Brookhaven National Laboratory

Jefferson Lab

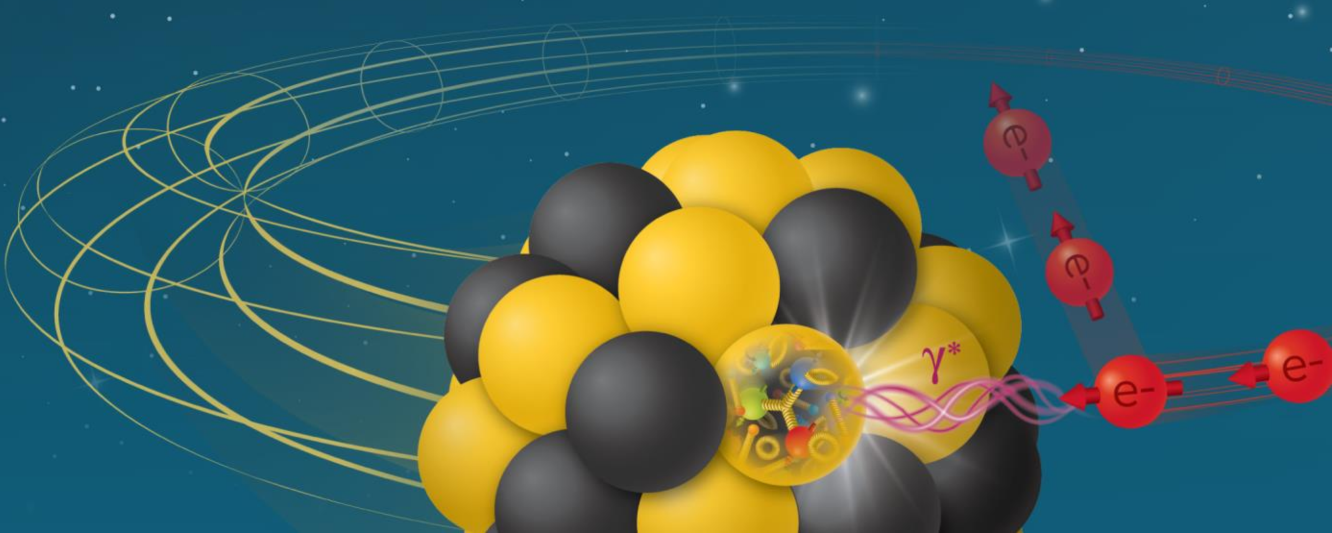
U.S. DEPARTMENT OF ENERGY

Status of Q2PF Quad EM Design

Ramesh Gupta

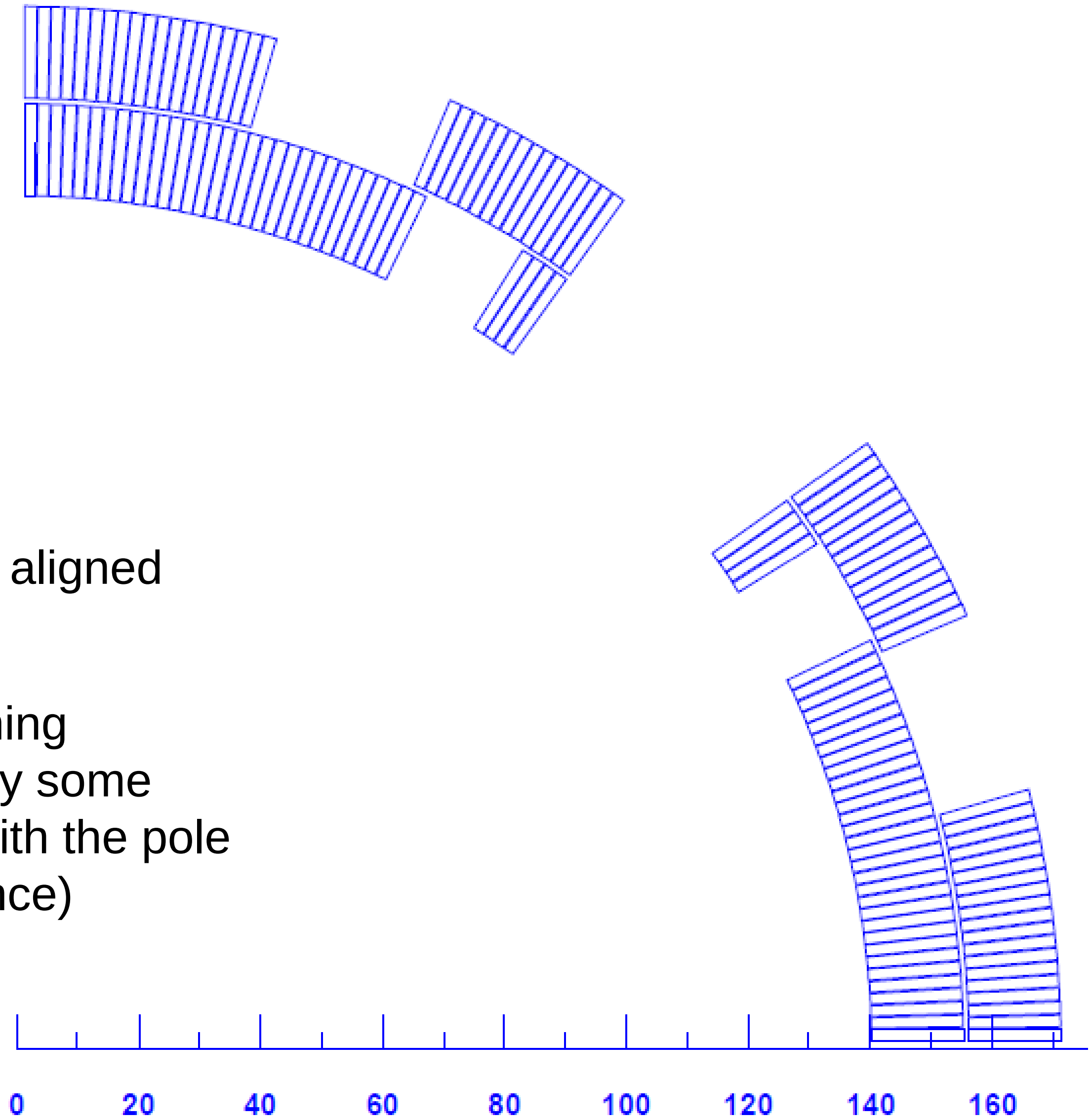
Meeting with Fermilab on Options for EIC SC Forward Quadrupoles

April 18, 2024



Electron-Ion Collider

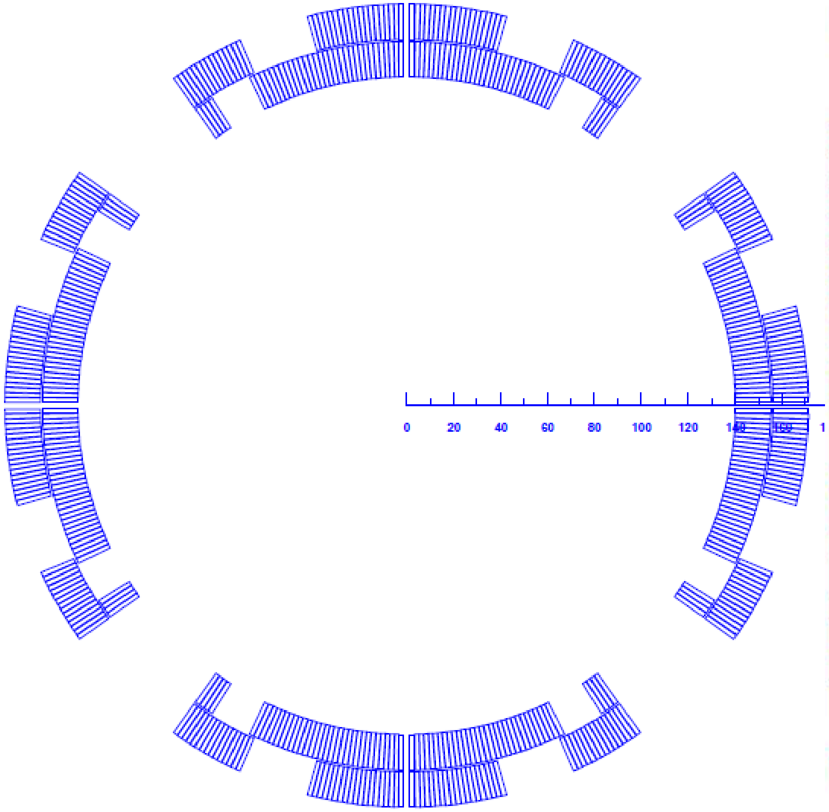
Q2pF Coil Cross-section

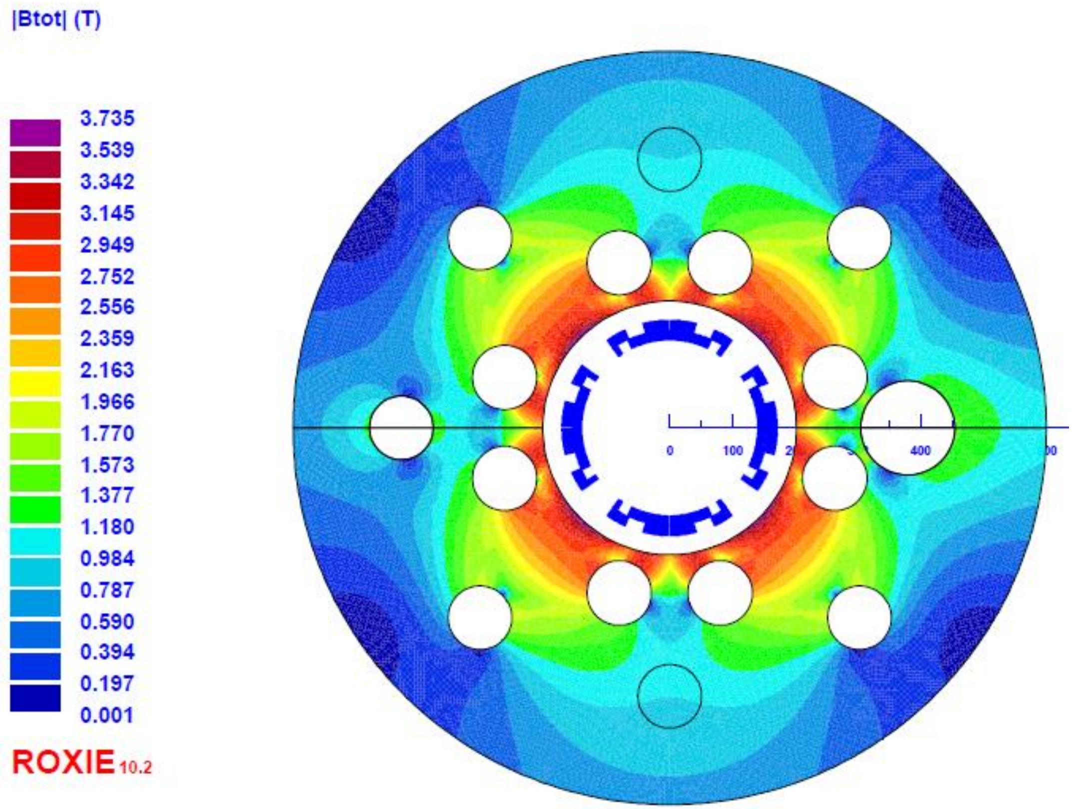


Main Features:

- Two layers, 69 turns
- Only one wedge in each layer
- Poles of Outer and Inner layers aligned
- Symmetric wedges
- Significant midplane gap for tuning allowed harmonics, and possibly some non-allowed also, when used with the pole shims (RHIC and SSC experience)

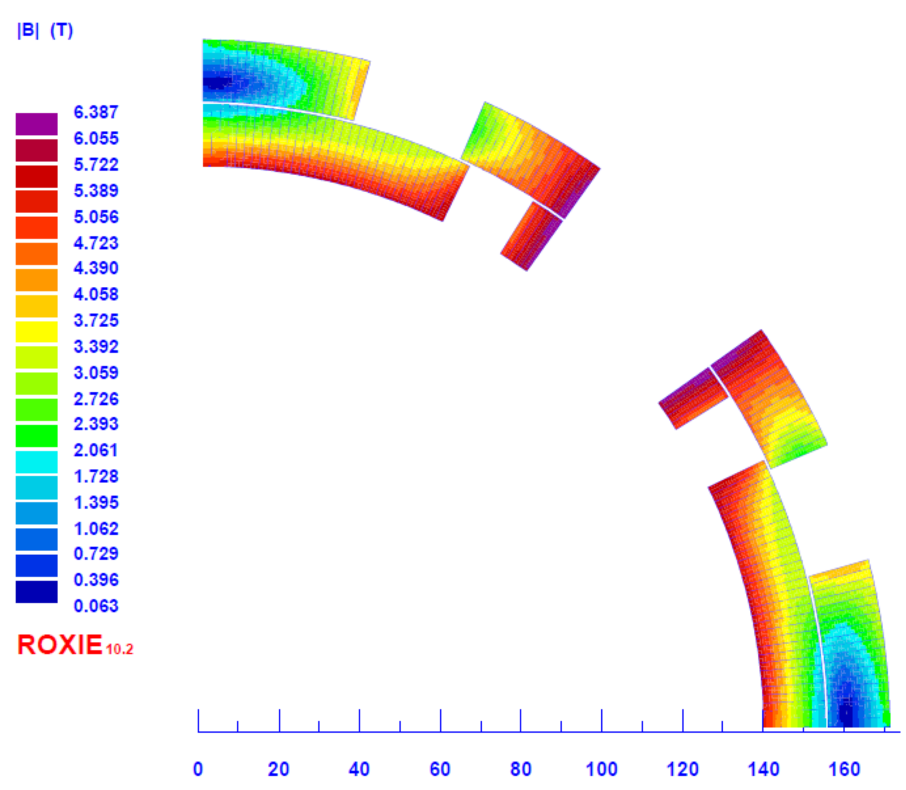
Coil and Yoke Cross-section

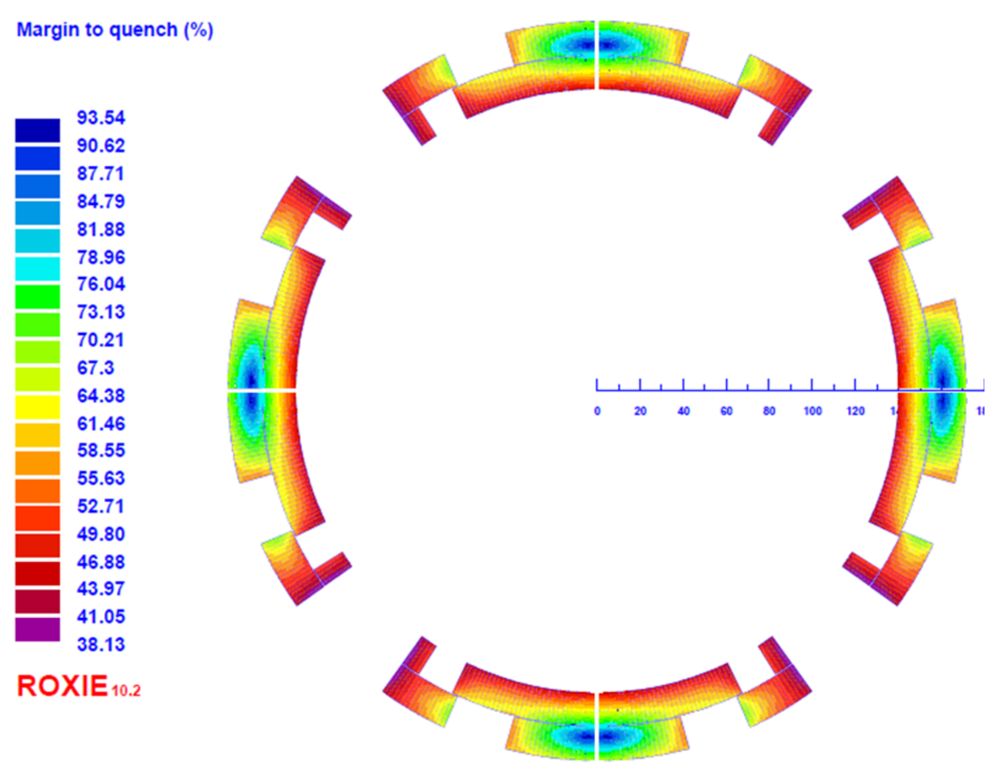




Electron-Ion Collider

Peak Field and Margin



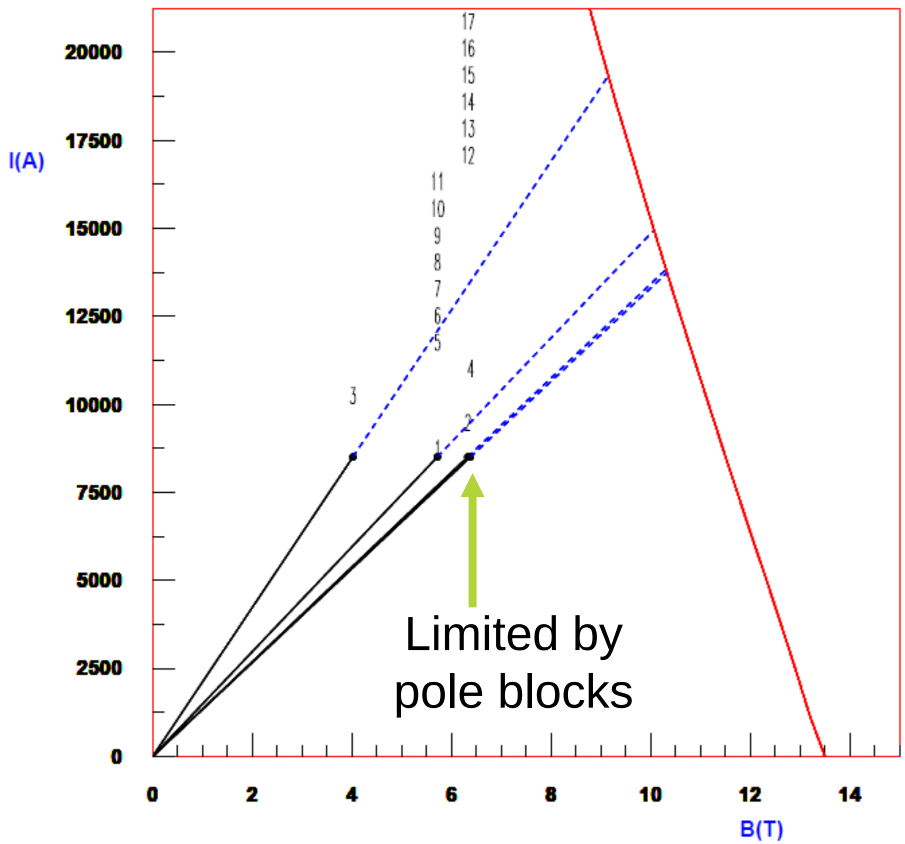


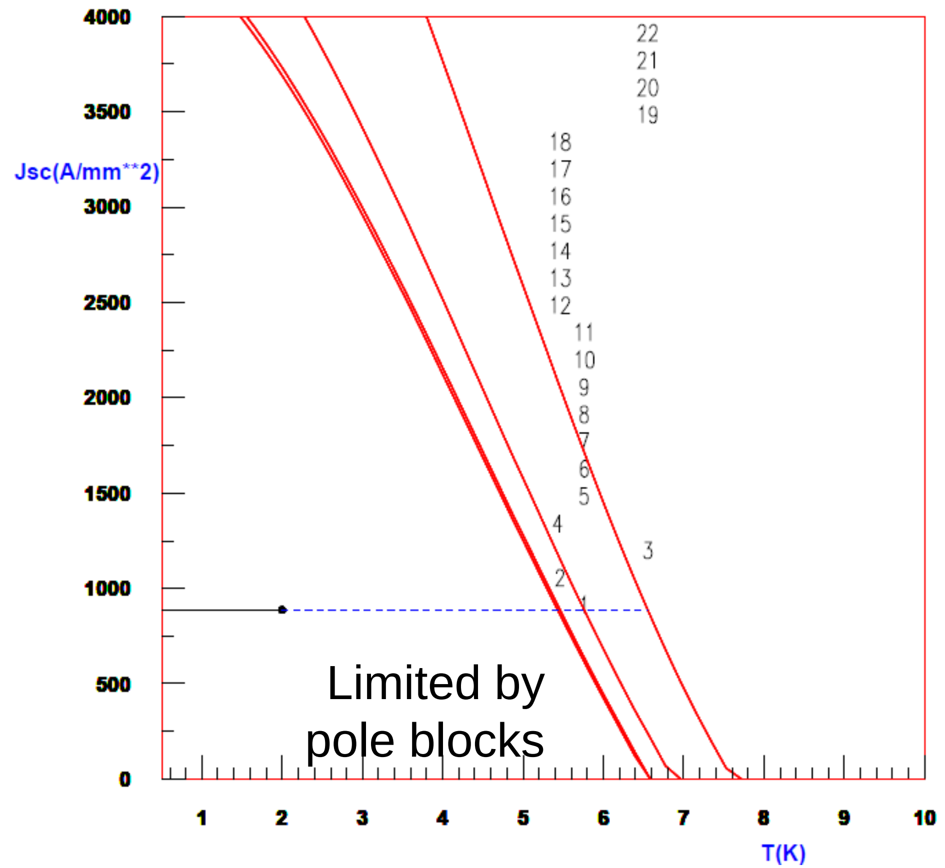
Design gradient reached at ~8.5 kA

Peak field Enhancement: 18%
(max field over the midplane field)

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

Field and Temperature Margins
(in individual blocks)





Quench margins in the body of the magnet

Field Harmonics at the Design Field

```
HARMONIC ANALYSIS NUMBER ...............................          1
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 ...................    0.9964E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) .........................................   3.176139
MAGNET STRENGTH (T/(m^(n-1)) ...........................    38.2667

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:     -0.30804  b 2:  10000.00000  b 3:      0.06621
b 4:     -0.02748  b 5:     -0.02339  b 6:      0.21543
b 7:     -0.00139  b 8:     -0.00180  b 9:     -0.00012
b10:      0.03688  b11:     -0.00009  b12:     -0.00000
b13:      0.00001  b14:     -0.29429  b15:      0.00000
b16:      0.00000  b17:      0.00000  b18:     -0.00151
```

All harmonics < 1 unit

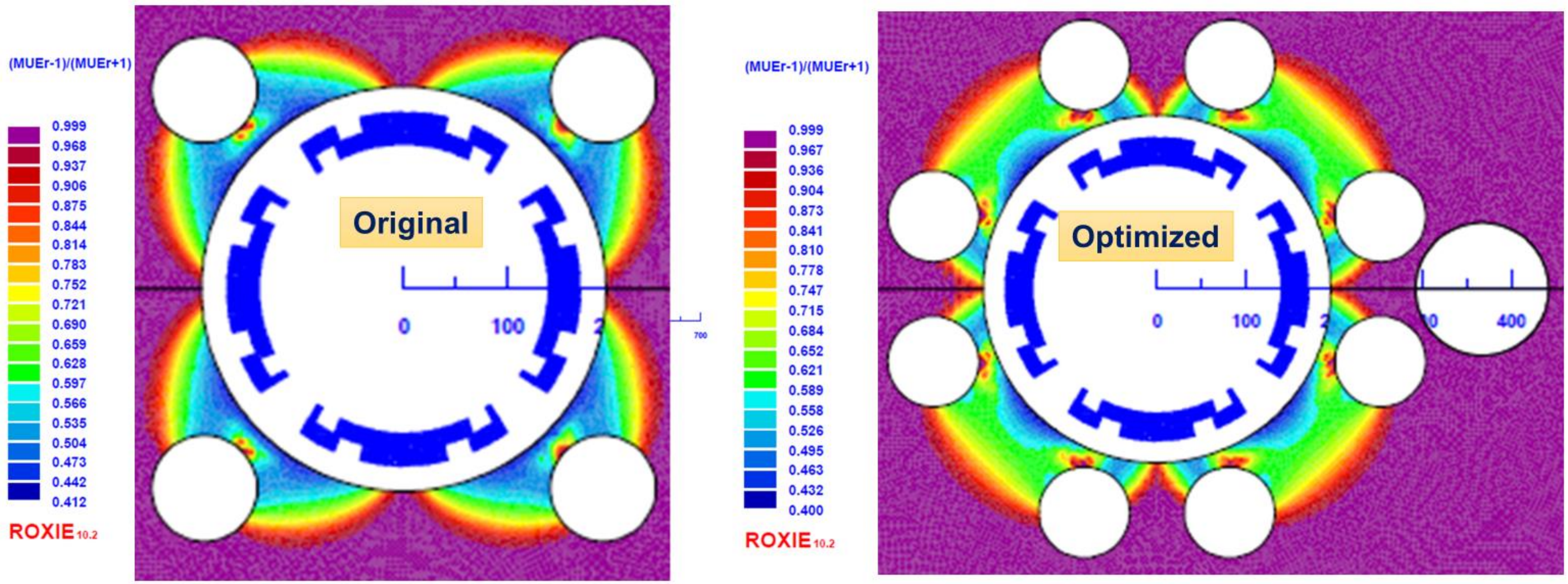
Yoke Optimization for EIC Magnets

- Yoke must be optimized to make sure that field harmonics due to iron saturation, don't get out of specifications through-out the range of operation.
- Fringe field in the hole (where electron beam traverses), stays within acceptable limit. This is not common in other colliders, but critical for EIC, and is expected to be worse at high fields.

EM Yoke Optimization (1)

Holes for Tie Rods – Turning them in to an opportunity

- Strategy: Large holes for tie rods clearly make a significant impact on iron saturation. Let's try to make use of those large holes as a tool of opportunity!



Note: $(\mu-1)/(\mu+1)$ in the yoke near i.r. has now become more uniform

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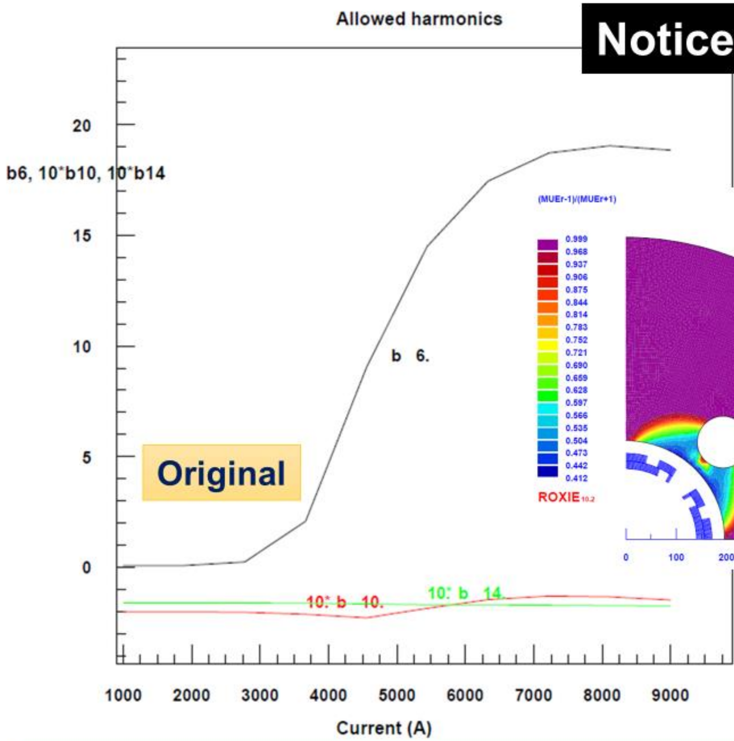
Tie rods are strategically placed to control saturation

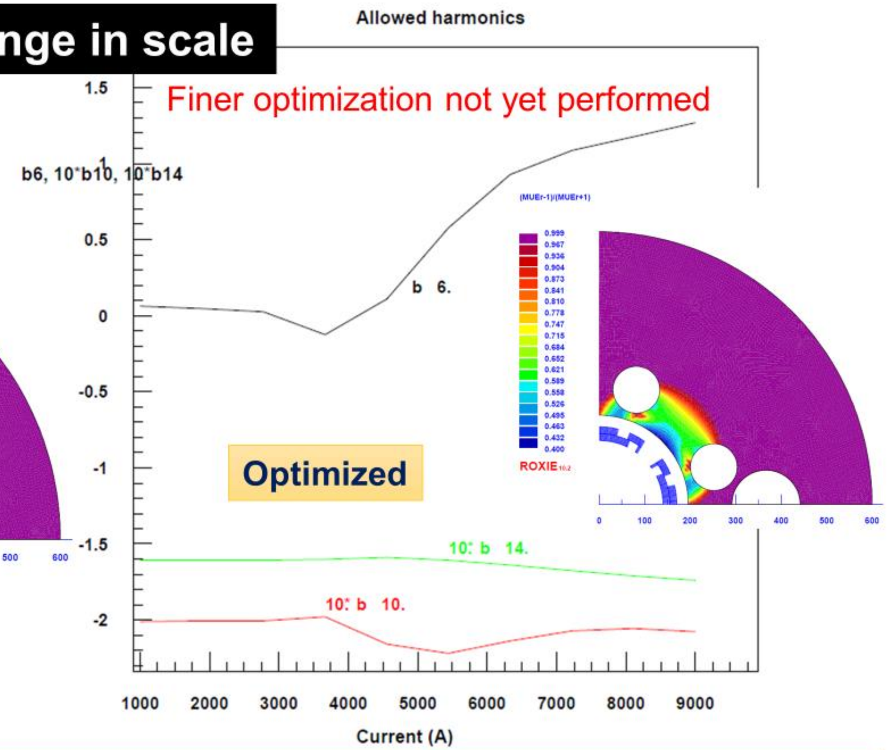
Electron-Ion Collider

EM Yoke Optimization (2)

Tie Rods to Reduce Saturation-induced Harmonics

Notice a change in scale





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)

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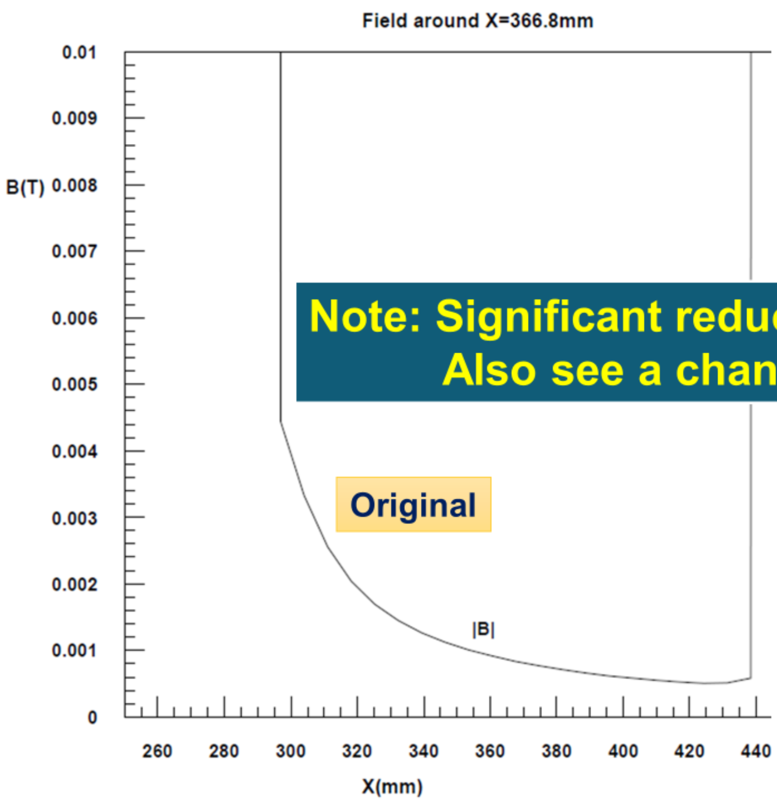
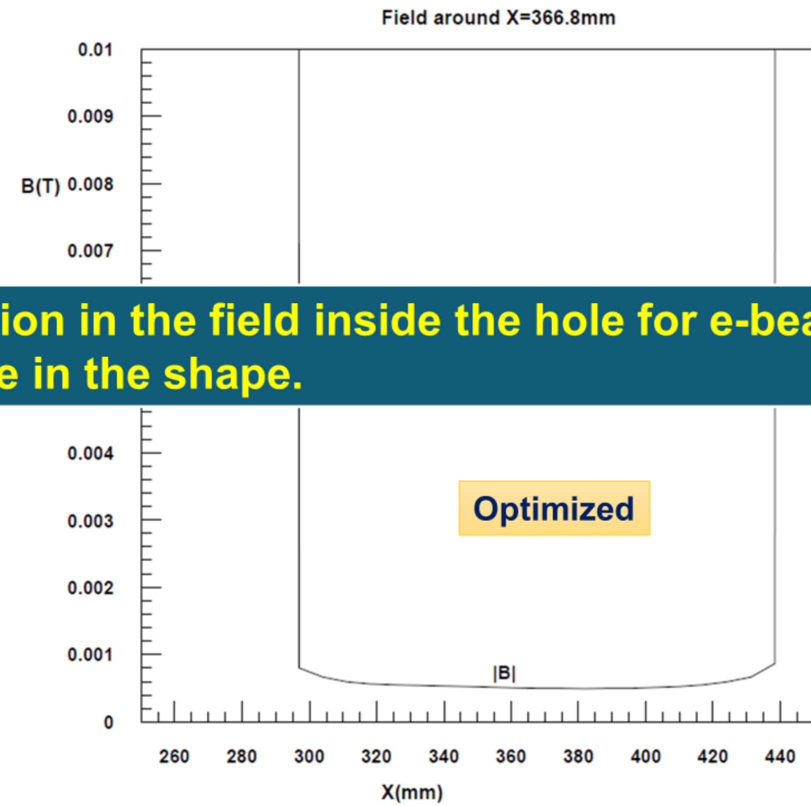
A large reduction in saturation induced b_6

Electron-Ion Collider

EM Yoke Optimization (3)

The location and size of holes for tie rods is used to divert field away from the electron beam hole





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

Uniform field brings a much larger reduction in B_n's

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

Evaluation of the impact of the fringe field on the electron beam from the nearby hadron magnets

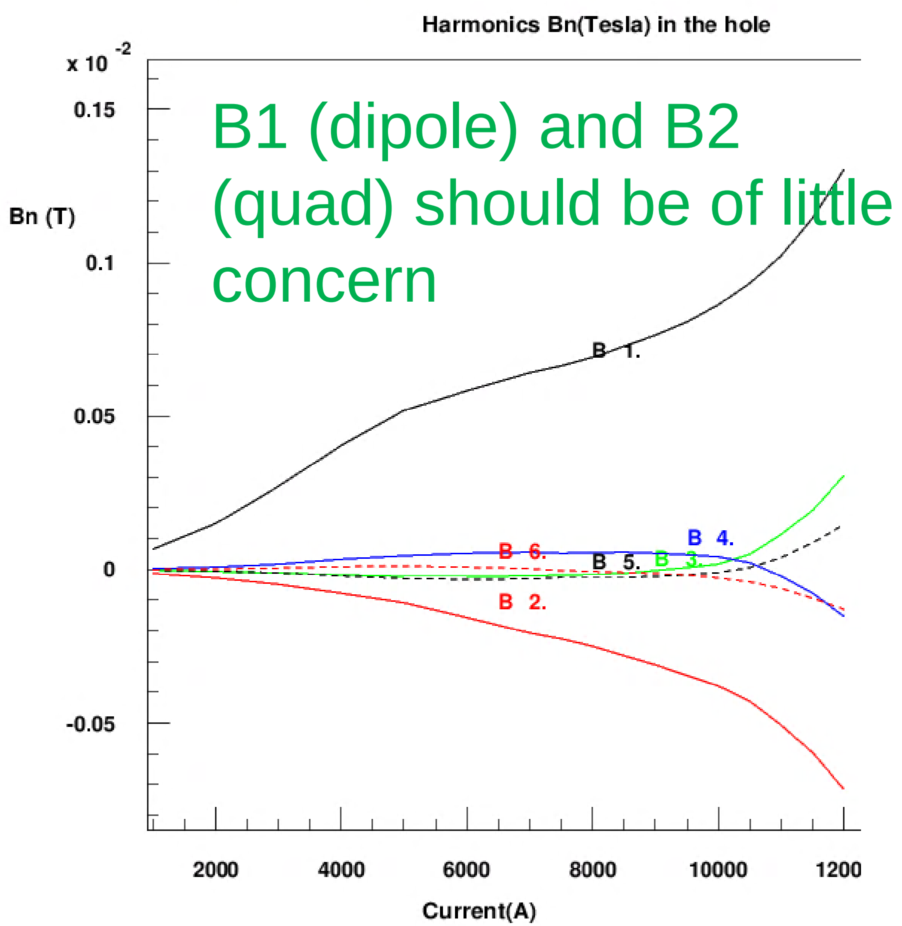
- Current approach is to make the fringe field below the earth's magnet field.
- Shouldn't this be evaluated as the harmonic errors?
- Otherwise, we may be putting unnecessarily stringent requirements on the magnets and infrastructure cost.

➢ Suggestion: Study the beam dynamics impact of the computed error harmonics on the electron beam from the excitation of the nearby hadron magnet.

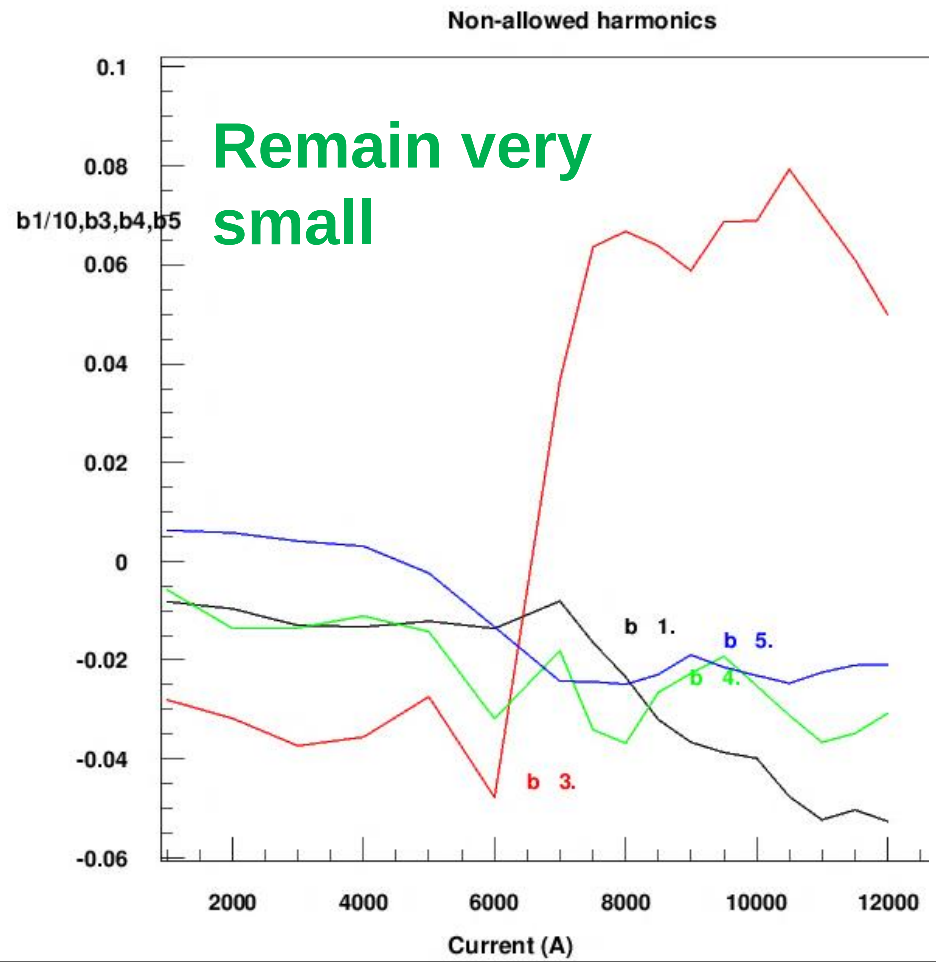
➢ There are other sources and ways to deal with small field or field gradient

Cross-talk in the current design of Q2pF

Cross-talk for electron beam (harmonics are in Tesla.unit)



Cross-talk for hadron beam (harmonics normalized to quad field)

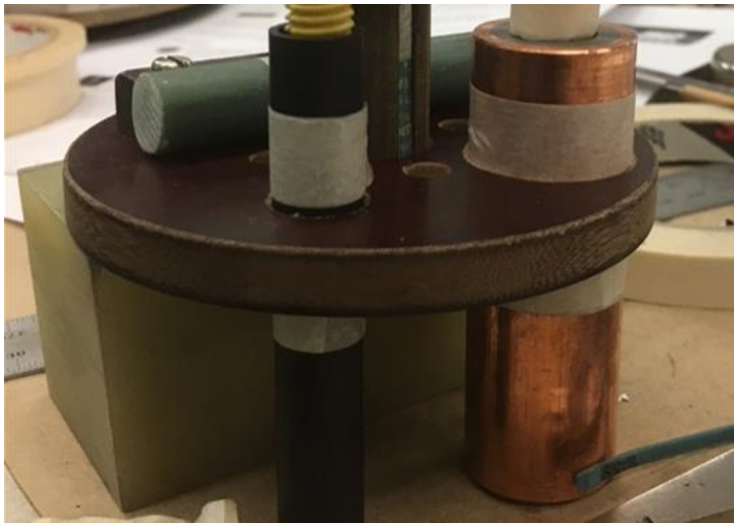


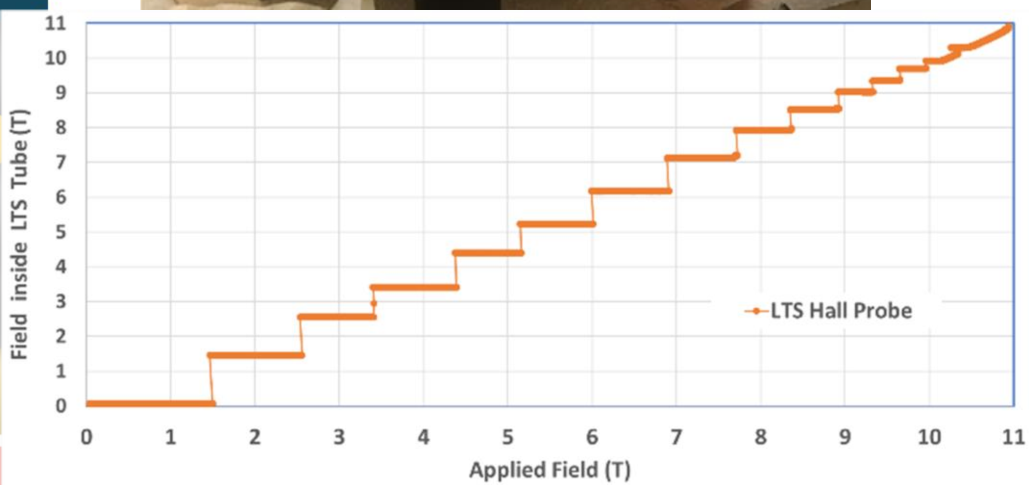
Design current: ~8500 A, error harmonics remain small 30% above that

Superconducting Shield for electron Beam (1)

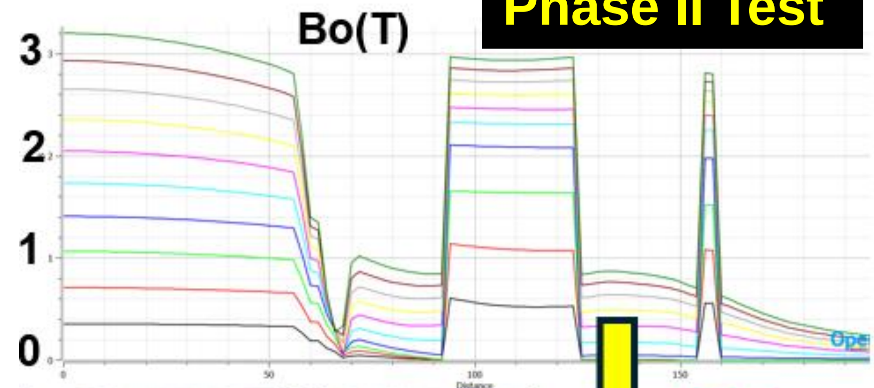
*Work supported by two Phase I SBIR/STTR and one Phase II, specifically for EIC

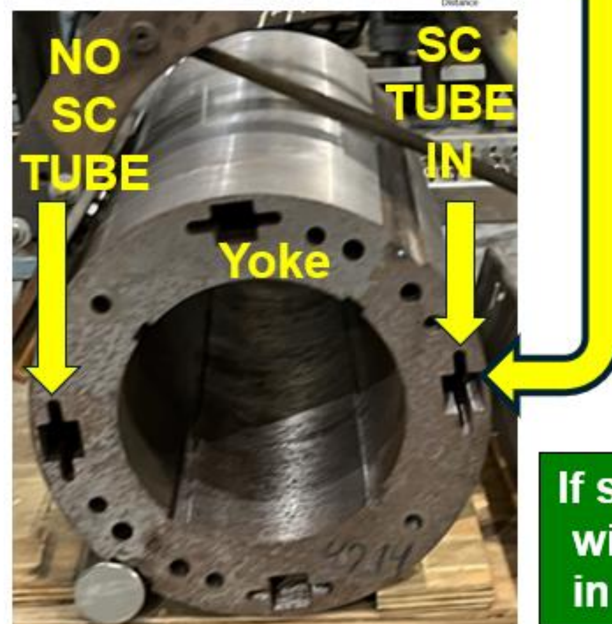
Demo of SC Shielding in Phase I





Phase II Test





If SC shield works, field in this cutout should become zero!

If successful, will be used in Phase IIA

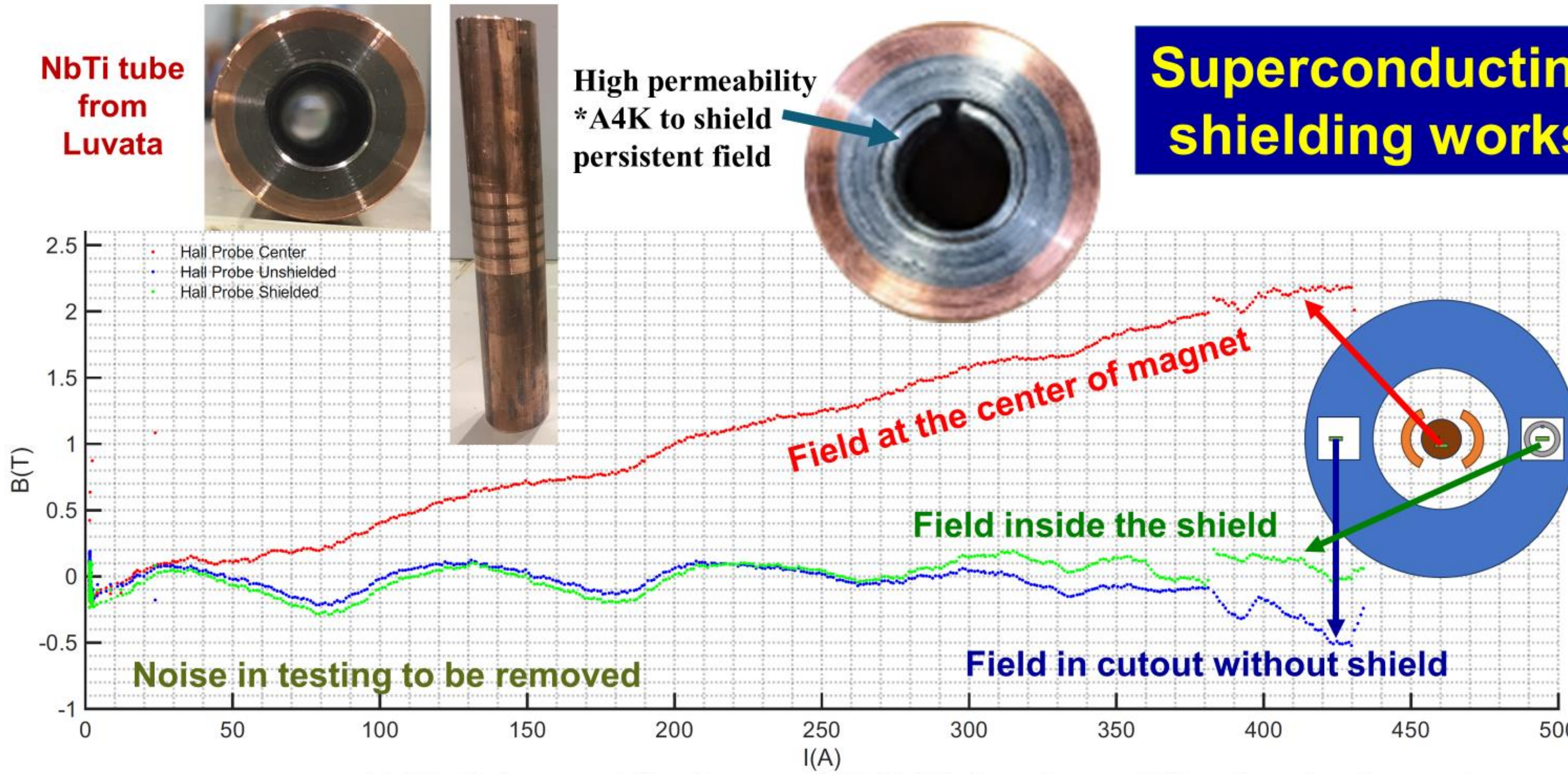
Compare the fields in two cutouts: one without SC shield, another with shield

Superconducting Shield for electron Beam (2)

*Work supported by two Phase I SBIR/STTR and one Phase II, specifically for EIC

Demonstration of Superconducting Shielding in a Phase II Magnet

Demonstration of Superconducting Shielding (with Additional A4K)



*A4K: High permeability Amumetal 4K (A4K) from Amuneal Manufacturing Corporation

Brookhaven National Laboratory Magnet Division

PBL

Ramesh Gupta for PBL/BNL Team, A Novel, Medium-field Optimum Integral Dipole, MT-28

Electron-Ion Collider

Slides on the End design

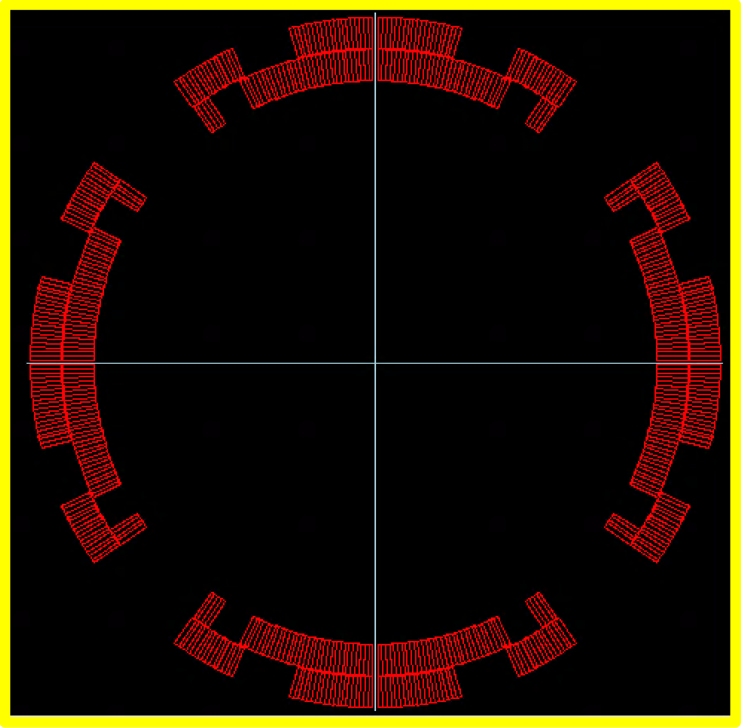
(if time permits)

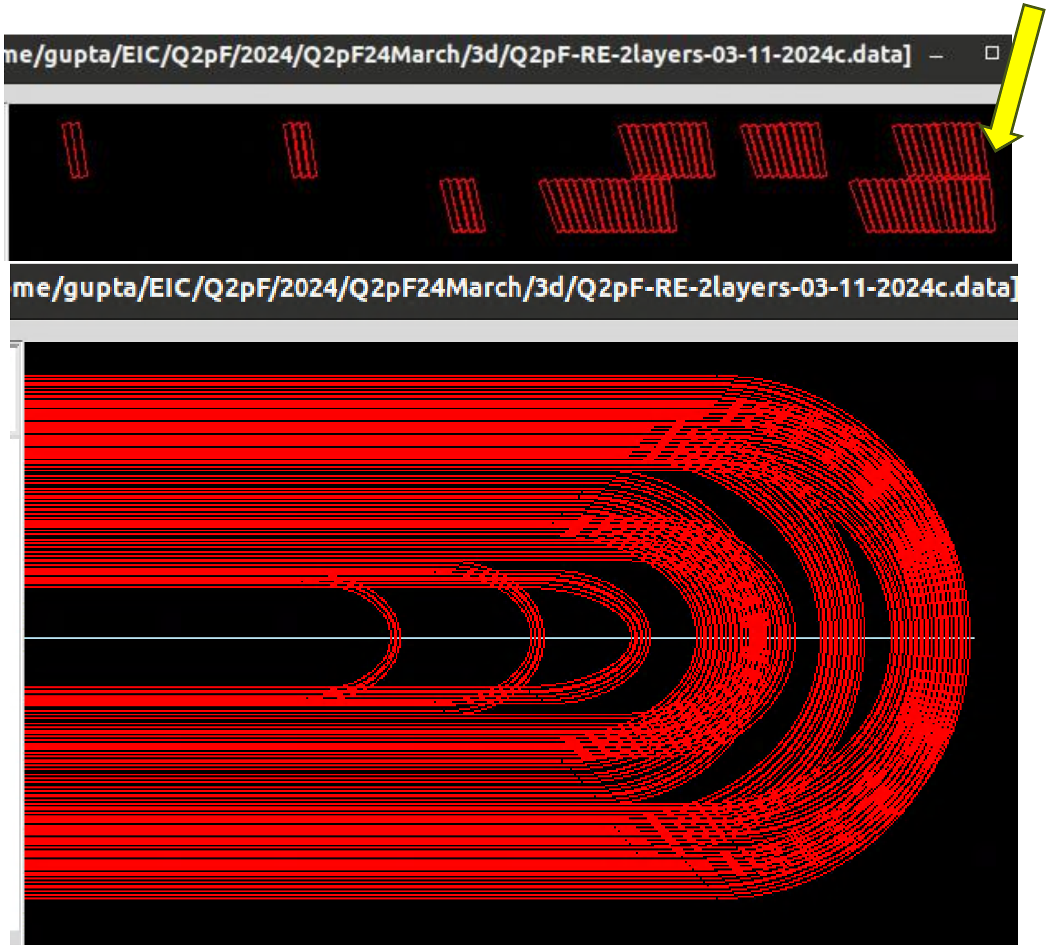
Strategy for Optimizing Layout of Turns in EIC Magnet

- EIC IR cable magnet coils have much larger aperture than that in typical NbTi accelerator magnets
- Therefore, the criterion or optimization methods used in designing ends of previous cable magnets (as in ROXIE or bend or in earlier BNL design), may not be valid.
- This was realized early in the program, and a single turn winding test with similar cable was planned for an initial check.
- A request was made to CERN for leftover LHC cable (same width but a slightly different keystone). CERN provided. THANKS.
- Single turn winding tests were performed for B1pF. It was found that it is best to use ROXIE for creating layout of turns in the ends, but not for optimizing as they produce excessive tilt.
- A similar strategy is being followed on all EIC cable magnets.

Return End (min tilt angle 70°)

- **End turns of the outer layer and the inner layers aligned**





Peak Field Enhancement in the Ends

End configuration iterated for smaller peak fields in the ends. Final optimization after the winding trials.

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 (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
```

Turn #34 is the pole turn in the outer layer

Integrated harmonics (3-d) in the Return End

End configuration for lower integrated harmonics in the ends.

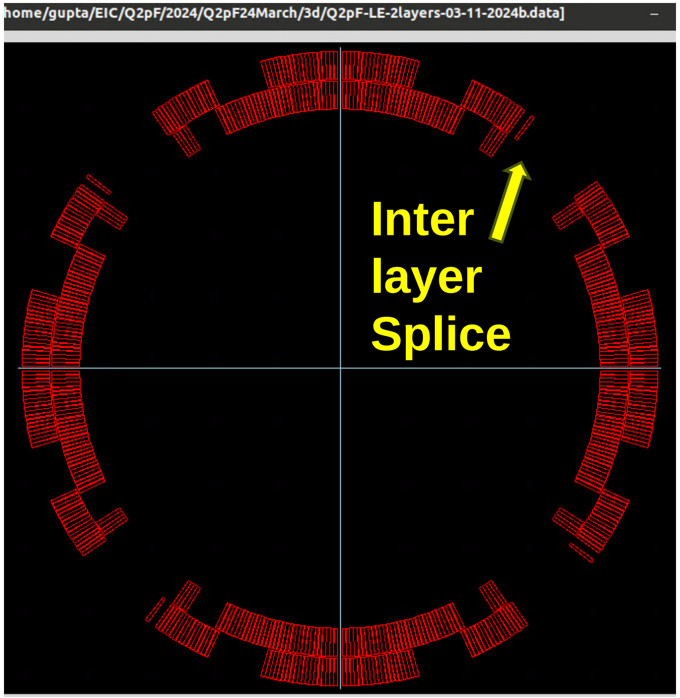
```
HARMONIC ANALYSIS NUMBER ..........................             1
MAIN HARMONIC .....................................             2
REFERENCE RADIUS (mm) .............................       83.0000
X-POSITION OF THE HARMONIC COIL (mm) ..............        0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ..............        0.0000
NUMBER OF ANALYSES ALONG Z ........................           200
LENGTH OF VIRTUAL COIL (mm) .......................     5000.0000
REFERENCE POSITION NUMBER .........................           100
MEASUREMENT TYPE ......................... ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................    0.7379E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

3D REFERENCE MAIN FIELD (T) .......................       -3.4447
REFERENCE MAGNET STRENGTH (T/(m^(n-1)) ............      -41.5020
MAGNETIC LENGTH (mm) ..............................     3449.5399

NORMAL 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):
b 1:      0.00000  b 2: 10000.00000  b 3:     -0.00000
b 4:      0.00000  b 5:     0.00000  b 6:     -0.34649
b 7:     -0.00000  b 8:    -0.00000  b 9:     -0.00000
b10:     -0.02086  b11:     0.00000  b12:      0.00000
b13:     -0.00000  b14:    -0.27946  b15:     -0.00000
b16:     -0.00000  b17:     0.00000  b18:     -0.00529
```

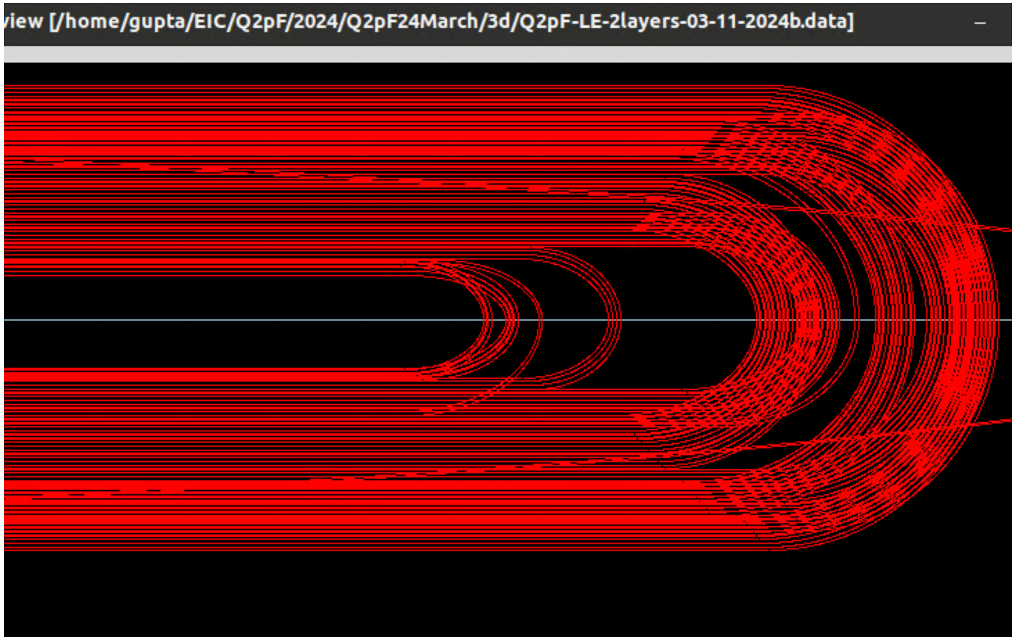
A reasonable end design:

- **All integrated field harmonics are well within 1.**
- **Final optimization to be performed after the winding trials and with non-linear iron.**

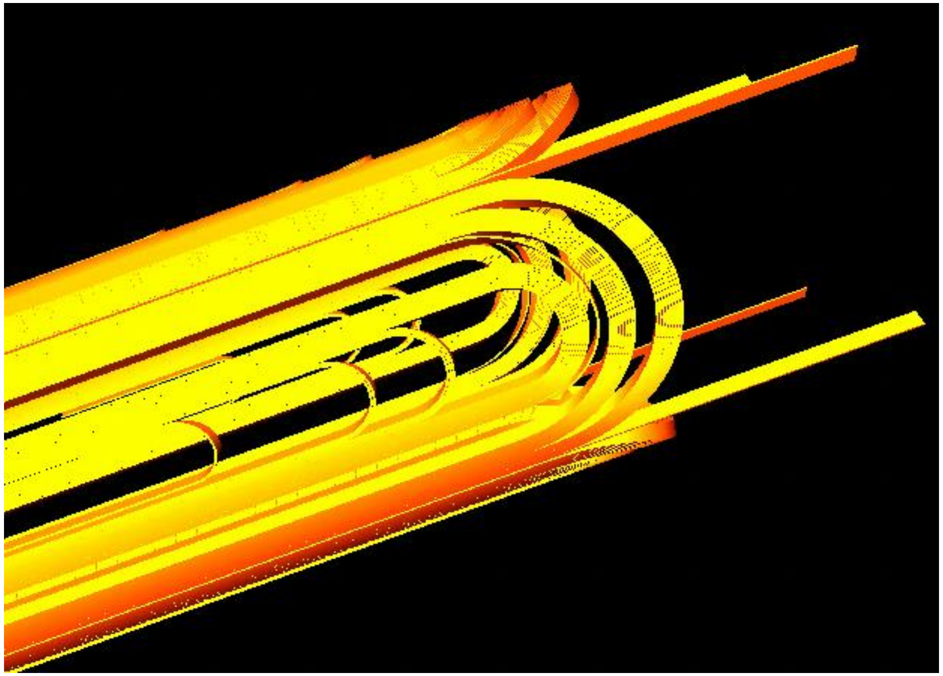
Lead End (min tilt angle 70º)

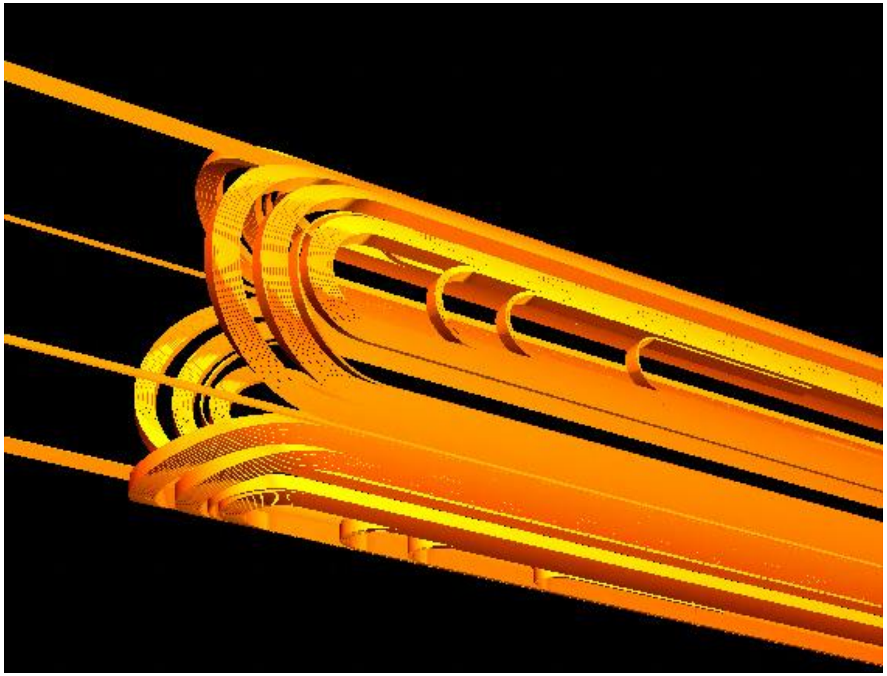
➢ **End turns of the outer layer and the inner layers aligned**





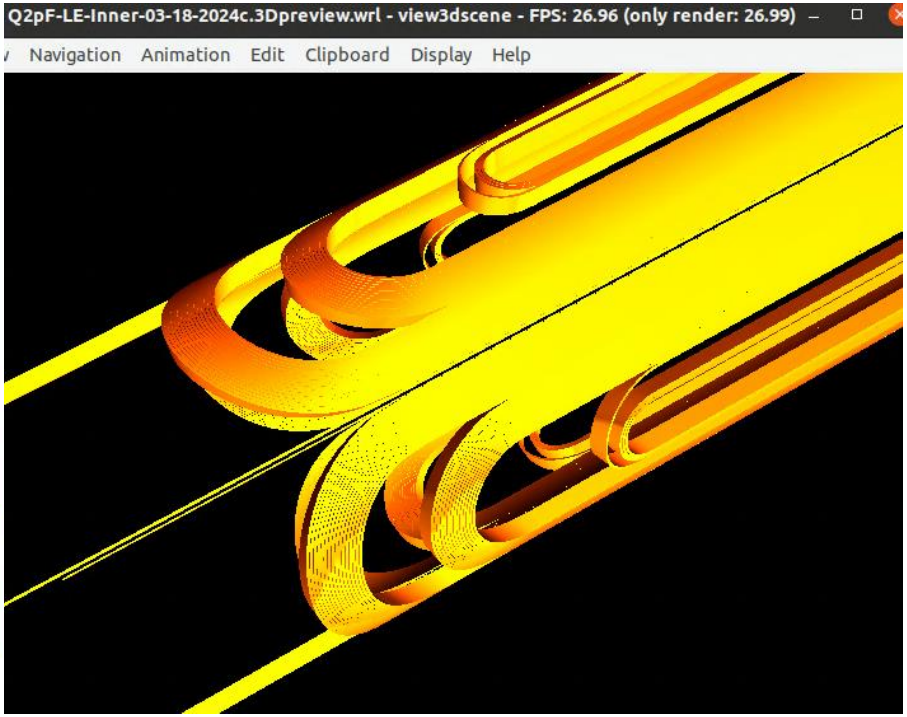
Renderings of the Outer Layer of Lead End

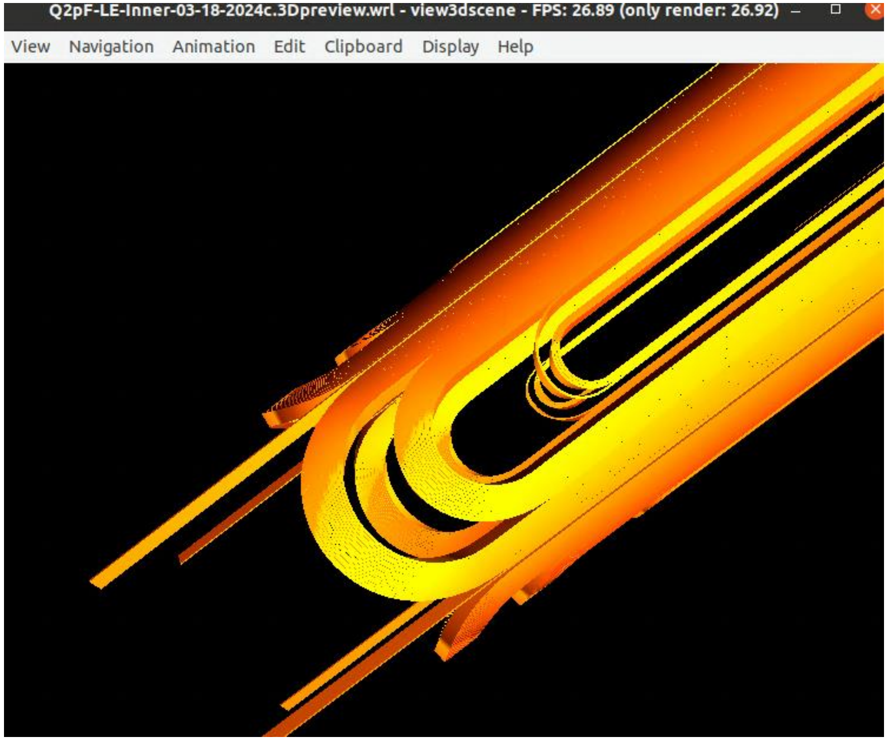




Looks reasonably ok; to be examined more carefully

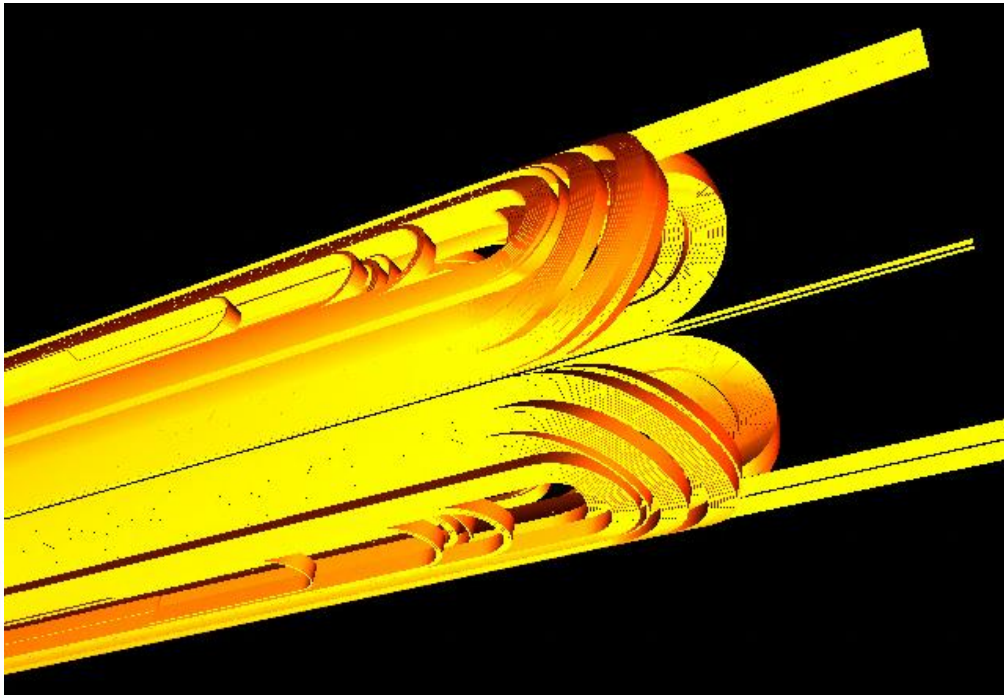
Renderings of the Inner Layer of the Lead End

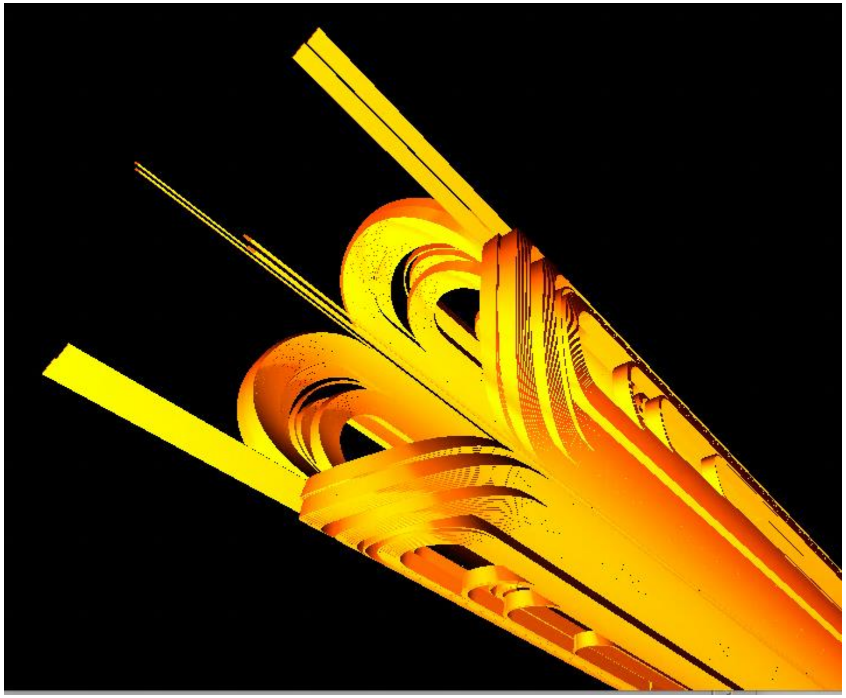




Looks reasonably ok; to be examined more carefully

Renderings of Both Layers of the Lead End

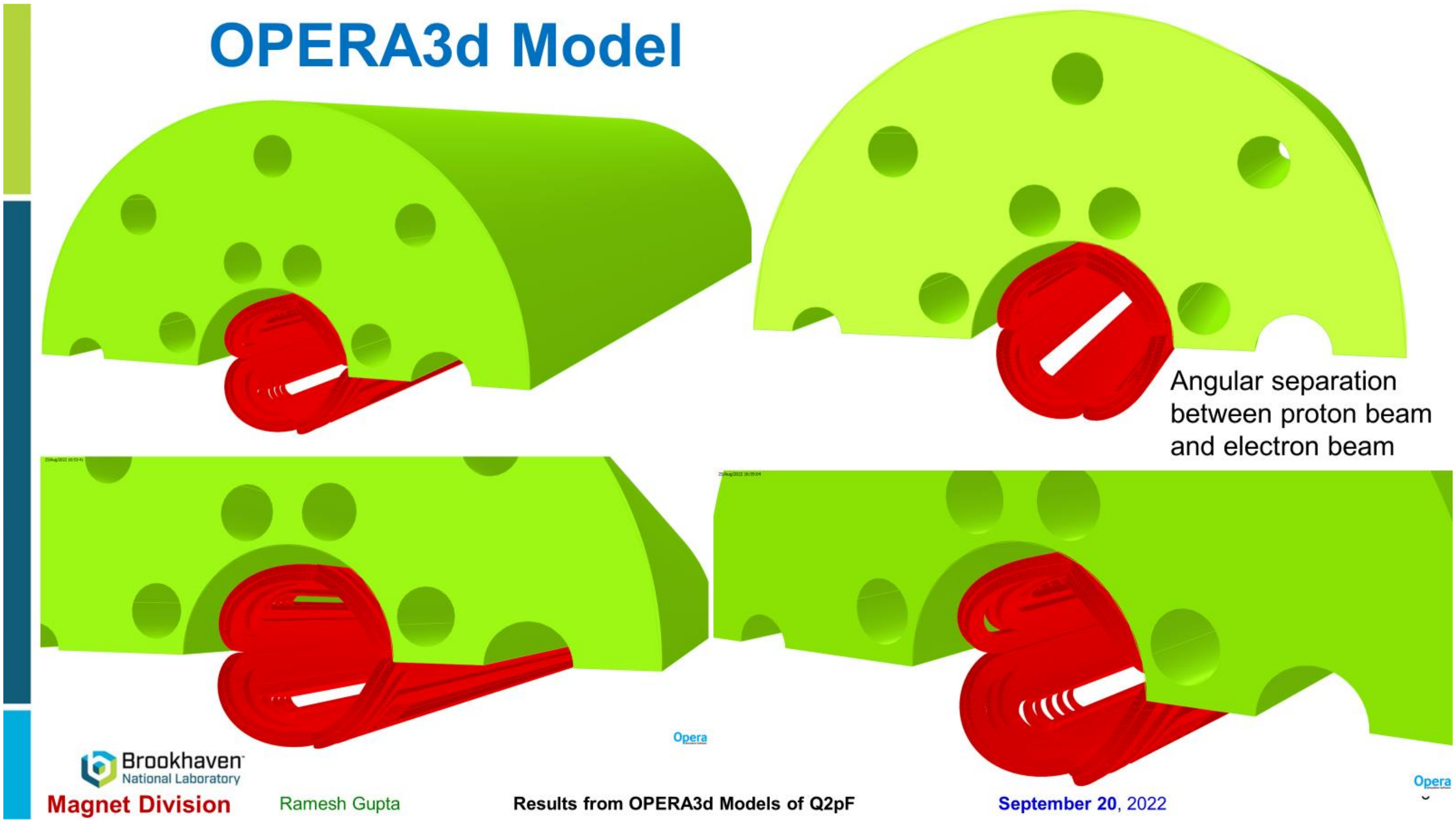




Looks reasonably ok; to be examined more carefully

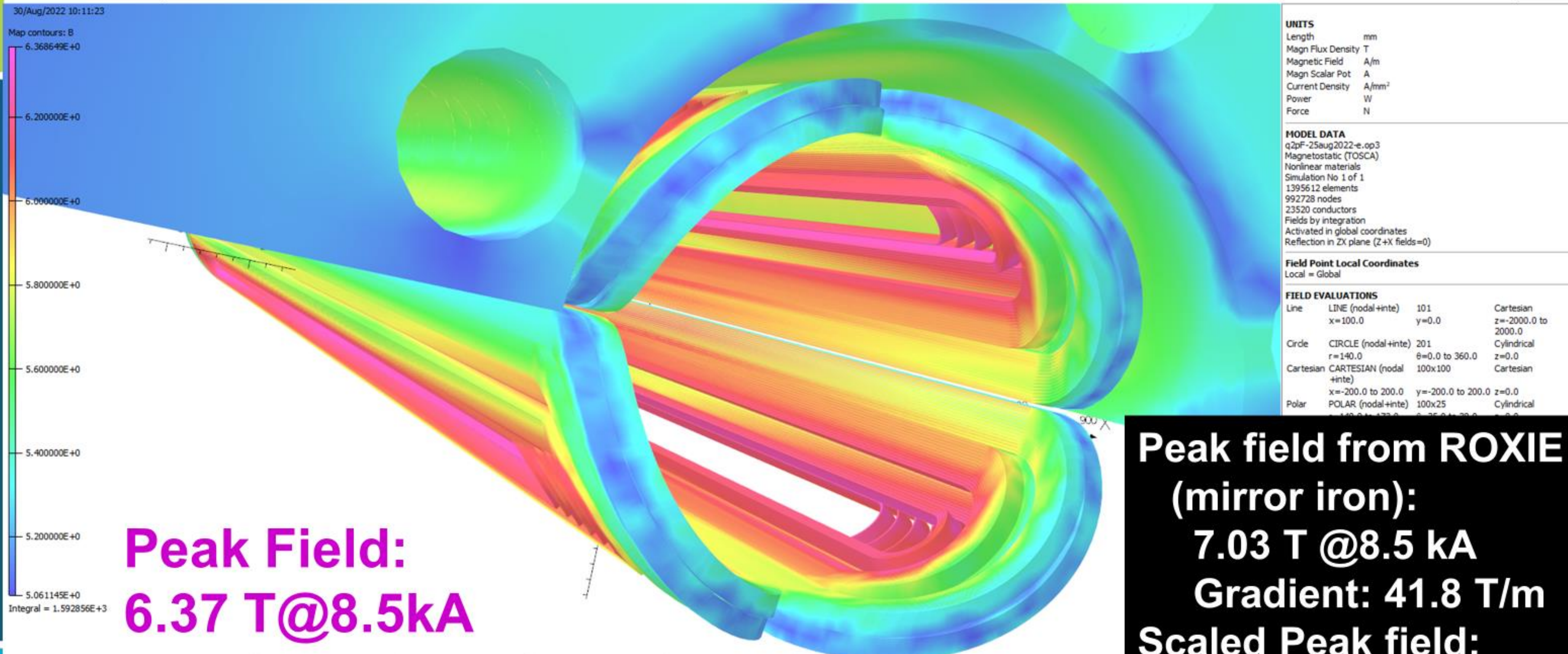
EM 3-d yoke

(earlier coil ends but for yoke it shouldn't matter much)



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

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

Gradient @ center	38.218	T/m