Q2pF EM Design Updates

Ramesh Gupta

Meeting with Fermilab Colleagues

April 10, 2025

Summary of EM Design Updates on Q2pF

(since last presentation to Fermilab team on April 18, 2024)

- Coil 2d design updated based on the updated cable thickness.
- Coil 3d design updated based on the updated cable thickness. In addition, these updates took advantage of the single turn winding test for Q2pF and the short coil winding test of B0ApF dipole which has a similar coil radius.
- Updated yoke design is being examined to reduce the overall weight of the magnet in cryostat (to allow using the cranes in magnet division with minimum upgrades).
- Whereas the EM design got some updates, engineering updates were rather limited. This is partially since the EM dates requires lesser effort.

Q2pF EM design status and progress is documented at:	https://wpw.bnl.gov/rgupta/eic-q2pf-em/

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

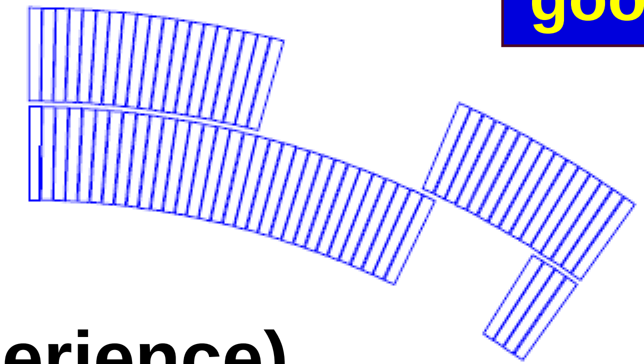
Coil temperature (for calculation)	2	K
Stored energy @design gradient	2.7	MJ
Inductance	75	mH
Quench current	14440	A
Gradient @Quench	60.5	T/m
Peak field @design	**6.4**	**T**
Peak field @quench	10.2	T
Loadline Margin	**38**	**%**
Temperature Margin	**3.4**	**K**

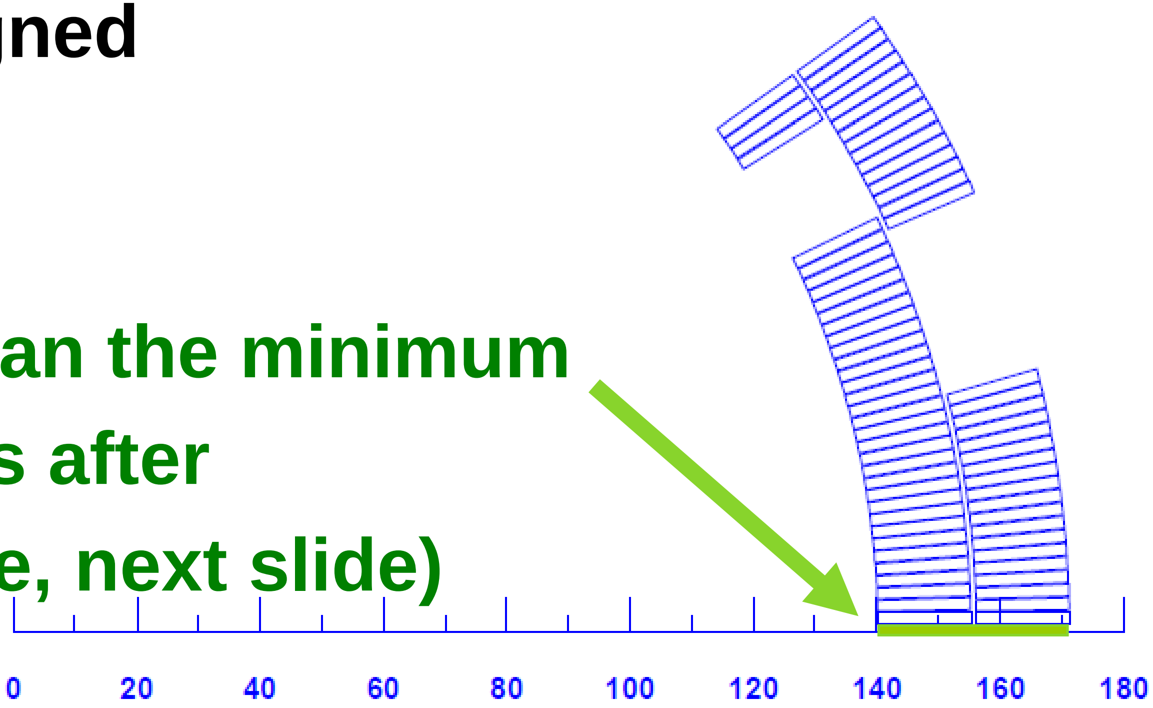
Superconductor	NbTi	
Cu/Sc Ratio (nominal)	1.6	
Strand diameter (mm)	1.065	
Number of strands in cable	28	
Cable width, bare (mm)	15.1	mm
Cable mid-thickness, bare (mm)	1.9	mm
Cable insulation radial	0.15	mm
Cable insulation azimuthal	0.965	mm
Cable width, insulated	15.4	mm
Cable mid-thickness, insulated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

Coil Cross-section (updated)

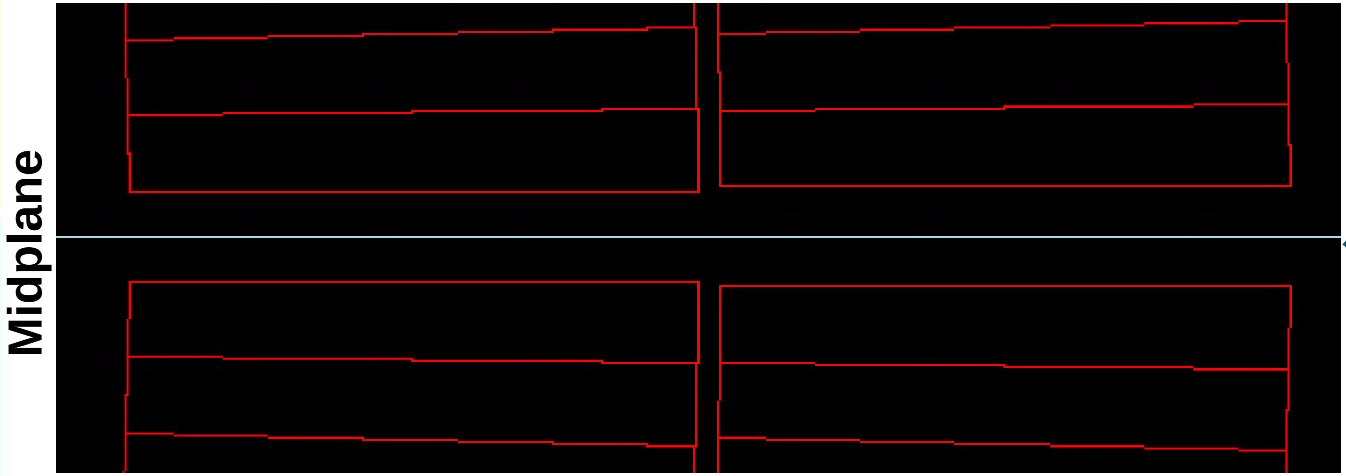
Visually looks good mechanically

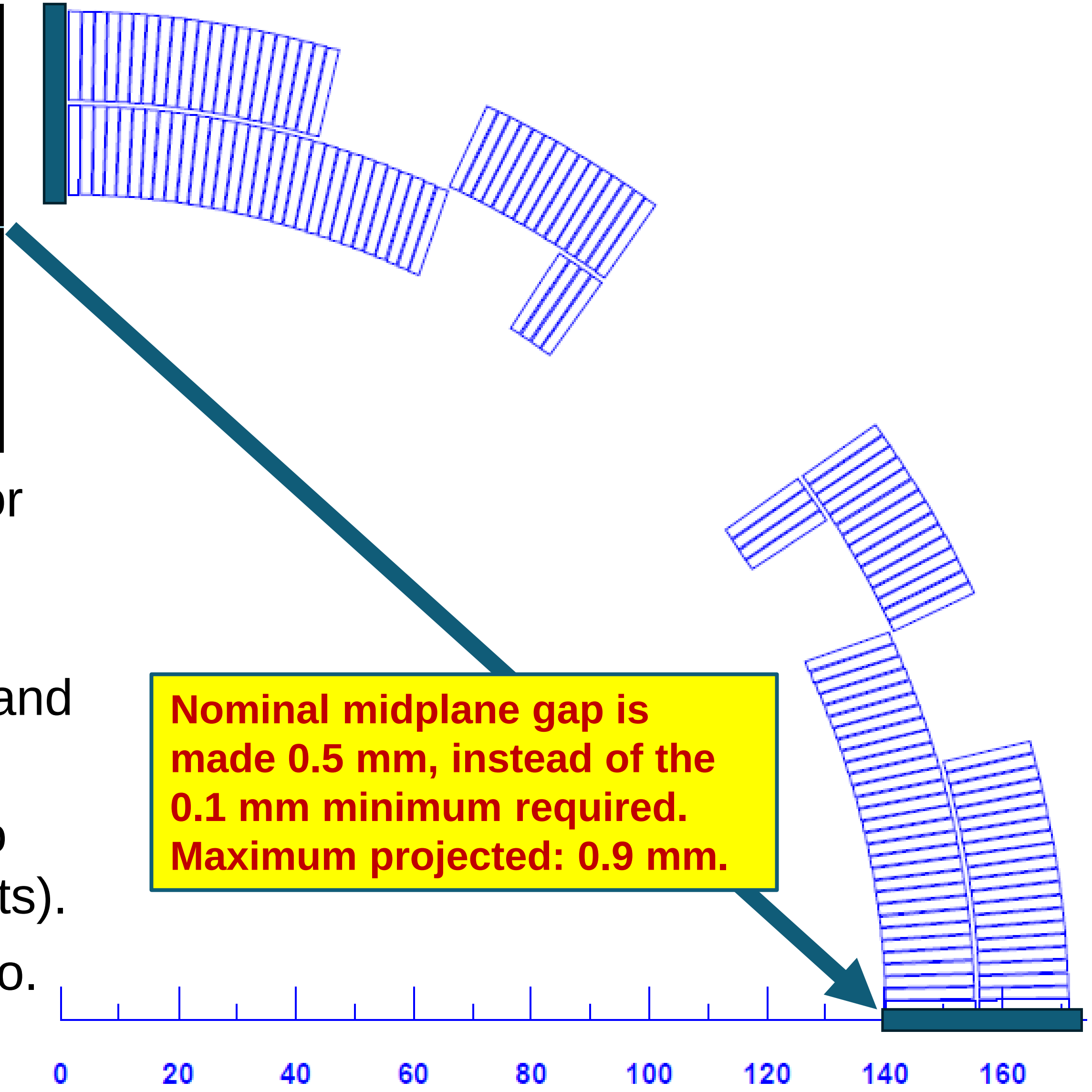
- **Uses EIC Quad cable with the updated turn-to-turn spacing**
- **Two layers, 69 turns (35+34)**
- **Symmetric wedges (RHIC/SSC experience)**
- **Poles of outer and inner layers aligned**
- **Peak field optimized**
- **Field quality optimized**
- **Midplane gap made much larger than the minimum required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





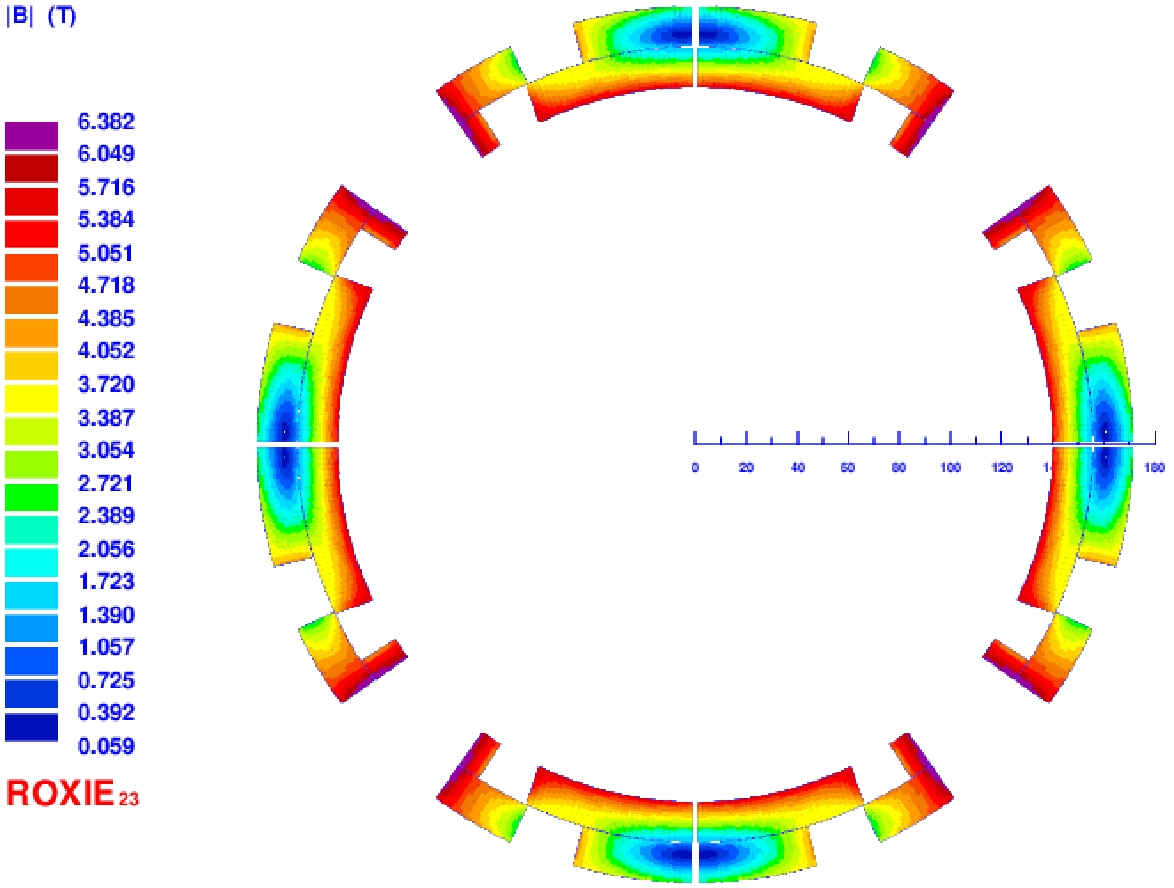
Flexible Coil Design from the Start (midplane gap)

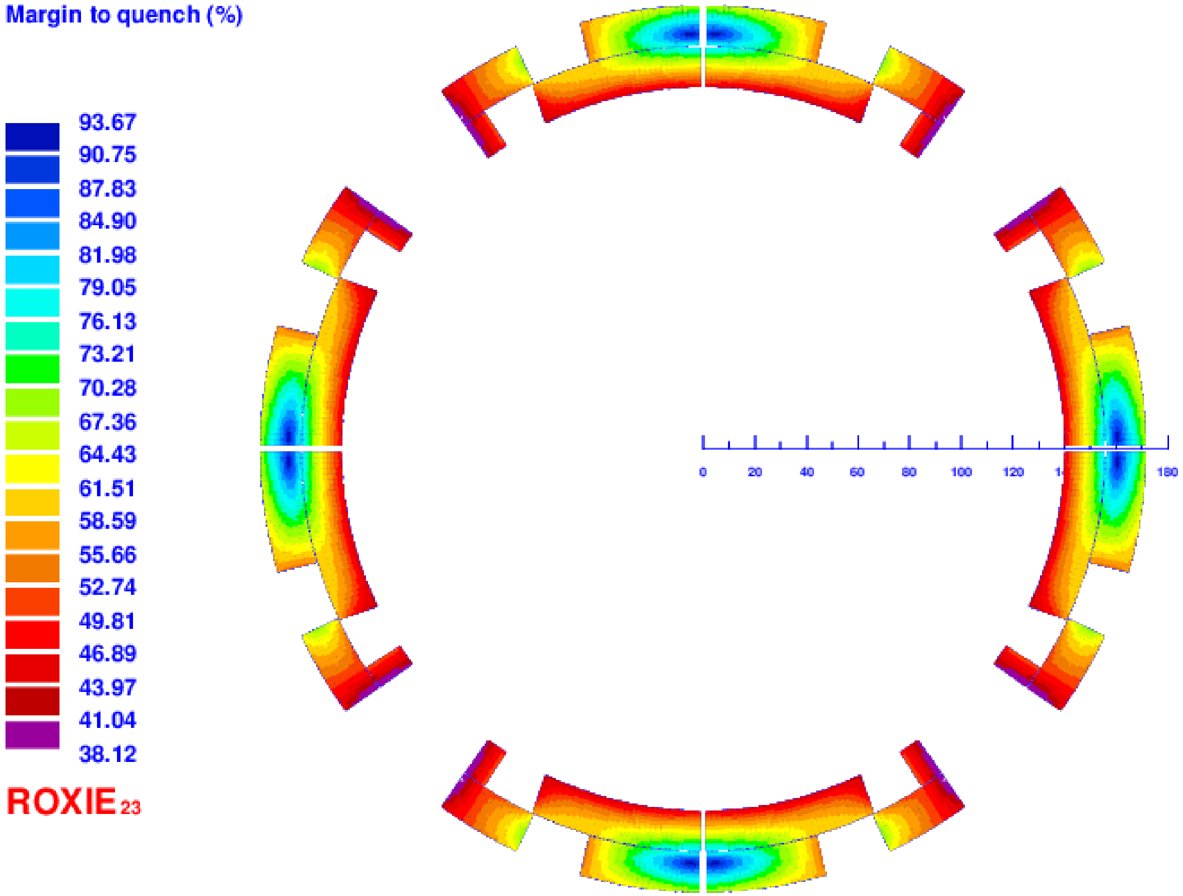




- This simple tool offers +/- 7.2 units adjustment in b_6 for <0.1 units change in b_{10}, while using the same coils.
- A powerful tool (along with the pole shims), used extensively in RHIC magnets, both in small in-house and in large industrial production at Northrop Gruman.
- Difference between horizonal 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.

Peak Field and Operating Margin

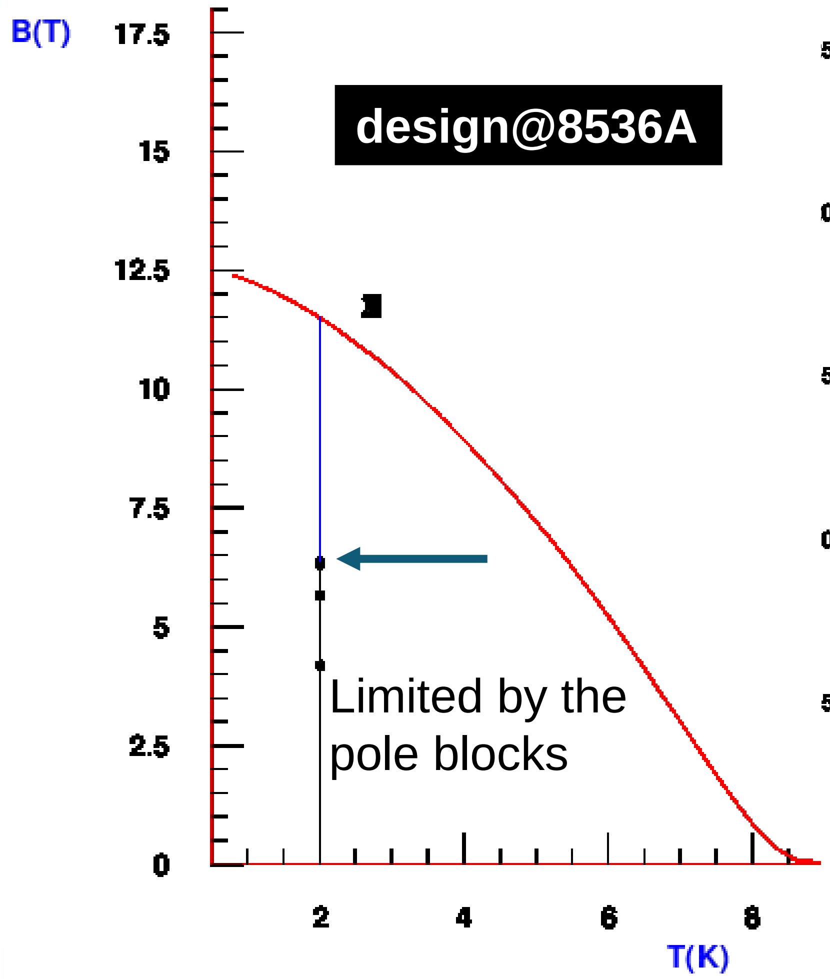


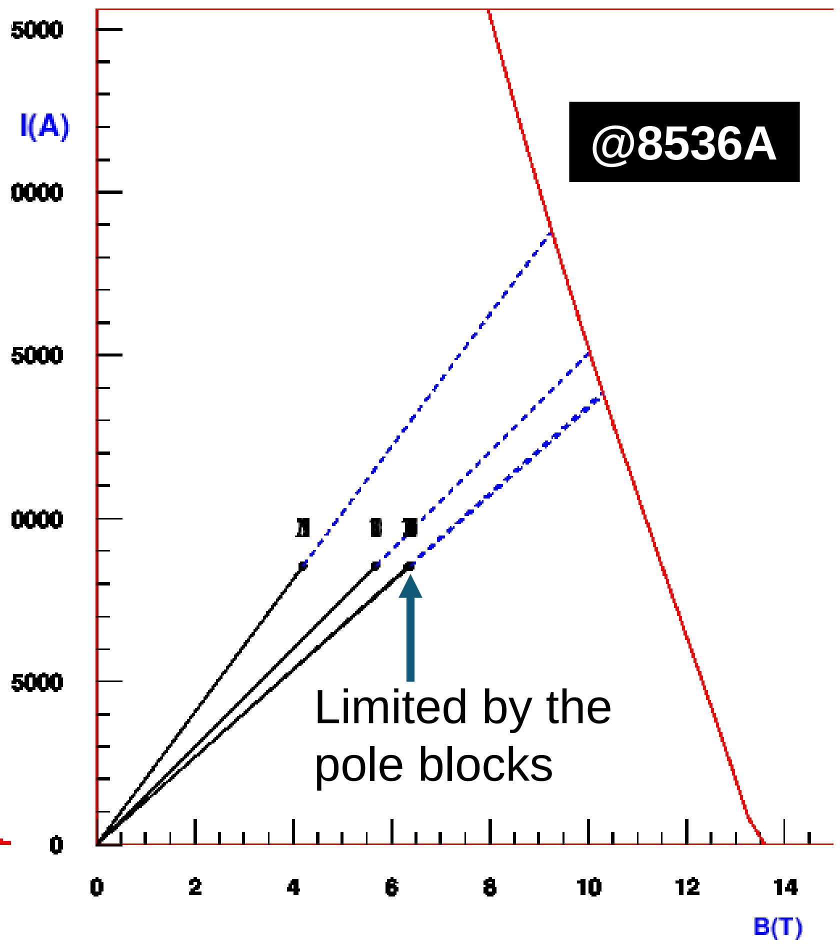


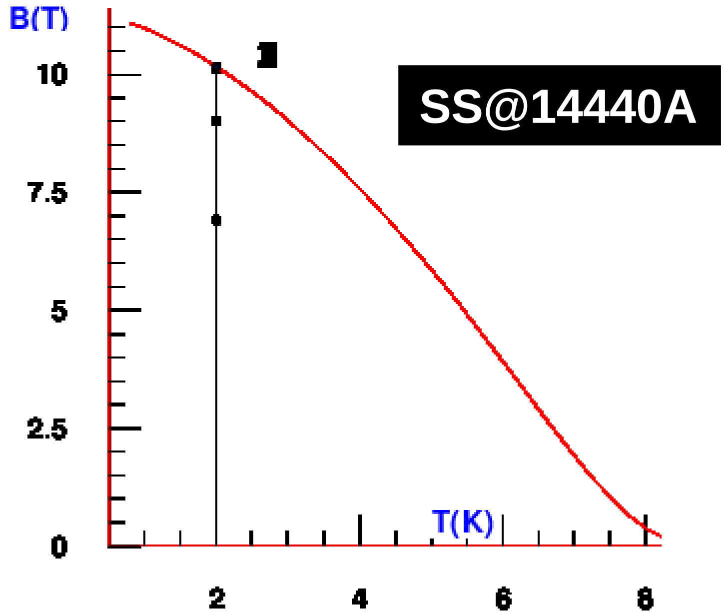
Design optimized to reduce peak field enhancement (max field on the cable over the field at midplane) to~18%

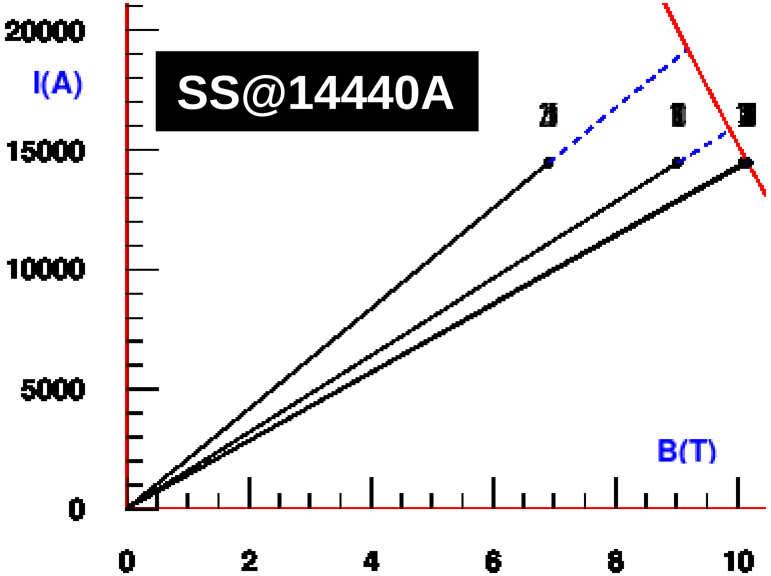
Margin on Load-line: 38%
Conventional definition (short sample over design): 56%

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









Temperature margin: 3.4 K

Load line margin: 38%

Field Harmonics at the Design Gradient

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MAIN HARMONIC .....................................          2
REFERENCE RADIUS (mm) .............................    83.0000
X-POSITION OF THE HARMONIC COIL (mm) ..............     0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..............     0.0000
MEASUREMENT TYPE ........................ ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................  0.9031E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) ....................................   3.170674
MAGNET STRENGTH (T/(m^(n-1)) ......................    38.2009

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
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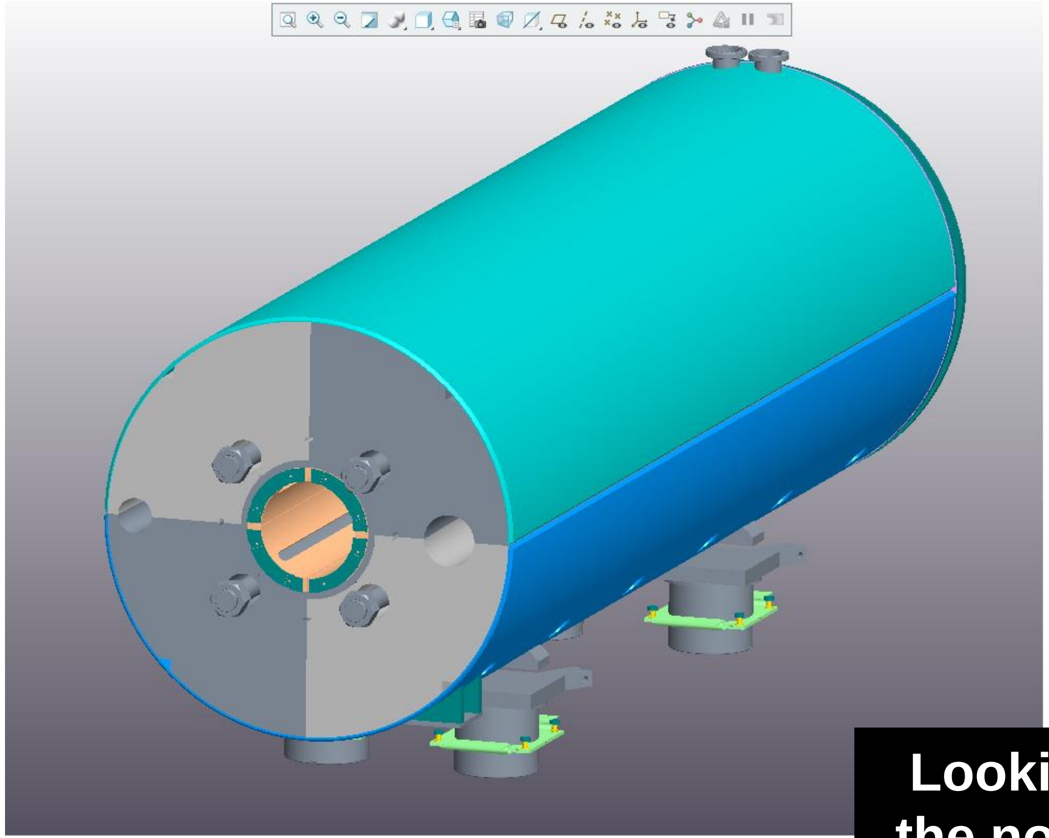
All harmonics <1 unit @ design

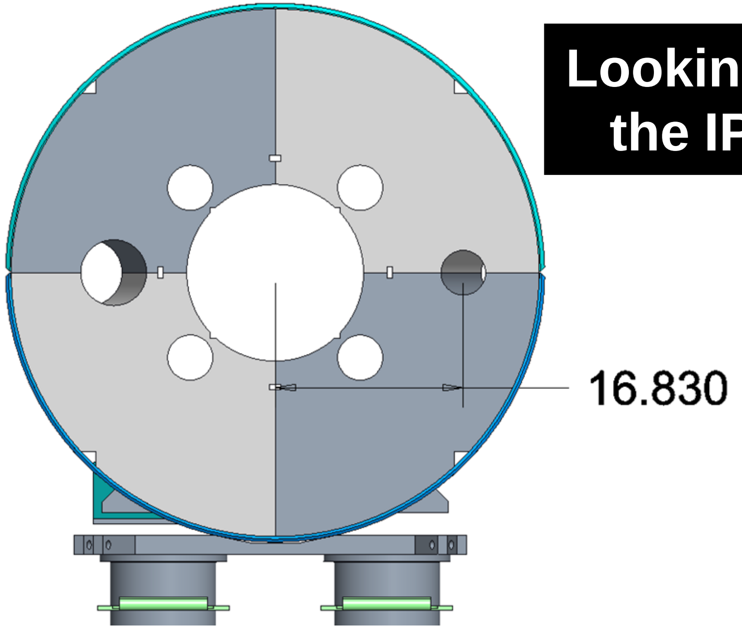
Yoke Optimization

- 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.
- Field in the hole (where electron beam traverses), must stay within acceptable limit. This requirement is specific to EIC.

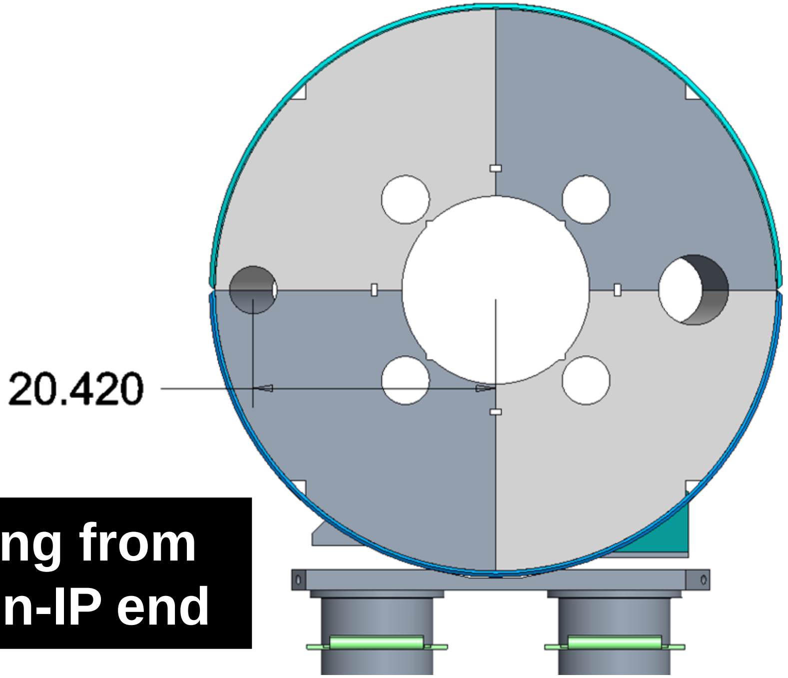
Yoke EM Design

Caution: This drawing does not match to the latest magnetic design (magnetic design to be presented is optimized to the latest parameters)





Looking from the IP end

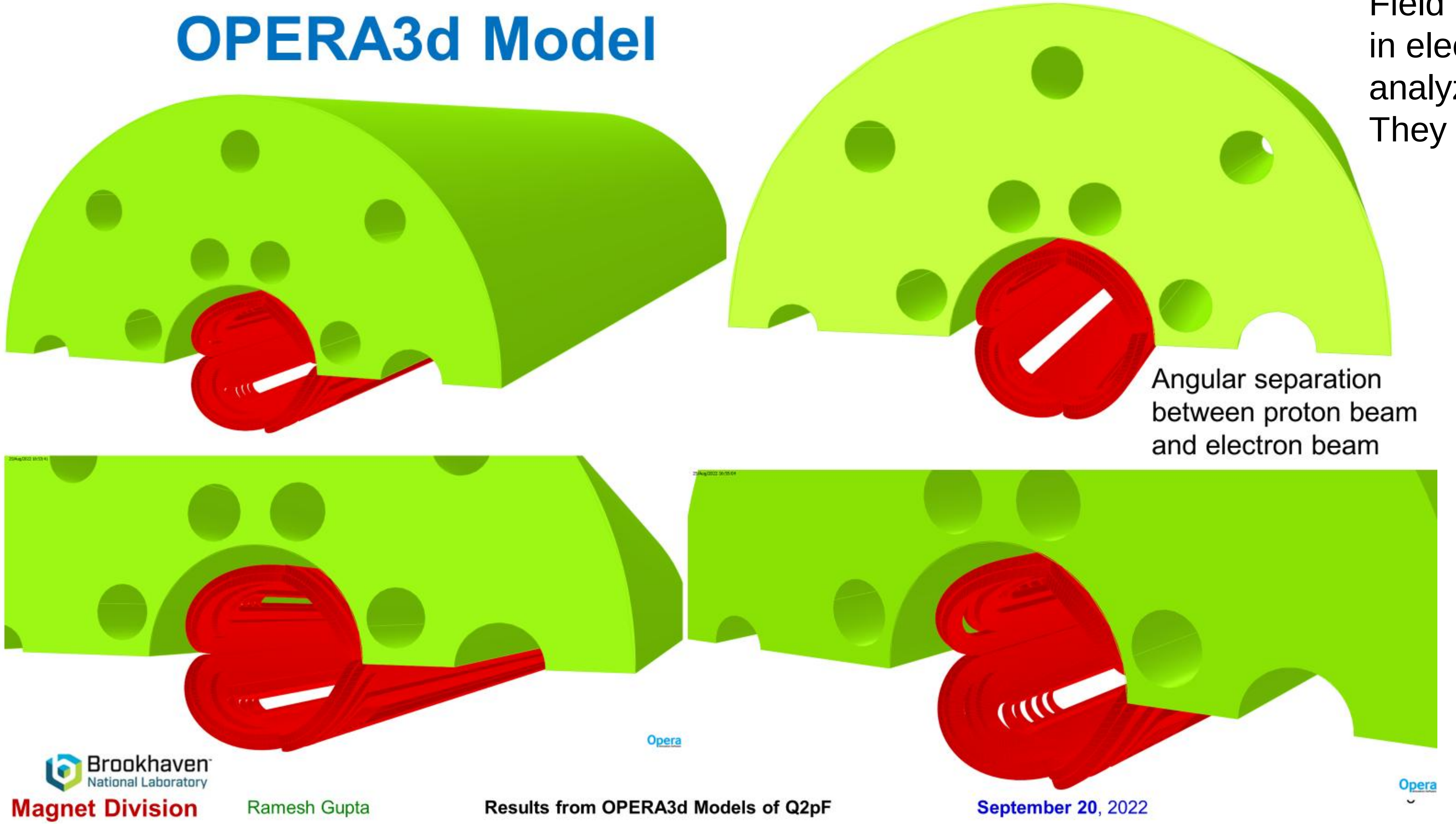


Looking from the non-IP end

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

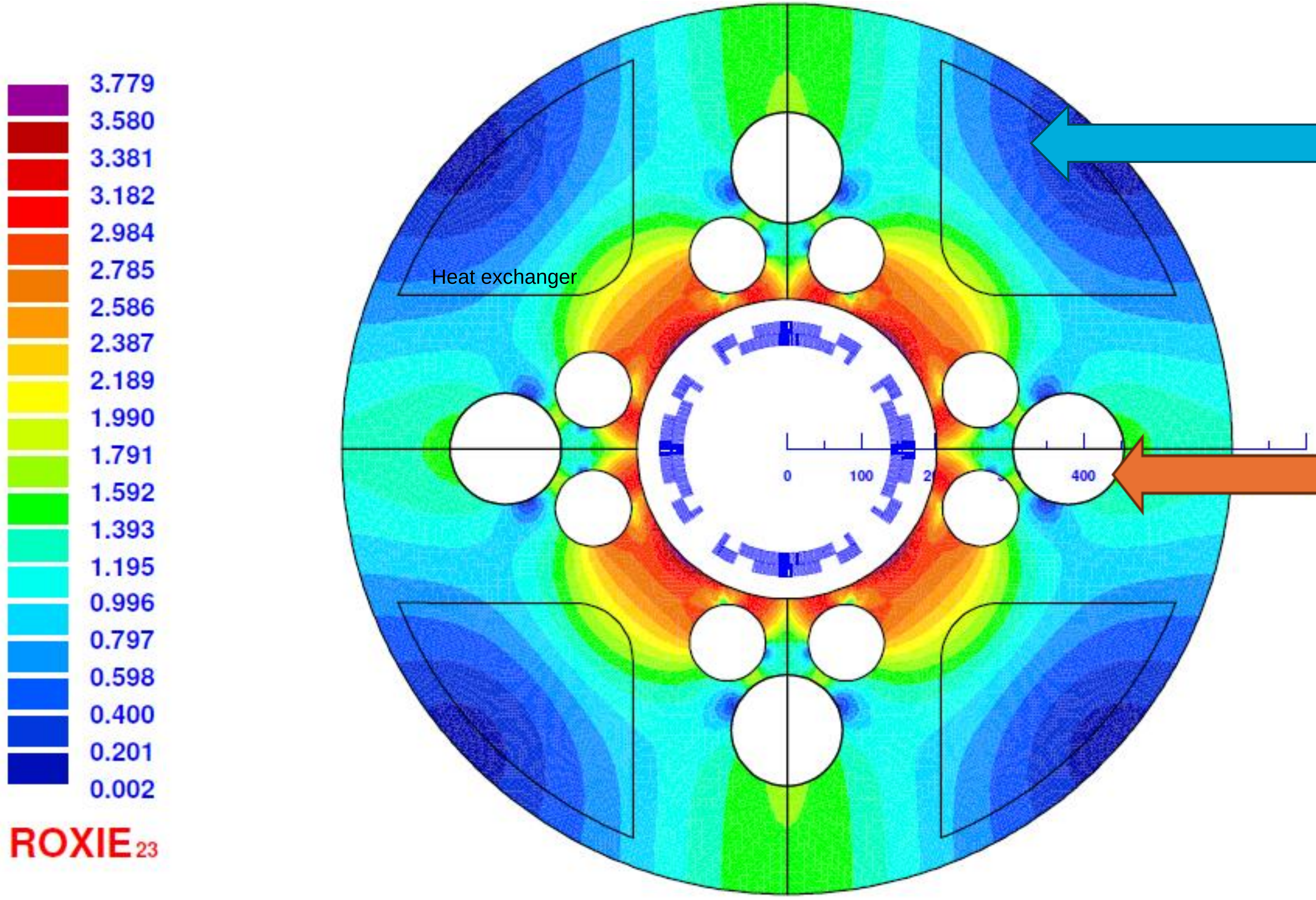
Yoke 3d design is then confirmed with the 3-d simulation with diverging cutouts.

EM 3-d yoke



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

Attempt to Reduce the Magnet Weight with a Lighter Yoke

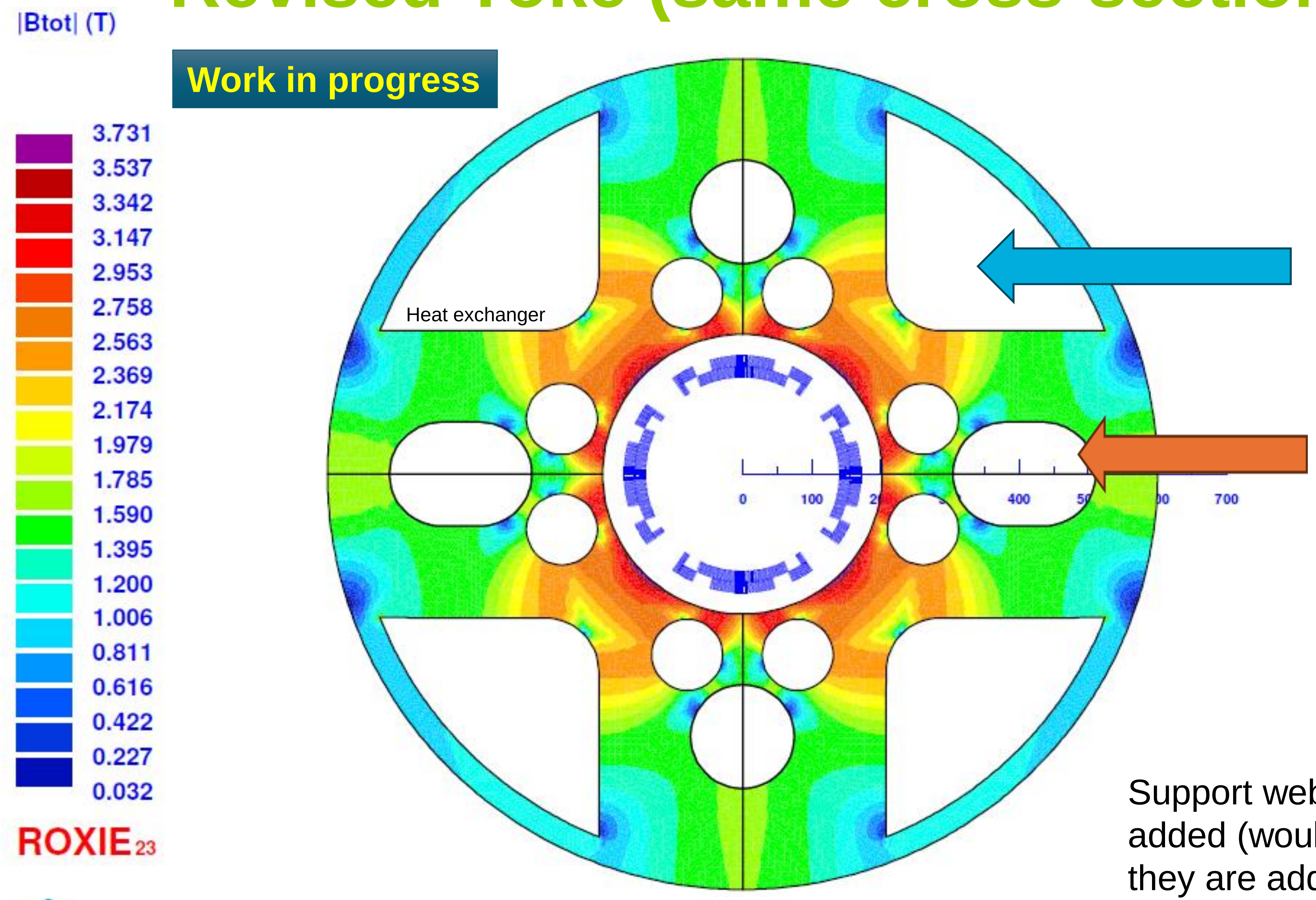


Remove iron from the areas where it is not saturated (includes heat exchanger)

Try to extend the e-holes further out (IP to Non-IP) so that the yoke has an identical x-section throughout

Revised Yoke (same cross-section end-to-end)

Work in progress

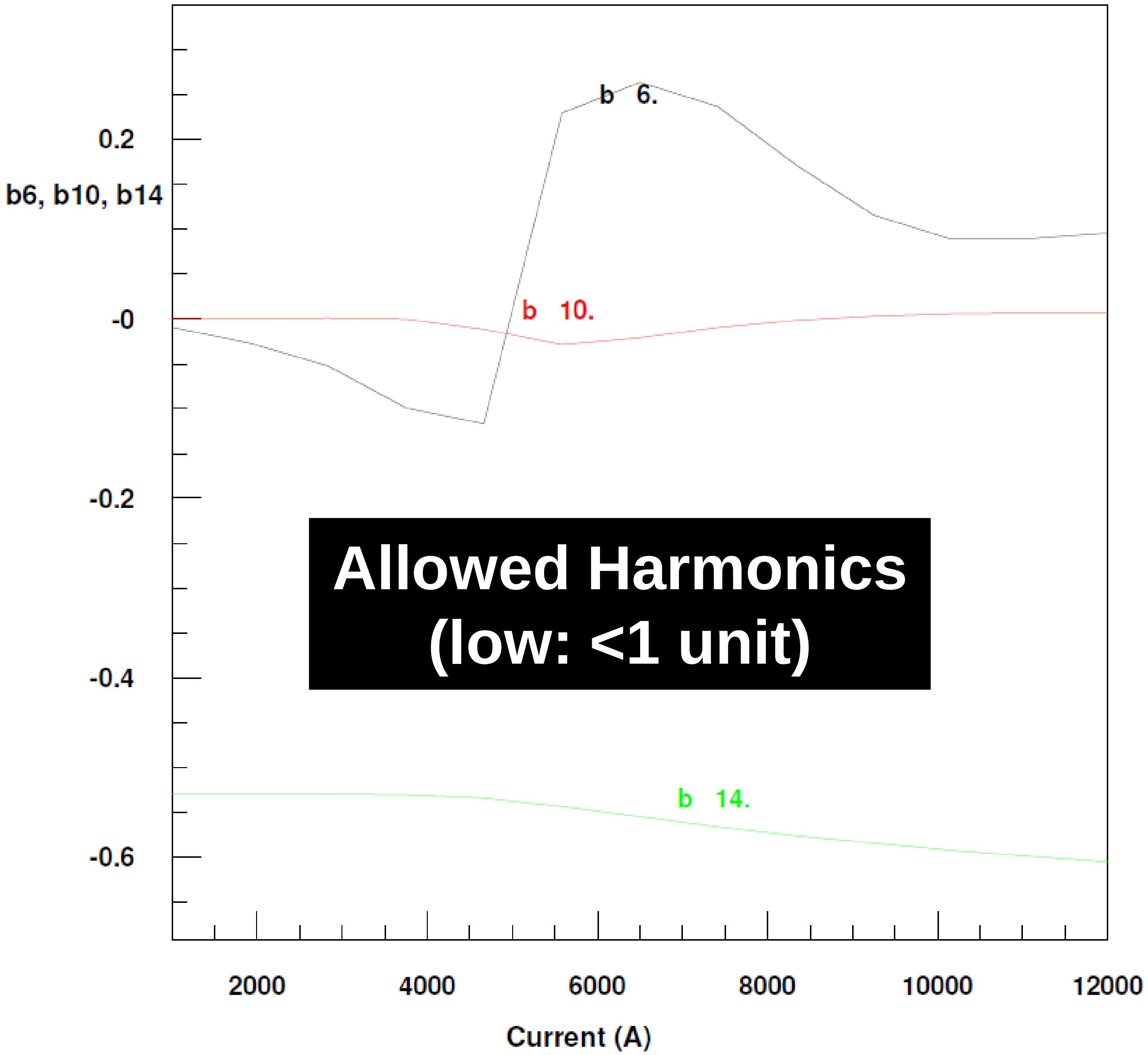


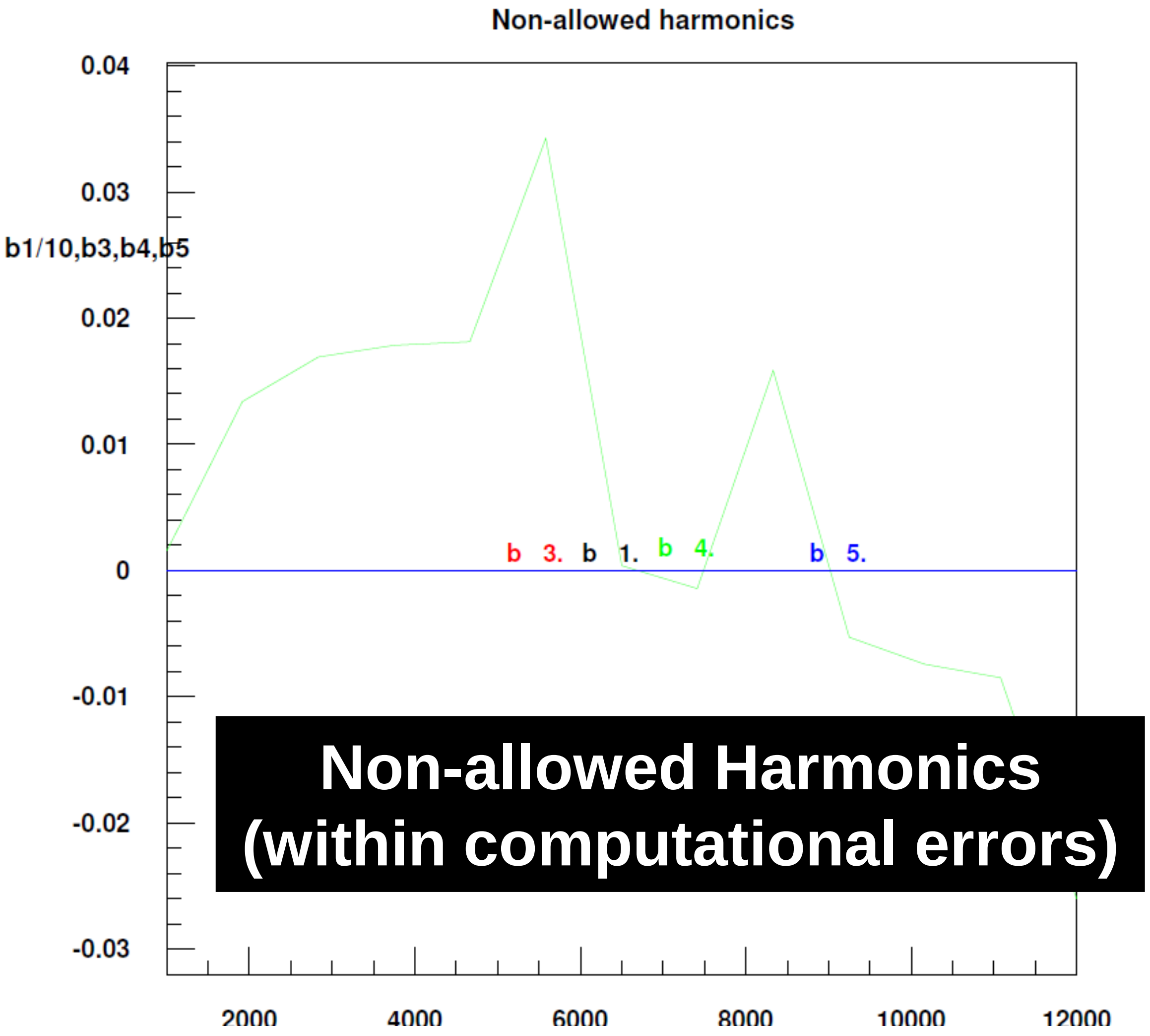
Iron removed to make yoke lighter

Holes extended so that a single yoke can be used throughout

Support web and rounded corner to be added (wouldn't change results much at they are added in low field region).

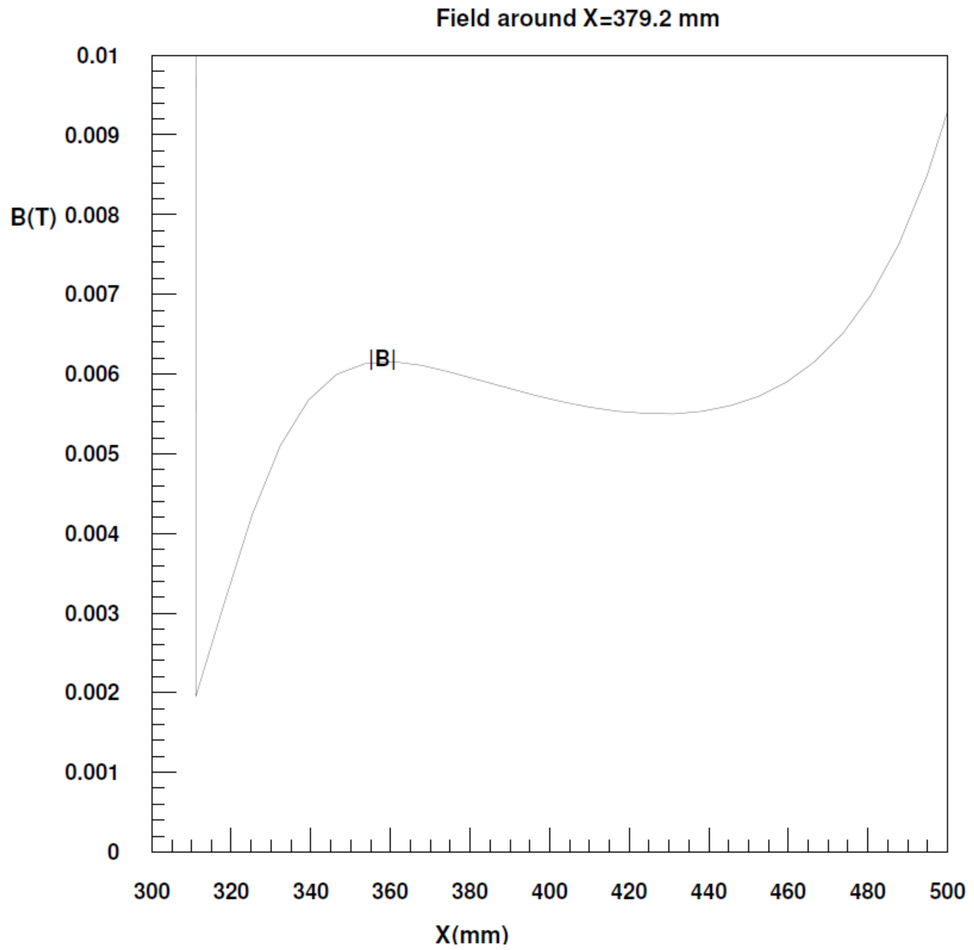
Current Dependence of Harmonics in Revised Yoke (remains good - low change in field harmonics)

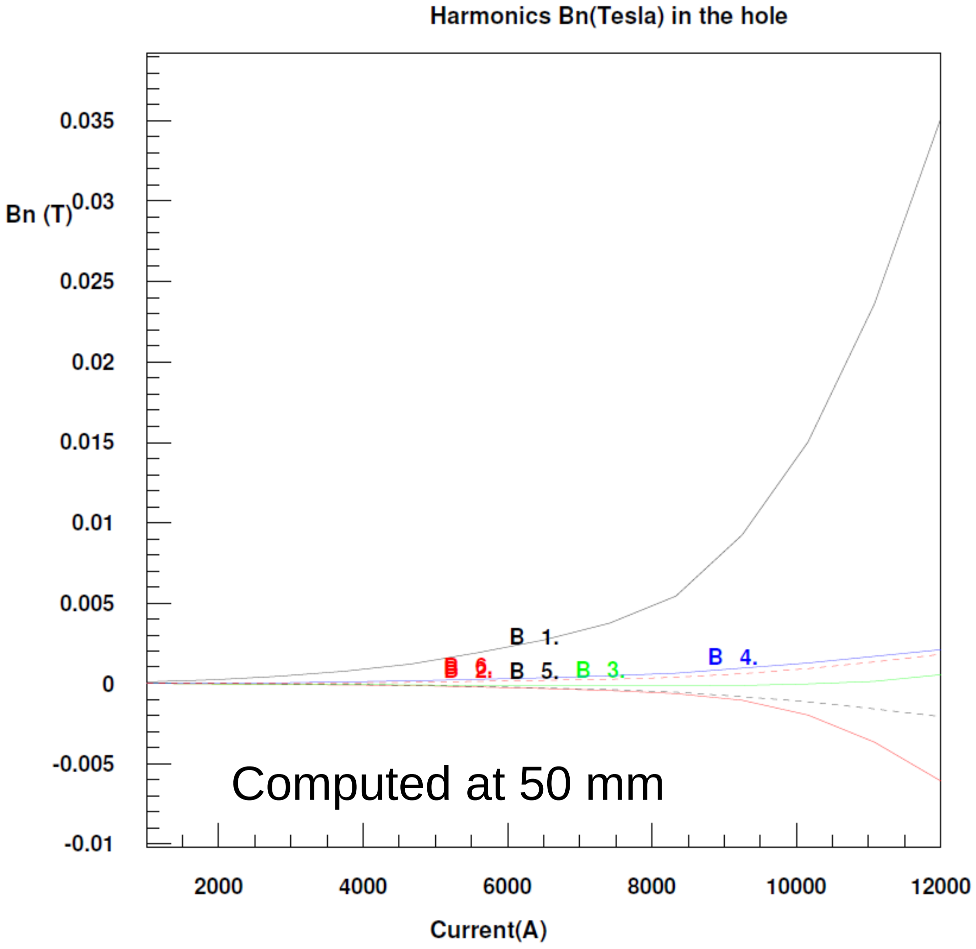




Field and field harmonics in Electron Hole (>1 mT, but not too high; requires some adjustment)

***Work in progress* (earlier designs had it <1 mT)**





End Design

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.

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:

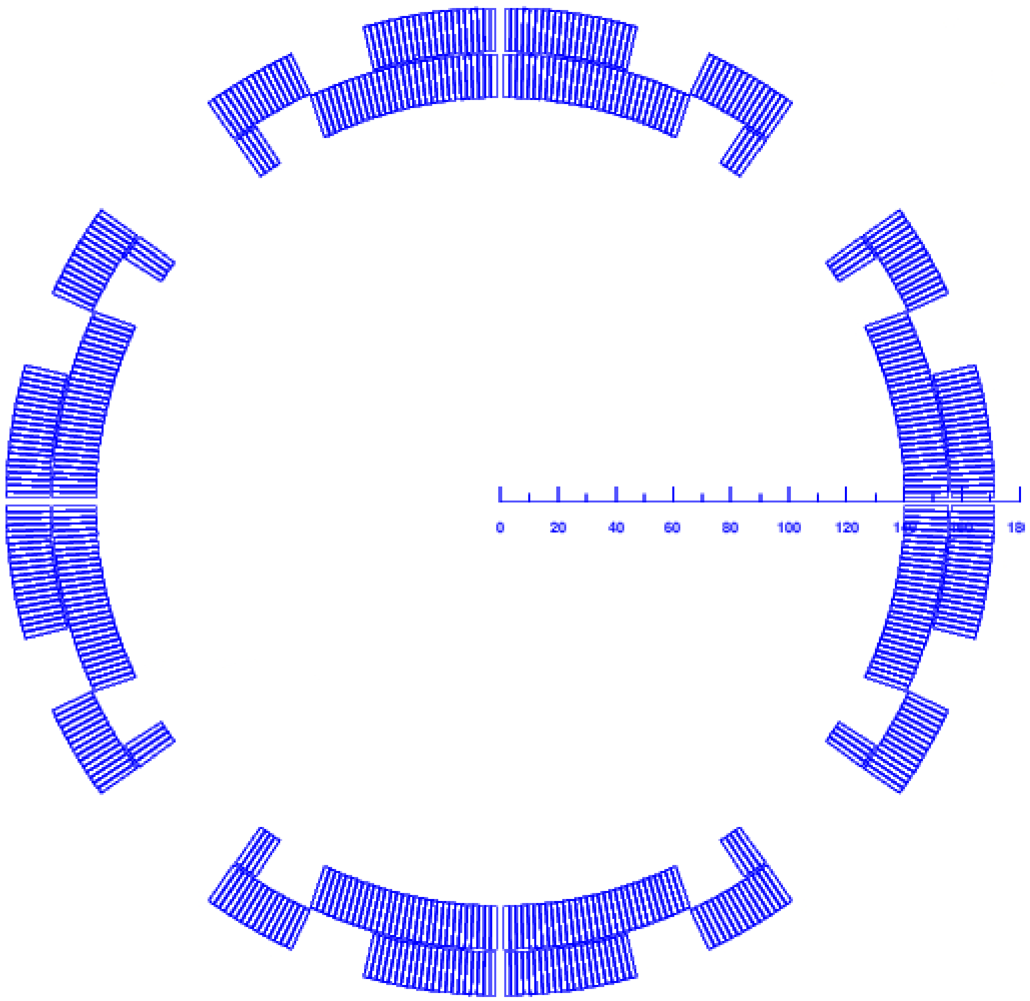
https://wpw.bnl.gov/rgupta/eic-q2pf-em/

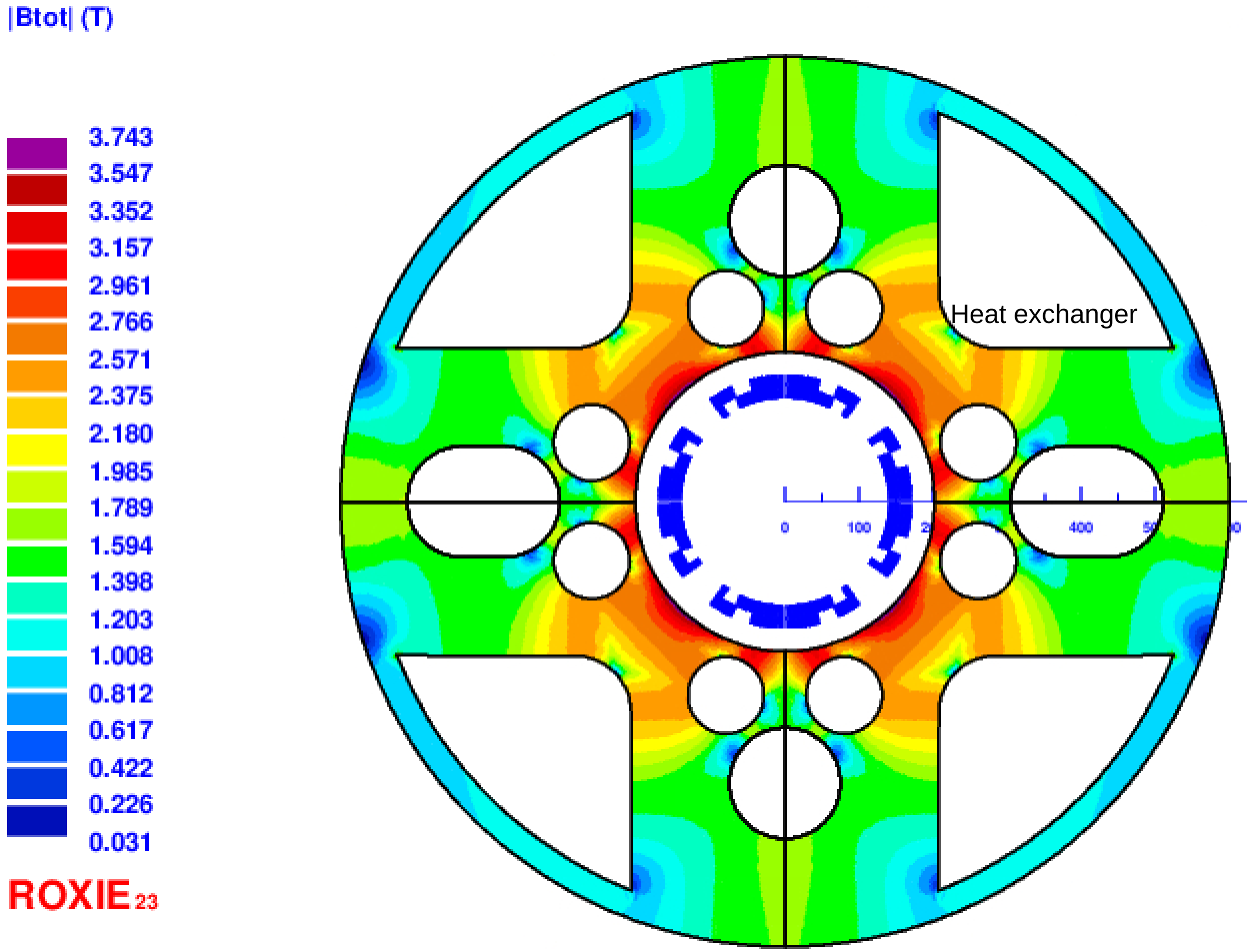
SUMMARY

- 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. Only the updates were presented today.
- 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 other EIC magnets as well.

Extra Slides

Overall Cross-section (coil and yoke)





- Large cutouts to reduce weight of the magnet
- Oblate hole at the midplane to allow using the same yoke despite e-beam traversing at an angle