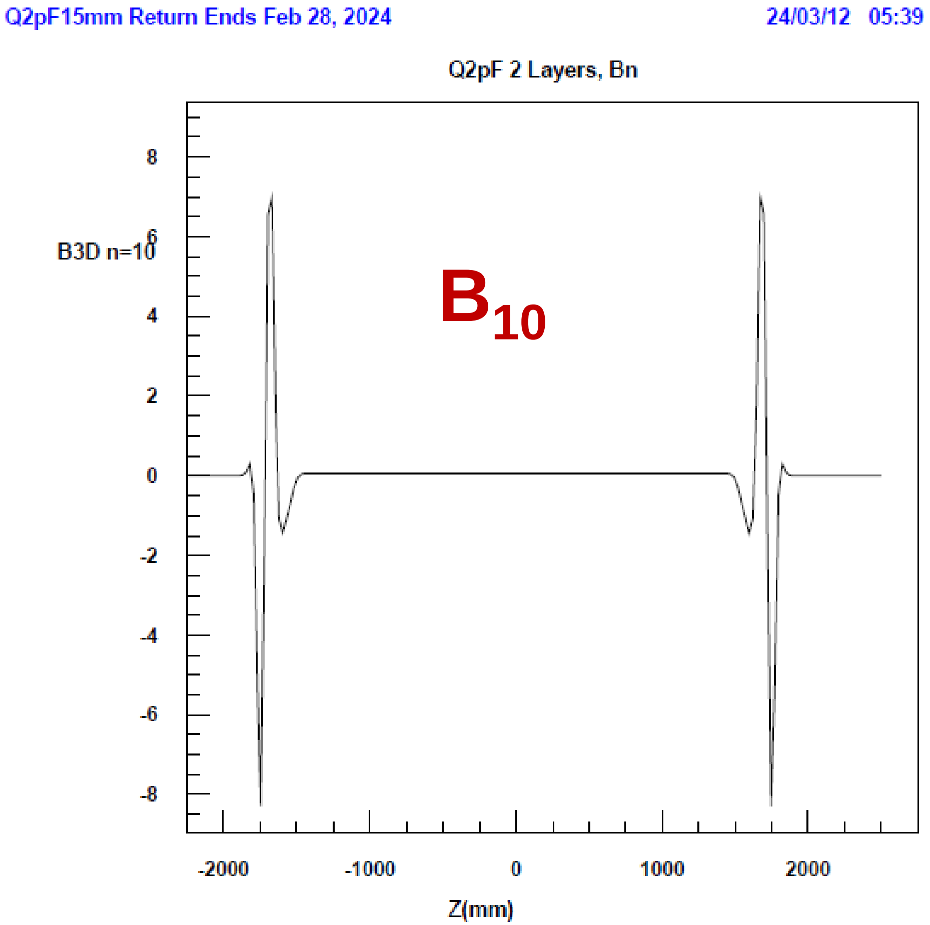


Coil End Design

Field harmonics B_6 and B_{10} along the z-axis



Integral made small



(symmetric return end)

Similar calculations performed for other harmonics and Lead End.
Designs not fully updated and optimized as Fermilab is likely to build this magnet.

End Optimization

- Ends are optimized for (a) keeping peak fields low (keep similar or close to that in body magnet), (b) integrated field harmonics low, and (c) layout of the turns mechanically sound.
- Whereas (a) and (b) can be assured with the computer codes, (c) is tricky primarily because of no previous experiences in such large aperture magnets. We are relying on a single turn winding test, and on winding test of coil for a similar aperture B1pF.
- Coil radii of 2 layers of Q2pF (140mm, 156mm) is in between B1pF radius (150mm).
- However, turns in quad extend to only 45^o from the pole, rather than to 90^o in dipole. Therefore, when applying B1pF dipole experience to Q2PF quad, coil winding results from B1pF are relevant only to the first few blocks (<40 turns) from the pole.
- Q2pF ends were initially designed for large tilt angles to make the pole turns as vertical as possible for better application of end loading. That is being relaxed now.
- Updating this design work has been very limited and should be done either by Fermilab or together with Fermilab, assuming Fermilab is building this magnet.

Peak Field Enhancement in the Ends

End configuration iterated for smaller peak fields in the ends.

ROXIE calculations

- **Peak field in 2-d: 6.89 T**
- **Peak field in 3-d: 7.09 T**

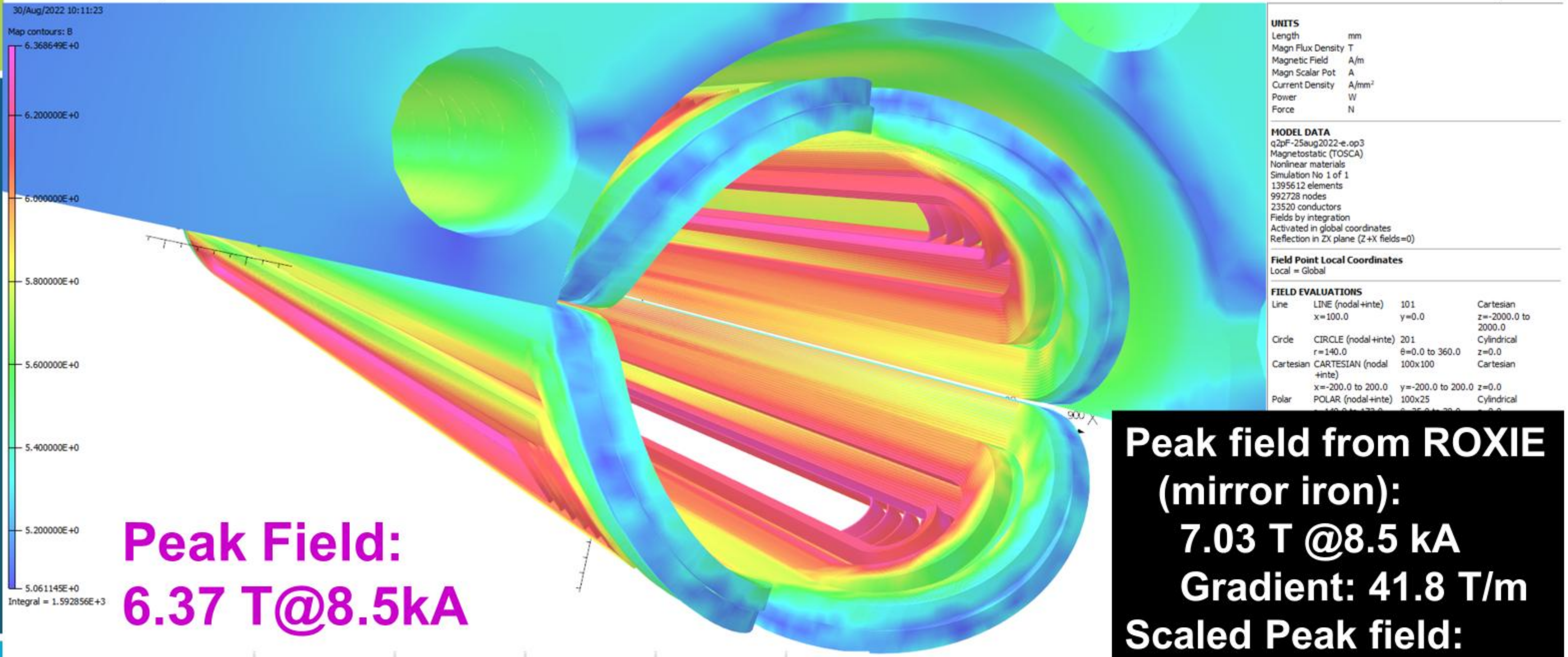
Only about ~2.9% higher peak field than that in the x-section

(within calculation errors?)

```
RESULTS OF THE 3D PEAK FIELD CALCULATION
PEAK FIELD IN CONDUCTOR   10 (T) ..................        3.0567
PEAK FIELD IN CONDUCTOR   10 (T) ..................        3.0567
RESULTS OF THE 3D PEAK FIELD CALCULATION
PEAK FIELD IN CONDUCTOR   19 (T) ..................        4.4683
PEAK FIELD IN CONDUCTOR   19 (T) ..................        4.4683
RESULTS OF THE 3D PEAK FIELD CALCULATION
PEAK FIELD IN CONDUCTOR   29 (T) ..................        6.7153
PEAK FIELD IN CONDUCTOR   29 (T) ..................        6.7153
RESULTS OF THE 3D PEAK FIELD CALCULATION
PEAK FIELD IN CONDUCTOR   32 (T) ..................        6.7893
PEAK FIELD IN CONDUCTOR   32 (T) ..................        6.7893
RESULTS OF THE 3D PEAK FIELD CALCULATION
PEAK FIELD IN CONDUCTOR   34 (T) ..................        7.0905
PEAK FIELD IN CONDUCTOR   34 (T) ..................        7.0905
RESULTS OF THE 3D PEAK FIELD CALCULATION
PEAK FIELD IN CONDUCTOR   45 (T) ..................        5.8845
PEAK FIELD IN CONDUCTOR   45 (T) ..................        5.8845
RESULTS OF THE 3D PEAK FIELD CALCULATION
PEAK FIELD IN CONDUCTOR   65 (T) ..................        6.8664
PEAK FIELD IN CONDUCTOR   65 (T) ..................        6.8664
RESULTS OF THE 3D PEAK FIELD CALCULATION
PEAK FIELD IN CONDUCTOR   69 (T) ..................        6.8508
PEAK FIELD IN CONDUCTOR   69 (T) ..................        6.8508
```

Calculation of Peak Field with OPERA3d (non-linear iron)

Integration method for the coil field to assure a reasonable accuracy



Peak Field:
6.37 T@8.5kA

Gradient @ center	38.218	T/m

Peak field from ROIXE (mirror iron):
7.03 T @8.5 kA
Gradient: 41.8 T/m
Scaled Peak field:
6.42 T for 38.2 T/m

Brookhaven National Laboratory
Magnet Division   Ramesh Gupta   Results from OPERA3d Models of Q2pF   September 20, 2022   9

Strategies for building the 1st magnet, a good field quality magnet

Please visit following site for some initial thoughts:

https://wpw.bnl.gov/rgupta/wp-content/uploads/sites/9/2025/03/strategy-for-FQ-in-1st-magnet.pdf

Q2pF EM design status and progress are documented at:

https://wpw.bnl.gov/rgupta/eic-q2pf-em/

They have been on earlier location of sharepoint also.
They will be uploaded in the new location in a more organized way.

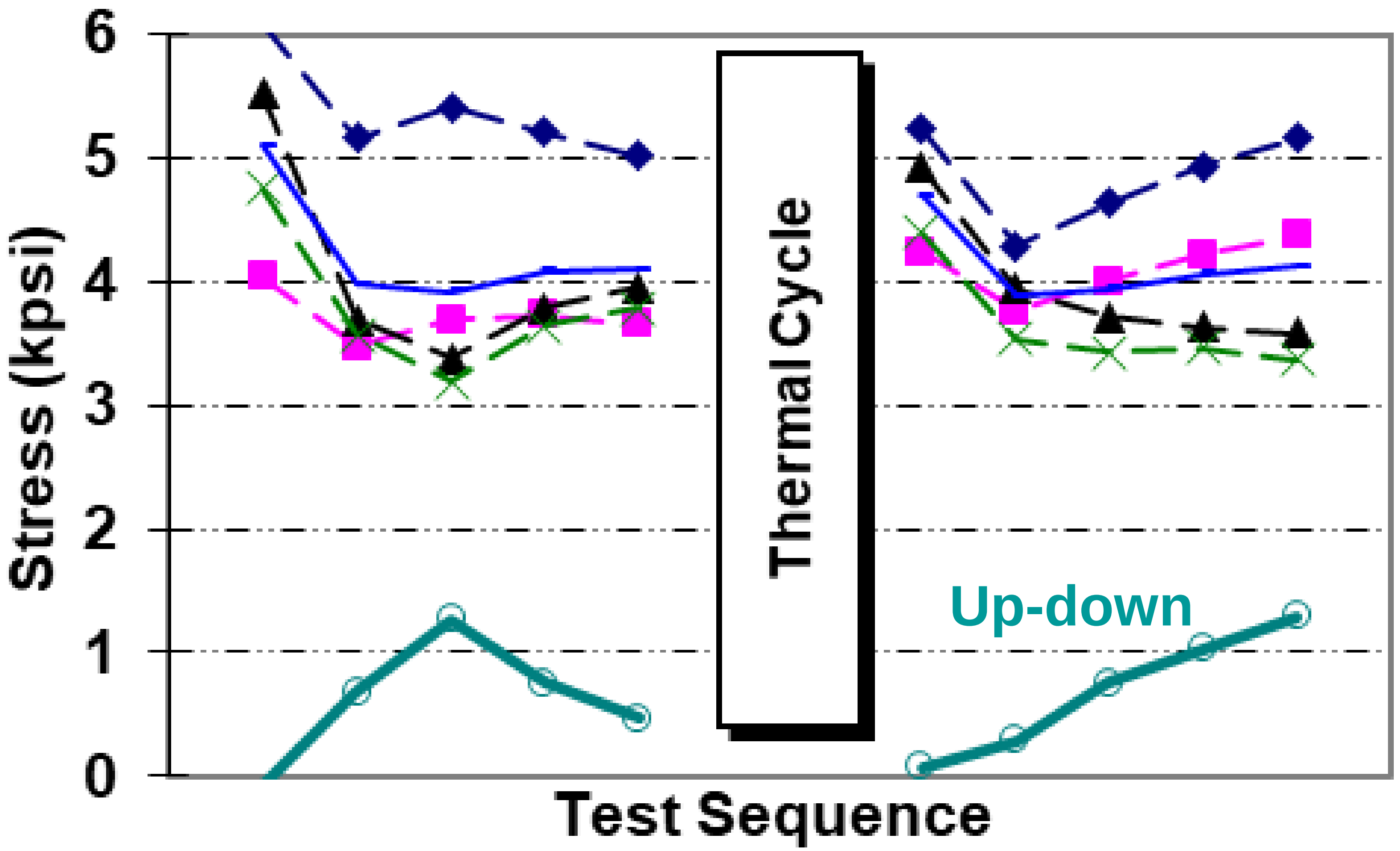
SUMMARY

- Q2pF is one of the most challenging cable magnet in the EIC. This is the largest aperture quadrupole (dipoles have even larger aperture) with a relatively high gradient for NbTi magnet.
- A significant amount of Electro-magnetic (EM), mechanical design and analysis, and engineering has been carried out in advancing the overall design of this magnet.
- Whereas the work on engineering updates was limited, EM design kept getting updated from the latest cable information and other inputs (e.g., winding experience), partially since the EM work requires lesser effort.
- Q2pF design benefited from the SSC and RHIC magnet design and construction experiences. They are being incorporated in all EIC magnets and is being shared with the community.

Extra Slides

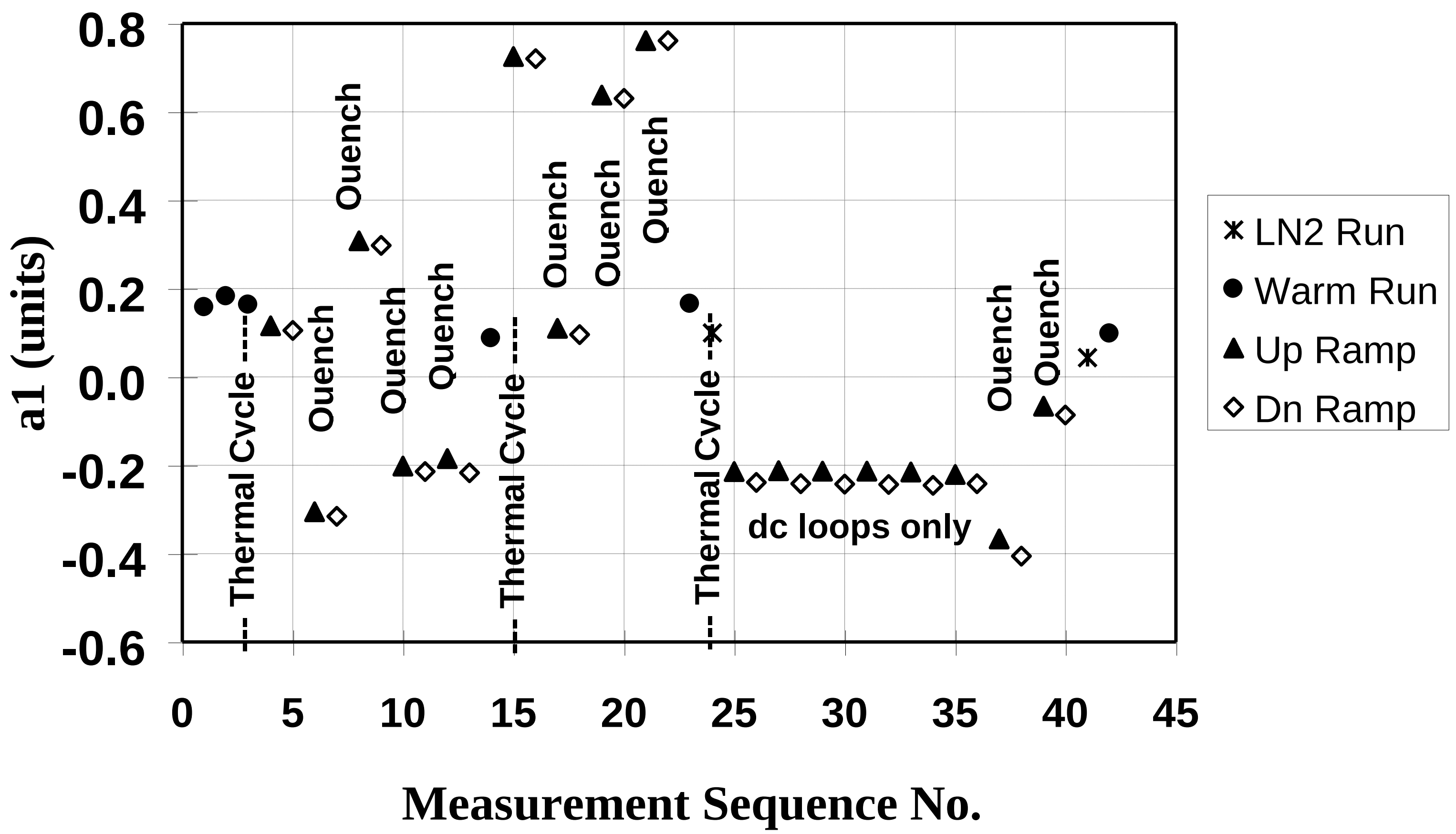
Related Mechanical Signature of the Small Change

Correlation with small changes in harmonics and prestress related to 10 micron 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.

Q. Was this limit specific to RHIC IR Quad? Ans. No!



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

On reviewing measured data of a large number of other magnets, we found that it was not limited to IR quad only. It was found in SSC magnets as well!

What causes this change and what doesn't?

- **Thermal shocks do**
- **Quench shocks do**
- **But ramping up and down don't (no shocks)**