Brookhaven National Laboratory

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U.S. DEPARTMENT OF ENERGY

Q3pF Package with Longer Yoke

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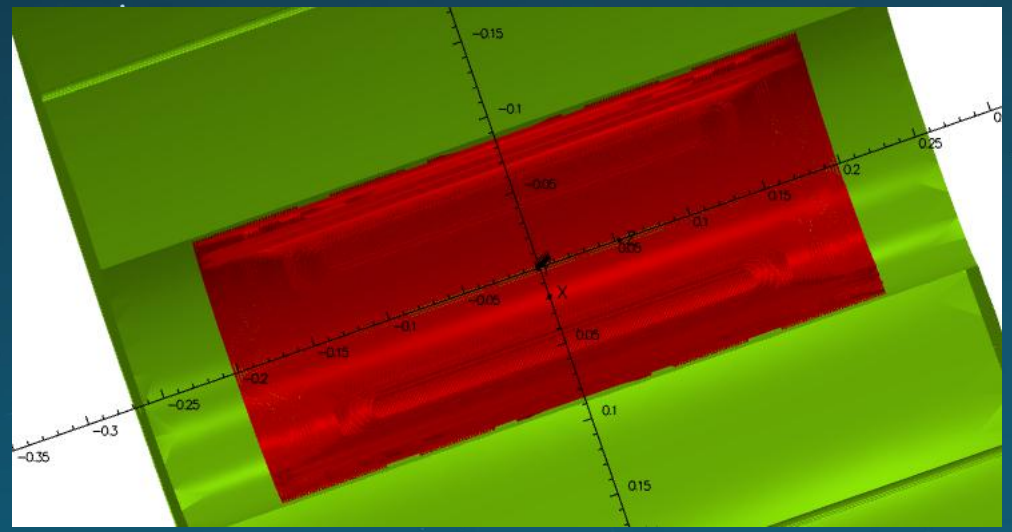




Electron-Ion Collider

October 13, 2026

Current Modelling Strategies for PDR

- Plan for PDR: Capture the essentials while limiting mechanical analysis to 2D only.
- With the increased yoke length, 2D mechanical analysis further departs from the 3D magnetic analysis. Coil length = 400 mm, yoke length = 520.1 mm, coil id=137.4 mm.
- This creates a tricky situation for PDR. Since the differences are significant, magnetic analysis is performed for 3D for computing the load line margins, magnetic length, current needed for the power supplies and for the quench protection calculations.
- However, to create a relatively closer 2D magnetic and mechanical modelling for the forces, for a part of the analysis for PDR the coil and yoke are assumed to have the same length. The coil is optimized for that design and is parsed to the longer yoke.
- This may or may not be the best choice. The other choice is do the coil design for actual yoke and use that design for 2D mechanical analysis. That will, however, increase the difference between 2D and 3D and hence not chosen at this time.
- With normal & skew quads and normal & skew dipoles, the 2D mechanical model must be made for full 360-degree (use NO symmetry, NO 180-degree model).

Summary from the last presentation

Magnetic requirements of SC B2pF-Q3 Package:

- ❑ 0.1 T-m horizontal corrector
- ❑ 0.1 T-m vertical corrector
- ❑ 3 T skew quadrupole corrector
- ❑ 8.4 T normal quad (NOT a corrector, field quality must be good)

Inner diameter of the 1st winding: 137.4 mm

Coil length : 400 mm (B2pF: coil i.d. =120 mm, length > 3400 mm)

Q3 package has a very small length/aperture ratio (<3)

✓ **Optimum Integral Design (OID) makes a big difference such cases.**

Initial feasibility of OID for Q3 package was been presented earlier.

➢ **This iteration is for (a) complying with the latest parameters and (b) minimizing the number of layers for reducing cost.**

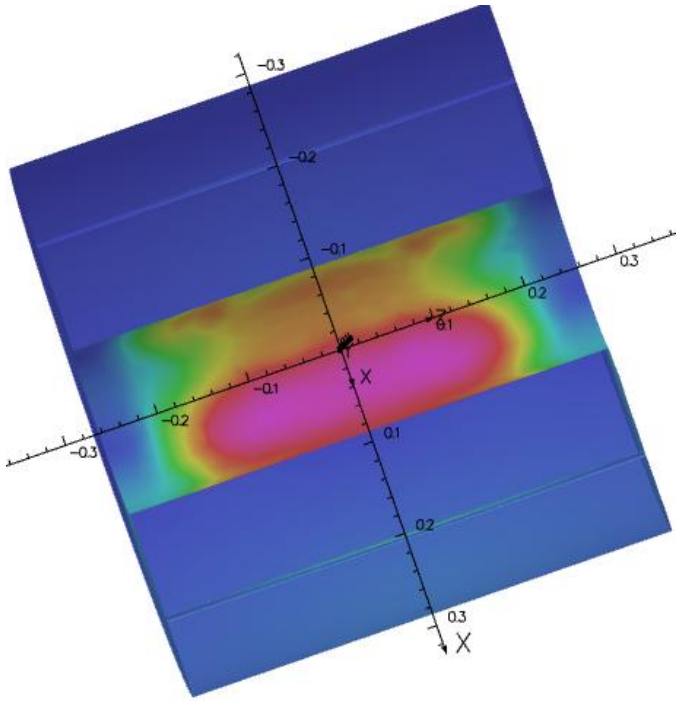
Impact of Longer Yoke

Coil i.d.: ~134.4 mm, coil length: 400 mm, **yoke now increased to 520.1 mm**

This reduces the operating current, increases margin, reduces Lorentz forces and should help in quench protection (all in positive direction).

Following still remains the same for the coil design

- Normal Quad: two coil sets (4 layers, earlier reduced from 6)
  - Two coil sets allow iteration in field harmonics based on the measurements in the first coil set
- Skew Quad corrector: one coil set (2 layers)
- Horizontal dipole corrector: one layer **(OID allows it)**
- Vertical dipole corrector: one layer (gap at midplane to avoid interference in coil winding)



- Meets field quality requirements. Next: iterate for longer yoke (magnetic design only)

Computed Optimized Harmonics @33 mm in Three Coil Sets of Quad

Spec <1 units for normal Quad; <10 units for skew quad (?check?)

Two coil sets for normal quad and one coil set for skew quad

(second coil set in normal quads helps iterate the field quality)

Coil set #1 (normal quad)

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.14984E+00	10000.0000
5	0.21611E-07	0.0014
9	0.45762E-07	0.0031
13	0.89712E-06	0.0599
17	-0.27749E-07	-0.0019
21	0.65381E-10	0.0000
25	-0.14494E-09	-0.0000
29	0.41595E-11	0.0000

Coil set #2 (normal quad)

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.14866E+00	10000.0000
5	0.21583E-07	0.0015
9	-0.10802E-07	-0.0007
13	0.56309E-06	0.0379
17	-0.19014E-07	-0.0013
21	-0.30955E-09	-0.0000
25	-0.55936E-11	-0.0000
29	0.54869E-12	0.0000

Coil set #3 (skew quad corrector)

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
1	0.15032E+00	10000.0000
5	-0.20352E-07	-0.0014
9	-0.20705E-08	-0.0001
13	0.10312E-06	0.0069
17	-0.15113E-08	-0.0001
21	-0.72268E-10	-0.0000
25	-0.13961E-11	-0.0000
29	0.16690E-12	0.0000

Very low computed design harmonics in all cases

- Old US definitions, b_2 is sextupole

Computed Optimized Harmonics @33 mm in 2 Coil Sets of Dipole

Low design harmonics for correctors

Coil layer #1

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.21753E+00	10000.0000
2	0.83591E-05	0.3843
4	0.17421E-04	0.8009
6	0.22942E-04	1.0547
8	-0.30589E-05	-0.1406
10	0.28072E-06	0.0129
12	-0.12634E-07	-0.0006
14	-0.38119E-08	-0.0002
16	0.79735E-09	0.0000
18	-0.13164E-09	-0.0000
20	0.93845E-11	0.0000
22	0.26488E-12	0.0000
24	-0.26125E-12	-0.0000
26	0.56983E-13	0.0000
28	-0.57724E-14	-0.0000
30	0.35600E-15	0.0000

Coil layer #2

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.20631E+00	10000.0000
2	0.75612E-06	0.0366
4	0.43698E-06	0.0212
6	-0.25212E-04	-1.2221
8	-0.32163E-05	-0.1559
10	-0.26696E-06	-0.0129
12	-0.60366E-07	-0.0029
14	-0.41239E-08	-0.0002
16	-0.13309E-08	-0.0001
18	-0.17356E-09	-0.0000
20	-0.27502E-10	-0.0000
22	-0.20295E-11	-0.0000
24	-0.26014E-12	-0.0000
26	-0.77201E-13	-0.0000
28	-0.13794E-13	-0.0000
30	-0.13916E-14	-0.0000

Spec <10 units

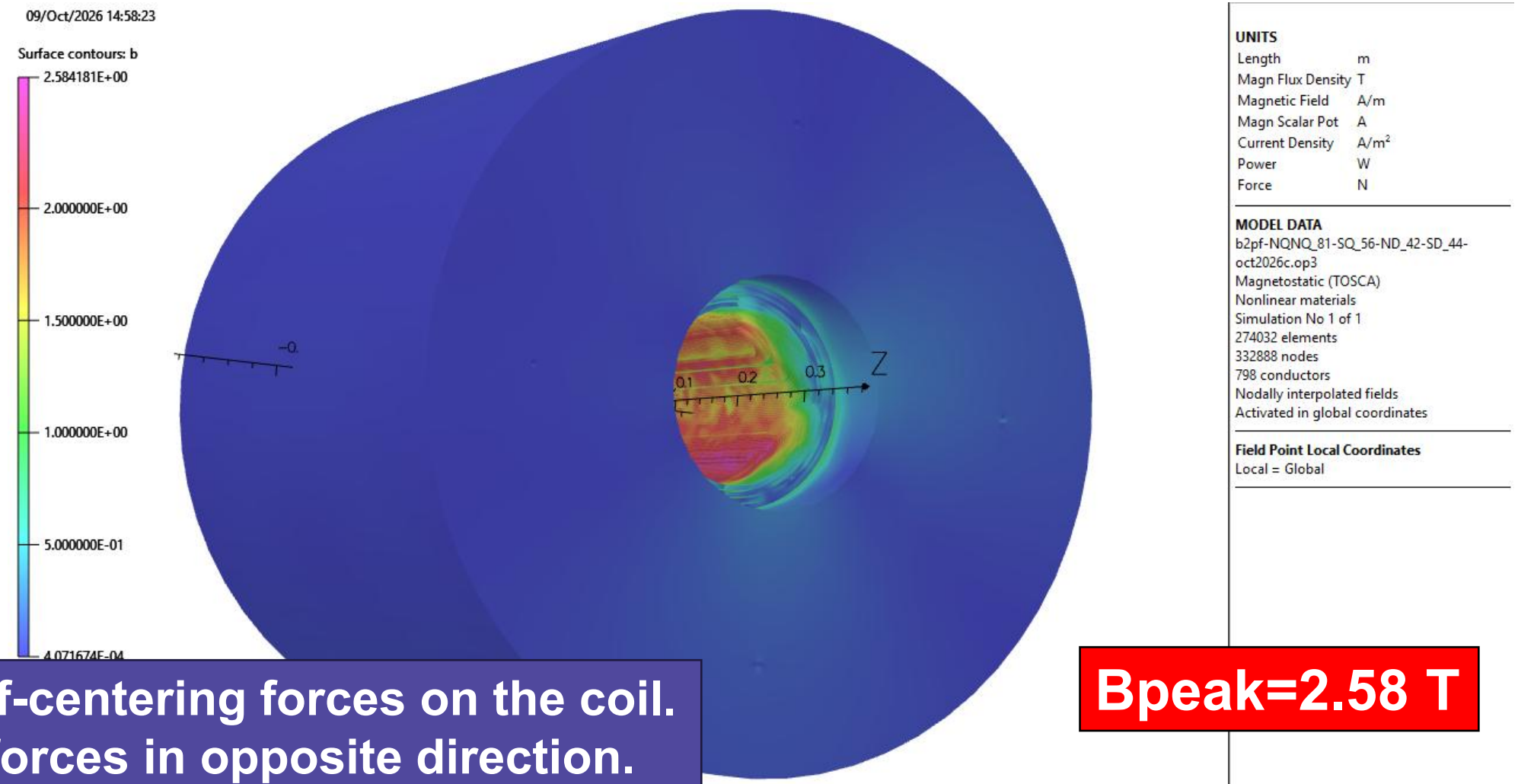
One coil layer for vertical corrector, one for horizontal (they can be in any order)

Optimum integral design allows a single layer coil

Old US definitions, b2 is sextupole

Magnetic Model with All Coils in Iron Yoke

- Normal quad
- Skew quad
- Normal dipole
- Skew dipole

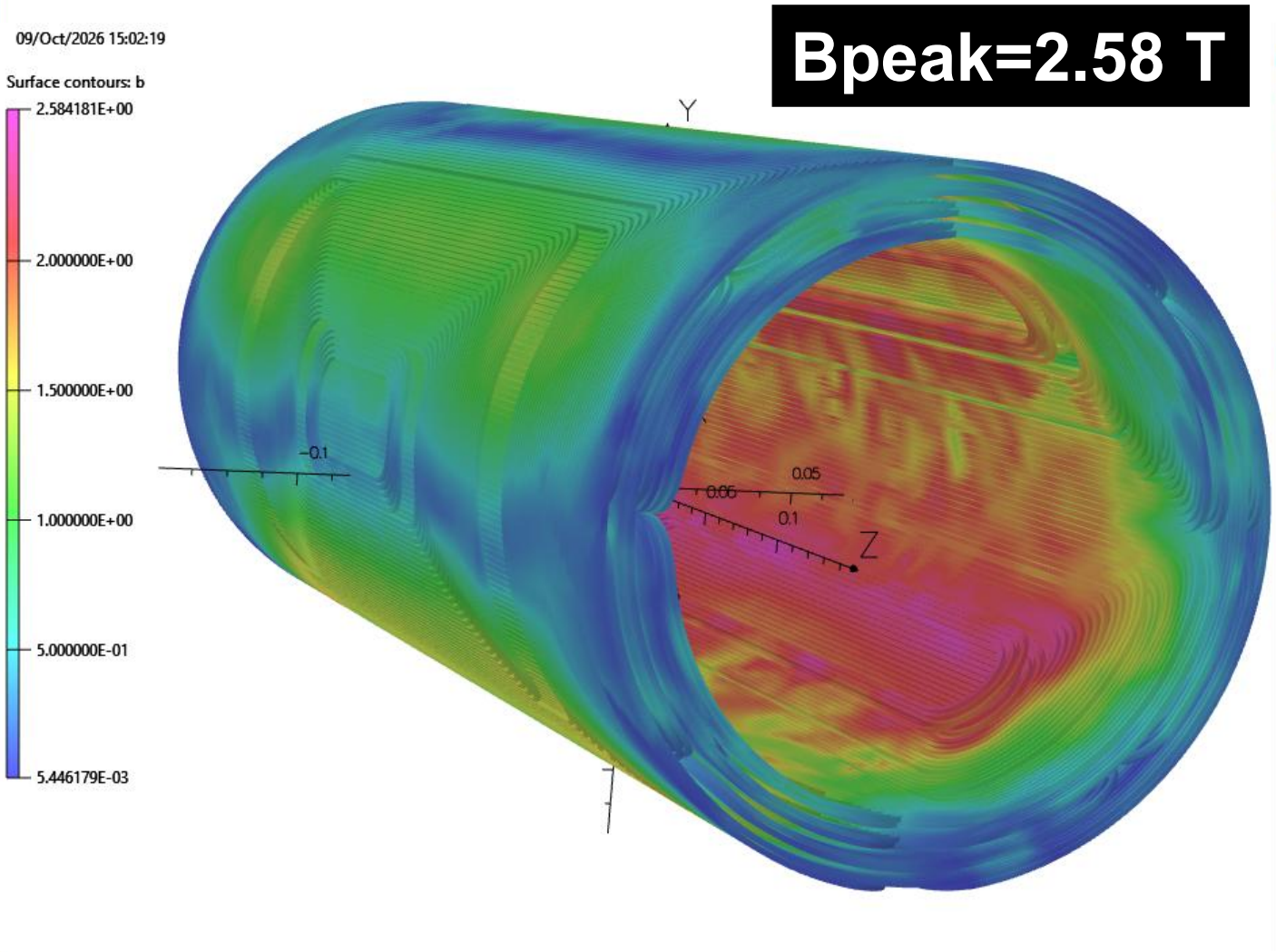


There will be off-centering forces on the coil. Yoke will have forces in opposite direction.

➢ **Net force must be ZERO !**

Bpeak=2.58 T

All coils (normal and skew quads, normal and skew dipoles)



UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m²
Power	W
Force	N

MODEL DATA
b2pf-NQNQ_81-SQ_56-ND_42-SD_44-oct2026c.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
274032 elements
332888 nodes
798 conductors
Nodally interpolated fields
Activated in global coordinates

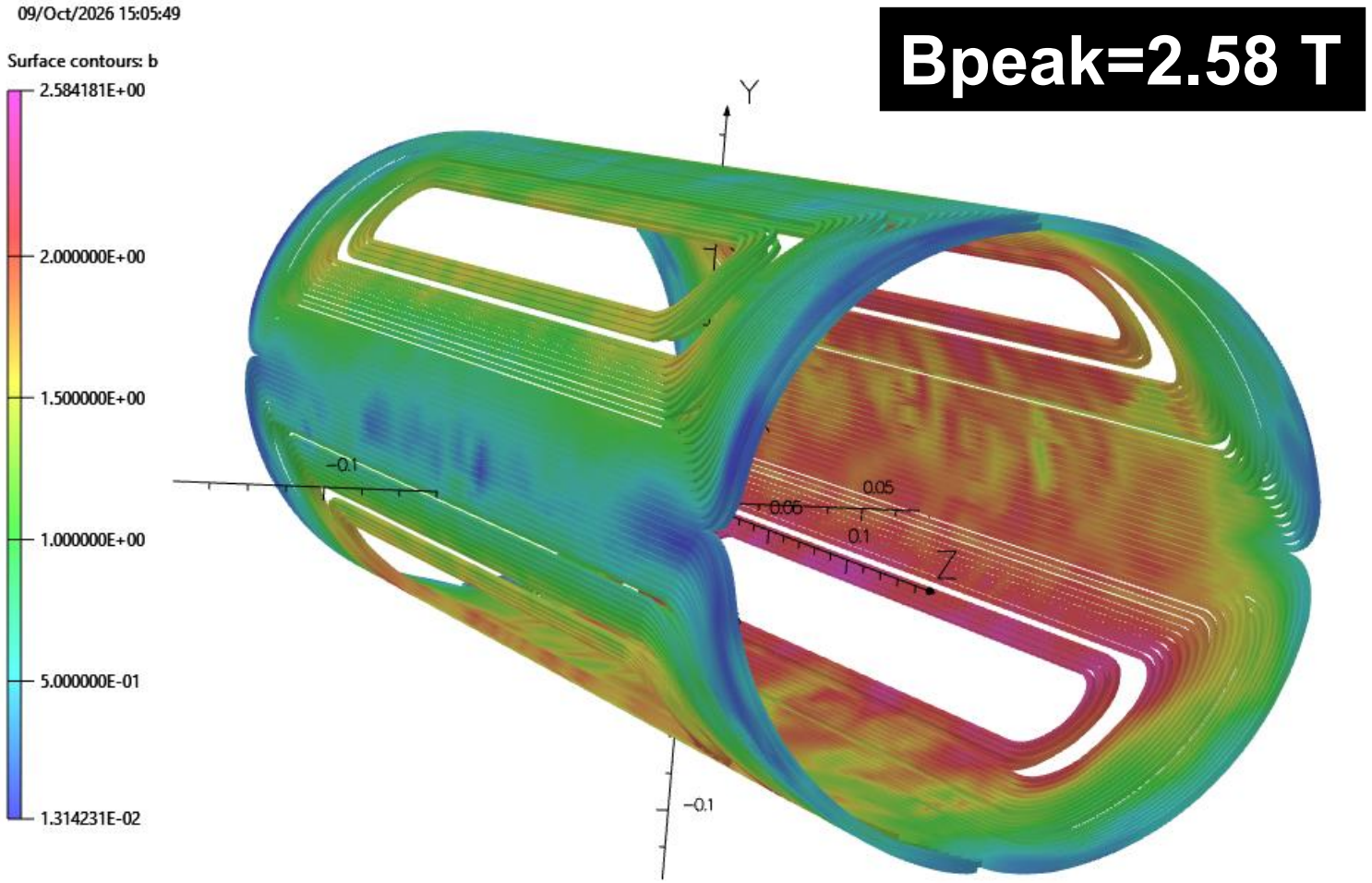
Field Point Local Coordinates
Local = Global

Currents to produce the design integrals:

- **NQ: ~810 A**
- **SQ: ~560 A**
- **ND: ~420 A**
- **SD: ~440 A**

(all are reduced from the last design with shorter yoke: ~910 A in quad to ~500 A in dipoles)

Coil set 1 (normal quad, I = 810 A)



Bpeak=2.58 T

UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m^2
Power	W
Force	N

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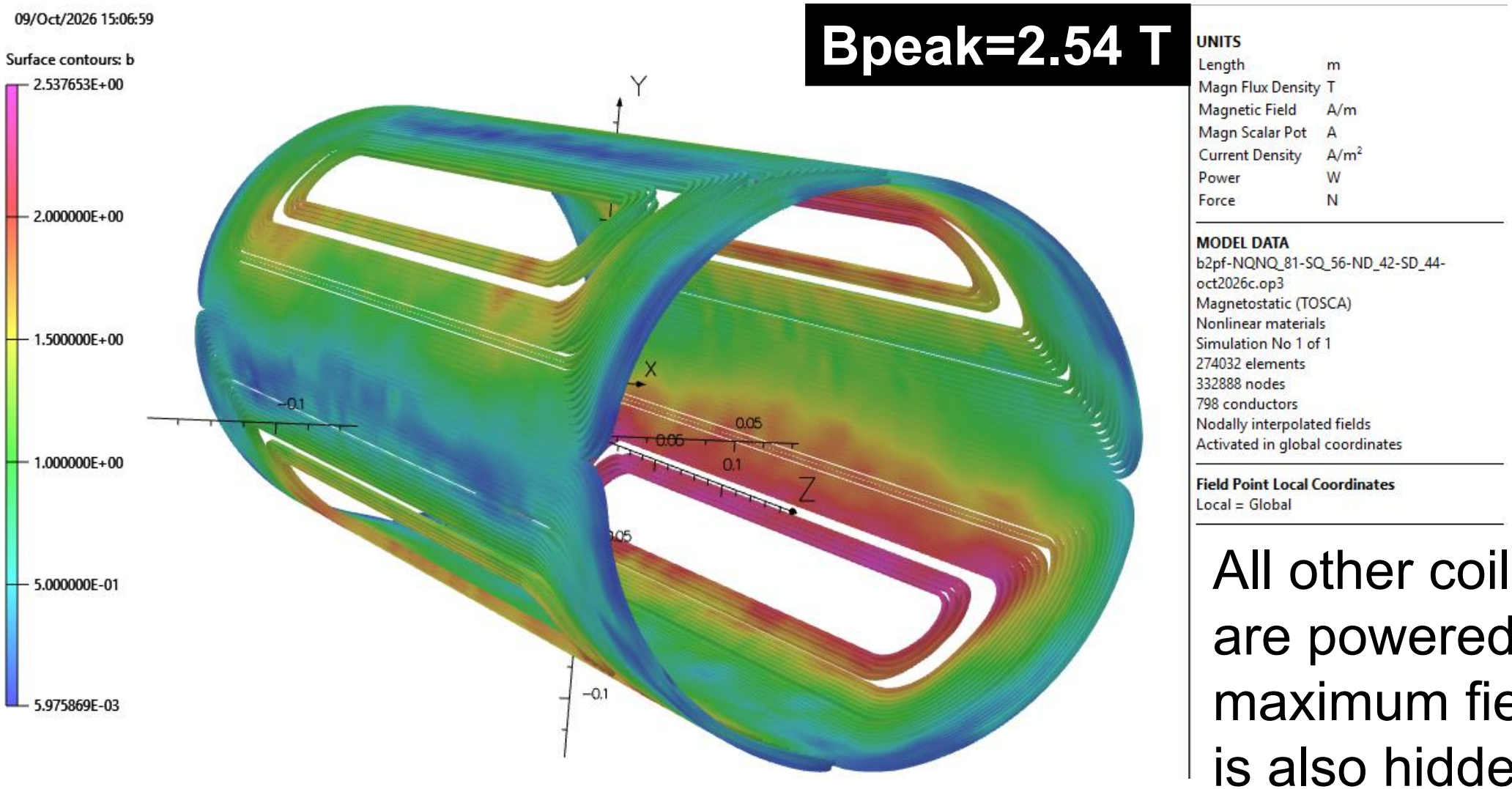
Field Point Local Coordinates

Local = Global

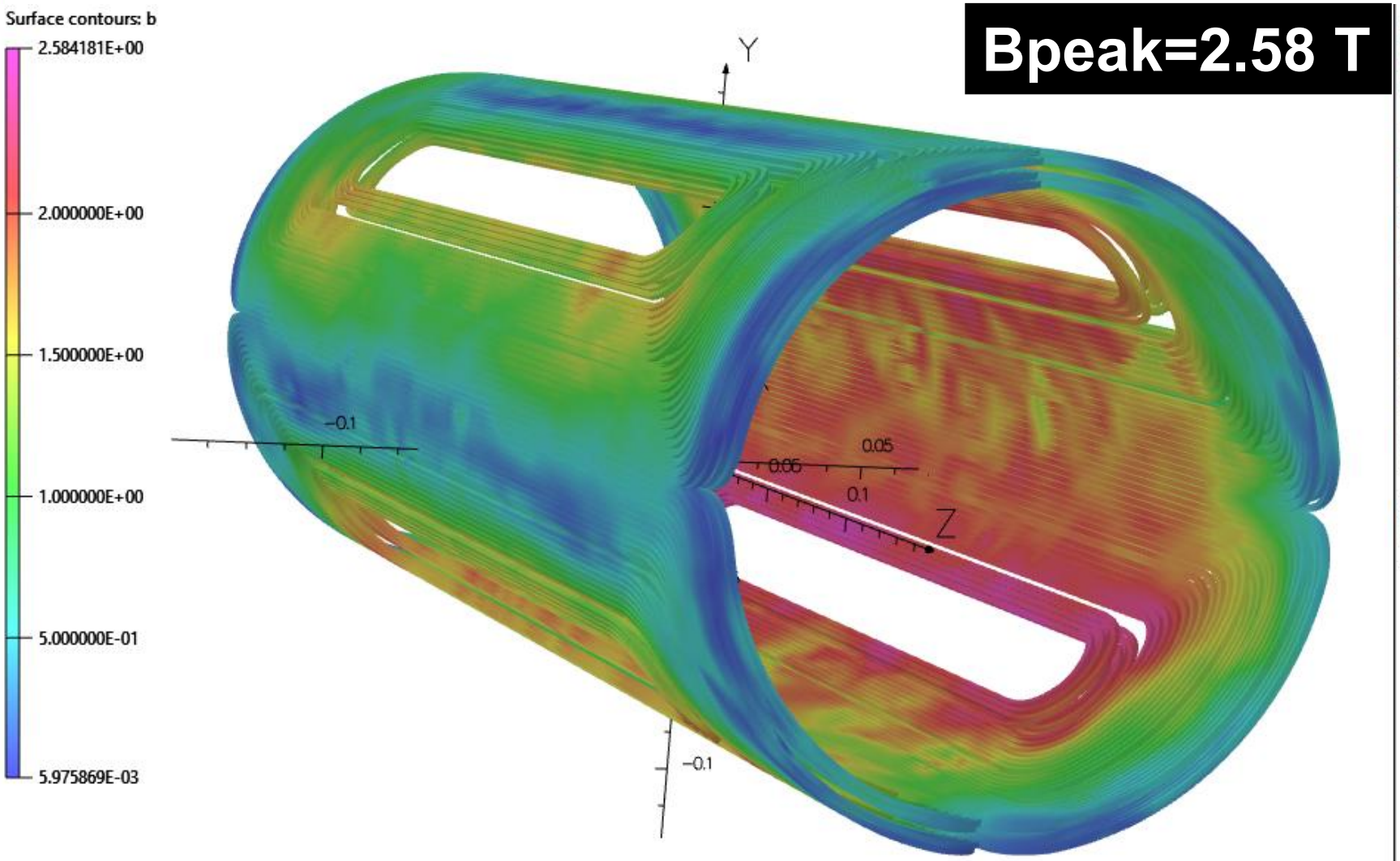
All other coils (hidden) are powered at the maximum field (yoke is also hidden)

Coil set 2 (normal quad, I = 810 A)



All other coils (hidden) are powered at the maximum field (yoke is also hidden)

Coil set 1 and coil set 2 (normal quad, I = 810 A)



Bpeak=2.58 T

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m^2
Power	W
Force	N

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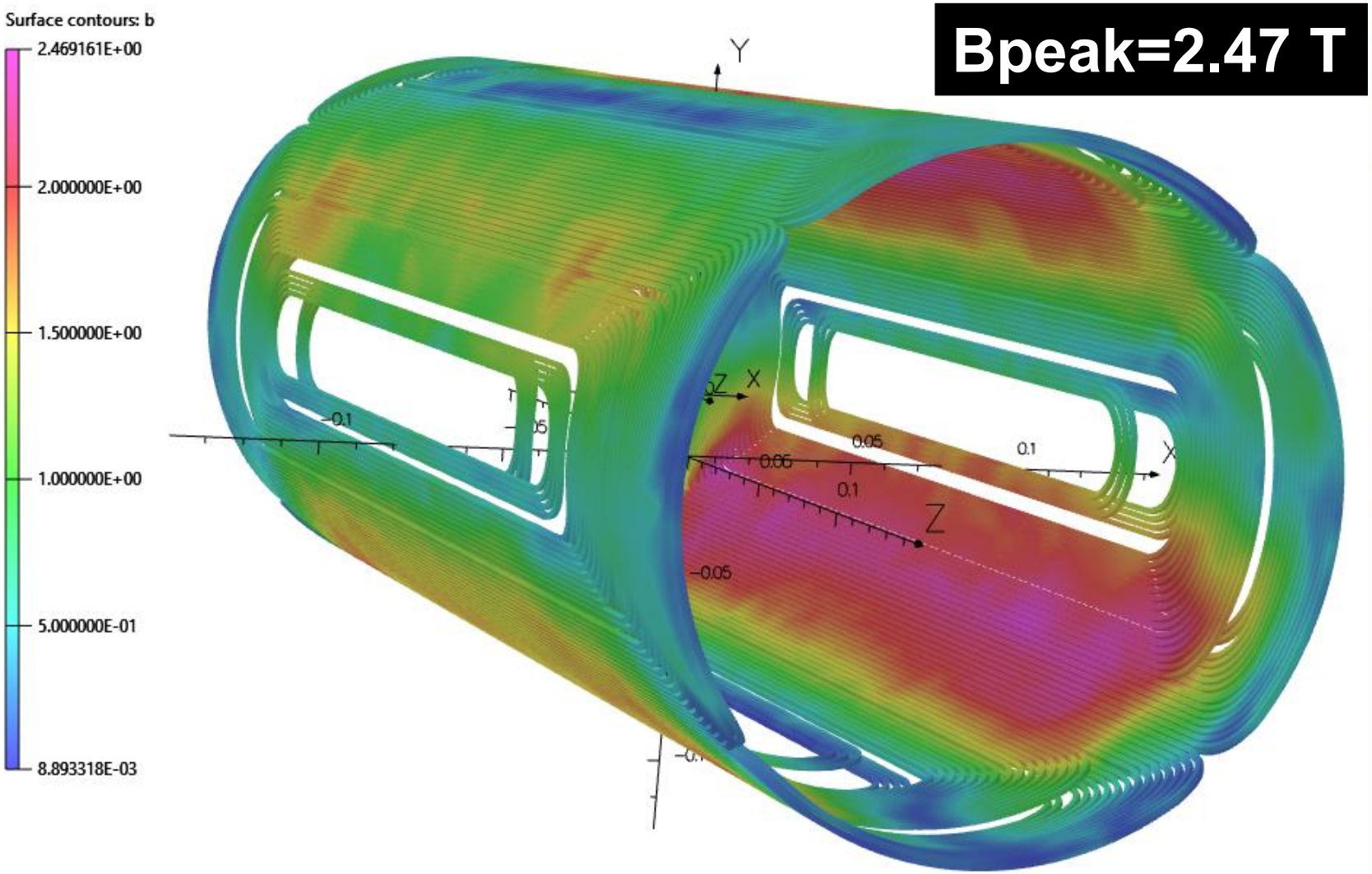
All other coils (hidden) are powered at the maximum field (yoke is also hidden)

Coil Set 3 (skew quad – 2 layers, I = 560 A)



Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m^2
Power	W
Force	N

MODEL DATA
b2pf-NQNQ_81-SQ_56-ND_42-SD_44-oct2026c.op3
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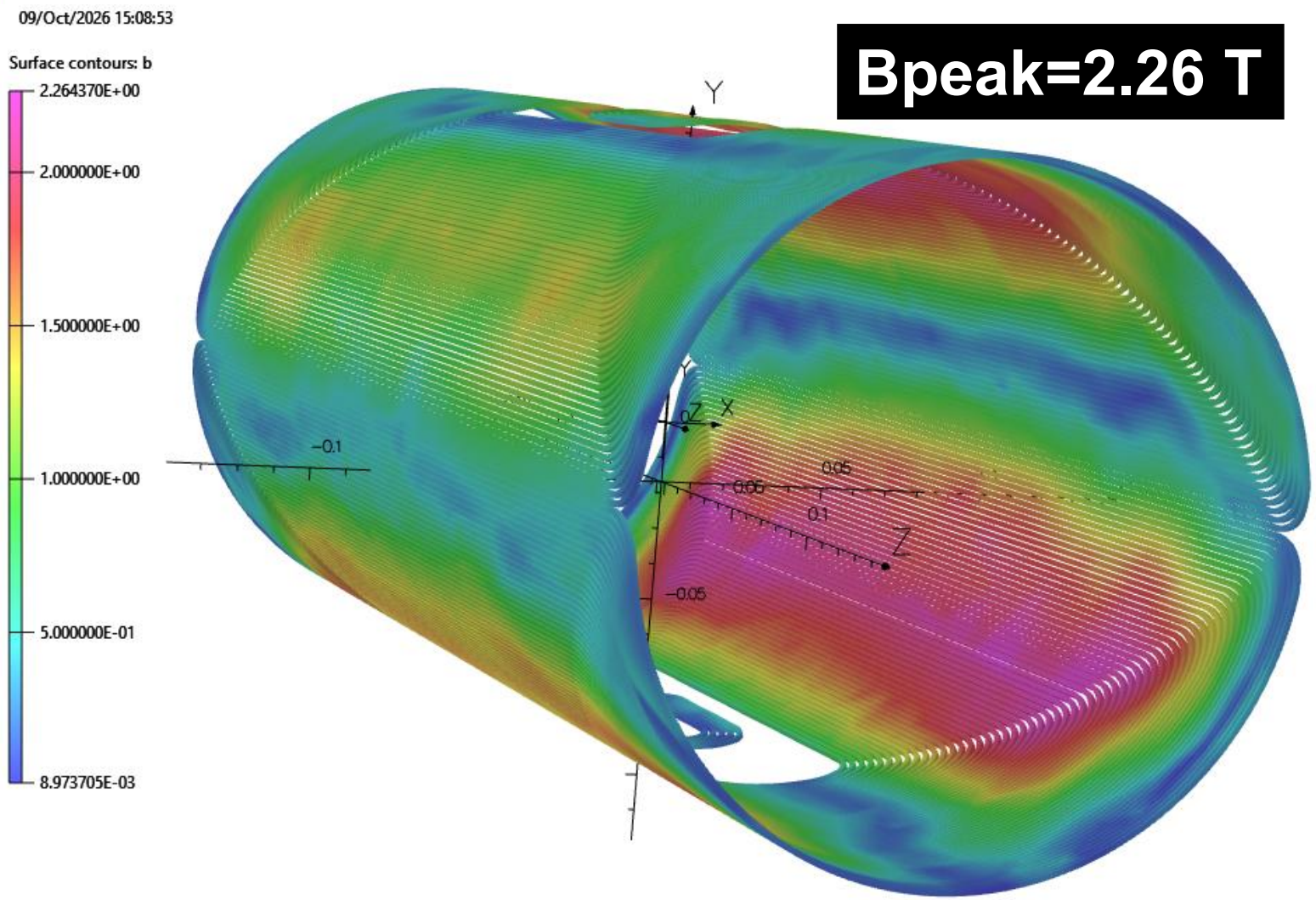
Field Point Local Coordinates
Local = Global

All other coils (hidden) are powered at the maximum field (yoke is also hidden)

Coil Set 4, layer #7 (normal dipole single layer)



UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m^2
Power	W
Force	N

MODEL DATA

b2pf-NQNQ_81-SQ_56-ND_42-SD_44-oct2026c.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
274032 elements
332888 nodes
798 conductors
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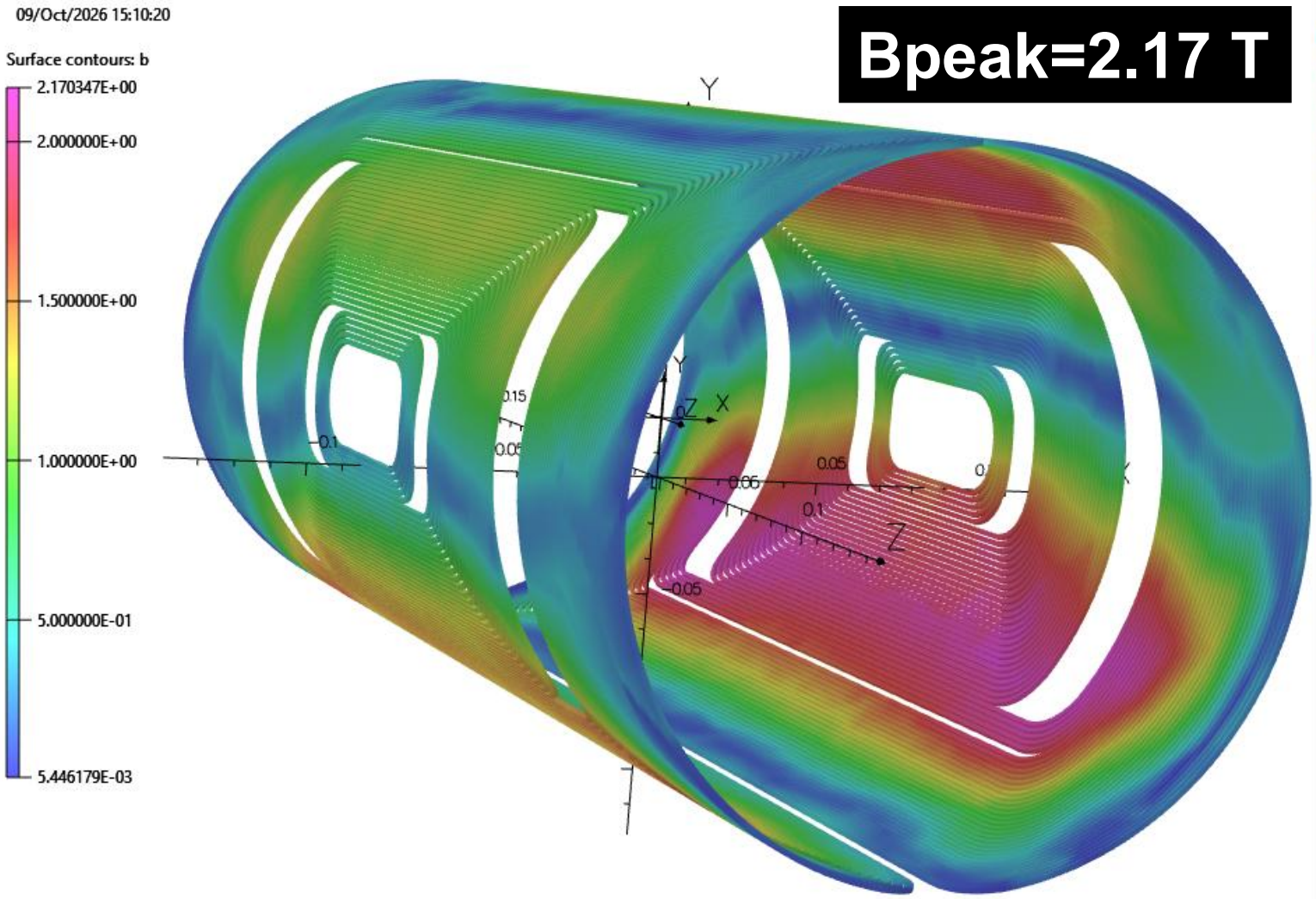
Activated in global coordinates

I = 420 A

All other coils and yoke are hidden. All coils are powered at the maximum. Peak field in this layer is determined by other coils.

Coil Set 5, layer #8 (skew dipole single layer)



UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m^2
Power	W
Force	N

MODEL DATA

b2pf-NQNQ_81-SQ_56-ND_42-SD_44-oct2026c.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
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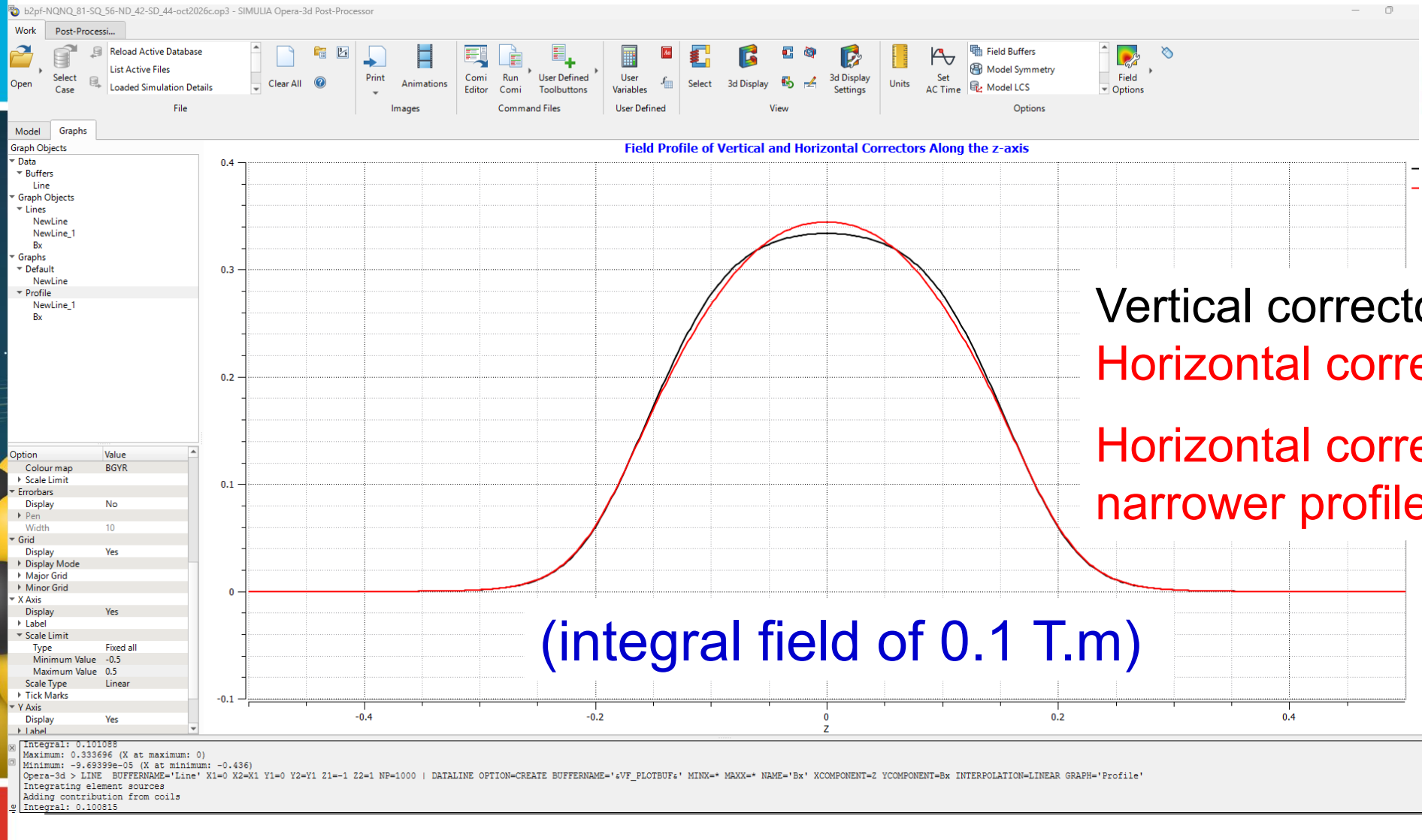
Nodally interpolated fields
Activated in global coordinates

I = 440 A

All other coils and yoke are hidden. All coils are powered at the maximum. Peak field in this layer is determined by other coils.

Field Profile along the z-axis of the Vertical and Horizontal Correctors

(NOTE: NO FLAT-TOP FOR SUCH A SHORT MAGNET)





Vertical corrector inner (7th Layer)

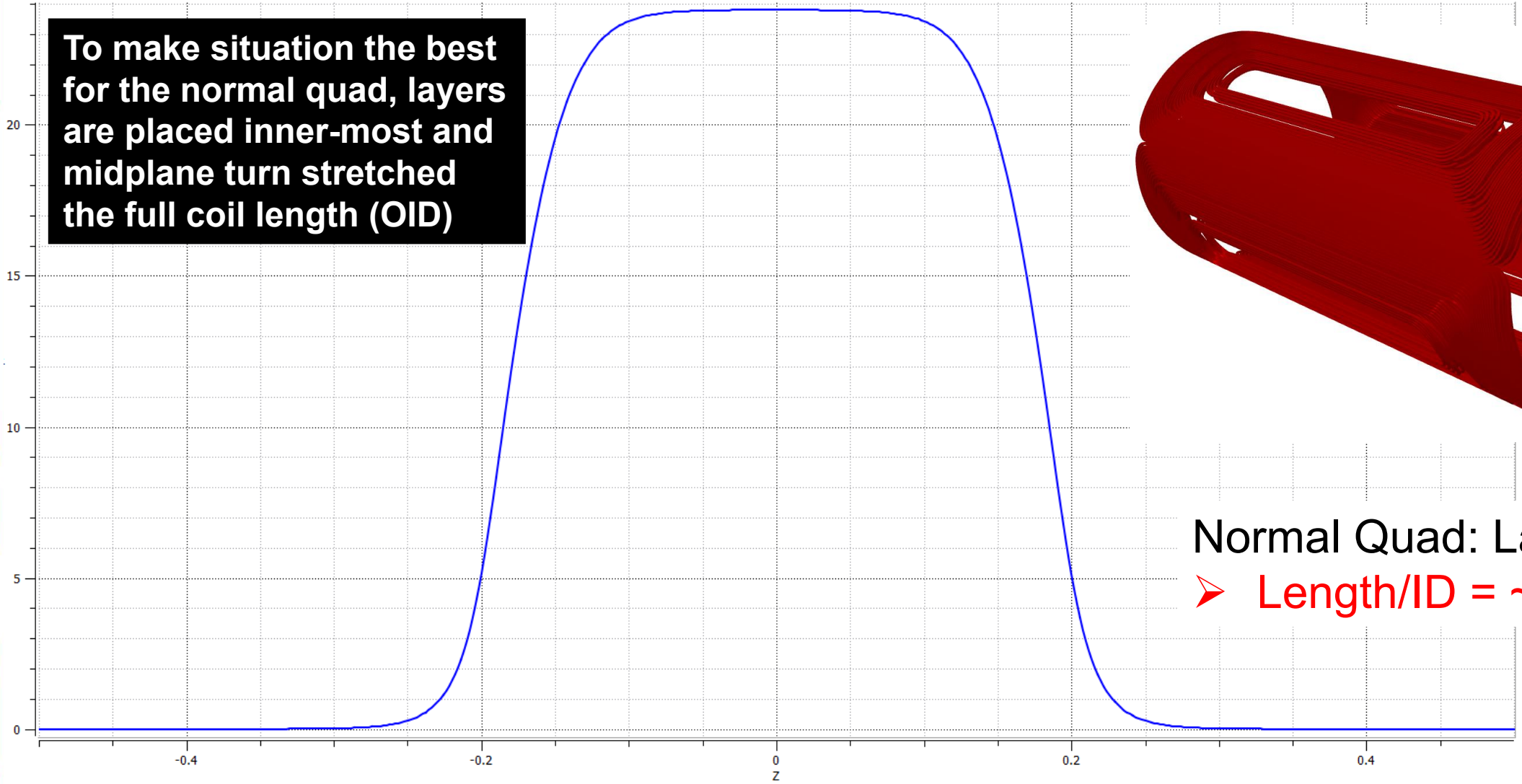
Horizontal corrector outer (8th Layer)

Horizontal corrector (outer) has even narrower profile: Length/ID = ~2.3

(integral field of 0.1 T.m)

Field Profile along the z-axis of the Normal Quadrupole
(normal quad needs maximum integral strength)

To make situation the best for the normal quad, layers are placed inner-most and midplane turn stretched the full coil length (OID)

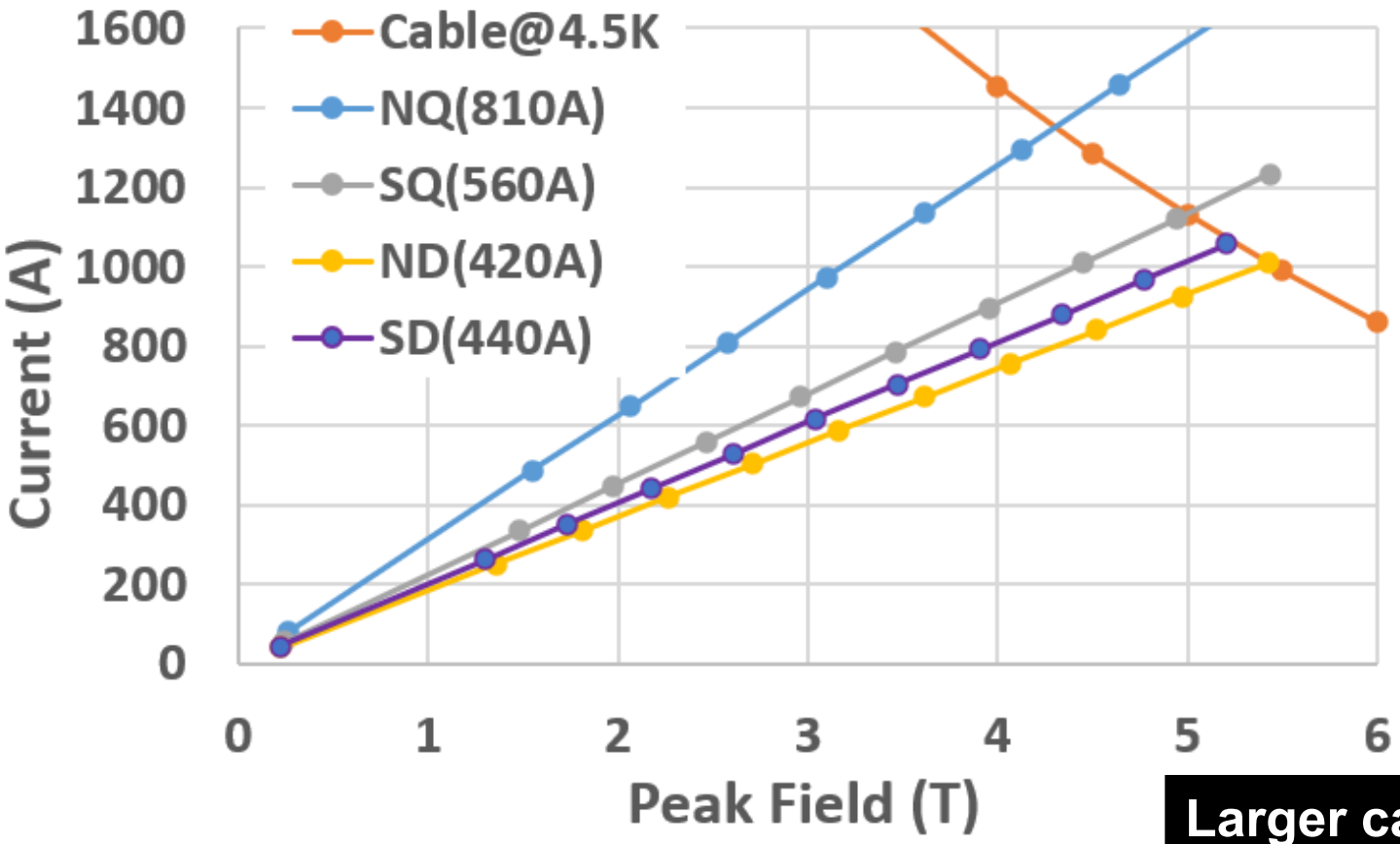


Normal Quad: Layers 1-4

- Length/ID = ~2.9

Computed Quench Performance – Generous Margin (with field from all coils changing together)

***Margins are computed for all are powered at maximum and then all together operate at a load line fraction of ~60%. Individual set will have higher margin.**



I(NQ) = ~810 A for 8.4 T, Iss = 1350A

- **Load line fraction*: 60%**

I(SQ) = ~560 A for 3 T, Iss = 1130 A

- **Load line fraction*: 50%**

I(ND) = ~420A for 0.1 T.m, Iss = 1010 A

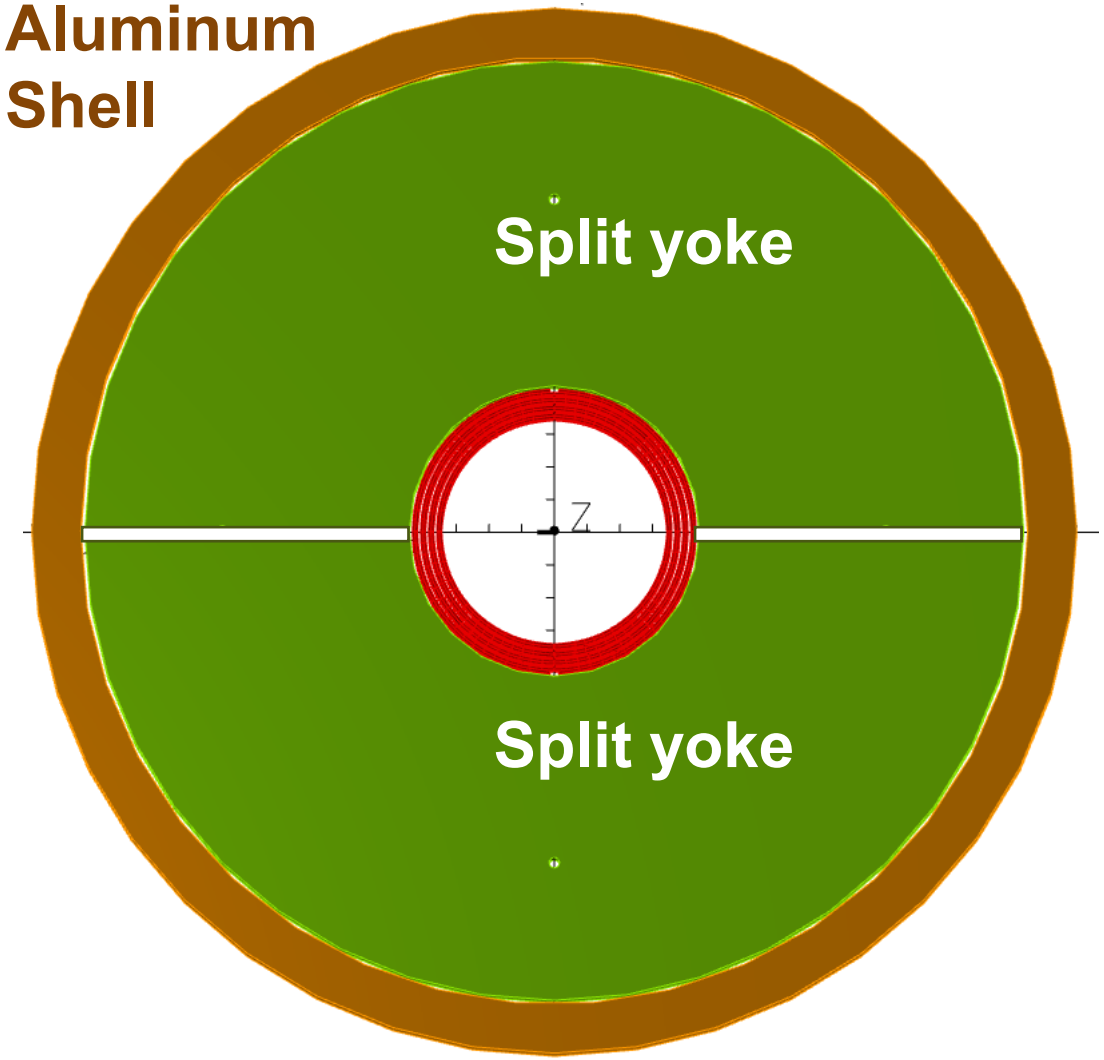
- **Load line fraction*: 42%**

I(SD) = ~440 A for 0.1 T.m, Iss =1060 A

- **Load line fraction*: 42%**

Larger cable should help in quench protection

Strategies to deal with off-center forces (and to deal with large Lorentz forces in high field direct wind magnets)



Core Issue:

- **Current direct wind designs keep a small gap between yoke and coil package.**

This allows coil to move towards the iron, if not clamped at the ends. This still leaves a possibility of a bow when energized in the body of the magnet.

This may be acceptable in low field magnets where we don't take benefit of the yoke and shell.

We should consider, Aluminum shell and split yoke so that we have a tight fit when it cools down.

There are sign that the performance of OID and high field quad suffered from this.

Harmonics in quad seems to be coming due to this.

We can test this concept in OID or in high field quad.

SUMMARY

- Design calculations confirm that the specified performance of superconducting Q3 package, placed in the same cryostat as the B2pF, can be obtained with a 400 mm long multilayer-direct wind coils based on the optimum integral design.
- Design of the Q3 package is optimized to meet the requirements with a minimum number of layers. It requires only 4 layers (2 coil sets) for the normal quad, 2 layers (1 coil set) for the skew quad and single layer each (OID allows that) winding for the vertical and horizontal dipole correctors. Yoke length is increased to 520.1 mm.
- The design has generous quench margin for all four (two quad and two dipoles).
- The design is ready to go for 2-d mechanical analysis. While 3-d analysis can be done later, 2-d analysis should be done for 360 degrees (no symmetry).
- Quench analysis can also be performed.
- Harmonics are excellent for coil length = yoke length design. Magnetic design, will be iterated for optimizing harmonics with longer yoke, in parallel. No issues expected.