Brookhaven National Laboratory | Jefferson Lab | U.S. DEPARTMENT of ENERGY | Office of Science

B0ApF and Correctors Electro-Magnetic Conceptual Design

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Magnet Steering Group Meeting
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Electron-Ion Collider



Charge Questions

1. Are the requirements for Q1pF, B0ApF and associated correctors sufficiently mature, understood and documented for this phase of the design? Are the plans to validate performance against those requirements sufficiently mature for this phase of the design?

2. Do the technical designs of B0ApF, correctors, Q1pF, FC-1 cold mass and cryostat fulfill the needs of the EIC project and meet the requirements? Specifically, are the chosen design options, operating temperature, margins and superconductor type adequate for the design?

3. Are the design analysis, simulations and specifications adequate for this phase of the design?

4. Have risks, including technical and safety risks, been identified? Are mitigation and fabrication plans, cost estimates and schedule adequate for this phase of the design?

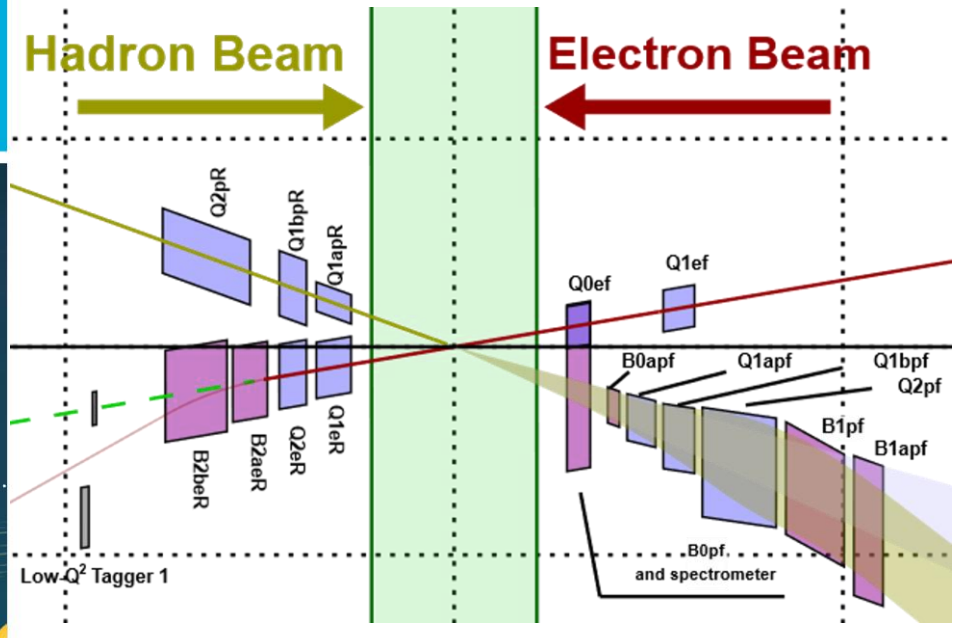
5. Are there any missing aspects in the design and is the overall design maturity sufficient to proceed towards preliminary design?

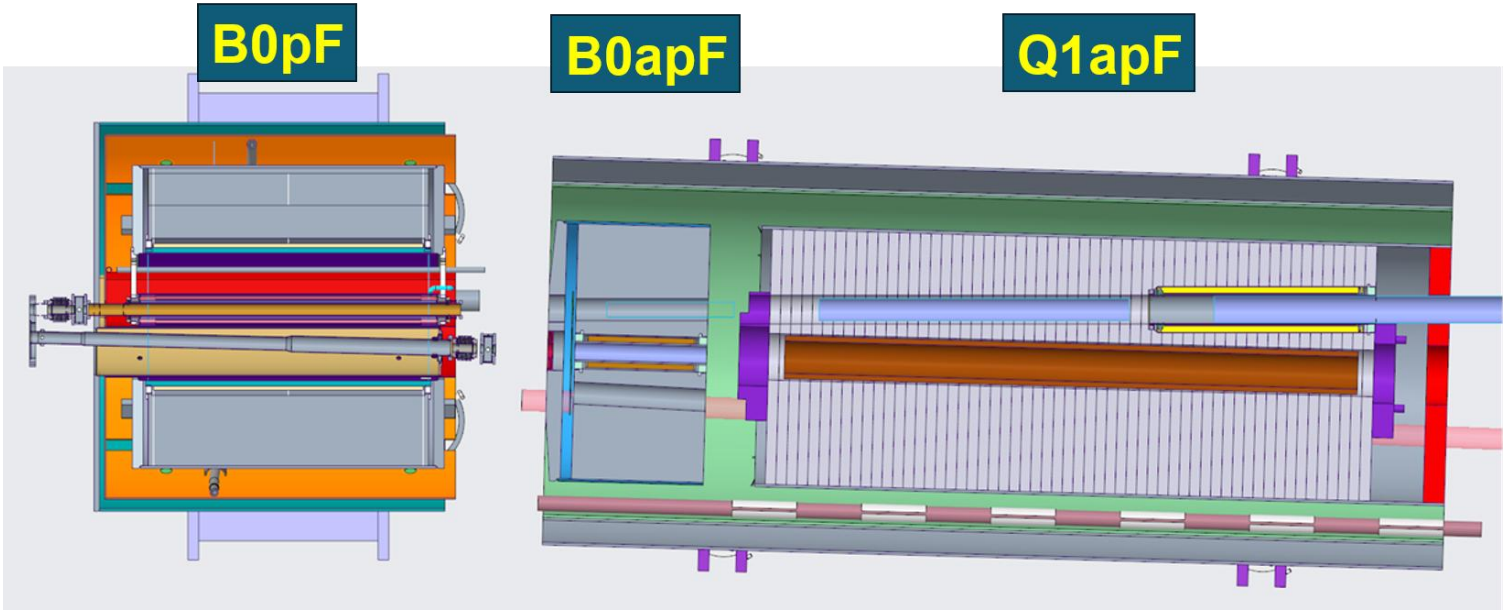
APR/CDR : 30% maturity

Outline

- Preface – EIC IR has a zoo of magnets. B0ApF is a unique creature:
  - ➢Uses a new design, untested formulation, untested code prior to EIC (negative)
  - ➢Only tested R&D magnet prior to APR (positive) - done with off-project funding
- Key requirements and impact on the design of other magnets
- Magnet based on the new Optimum Integral Design (OID) – Why, what?
- A brief review of the R&D dipole B0ApF based on OID, direct wind technology, construction and test results, level of their applicability to the current design
- Conceptual and electro-magnetic design of the current B0ApF, including correctors
- Field quality and plans to assure meeting the EIC requirements (risk mitigation)
- Computed margins
- Summary

Key Function and the Impact of Design Choice on Other Magnets





Function: B0ApF works with B0pF to provide desired vertical bend to hadron beam

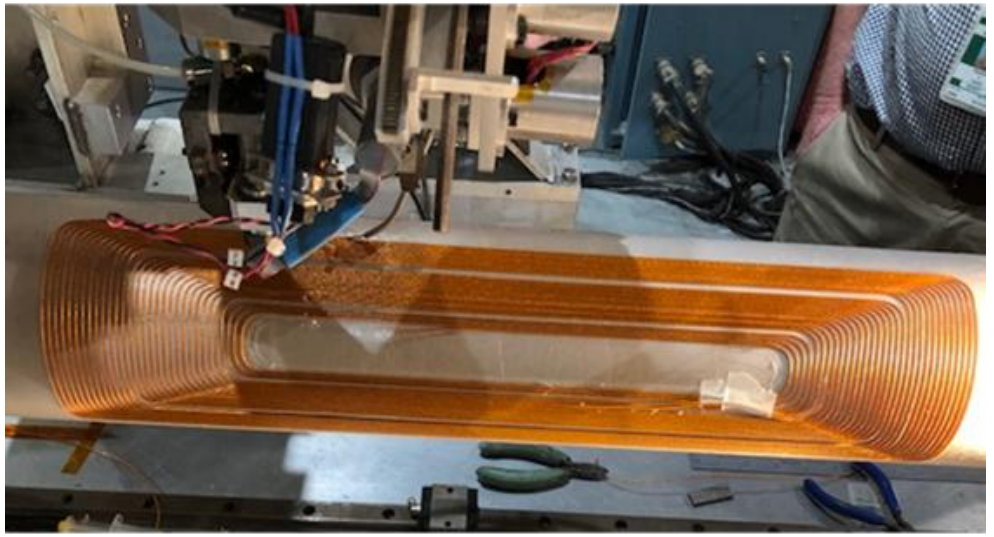
Required maximum integral dipole field in **B0ApF: 1.122 T.m** (includes 10% margin)

➢ Length of B0ApF impacts the length of other IR magnets (and hence the challenges)

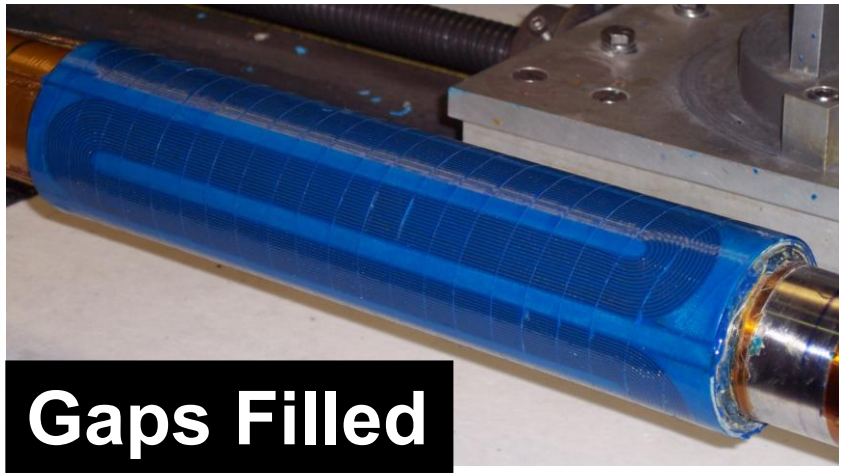
- **Key parameters: Coil length = 500 mm; Coil ID = 105.3 mm; Length/ID ratio = 4.7**
- Corrector (within the same space): **Skew dipole** (**0.6 T.m**) and **Skew Quad** (**1 T**)
- Field Quality: <2 units for dipole and <10 units for correctors (**plus cross-talk specs**)

A Key Technology for Short B0ApF: Direct Wind

- Wire is laid directly on the tube and bonded with ultrasound onto a substrate (a BNL technology).
- Gaps are filled with matched expansion material.
- Pre-stress is applied with S-glass pre-peg roving.
- Surface is machined before laying the next layer.
- An inexpensive technology for one-off magnets.
- Doesn't require tooling, and detailed design.
- Proven in many magnets (earlier at low fields only, recently at higher field R&D magnets, as well).



Direct Wind Machine Laying Wire on Tube



Gaps Filled



Cured Coil

Optimum Integral Design (OID)

Why and what?

Significant Loss in Integral Field Due to Ends in Short Magnets

- Typical mechanical length of <u>each</u> dipole end: ~ 2 coil diameters (*a*)
- Loss in integral field due to ends becomes significant in short magnets: coil length (*L*) < ~8 X diameter in dipoles; ~4 X in quads

RHIC Dipole Coil End



Coil ID: 80 mm
Coil Ends: ~160 mm
Coil Length: ~9.46 m
➢ L/a > 100

•<u>Coil length to coil diameter RATIOS in some EIC magnets:</u>

➢ B0ApF (this): *L* = 500 mm, *a* = 105.3 mm; RATIO ~4.7

➢ B0pF (quad layer): *L* = 1250 mm, *a* = 656 mm; RATIO ~1.9

➢ Q3pF: L = 400 mm, a = 137 mm; RATIO ~2.9

✓ **Strong motivation for developing designs that minimize the loss in integral field due to ends**

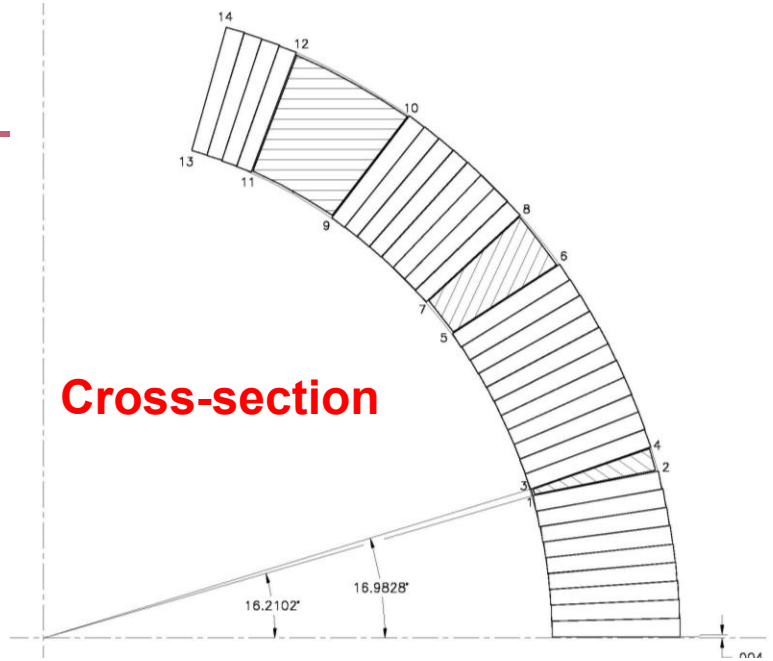
Conventional Design Approach

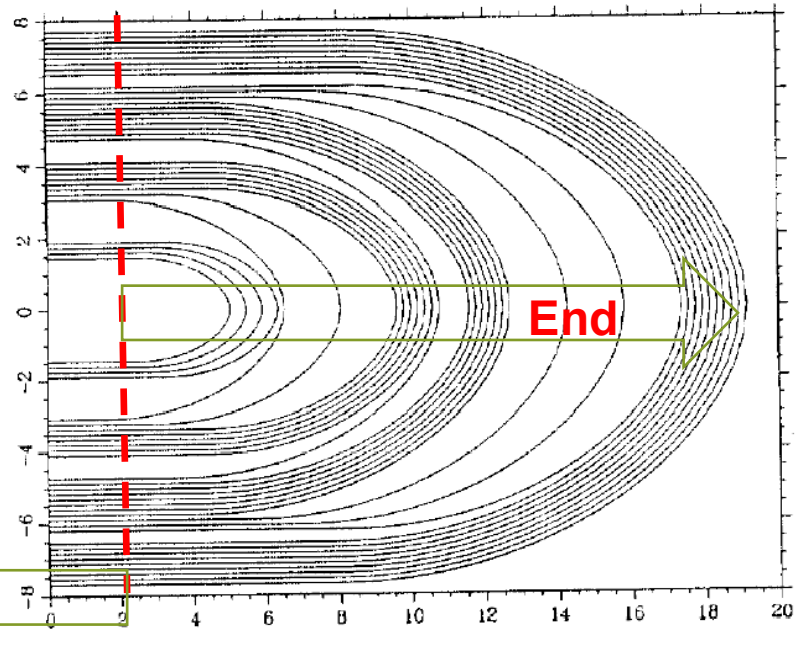
- **A two-step process:**
- **Step 1: Optimize coil cross-section to obtain cosine theta like distribution:**

$$I(\theta) = I_o \,.\, \cos(n\theta)$$

Step 2: Optimize ends for reducing harmonics and the peak field

Both limit the "Ampere-turns-length" that one can pack in the given volume, and hence the maximum integral field





Optimum Integral Design (OID) Approach

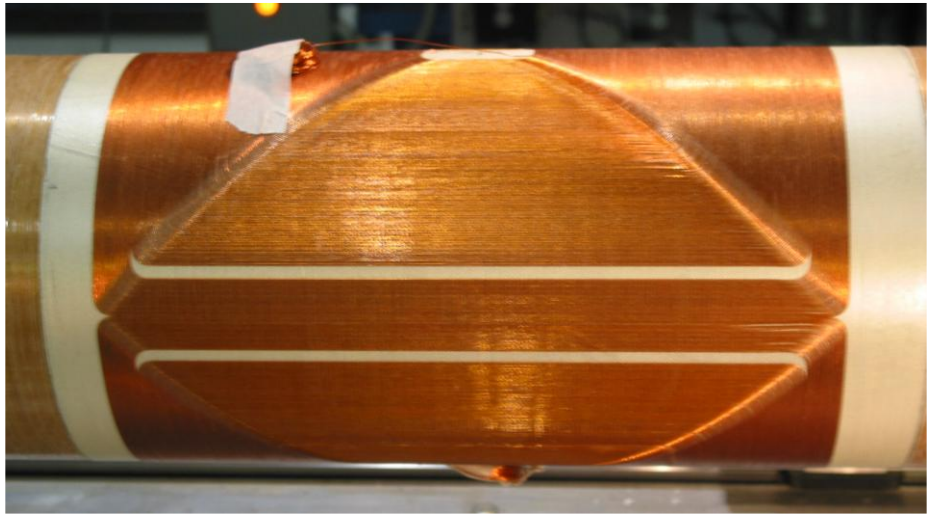
Optimize cross-section and ends together in a single step. And obtain a cosine theta current distribution in an integral sense:

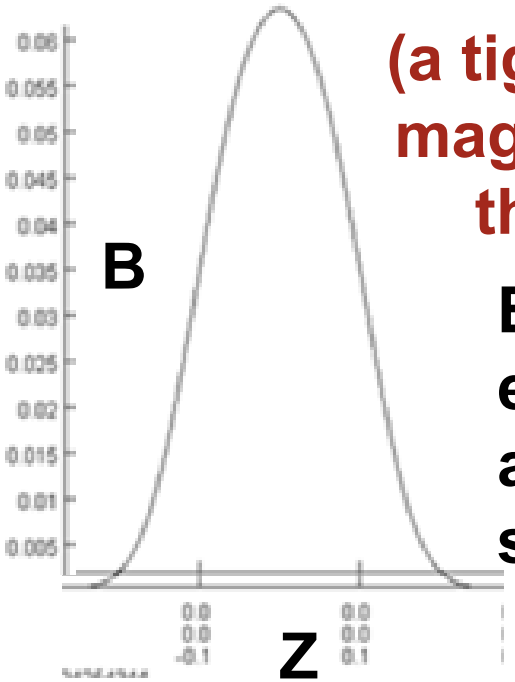
$$I(\theta) \,.\, L(\theta) \;=\; I_o \,.\; L_i(\theta) \;\propto\; I_o \,.\, L_o \,.\, \cos(n\theta)$$

(a) Midplane turns extend full-length and (b) length of turns decreases linearly with the angle to help create a *cos(nθ) function*

Length of coil ends, which determines the loss in magnetic length, made nearly zero

✓ **Loss due to ends essentially eliminated**





(a tightly packed magnet through the length)

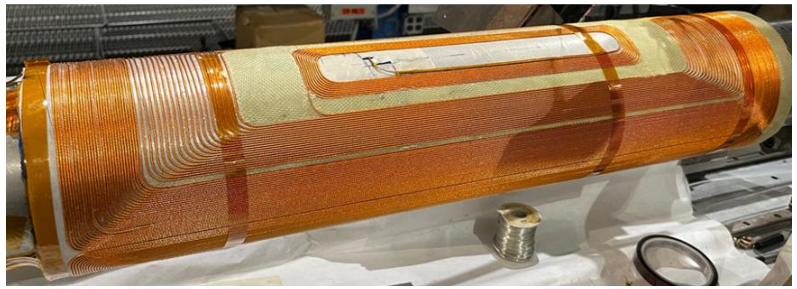
Benefits are enormous in a magnet with small flat-top

Why this design choice over the others considered?

- The ends in Rutherford cable magnets take too much space. COS theta design wouldn't leave much space for the magnet body when Length/ID is small. Therefore, this is not the best choice such short magnets.
- Serpentine design (and to some extent double-helix also) with the direct wind technology are better choice than the Rutherford cable magnet since the small dia cable can be bent at a smaller radius. That allows a longer body of the magnet. However, still a significant loss due to ends.
- Efficiency of the optimum integral design in creating the required field integral in such short magnets is significant due to a little loss from ends.
- This is the primary reason for choosing this design.

New Code for Rapid Optimization of 3-d Design

- Most codes first compute field (or vector potential) at several places along the length and then compute and integrate field harmonics and then optimize them. That takes too long and is not suitable for optimizing design where ends dominate.
- Optimum integral design code works differently. It directly computes and optimizes 3-d integral harmonics for each wire of length "*L*" at (a, φ)



Integral harmonics: $B_n = 10^4 \left(\frac{R_0}{a}\right)^n . L . cos\left[(n+1)\phi\right]$

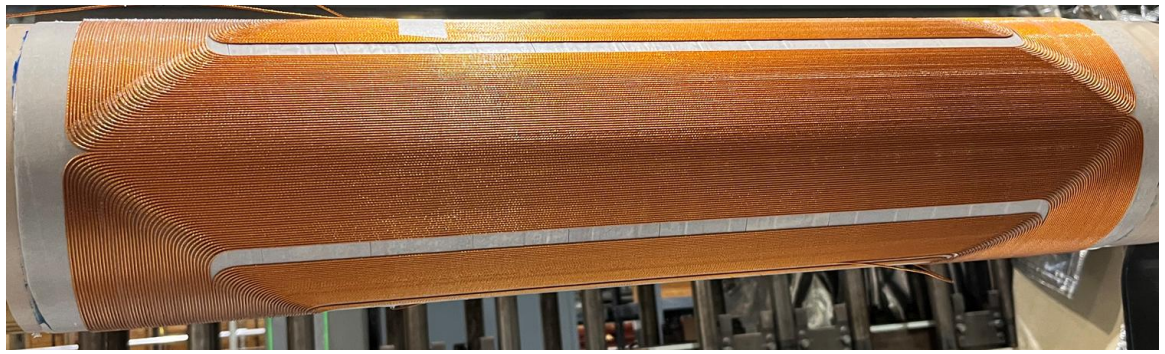
- Above formula is valid for 2-d and for 3-d when the field is integrated over the entire space (length). Iron is included in the software as the image current.
- This works fast. 3-d optimization of multi-layer coil typically takes only a few minutes (199 parameters allowed). Input files for OPERA3d, RAT & winding software created.
- A new GUI based code (MADEO) is almost ready. That has a better pre- and post-processors and performs peak fields and many other useful calculations, as well.

Proof-of-Principle R&D Dipole B0ApF

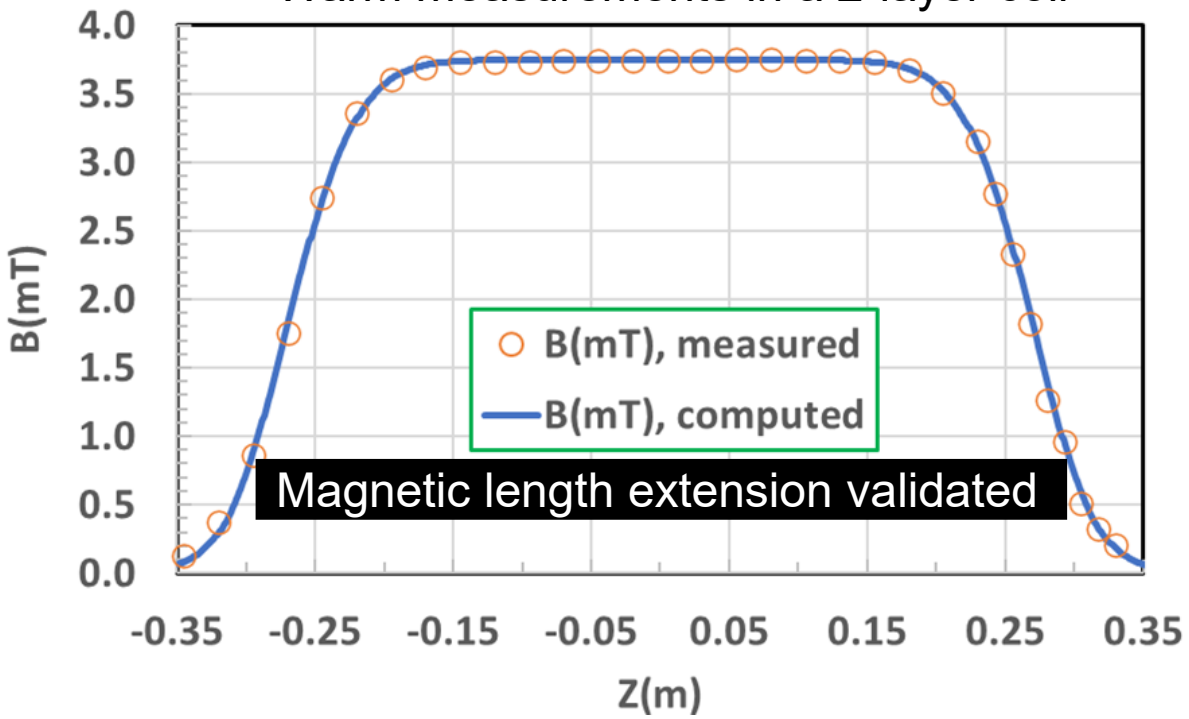
- A new design and a new software must be proven before it can be used in a machine like EIC
- These tasks were primarily carried out with the off-project funding (SBIR/STTR with PBL)

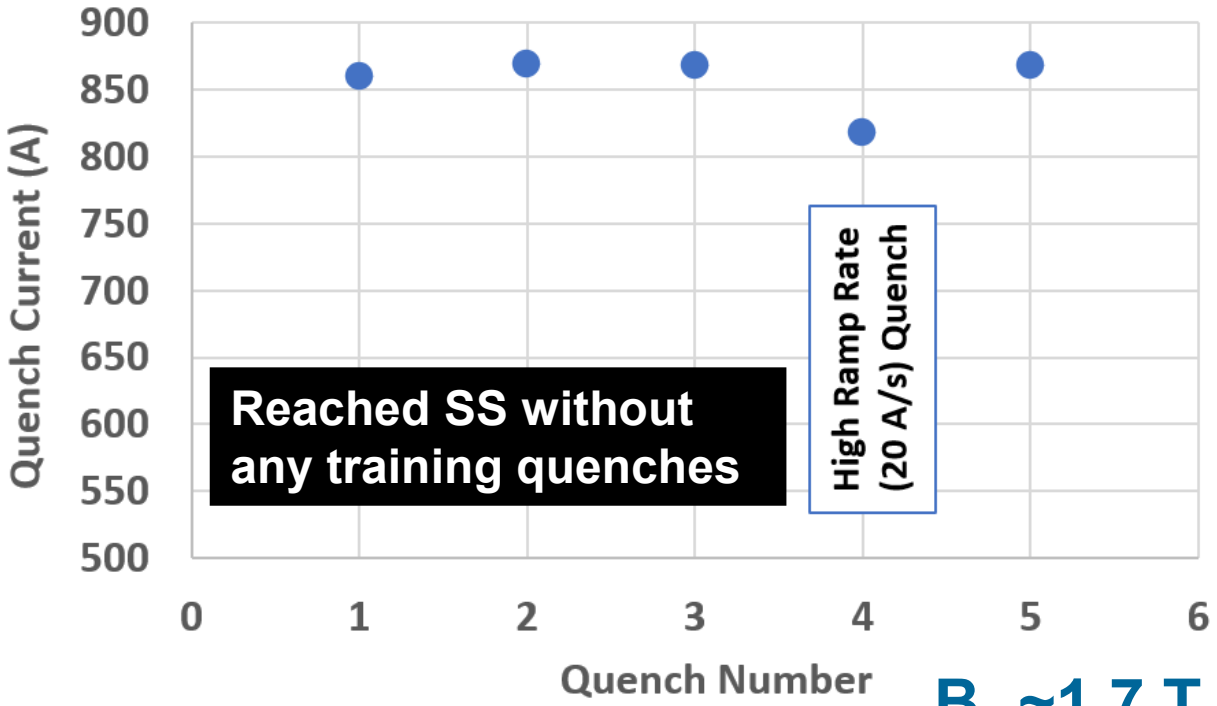
Validation of the Optimum Integral Design (1)

(gain in integral field/magnetic length and performance of a coil-set)



Warm measurements in a 2-layer coil







B_o ~1.7 T

B_{pk} ~2.2 T

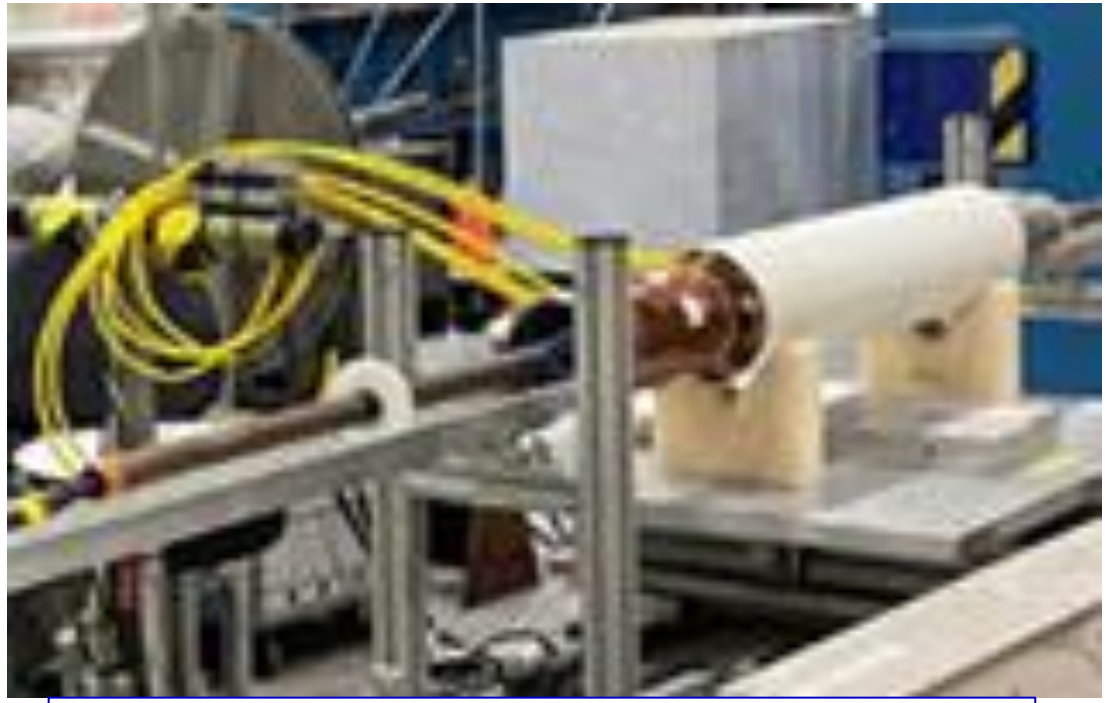
id 114 mm

One coil-set in a yoke

Validation of the Optimum Integral Design (2)

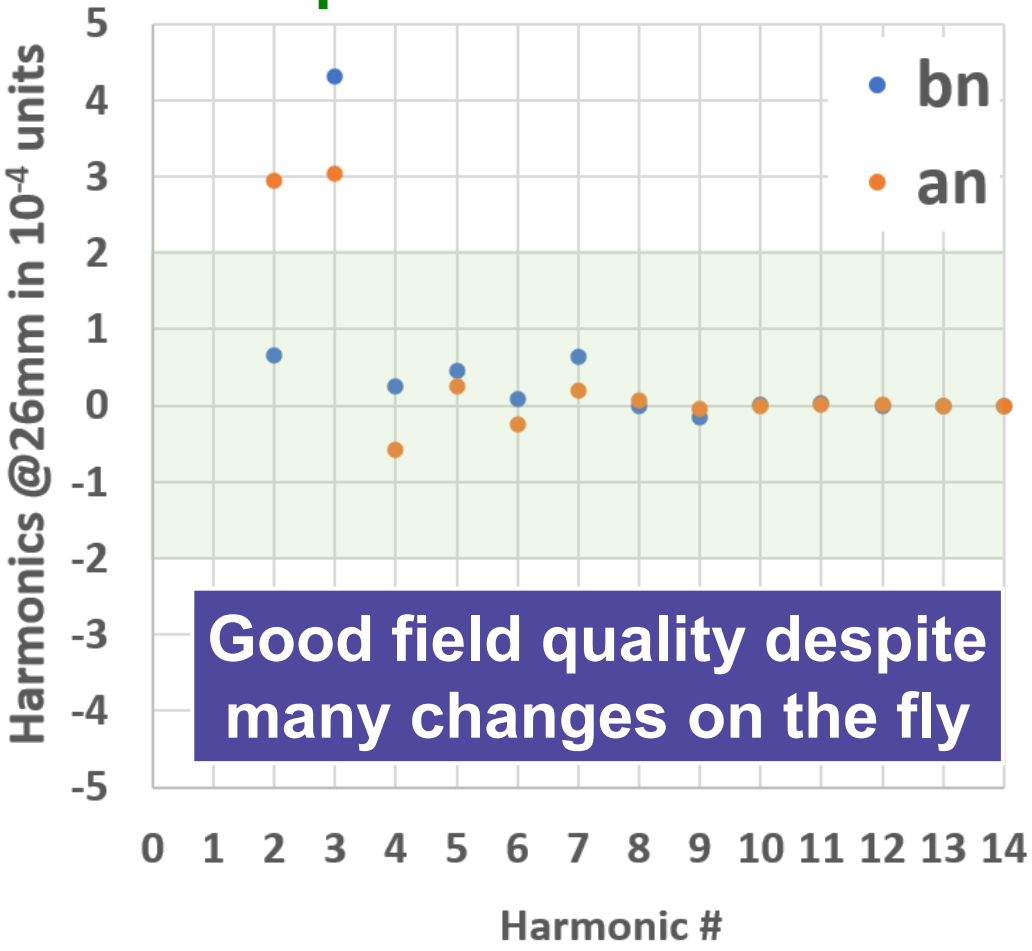
(good field quality - a new calculation method and a new code)

Warm measurements of 6 layers



Expect lower order harmonics from the testing leads (yellow, not part of the magnet)

Specifications: +/- 2

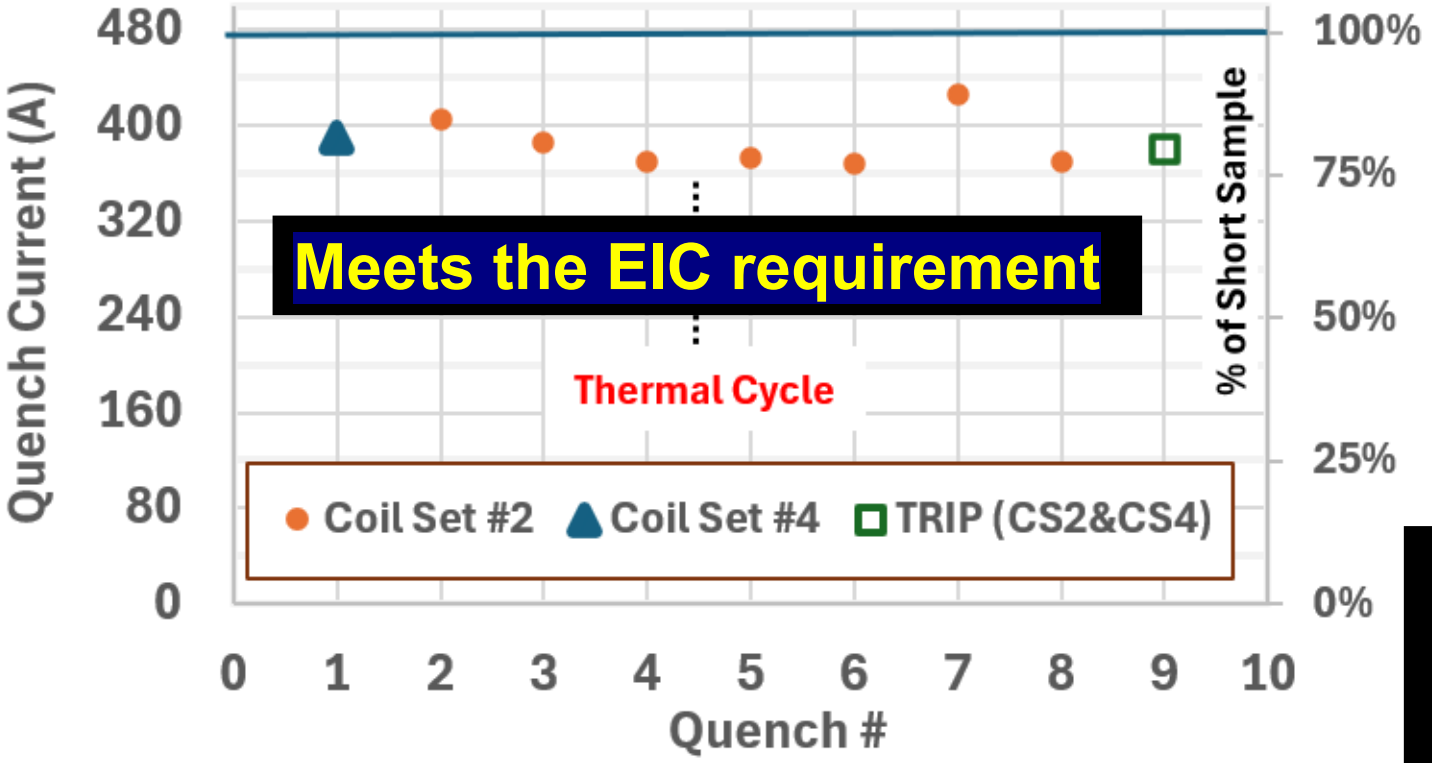


➢ **Non-zero harmonics can be compensated in the subsequent layers, if needed**

Validation of the Optimum Integral Design (3)

(construction techniques and quench performance of a 12-layer coil)

- All quenches were above 367 A (>76% of SS), highest at 426 A (89% of SS)
- B_o ~3.6 T, B_{peak} ~4 T, 114 mm aperture (RHIC arc dipole: 3.5 T, 80 mm aperture)
- An important demonstration of Direct Wind technology (achieved in a low-cost STTR program with limited engineering). The focus was on demonstrating OID



Relevance to the present design

- R&D dipole already reached a combined peak field of B0ApF plus full-strength correctors (reached ~4 T, need ~3.5 T).

Exceeds EIC target of 65% on load line. This is a larger aperture, longer length magnet with more stored energy and inductance than in the present design.

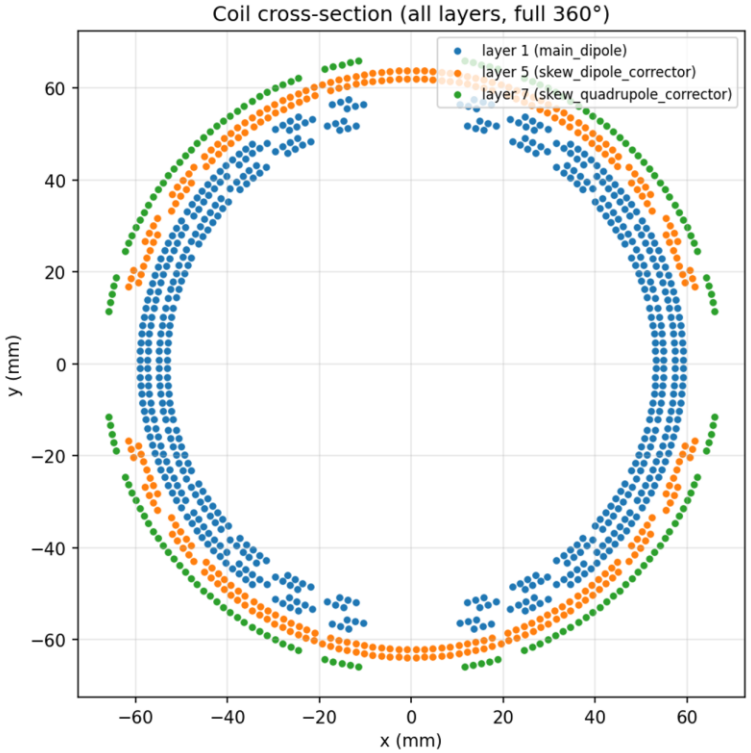
Overall Design for 500 mm Long Coil

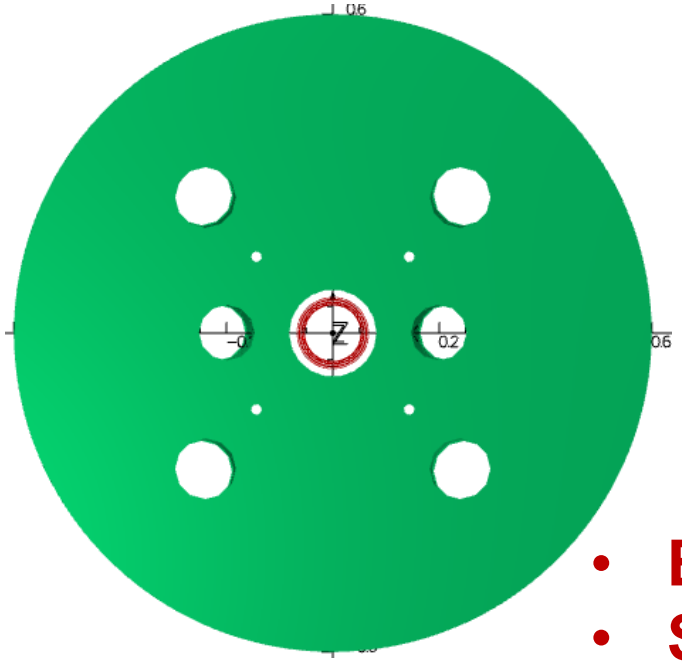
1. 4 layers (2 coil sets) creating 1.122 T.m Vertical Dipole (the main B0ApF)
2. 2 layers (1 coil set) creating 0.6 T.m Horizontal Dipole (a corrector magnet)
3. 1 layer creating 1 T Skew Quadrupole (a corrector magnet)

A single layer skew quad (ok for OID) with 6-aroubd-1 cable gives more than the required margin (may move to wire). Extra radial space for leads included.

- **The order of placement is chosen to balance out the margins between the magnets (maximize the minimum).**

Basic Design Parameters and Design Requirements





- Coil length 500 mm
- Coil inner diameter: 105.33 mm
- (Coil length) / (Coil i.d.) ratio: 4.7
- Wire diameter: 0.47mm
- Cable diameter: 1.7 mm
- Yoke length: ~0.62 m
- Yoke ID: ~164 mm

- B0ApF integral field: 1.122 T.m
- Skew dipole integral field: 0.6 T.m
- Skew quad integral gradient: 1 T

Field homogeneity (harmonics @26 mm)

- B0ApF dipole: -2 to +2 units
- Skew dipole: -10 to +10 units
- Skew quadrupole: -10 to +10 units

Crosstalk (harmonics in ESR@26 mm)

- Linear integral: <6.2 Gauss.m
- Non-linear integral: <6.2 μT.m

A few assumptions in various models

Detailed design work is not carried out at the APR phase. Most will be completed before the PDR (all before FDR).

Complete 3-d Model (coil length 500 mm, yoke length 622 mm):

- **Used in engineering design for determining spaces/length of the magnets**
- **Used in the magnetic design to compute margins, fringe field and cross-talk**

Basic 2-d model:

- **Used in the basic mechanical analysis**

Composite 2½-d model:

- **Coil optimization code assumes the same coil and yoke length (500 mm)**

Computed harmonics in each of 4 layers of B0ApF dipole

(slide to be updated for r=26 mm and for the standard convention of harmonics)

Harmonics at r=25 mm (spec for the magnet is 2 units). Coil optimization: <0.4 unit in each layer.

- **Plan is to do warm measurements after the 1st coil set and correct in the 2nd set, if required.**

Coil set #1

Mention geometric

Coil set #2

Layer #1

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.22495E+00	10000.0000
2	-0.50228E-07	-0.0022
4	0.26687E-06	0.0119
6	0.12206E-05	0.0543
8	0.79033E-05	0.3513
10	0.63732E-06	0.0283
12	-0.45702E-06	-0.0203
14	0.42771E-07	0.0019
16	-0.13175E-07	-0.0006
18	0.66411E-08	0.0003
20	0.48958E-09	0.0000
22	0.62671E-09	0.0000
24	-0.26005E-09	-0.0000
26	-0.36037E-10	-0.0000
28	0.14941E-10	0.0000
30	-0.19731E-11	-0.0000

Layer #2

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.22907E+00	10000.0000
2	0.15248E-06	0.0067
4	0.17412E-06	0.0076
6	0.74579E-07	0.0033
8	0.82817E-06	0.0362
10	0.18329E-05	0.0800
12	-0.31258E-06	-0.0136
14	0.94335E-07	0.0041
16	-0.13770E-07	-0.0006
18	0.23299E-08	0.0001
20	-0.57679E-09	-0.0000
22	0.97480E-10	0.0000
24	0.29447E-10	0.0000
26	-0.29753E-10	-0.0000
28	0.46975E-11	0.0000
30	0.25498E-12	0.0000

Layer #3

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.23960E+00	10000.0000
2	-0.19200E-05	-0.0801
4	0.13261E-05	0.0553
6	0.64908E-05	0.2709
8	0.17339E-05	0.0724
10	-0.80694E-06	-0.0337
12	-0.16230E-08	-0.0001
14	0.76363E-08	0.0003
16	0.22457E-08	0.0001
18	0.58117E-09	0.0000
20	-0.11915E-09	-0.0000
22	-0.19351E-10	-0.0000
24	-0.28607E-10	-0.0000
26	0.93693E-11	0.0000
28	-0.15744E-12	-0.0000
30	-0.22008E-12	-0.0000

Layer #4

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.24398E+00	10000.0000
2	0.48149E-08	0.0002
4	-0.39555E-06	-0.0162
6	0.11778E-05	0.0483
8	0.39820E-05	0.1632
10	-0.40564E-06	-0.0166
12	-0.17375E-06	-0.0071
14	0.33670E-07	0.0014
16	-0.10636E-08	-0.0000
18	0.24775E-09	0.0000
20	-0.27990E-09	-0.0000
22	0.63693E-10	0.0000
24	-0.72234E-11	-0.0000
26	-0.10427E-11	-0.0000
28	0.72962E-12	0.0000
30	-0.11265E-12	-0.0000

- Old US definition: b2 is sextupole (to be updated)

Computed harmonics in each layers of skew dipole & skew quad corrector

(slide to be updated for r=26 mm and for the standard convention of harmonics)

Harmonics at r=25 mm (specifications for corrector magnets is 10 units)

Easily met in the computer optimization (all <0.1 units).

✓ **Corrector magnets should not need any correction after the measurements.**

Coil set #3

Layer #1 (5th layer)

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.24636E+00	10000.0000
2	-0.38563E-08	-0.0002
4	0.87416E-08	0.0004
6	0.10205E-06	0.0041
8	0.10062E-05	0.0408
10	0.13980E-05	0.0567
12	-0.11663E-06	-0.0047
14	0.16705E-07	0.0007
16	-0.23573E-08	-0.0001
18	-0.41816E-09	-0.0000
20	0.35548E-10	0.0000
22	-0.32091E-10	-0.0000
24	0.10703E-11	0.0000
26	0.84901E-12	0.0000
28	-0.29643E-13	-0.0000
30	-0.25749E-14	-0.0000

Layer #2 (6th layer)

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.25769E+00	10000.0000
2	-0.81709E-08	-0.0003
4	-0.72441E-09	-0.0000
6	0.49680E-07	0.0019
8	0.41358E-06	0.0160
10	0.37347E-06	0.0145
12	-0.85961E-07	-0.0033
14	0.97279E-08	0.0004
16	-0.11632E-08	-0.0000
18	0.56965E-10	0.0000
20	-0.60949E-11	-0.0000
22	0.18232E-11	0.0000
24	-0.47166E-12	-0.0000
26	-0.11145E-12	-0.0000
28	0.72740E-13	0.0000
30	-0.10394E-13	-0.0000

Coil set #4

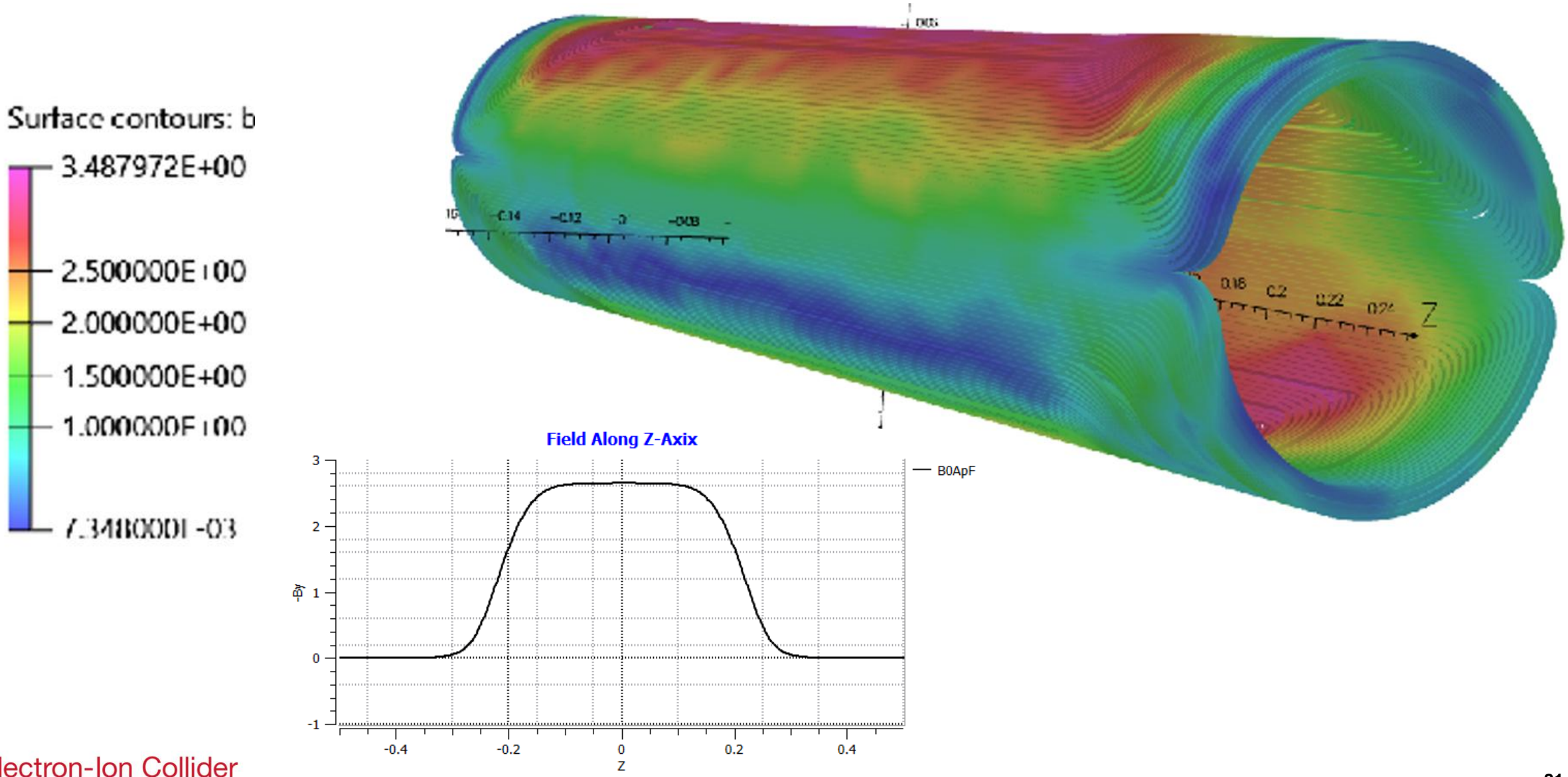
Layer #1 (7th layer)

INTEGRATED FIELD HARMONICS :

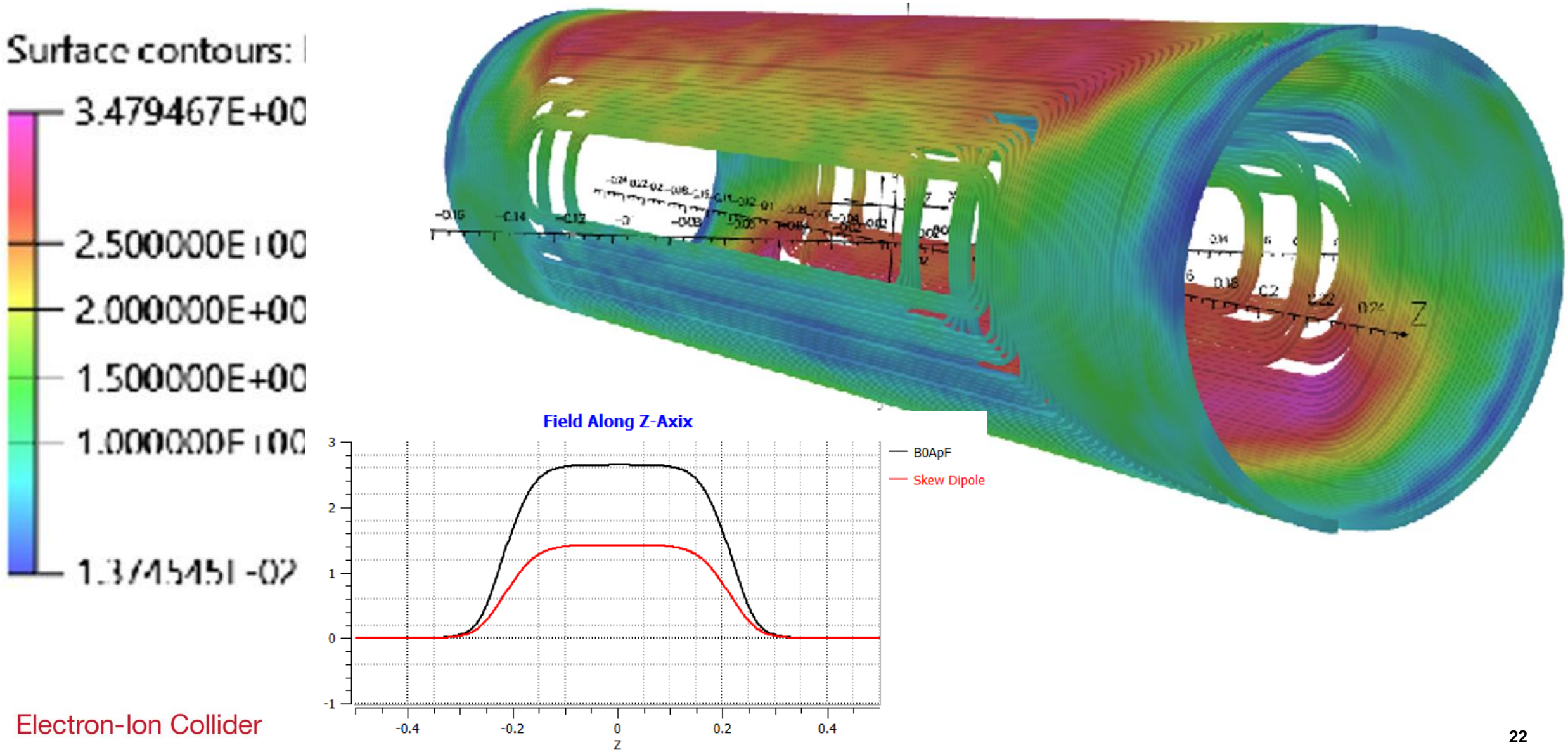
No.	Bn(T.m)	bn*10^4(units)
1	0.90411E-01	10000.0000
5	0.17988E-08	0.0002
9	0.22953E-07	0.0025
13	-0.17546E-07	-0.0019
17	-0.32137E-09	-0.0000
21	0.23958E-10	0.0000
25	-0.38364E-12	-0.0000
29	-0.34752E-14	-0.0000

➢ Old US definition: b2 is sextupole (to be updated)

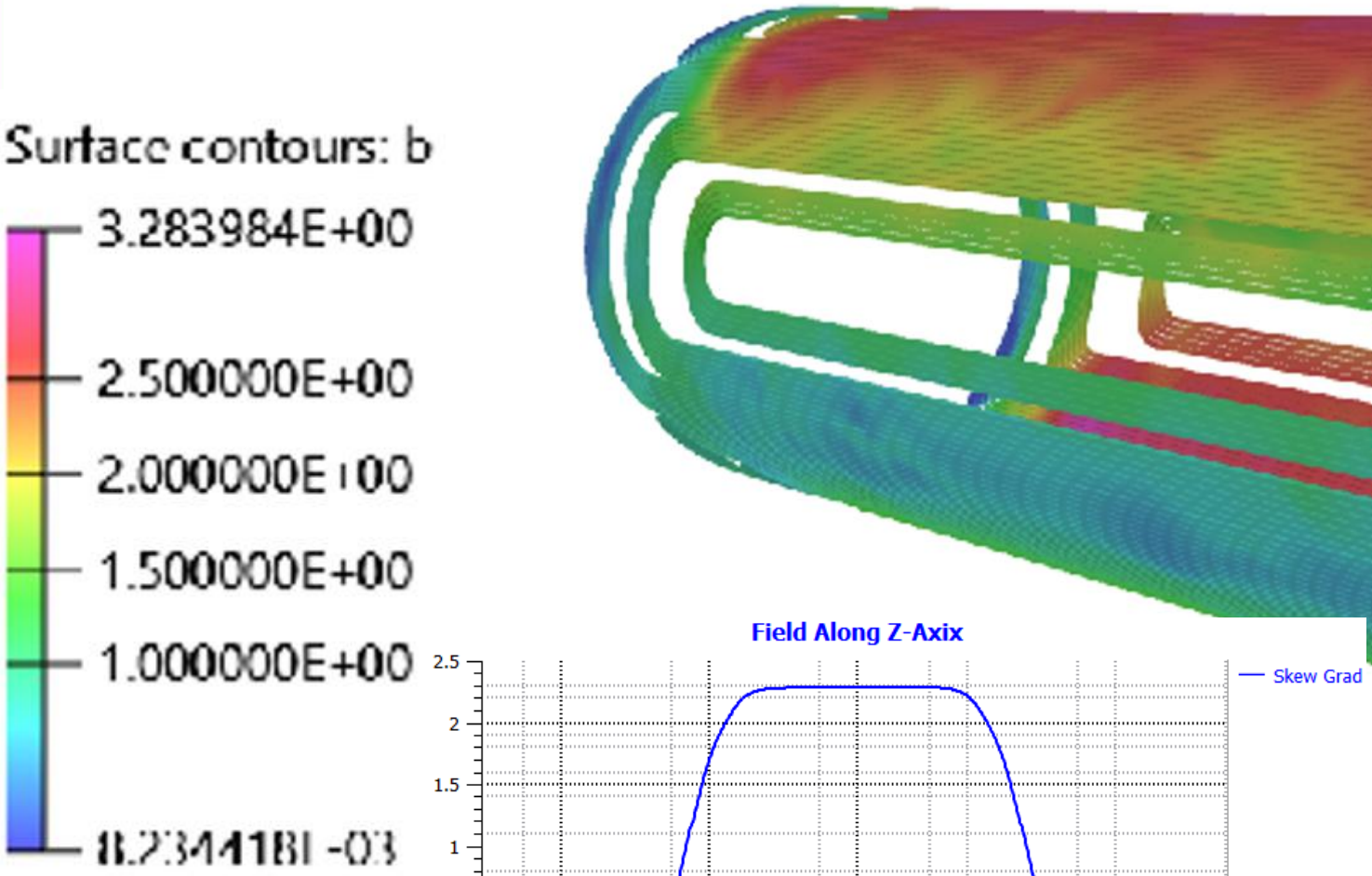
Optimized Coil Model of B0ApF with Field Superimposed (coils not shown are powered at their nominal current)



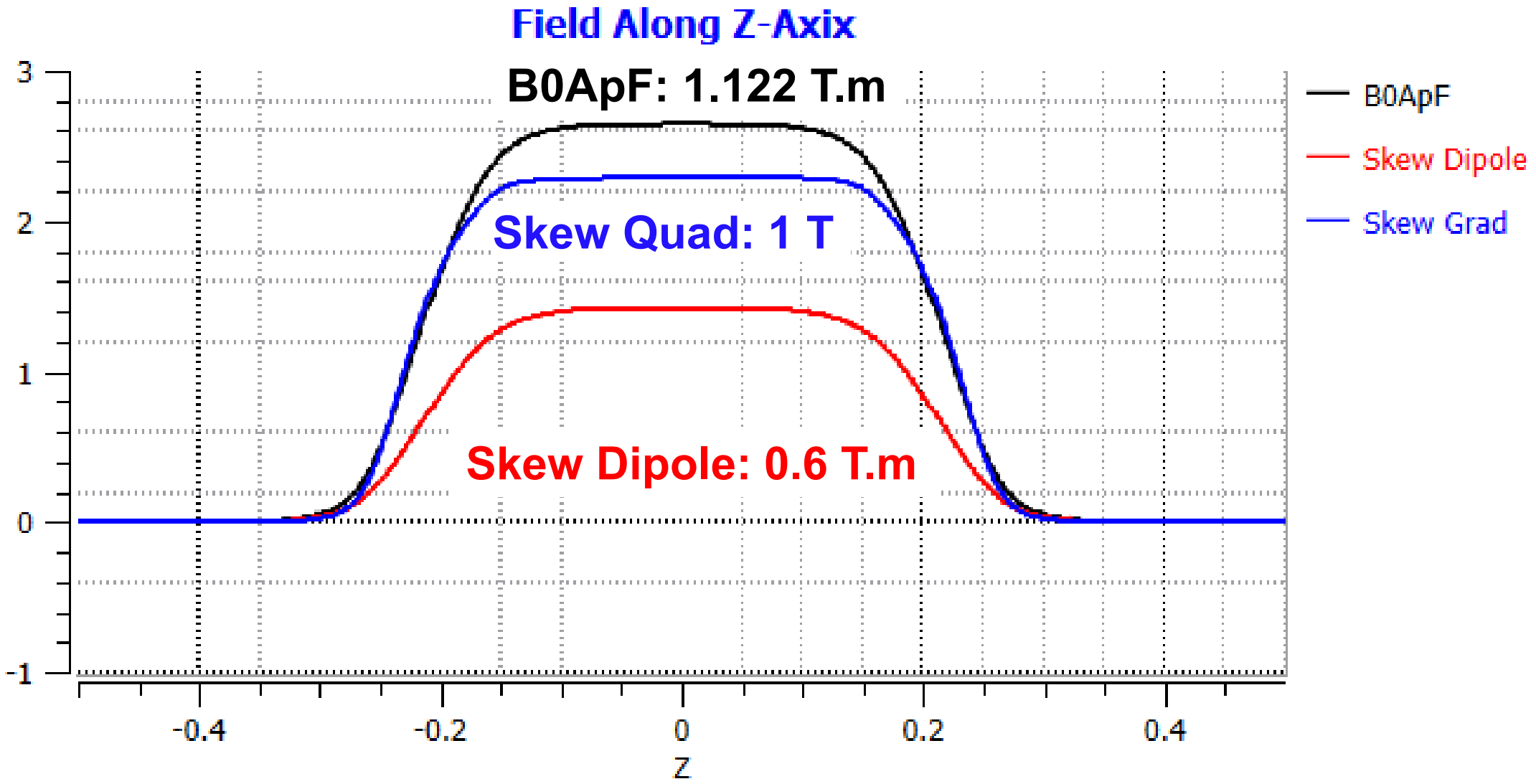
Optimized Model of Skew Dipole with Field Superimposed
(coils not shown are powered at their nominal current)



Optimized Model of Skew Quad with Field Superimposed
(coils not shown are powered at their nominal current)



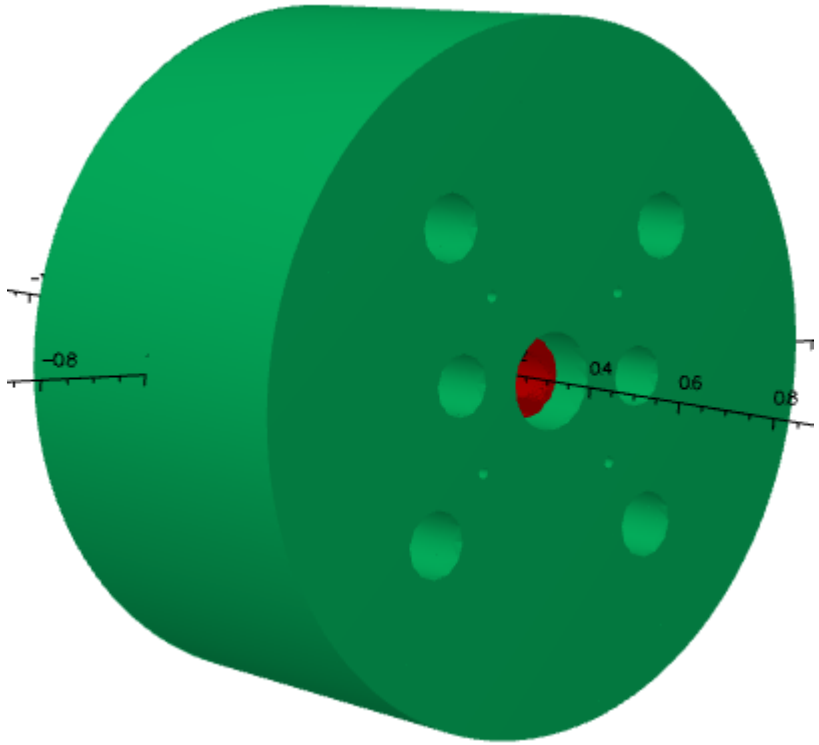
Field Integral, field and gradient along the z-axis



Cross-talk and fringe field on electron beam

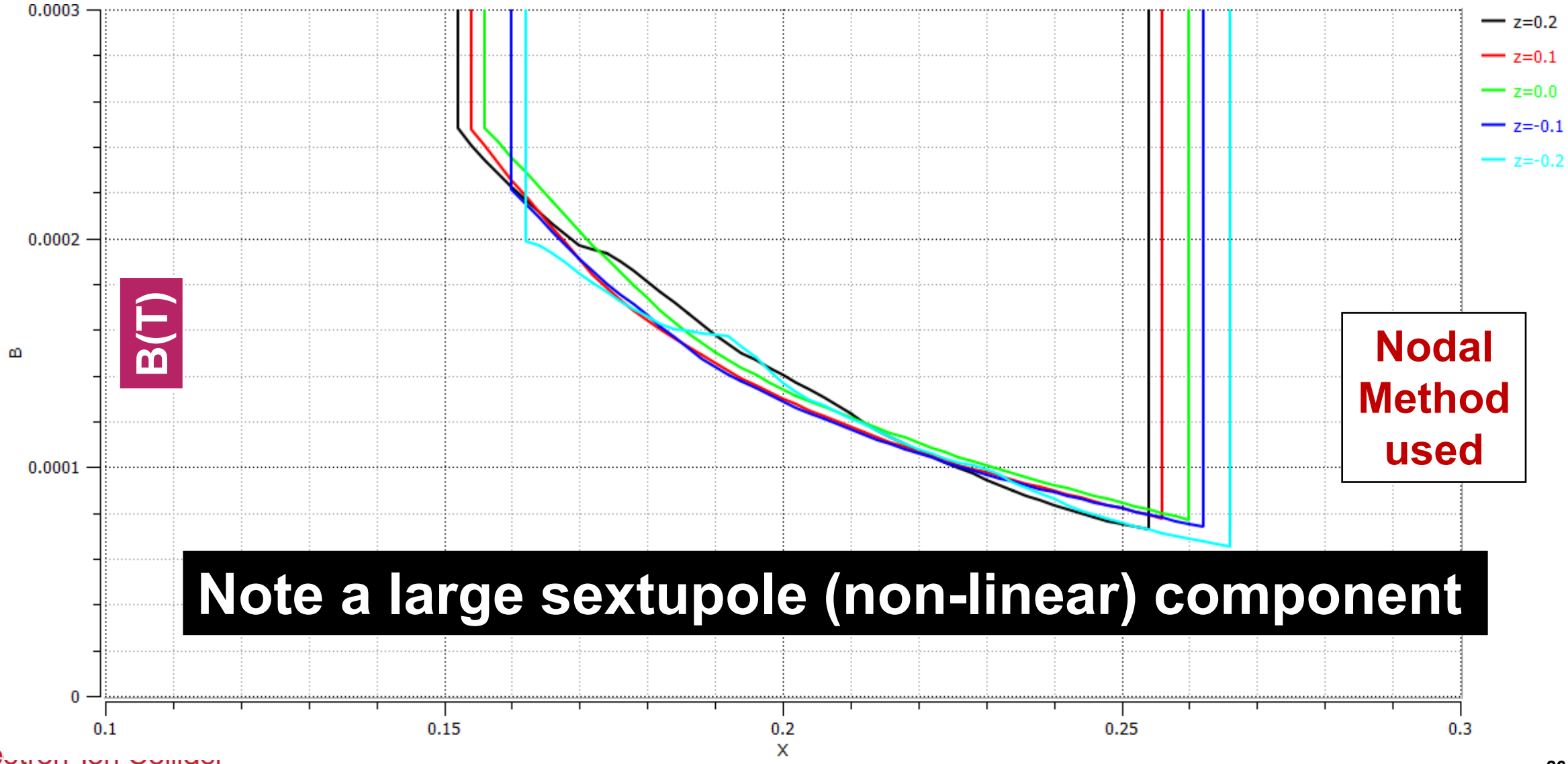
- The requirements for the maximum field and harmonic components for the electron beam travelling in the yoke cutout of the hadron magnet in EIC are rather tight (here referred to as cross-talk within the yoke and fringe field outside the yoke)
- These requirements demands us to be very careful in how we use the codes to make sure that we are not lost in the artificial errors of the model.

- Please see extra slide on computer modeling.
- Please also see extra slide on several techniques examined to meet these demanding requirements.



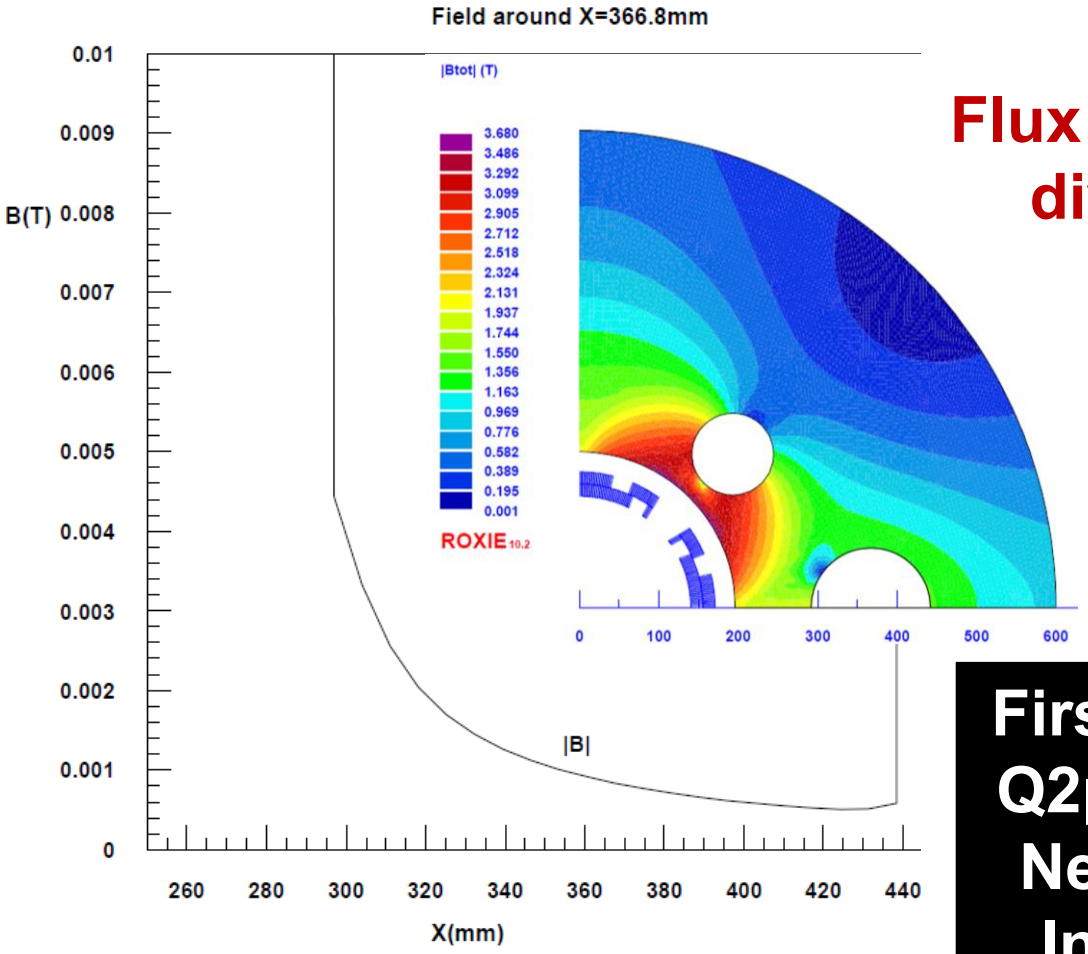
It is highly desirable to carry out proof-of-principle demonstration(s) of the chosen technique(s)

Field in the electron hole inside the yoke at various axial location



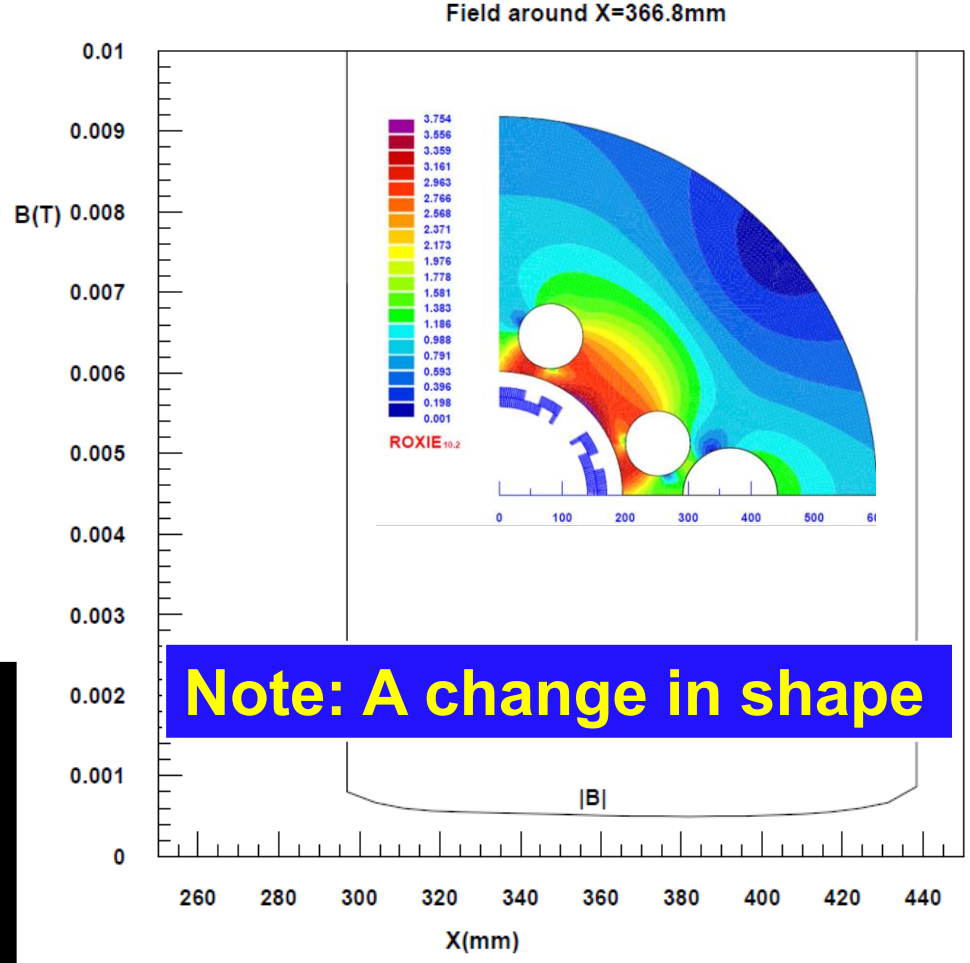
Reducing the Non-linear terms in electron hole (linear terms – field and gradient can be 100 times more than linear)

Holes in the yoke can be strategically placed to reduce the field inside the hole for e-beam and modify the shape to significantly reduce the field harmonics



Flux lines get diverted

First used in Q2pF deign. Next slide: In B0ApF

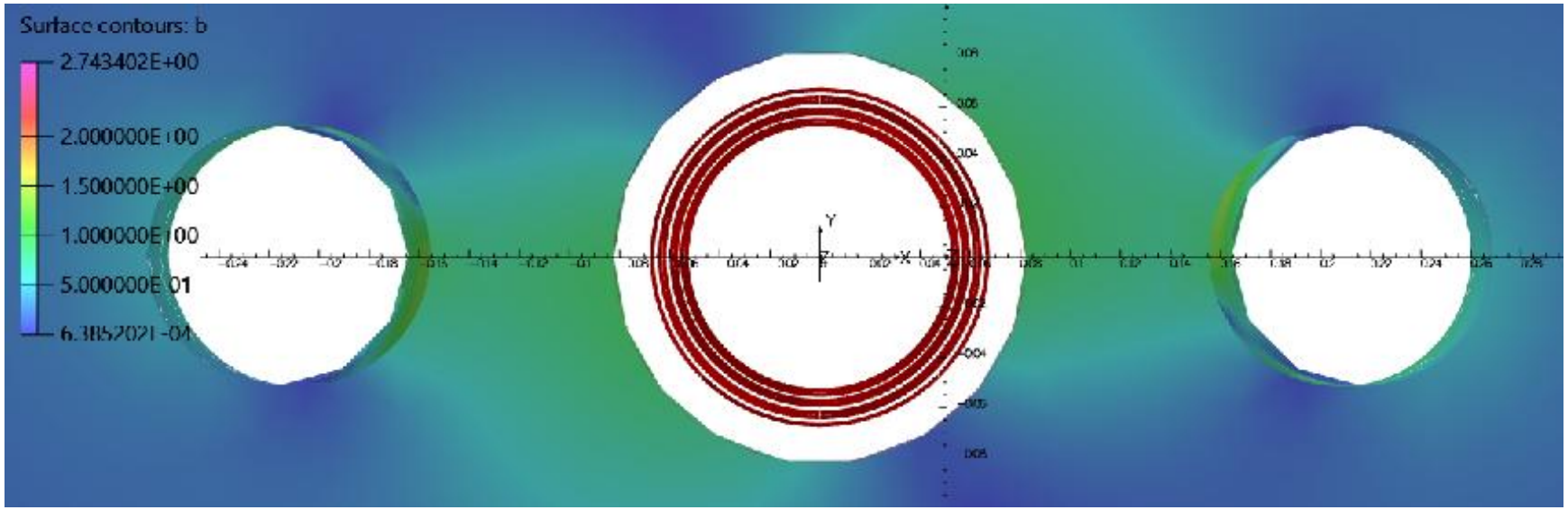


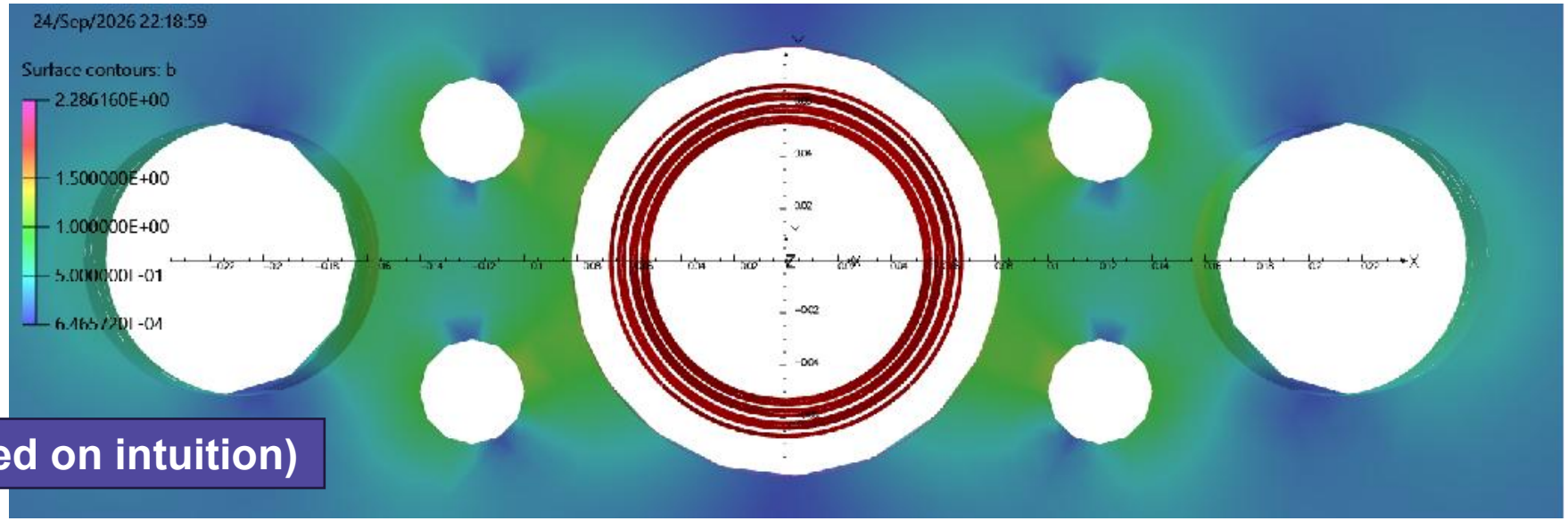
Note: A change in shape

Field in Yoke Without and With Strategically Placed Holes in B0ApF

Compare the field in the yoke in the area between the hadron and electron beams:

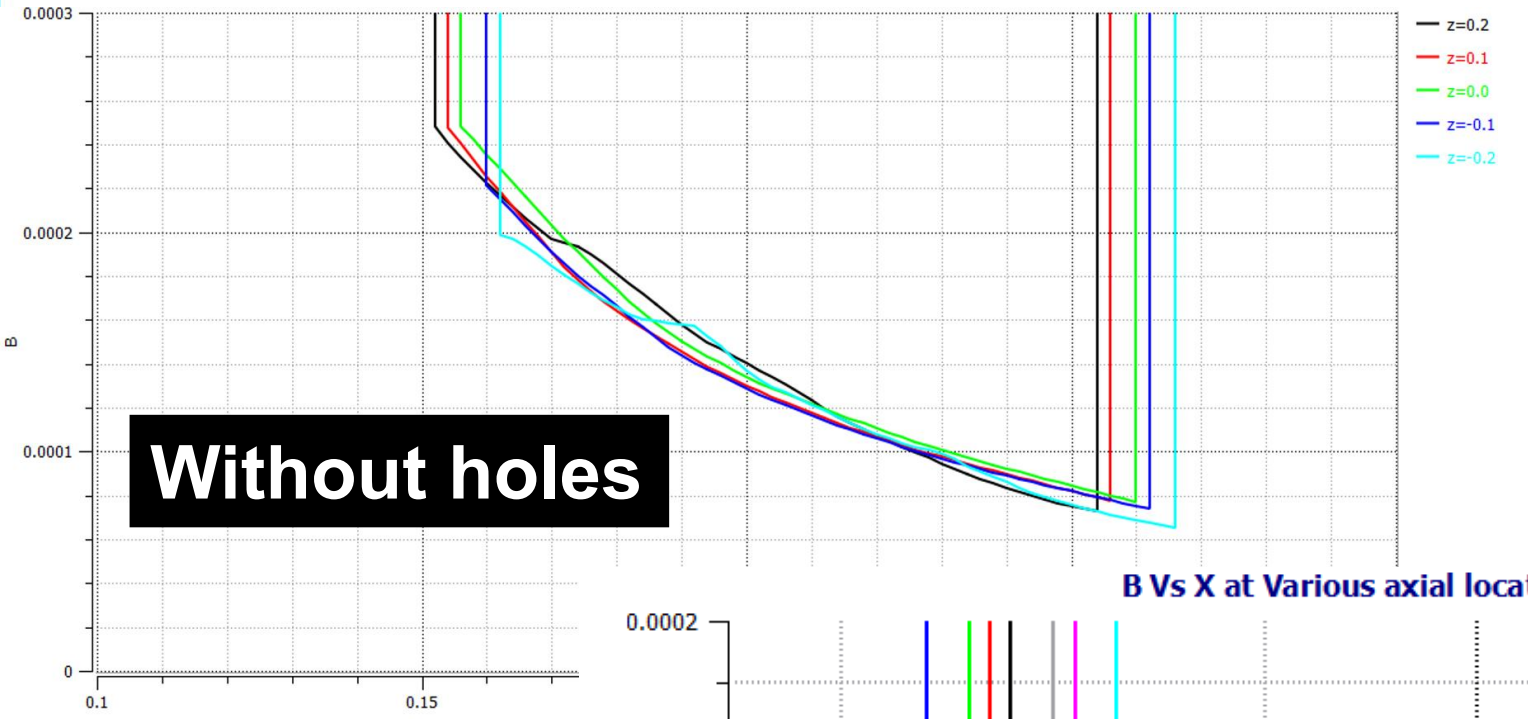
- Holes reduce the field (better shielding)
- Holes reduce the difference in field between the left and right side of the yoke
- Holes reduce the difference in field between the up and down (skew)





(not optimized, 1st attempt based on intuition)

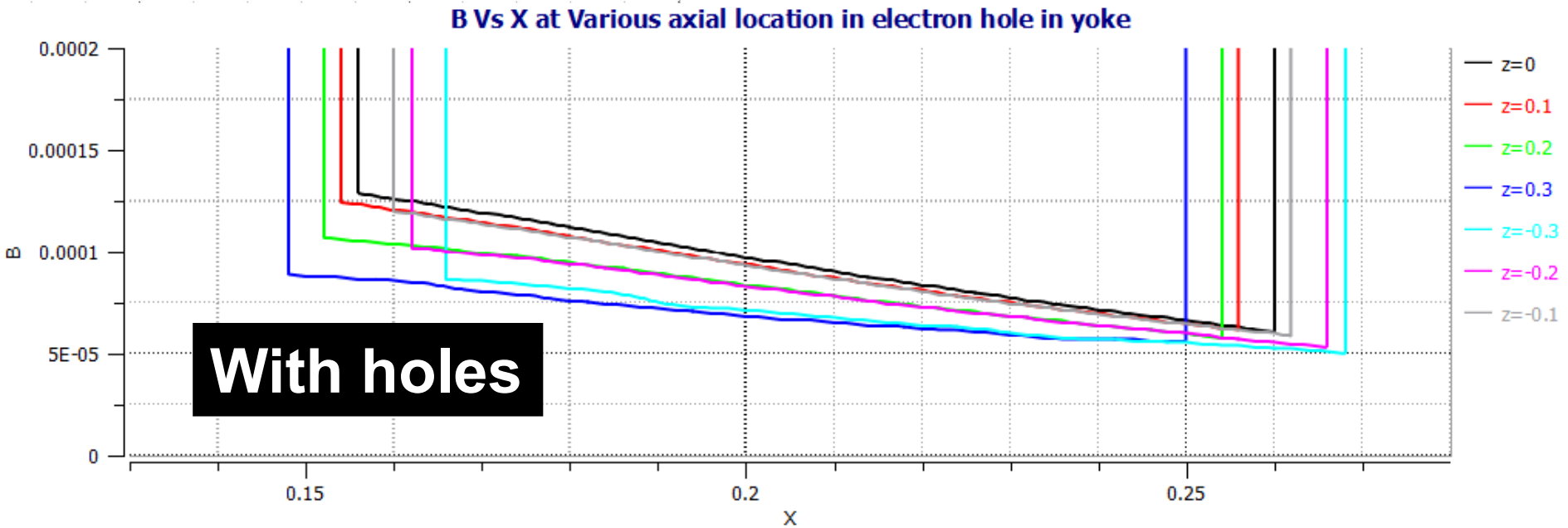
Impact of holes in reducing non-linearity



Without holes

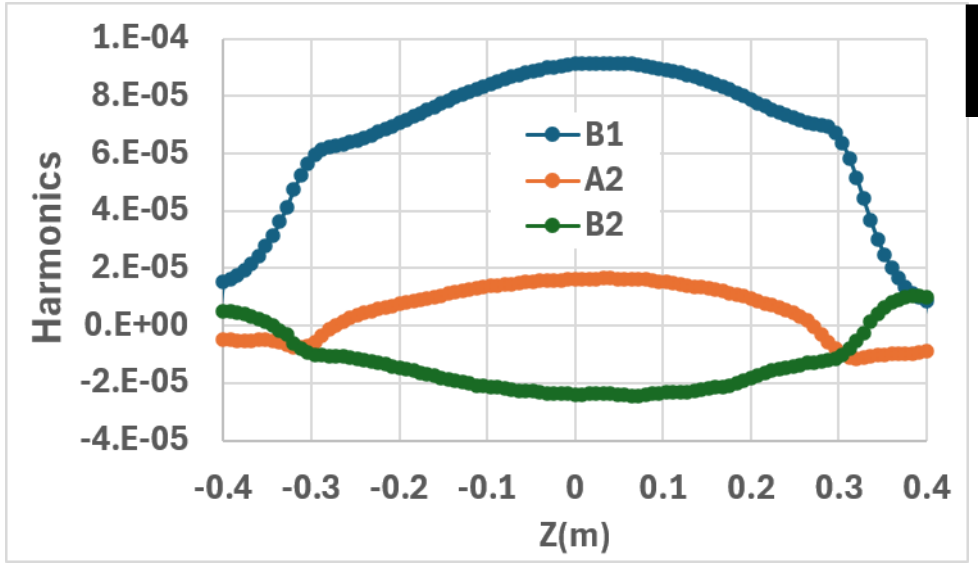
Reduced saturation in yoke in between means better shielding.

- Lower field.
- It also becomes more linear,



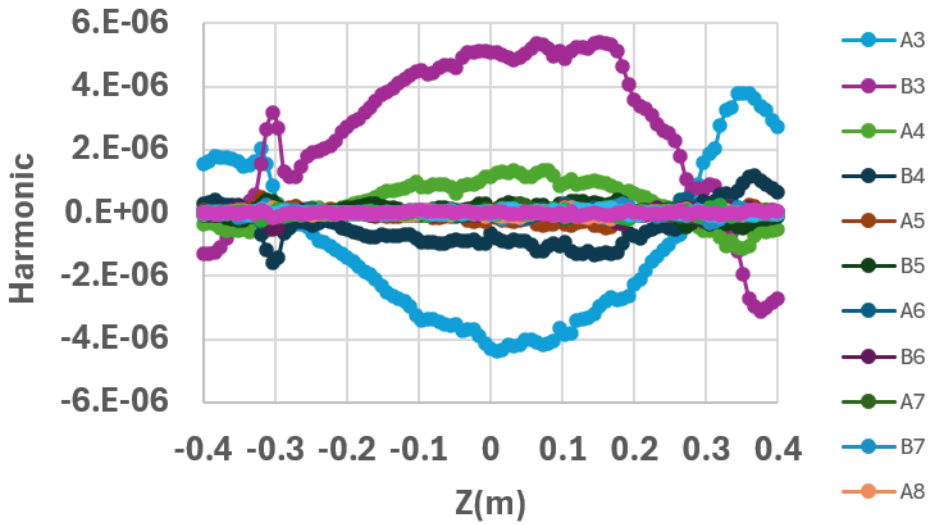
With holes

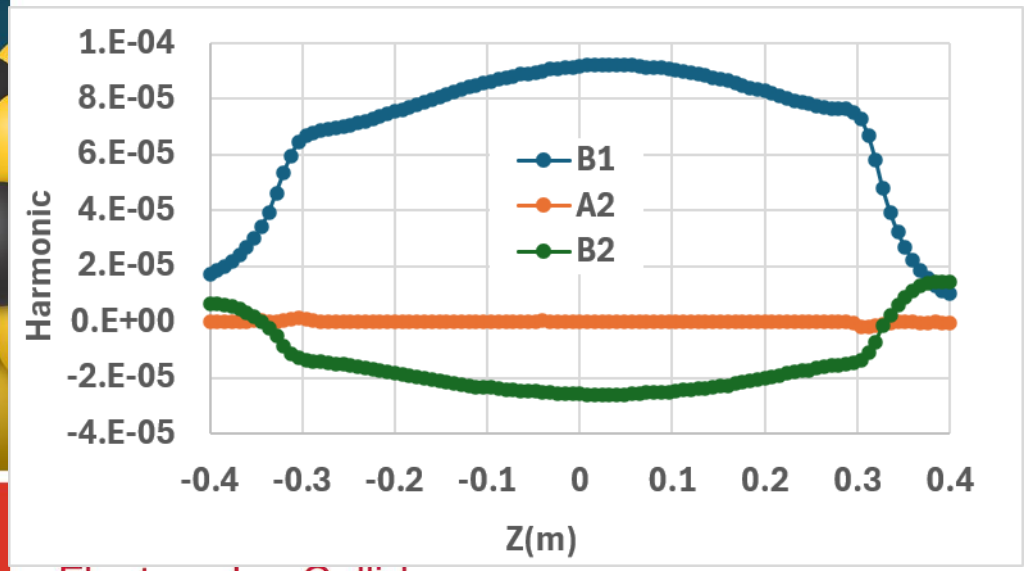
Impact of holes in reducing harmonics



Without holes

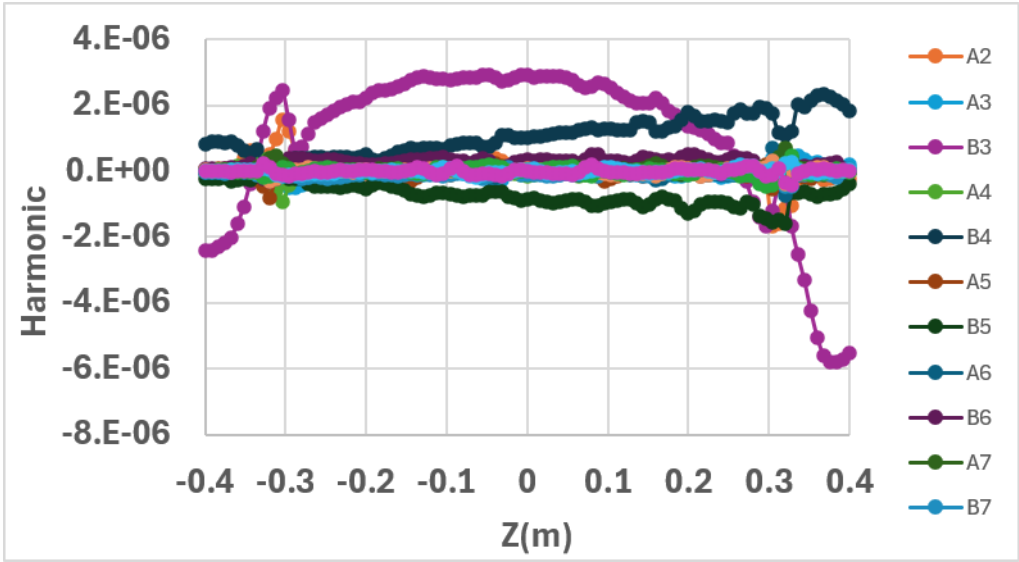
=> Holes essentially suppress the skew terms.





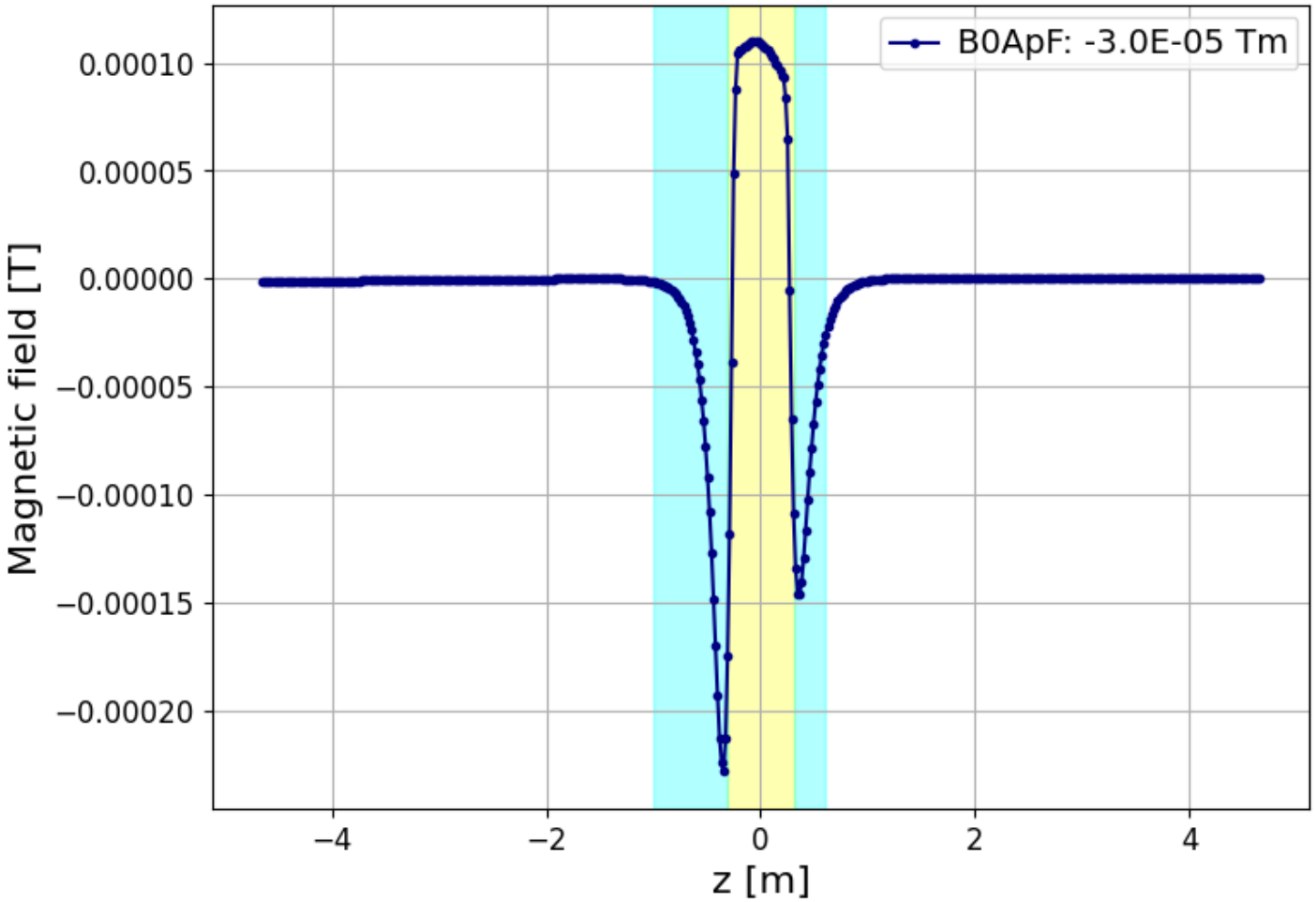
=> Holes reduce non-linear harmonics.

With holes



Field at center of electron beam (including fringe field)

Without additional hole case

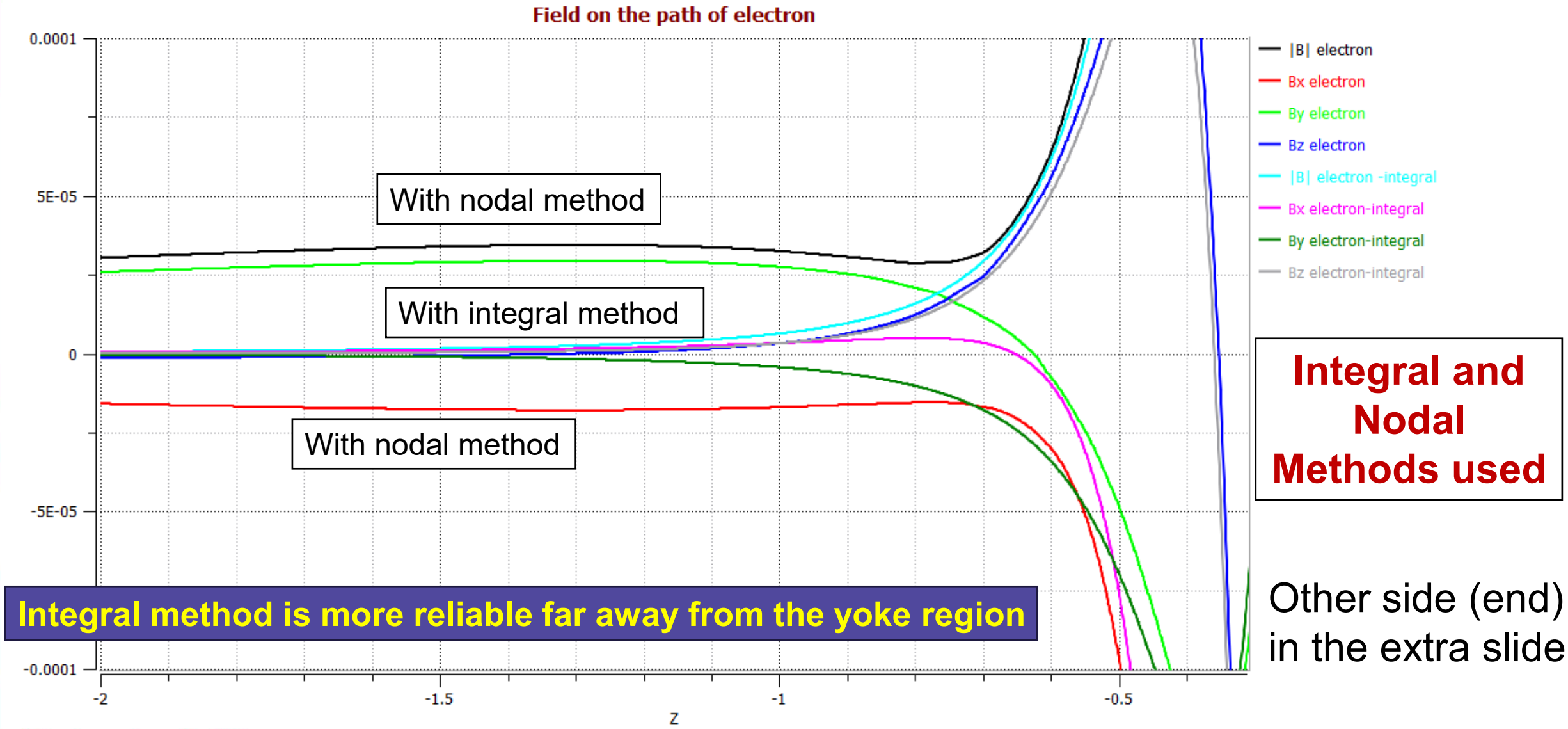


Fringe field outside the yoke give significant field errors (Emmanuele Ravaioli)

electron beam is very close to the hadron magnet

Nodal Method used (must be used in the electron hole region)

Fringe field on the electron beam at two sides of the yoke



Integral method is more reliable far away from the yoke region

Integral and Nodal Methods used

Other side (end) in the extra slide

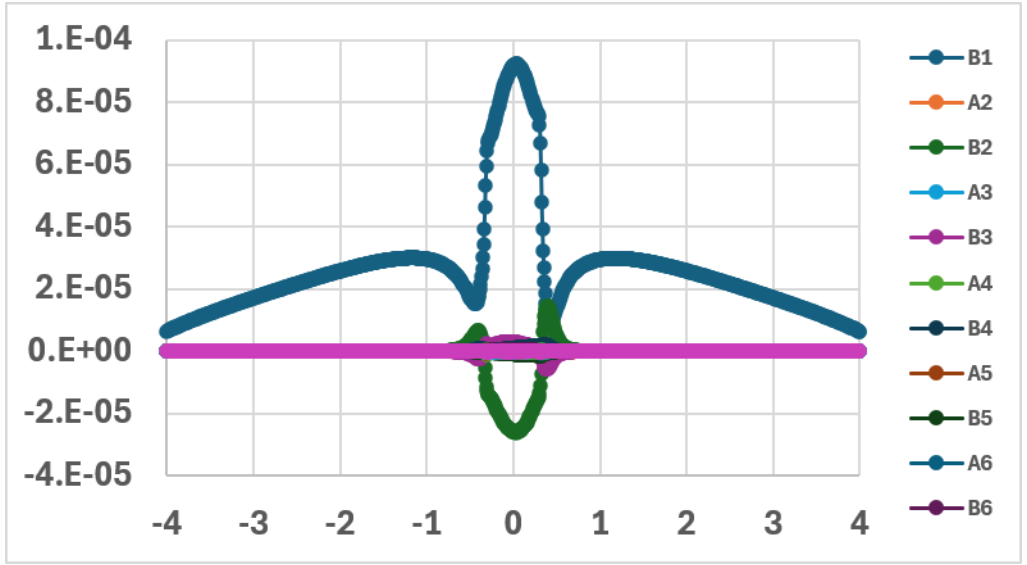
Integrated Harmonics along the electron path (outside region – fringe field- included)

Cross-talk/fringe field integrated harmonics harmonics

B0ApF and correctors at full strength together

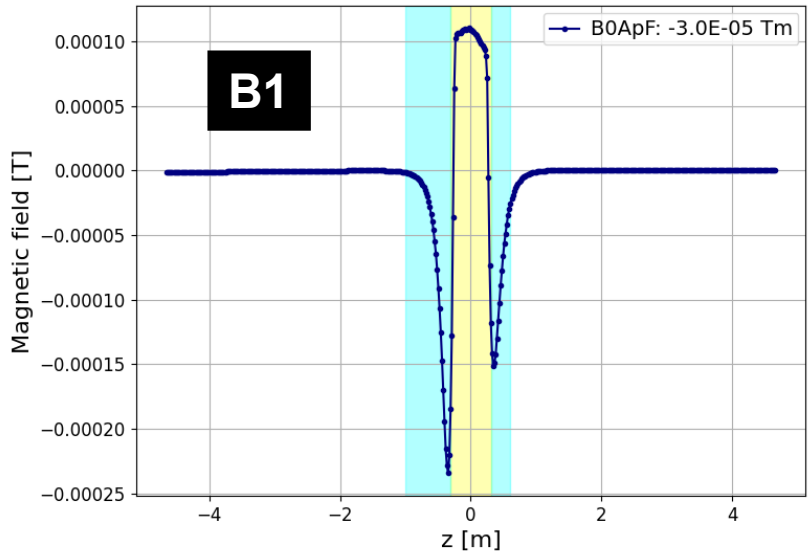
Harmonic	Spec(T.m)@26mm	Computed	Ratio
B1	6.2E-04	2.1E-04	34%
A2	6.2E-04	5.7E-09	0%
B2	6.2E-04	-1.0E-05	2%
A3	6.2E-06	-2.4E-08	0%
B3	6.2E-06	1.8E-07	3%
A4	6.2E-06	2.2E-08	0%
B4	6.2E-06	1.0E-06	16%
A5	6.2E-06	-1.8E-08	0%
B5	6.2E-06	-6.0E-07	10%
A6	6.2E-06	-1.3E-08	0%
B6	6.2E-06	2.1E-07	3%
A7	6.2E-06	3.2E-08	1%
B7	6.2E-06	-7.9E-08	1%
A8	6.2E-06	1.4E-09	0%
B8	6.2E-06	-6.0E-10	0%
A9	6.2E-06	-2.6E-09	0%
B9	6.2E-06	-8.4E-09	0%

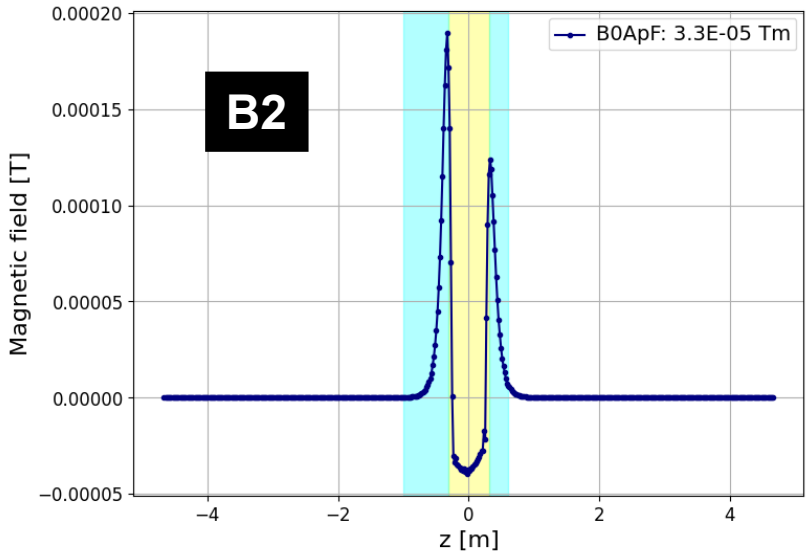
Specifications are easily met with holes (Emmanuele will be cross-checking)

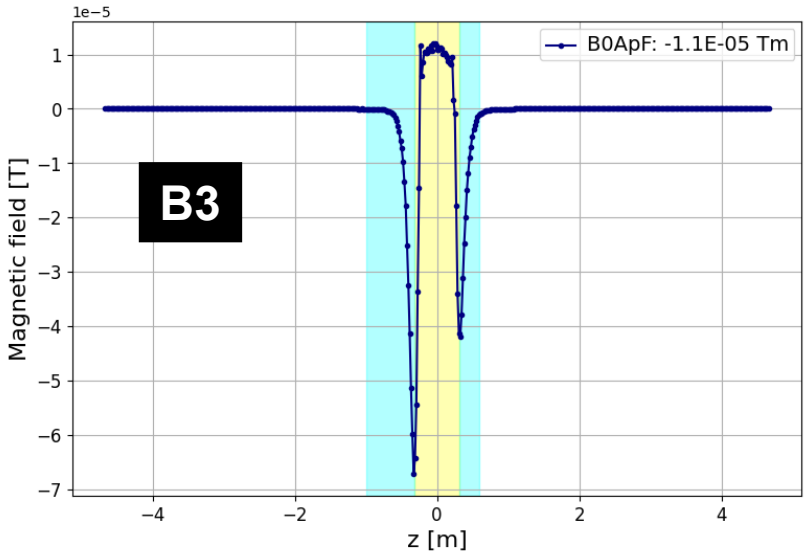


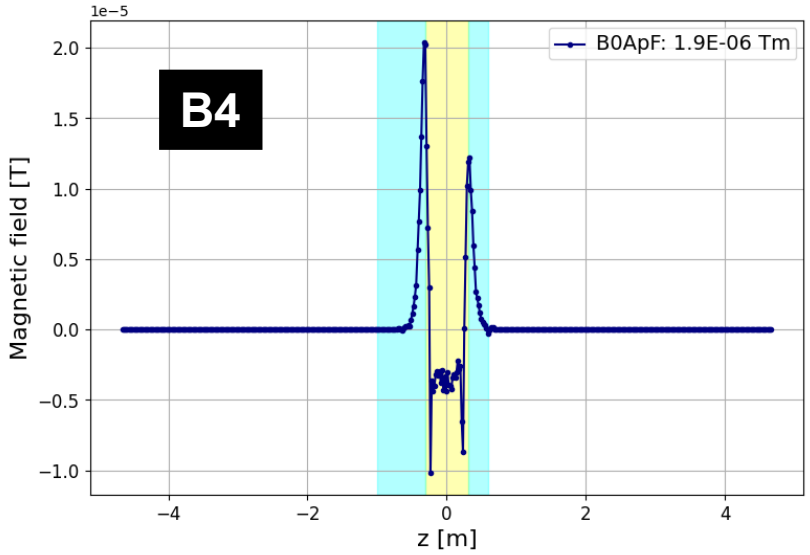
Integrated Harmonics from -4 m to +4 m along the electron path (field from other magnets must be included)

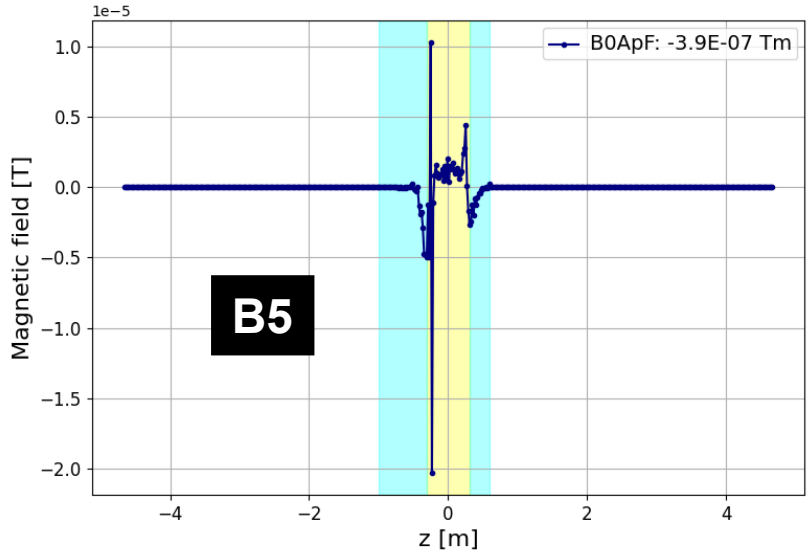
Model Calculations by Emmanuele Ravaioli (to be updated)

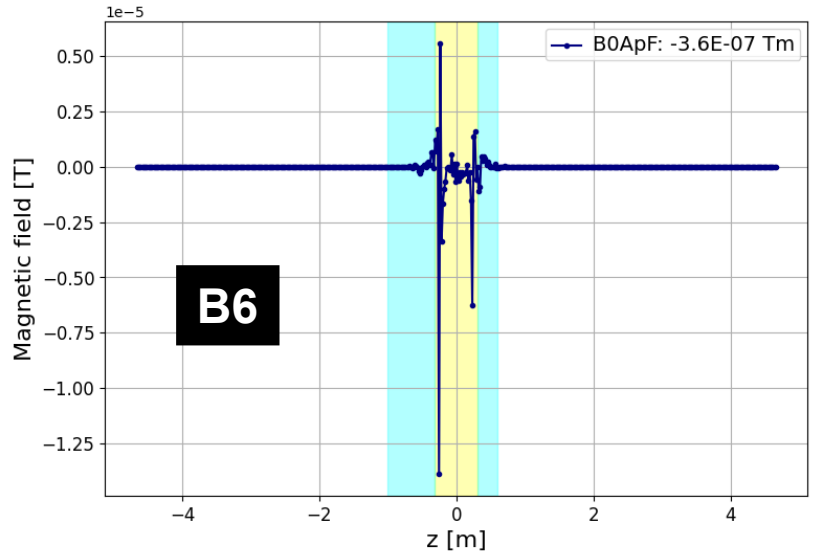




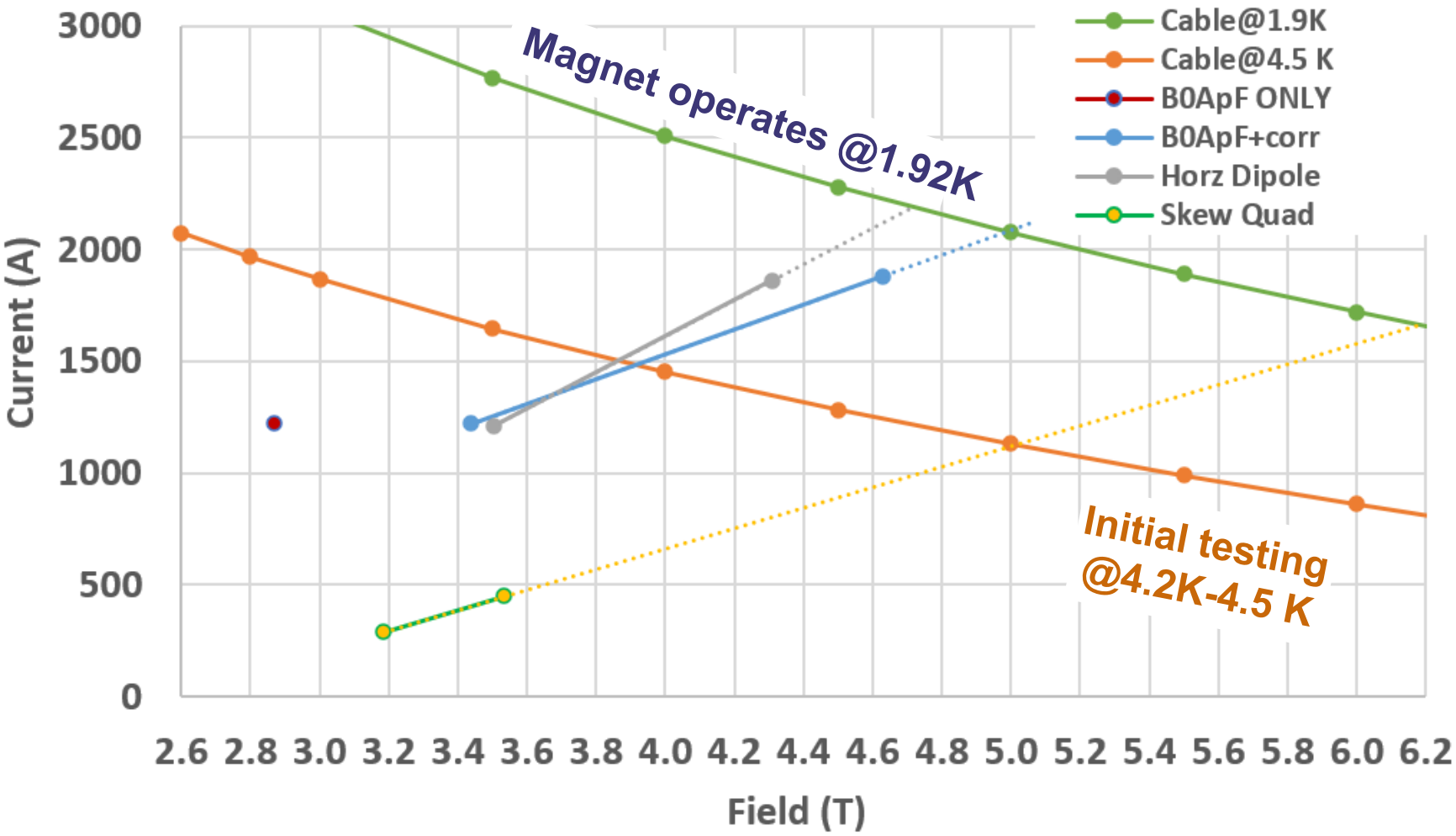








Load line Fraction Margins



B0ApF:

1220A/2074A = 0.59

Horizontal Corr:

1210A/2190A = 0.55

Skew Quad:

290A/1650A = 0.18

Load line Fractions

Requirement: <0.65

✓ **Easily met despite a short length**

Quench performance are met at 4.2 K.
Can be tested to full performance at 4.2 K.

Major Task Remaining on the EM Design

- Yoke optimization to meet harmonics over the entire range of operation of hadron beam (yoke is already optimized to reduce cross-talk on electron beam)
- Will be done once all features and details are included (including possible reduction in yoke i.d. from 1.2 meter to 1 meter (should not be an issue).

Summary

- Optimum integral design with the direct wind technology allows a relatively short B0ApF with desired margin to help other magnets in the lattice.
- Even shorter length than this is possible, but that requires more layers (cost).
- The main B0ApF design is based on two coil-sets, which allows harmonic correction after the measurement of the first coil set. Other magnets are corrector magnets where larger errors are allowed and thus a minimum risk in pursuing a single coil set.
- Various aspects of the optimum Integral design have been previously validated in PBL/BNL R&D magnet and thus the risk to project should be minimum.
- Yoke design to optimize the saturation-induced harmonics yet to be performed.
- Cross-talk requirements on the electron beam are rather tight. An inexpensive R&D plan to demonstrate model and measurement techniques will be useful.
- The design concept presented here seems to meet all requirements at the APR level.

Extra slides

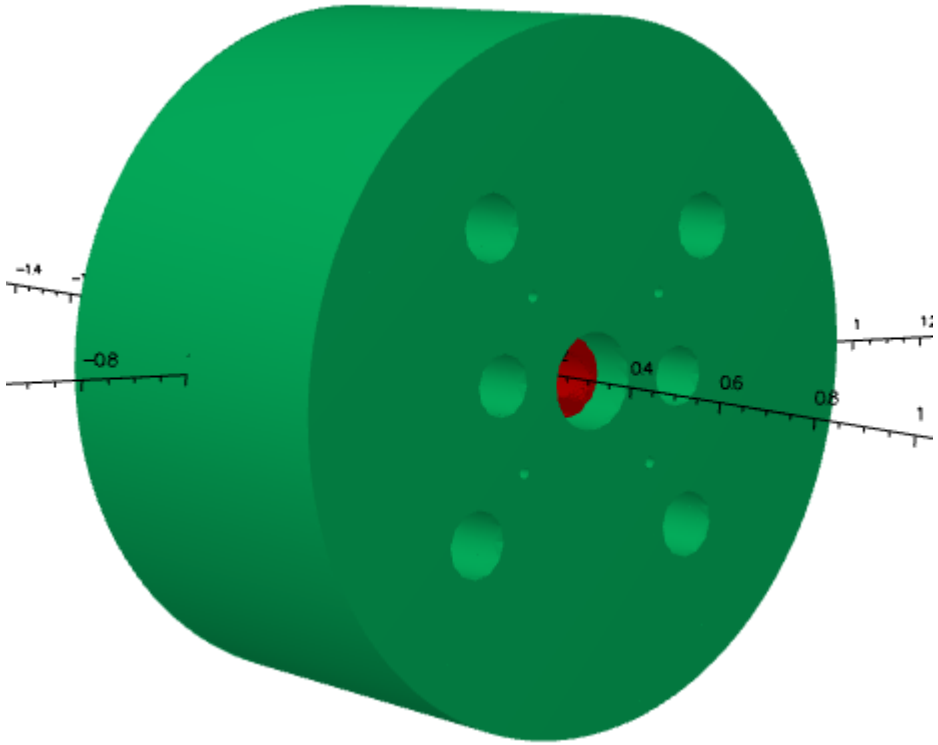
Main requirements, overview

Charge #1

Parameter	B0ApF	B0ApF_VC	B0ApF_SKQ	Q1pF	Q1eF	Driven by
Nominal Integral Field	1.122 T.m	0.6 T.m	1 T			Physics, lattice
Beam stay clear radius (cold)	≥39 mm	≥39 mm	≥39 mm			Beam size, lattice, sync. Rad
Ramp time (Inj. to store)	≤300 s	N/A	N/A			Transition crossing
Harmonics	All <2 units (@26 mm)	All <10 units (@26 mm)	All <10 units (@26 mm)			Beam dynamics
Linear Cross Talk	≤6.2 gauss.m within 26 mm	N/A	N/A			E-Beam dynamics
Non-Linear Cross Talk	<6.2 μT.m within 28 mm	N/A	N/A			Beam dynamics
Displacement tolerance	±1.0 mm	±1.0 mm	±1.0 mm			Beam dynamics
Roll tolerance	X/Y: ±0.5 mrad Z: ±0.2 mrad	X/Y: ±0.5 mrad Z: ±0.2 mrad	X/Y: ±0.5 mrad Z: ±0.2 mrad			Beam dynamics

Cross-talk and Fringe field – Computer Modeling

- The requirements for the maximum field and harmonic components for the electron beam travelling in the yoke cutout of the hadron magnet in EIC are rather tight (here referred to as cross-talk within the yoke and fringe field outside the yoke)
- These requirements demands us to be very careful in how we use the codes to make sure that we are not lost in the artificial errors of the model.
- For example, change the default potential of OPERA3d to “Total” in the air region where field electron is traveling. Coil should still use “Reduced” vector potential.
- Also, one should use “nodal method” for computing cross-talk field inside the yoke and “integral method” away from the yoke. Please see a few slides to follow.

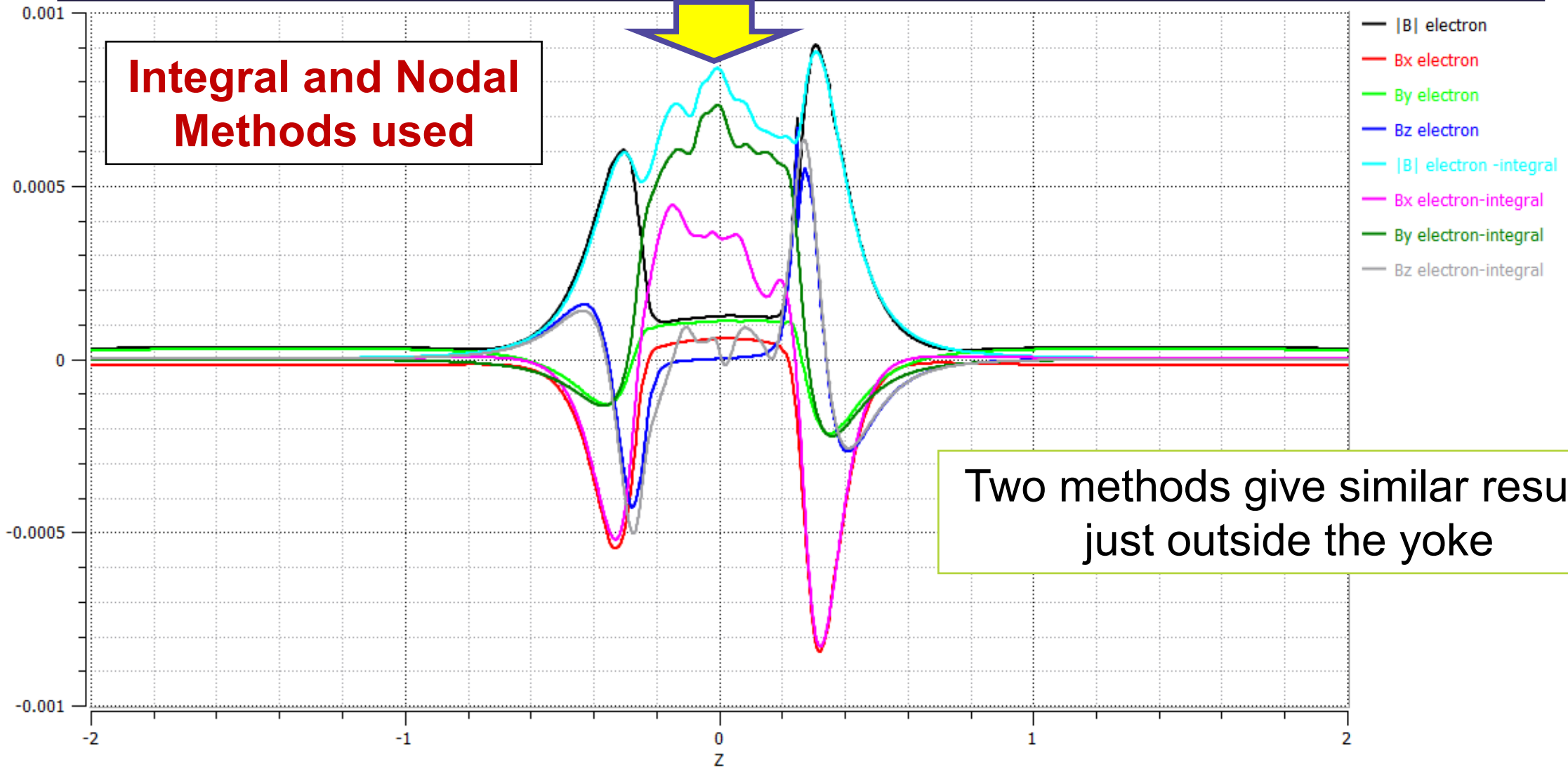


Cross-talk and Fringe field – Additional Techniques

- If the integral of cross-talk and fringe field exceeds the specifications even after doing the best modeling, then special techniques must be used to reduce them.
- Techniques that can be used (in the order of my preference):
  - ❑ Holes in the yoke to move flux lines away and/or homogenize field to reduce non-linear harmonics
  - ❑ High permeability sheet wrap over the electron beam tube inside and outside the yoke region
  - ❑ Iron rings (onion rings) over the electron beam tube
  - ❑ High saturation steel in a small region inside the yoke in between the hadron and electron beam
  - ❑ Superconducting shield (already tested successfully in PBL/BNL STTR)
- Proof-of-principle demonstration of the chosen technique(s) should be carried out

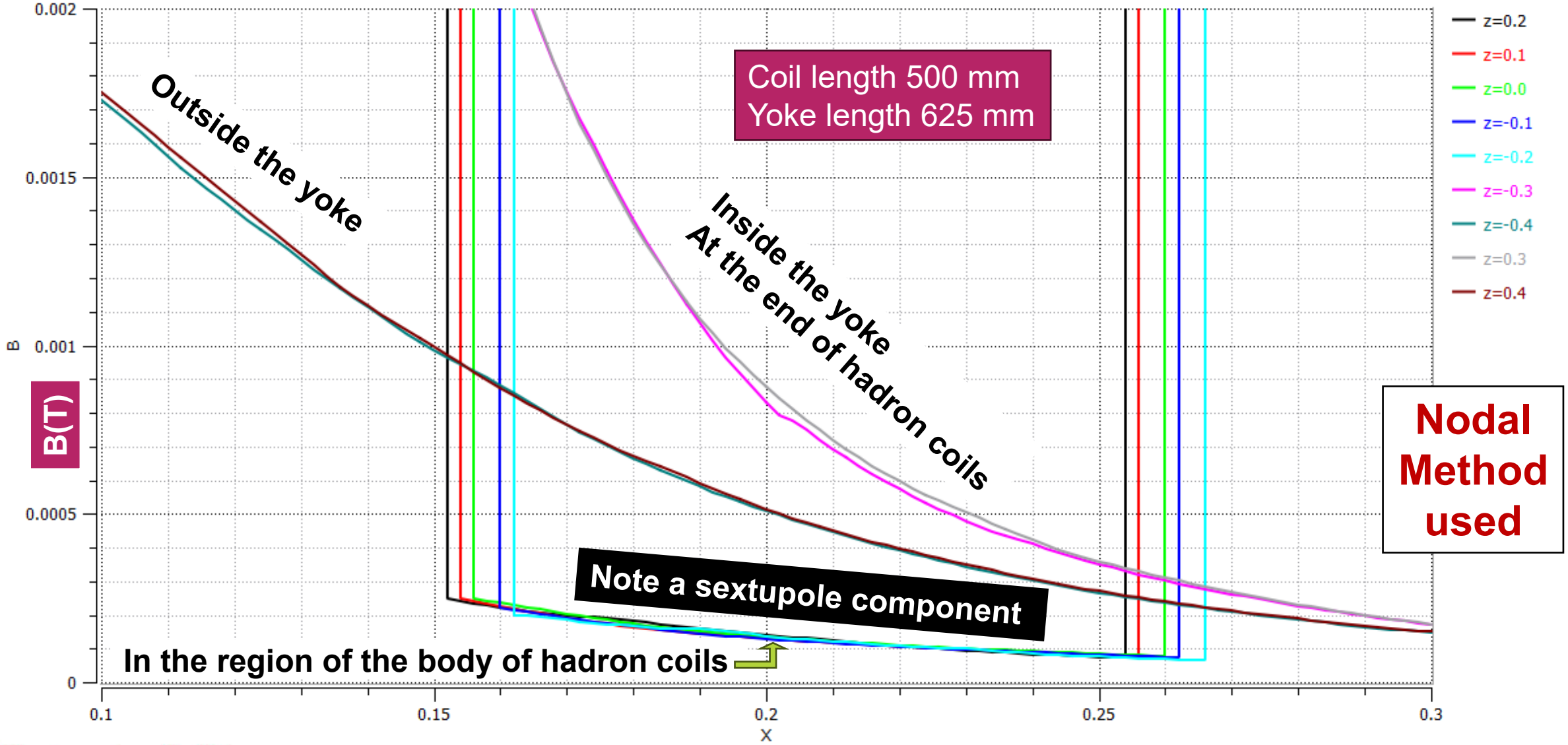
Field at center of electron beam (with two methods)

Integral method gives large errors for the field inside the yoke (-0.31 m to +0.31 m)



Two methods give similar results just outside the yoke

Field on the electron path inside and just outside the yoke



Fringe field on the electron beam at two sides of the yoke (2)

