500 mm B0ApF design with correctors

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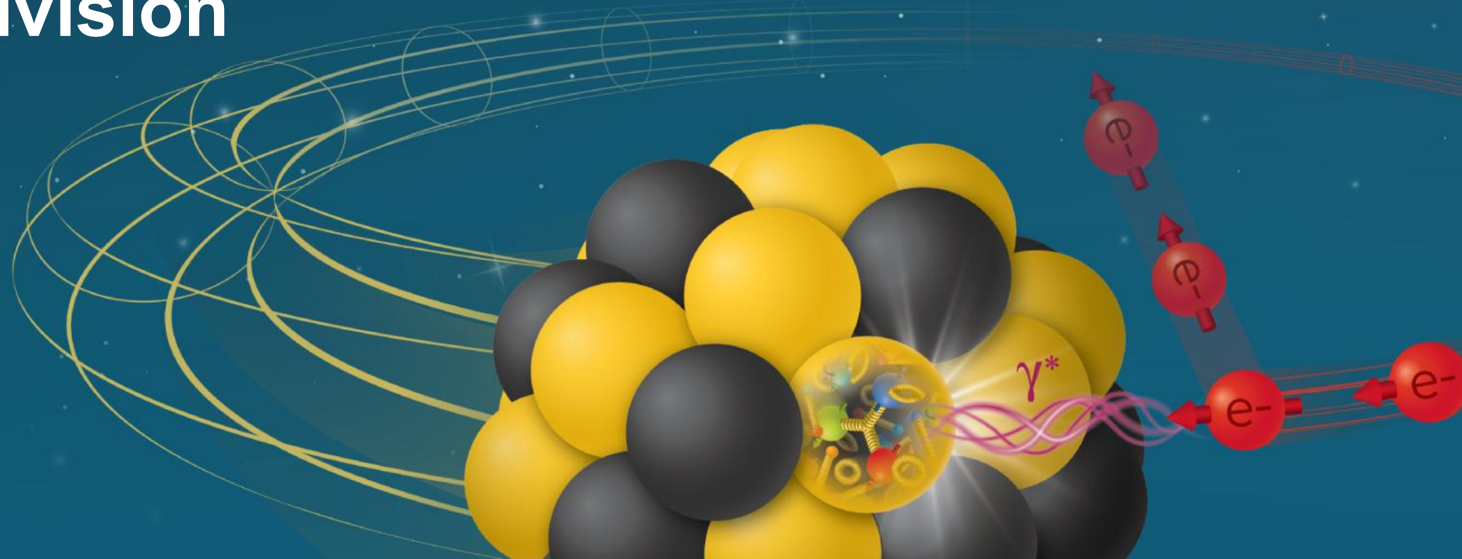
FC1 Tracking Meeting

July 29, 2026

Electron-Ion Collider



OVERVIEW

Coil length: 500 mm, Inner diameter of the 1st winding: ~105.4 mm

- **Optimum integral design is valuable in such short magnets.**

Magnetic design requirements of B0ApF with the Corrector Package:

- **1.05 T.m for B0ApF (highest among the recent options)**
- **0.6 T.m horizontal dipole corrector (includes 20% margin)**
- **3 T skew quadrupole corrector (includes 20% margin)**

Topics to be covered:

1. **Overall magnet design**
2. **Assuring desired margin – a minimum of 65% on the load line**
3. **Field along the path of electron beam – both inside and outside the magnet (a recent area of major concern)**

Overall Design for 500 mm Long Coil

- 4 layers (2 coil sets) creating 1.05 T.m Vertical Dipole
- 2 layers (1 coil set) creating 0.6 T.m Horizontal Dipole
- 2 or 1 layer(s) (1 coil set) creating 3 T Skew Quadrupole

It turns out that the 2-layers for skew quad gives too much margin.
Therefore, a single layer skew quad design is preferred (total seven layers).
A single layer option is accetable in the optimum integral design.

➢ **Extra radial space allowed for leads to reduce construction time and cost.**

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

Computed harmonics in each of 4 layers of B0ApF dipole

Harmonics at r=25 mm (spec for magnet 1 units?). Easily met (<0.3 unit) in the models.

- **In direct wind coils, measured harmonics can easily be corrected in the subsequent layers.**

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

Computed harmonics in each of the 2 layers of Horizontal Corrector Dipole

Harmonics at r=25 mm (specifications for corrector magnets ~10 units?)
Easily met in the computer models (all <0.1 units).

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

Layer #1 (5^{th} 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 (6^{th} 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

- Old US definition:
- b2 is sextupole

Computed harmonics in each of the 2 layers of Skew Quad Corrector

Harmonics at r=25 mm (specifications for corrector magnets ~10 units?)
Easily met in the computer models (all <0.1 units).

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

Layer #1 (7th layer)

INTEGRATED FIELD HARMONICS :

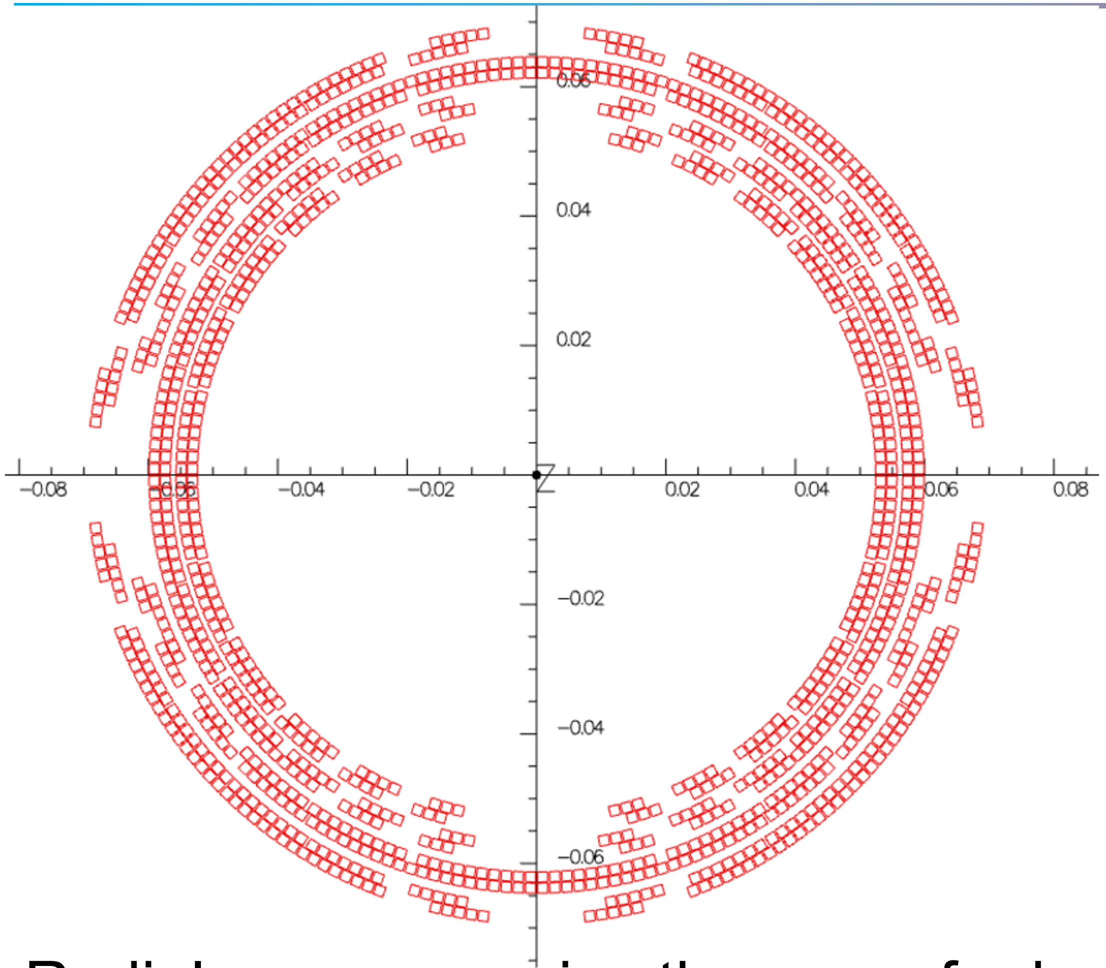
No.	Bn (T.m)	bn*10^4 (units)
1	0.90411E-01	10000.0000
5	0.17988E-08	0.0002
9	0.22953E-07	0.0025
13	-0.17546E-07	-0.0019
17	-0.32137E-09	-0.0000
21	0.23958E-10	0.0000
25	-0.38364E-12	-0.0000
29	-0.34752E-14	-0.0000

Layer #2 (8th layer), if needed

INTEGRATED FIELD HARMONICS :

No.	Bn (T.m)	bn*10^4 (units)
1	0.92650E-01	10000.0000
5	0.30793E-08	0.0003
9	-0.44311E-06	-0.0478
13	-0.23922E-07	-0.0026
17	0.33499E-09	0.0000
21	0.98084E-11	0.0000
25	-0.36027E-12	-0.0000
29	0.26450E-14	0.0000

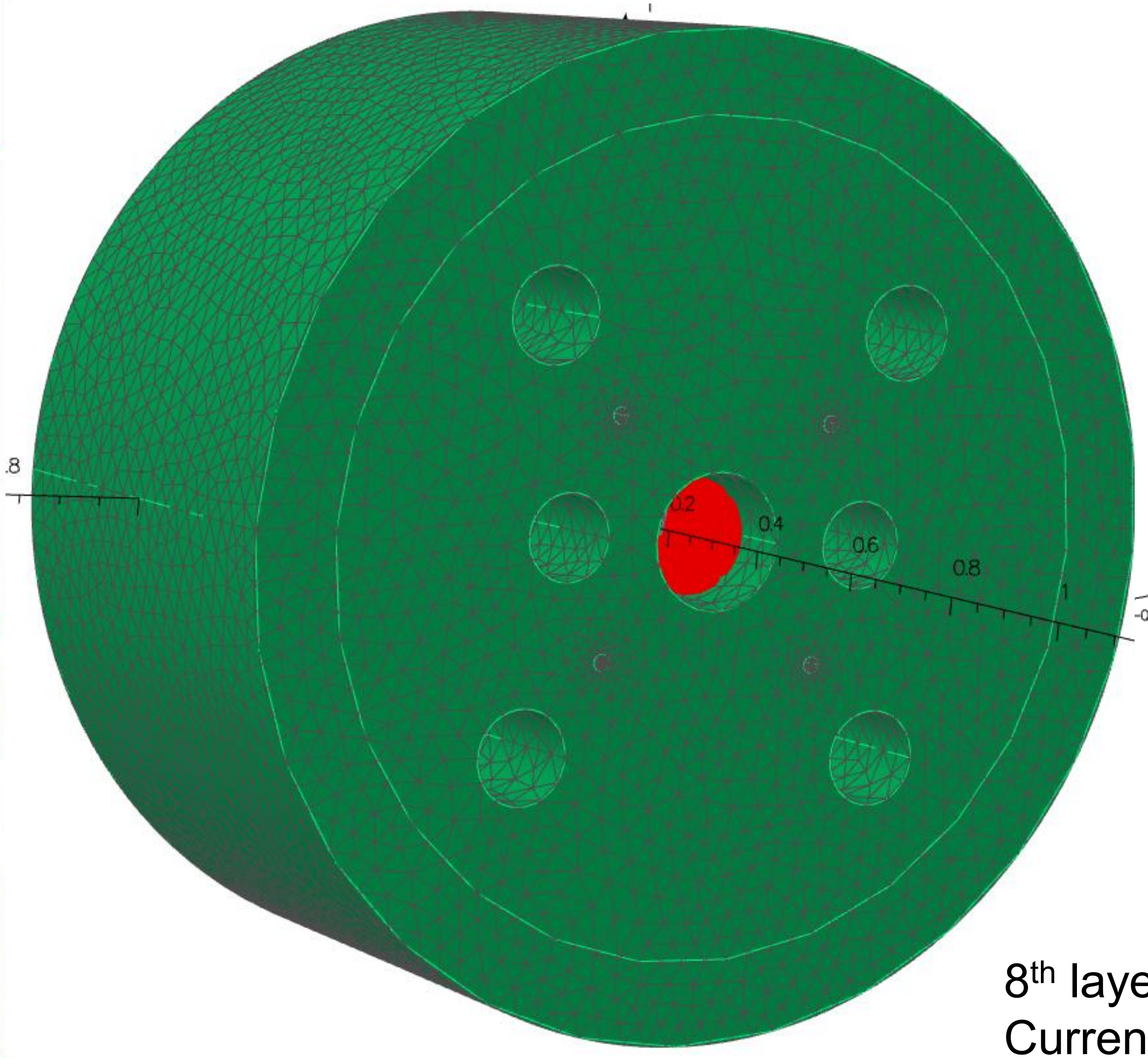
Basic Model of the 8-layer design for 500 mm-long B0ApF

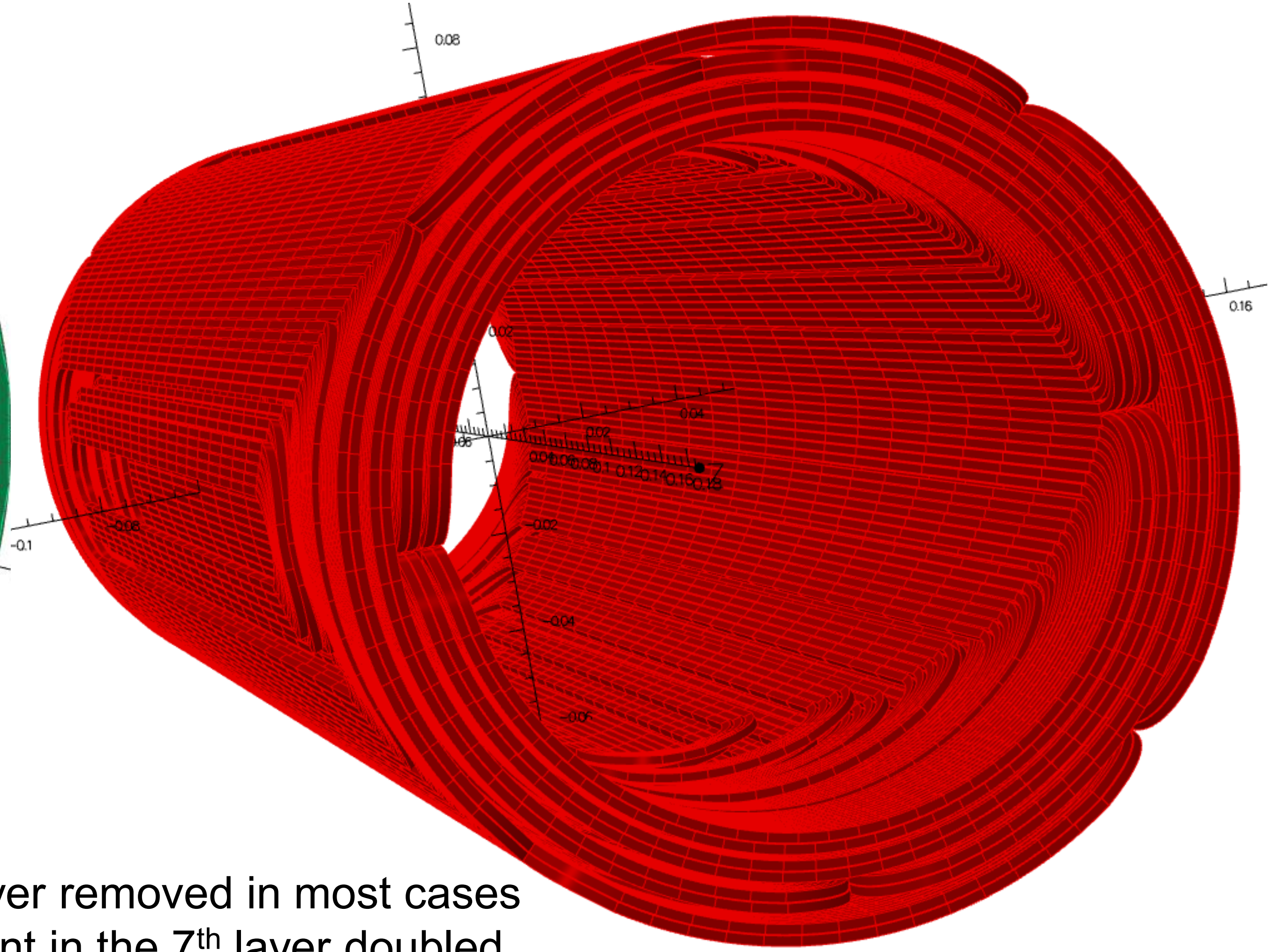


- 4 layers (2 coil sets)
  - creating 1.05 T.m Vertical Dipole
- 2 layers (1 coil set)
  - 0.6 T.m Horizontal Dipole
- 1 layer or 2 layers, if needed (1 coil set)
  - creating 3 T Skew Quadrupole

Radial space remains the same for both 8-layer design (double layer skew quad) or in 7-layer design (space for the lead in a single layer quad). Overall design can be fixed.

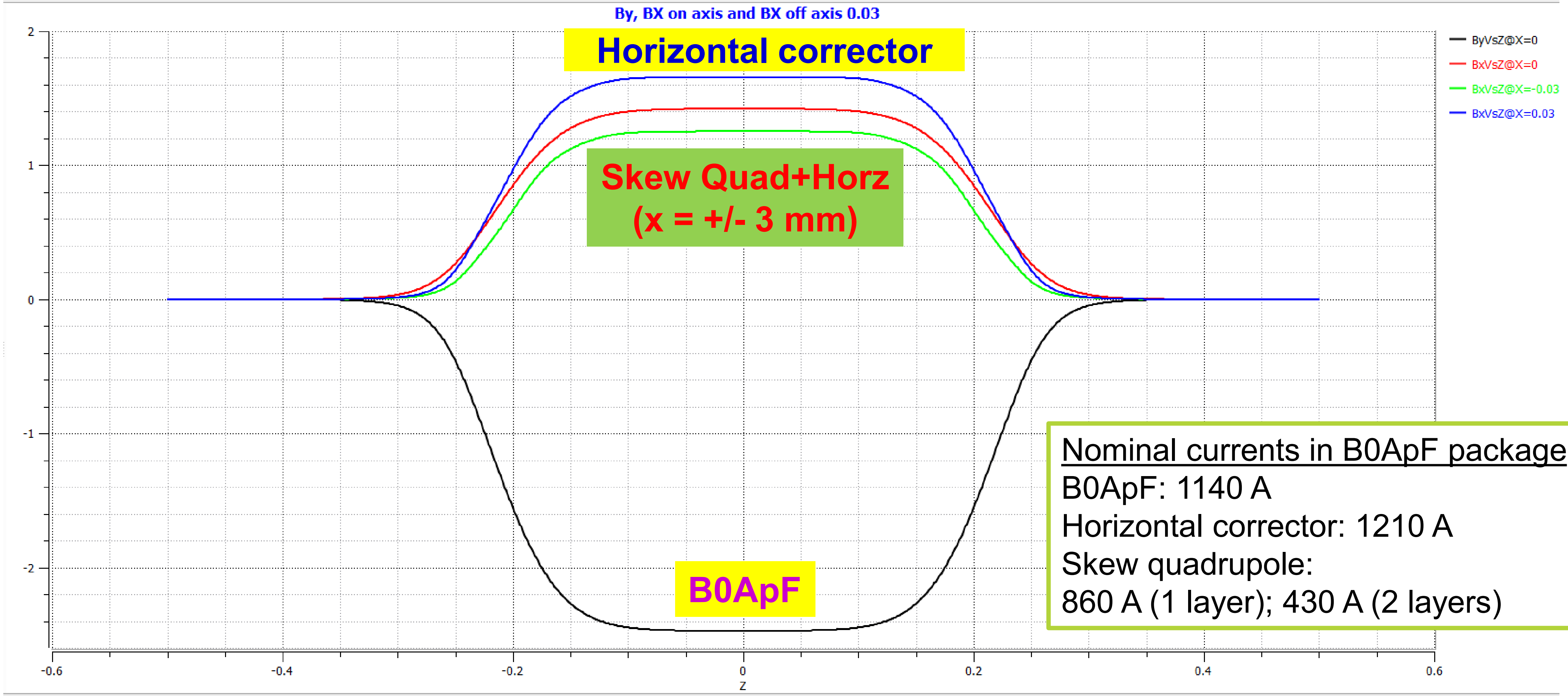
Basic Model of the 8-layer design for 500 mm-long B0ApF





8th layer removed in most cases
Current in the 7th layer doubled

Field Profile along the z-axis at the Nominal Currents



<u>Nominal currents in B0ApF package</u>:
B0ApF: 1140 A
Horizontal corrector: 1210 A
Skew quadrupole:
860 A (1 layer); 430 A (2 layers)

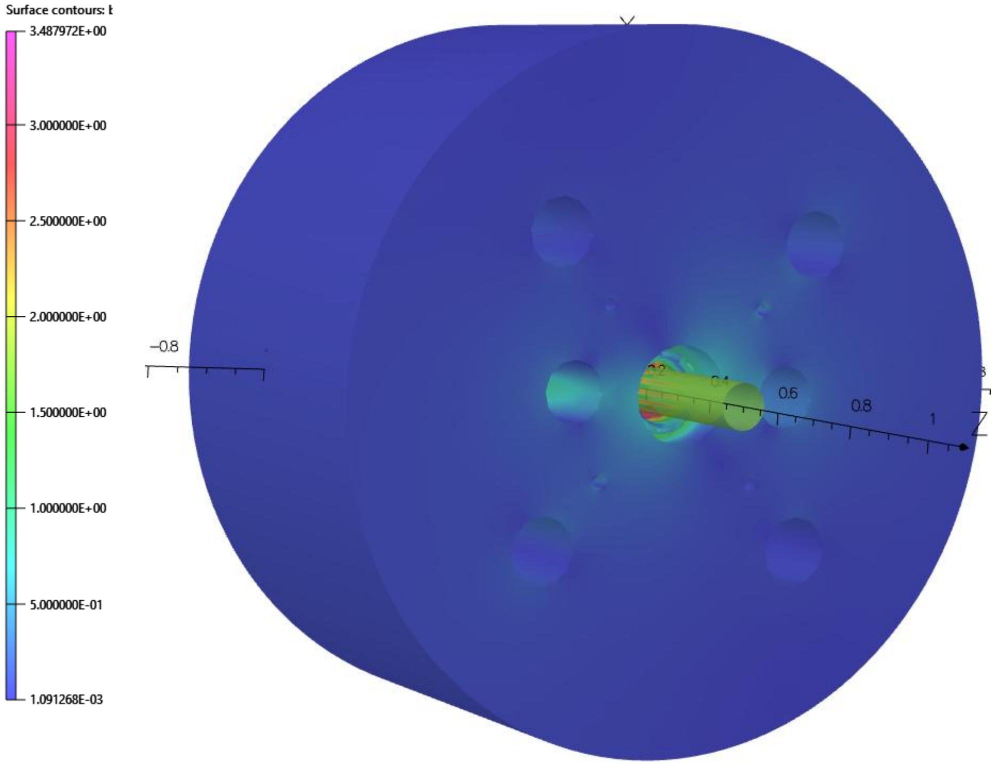
Margin Calculations

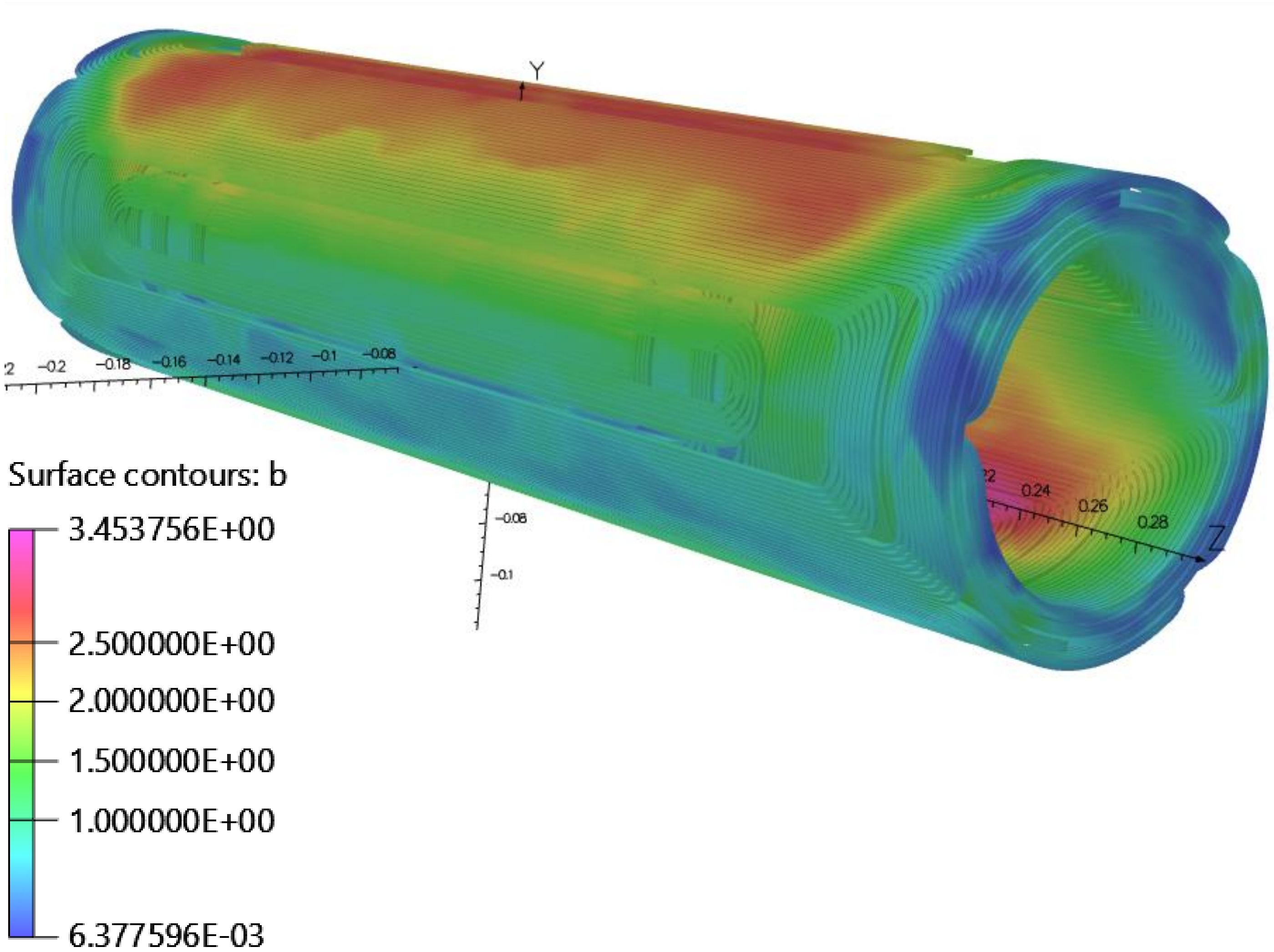
Operating margins needs to be defined not only for an individual magnet (e.g. B0ApF) operating by itself, but also when all magnets (B0ApF and correctors) are energized to their maximum required specifications.

Once all magnets are energized to their full strength, the current in the individual magnet is increased from its nominal 65% strength to 100%.

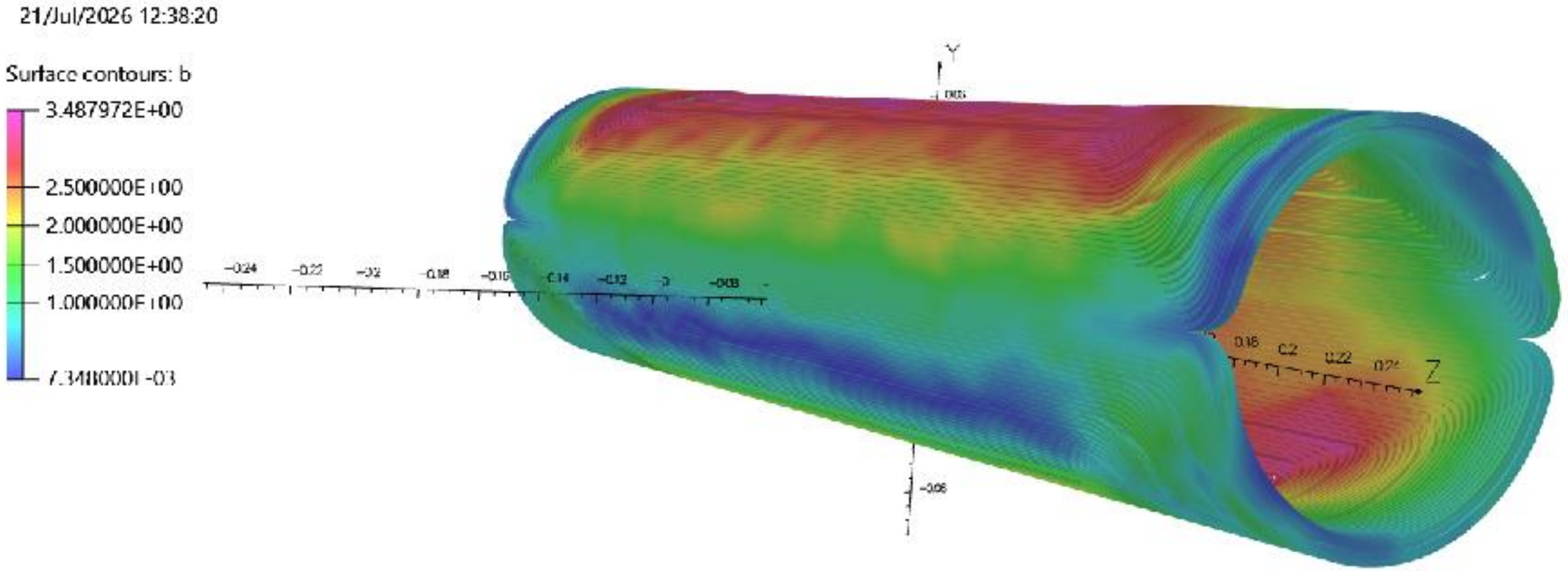
Margin is defined for the individual magnet, unless the combination is limiting the performance (e.g., when the current in skew quad is @100%, the margin could be limited by the dipole because of the additional field created by the skew quad).

Field at the Nominal Current in 7-layer B0ApF with Correctors

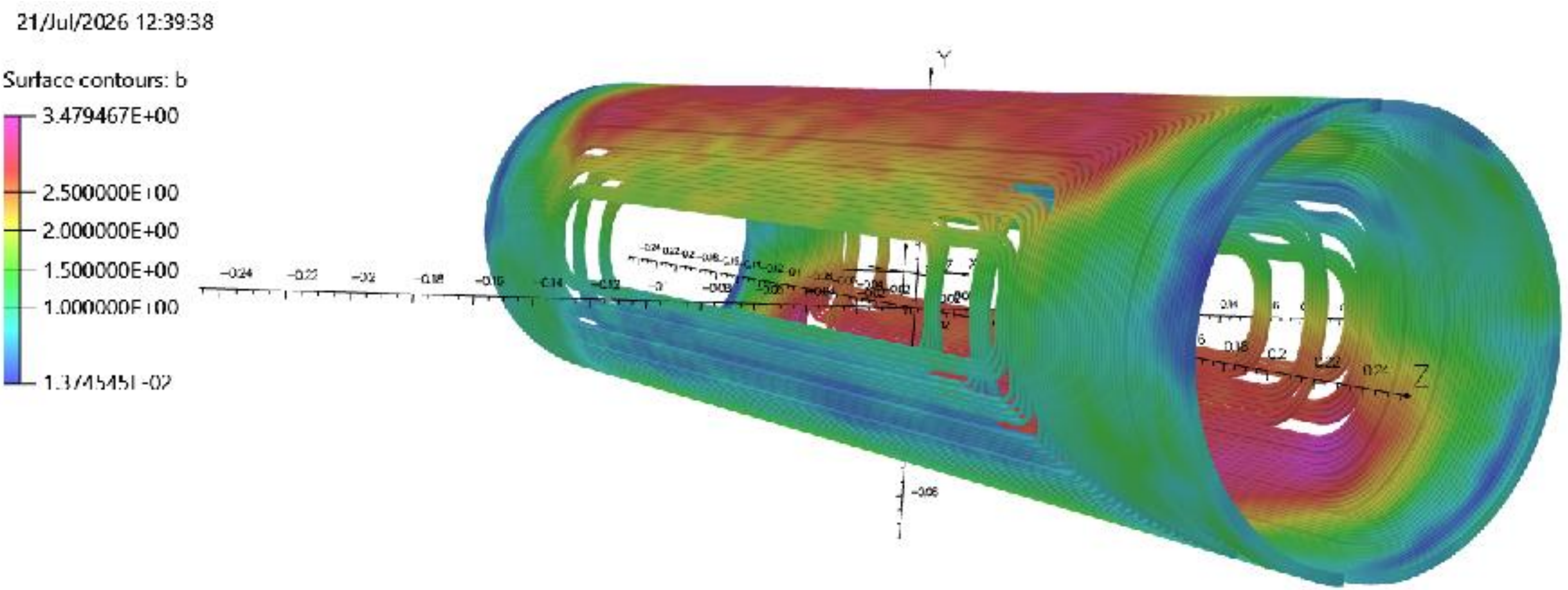




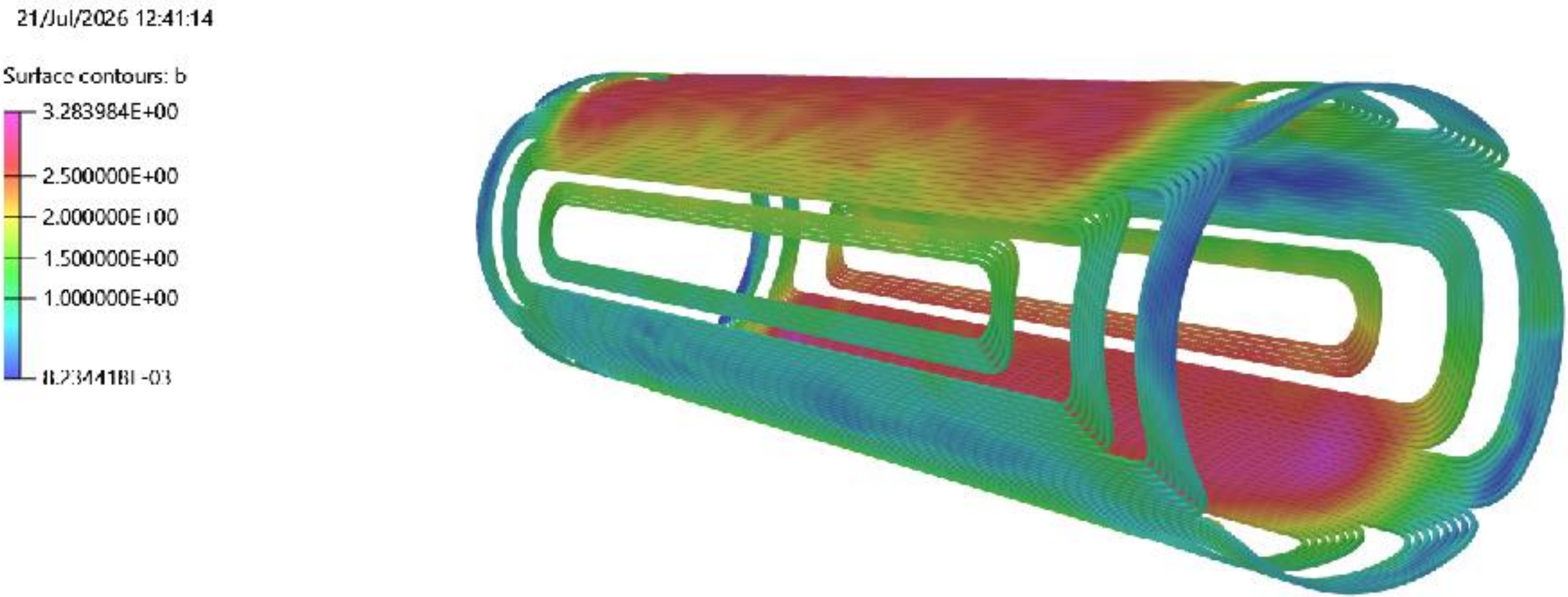
Field on B0ApF Only (all coils powered @ nominal but hidden)



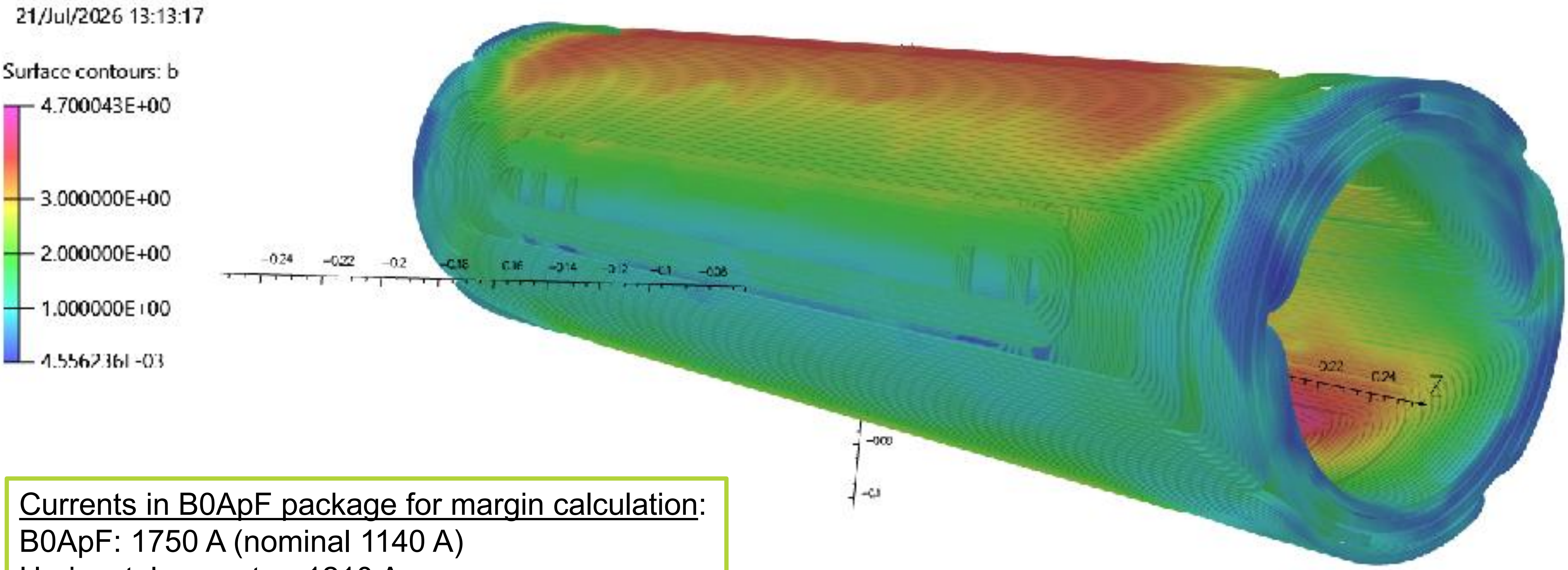
Field on the Horizontal Dipole Corrector Coils (all coils powered @ nominal but hidden)



Field on the Skew Quad Corrector Coil
(all coils powered @ nominal but hidden)

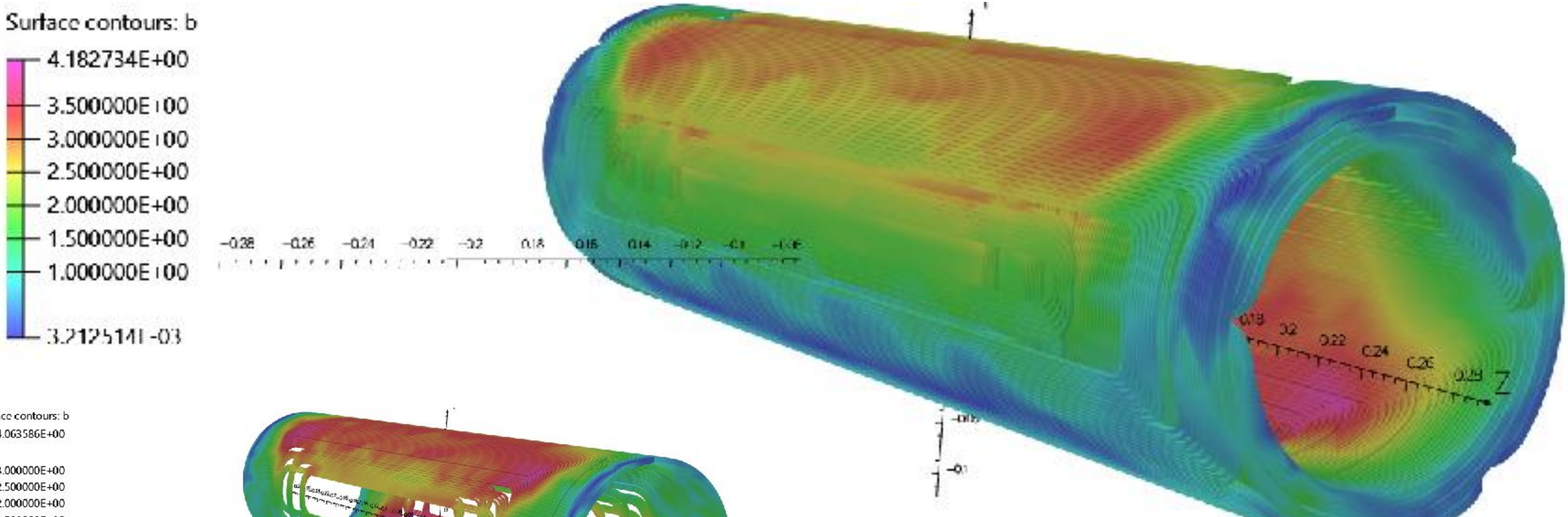


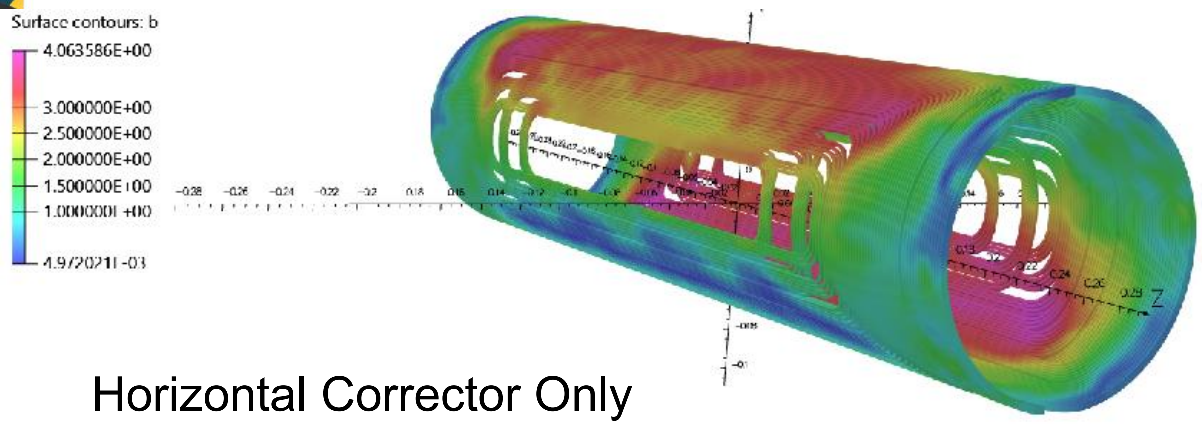
Field on All Coils for Margin Calculations in B0ApF (B0ApF at 100% all other coils @ nominal 65%)



Currents in B0ApF package for margin calculation:
B0ApF: 1750 A (nominal 1140 A)
Horizontal corrector: 1210 A
Skew quadrupole: 860 A (single layer coil)

Field on All Coils for Margin Calculations in Horizontal Corrector (Horizontal corrector at 100% all other coils @ nominal 65%)

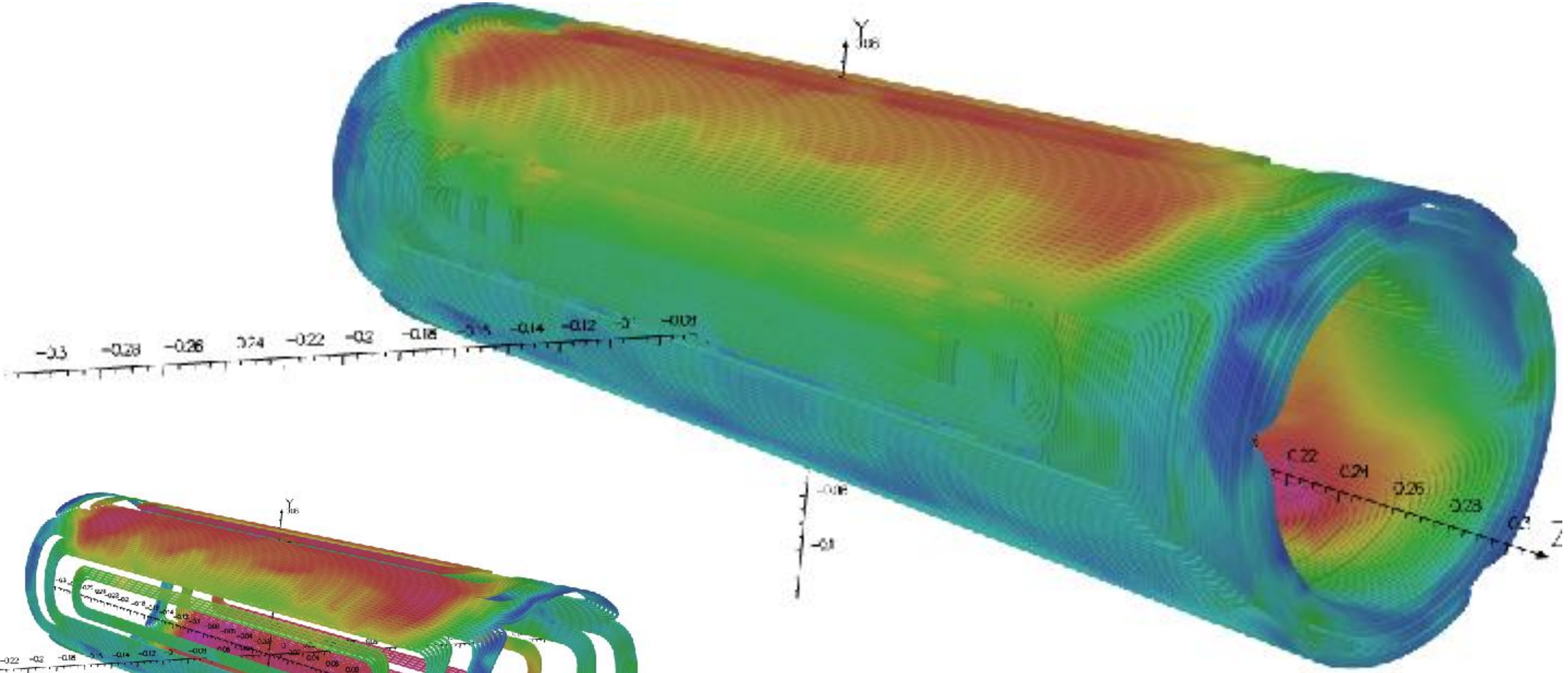


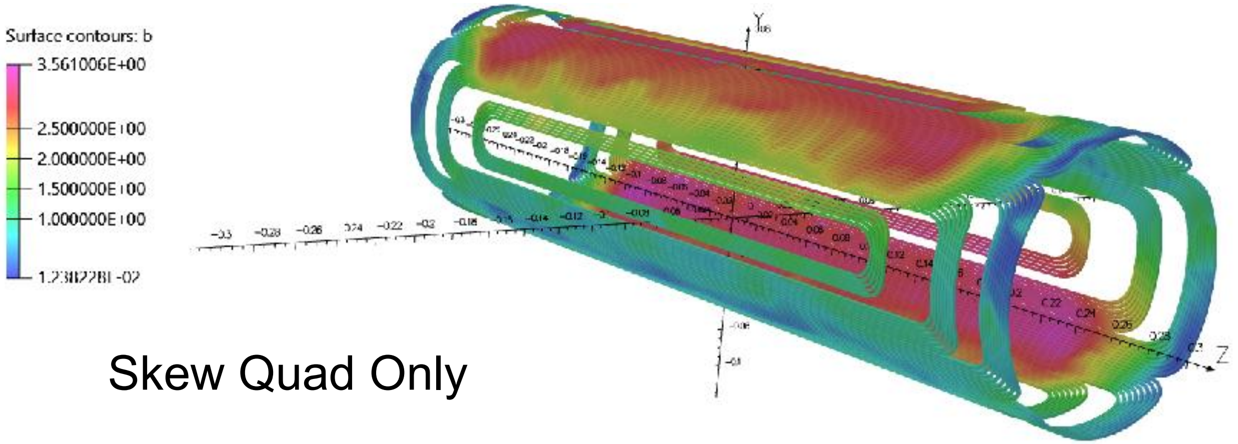


Horizontal Corrector Only

<u>Currents in B0ApF package for margin calculation</u>:
B0ApF: 1140 A
Horizontal corrector: 1860 A (nominal 1210 A)
Skew quadrupole: 860 A (single layer coil)

Field on All Coils for Margin Calculations in Skew Quad Corrector (skew quadrupole corrector at 100% all other coils @ nominal 65%)

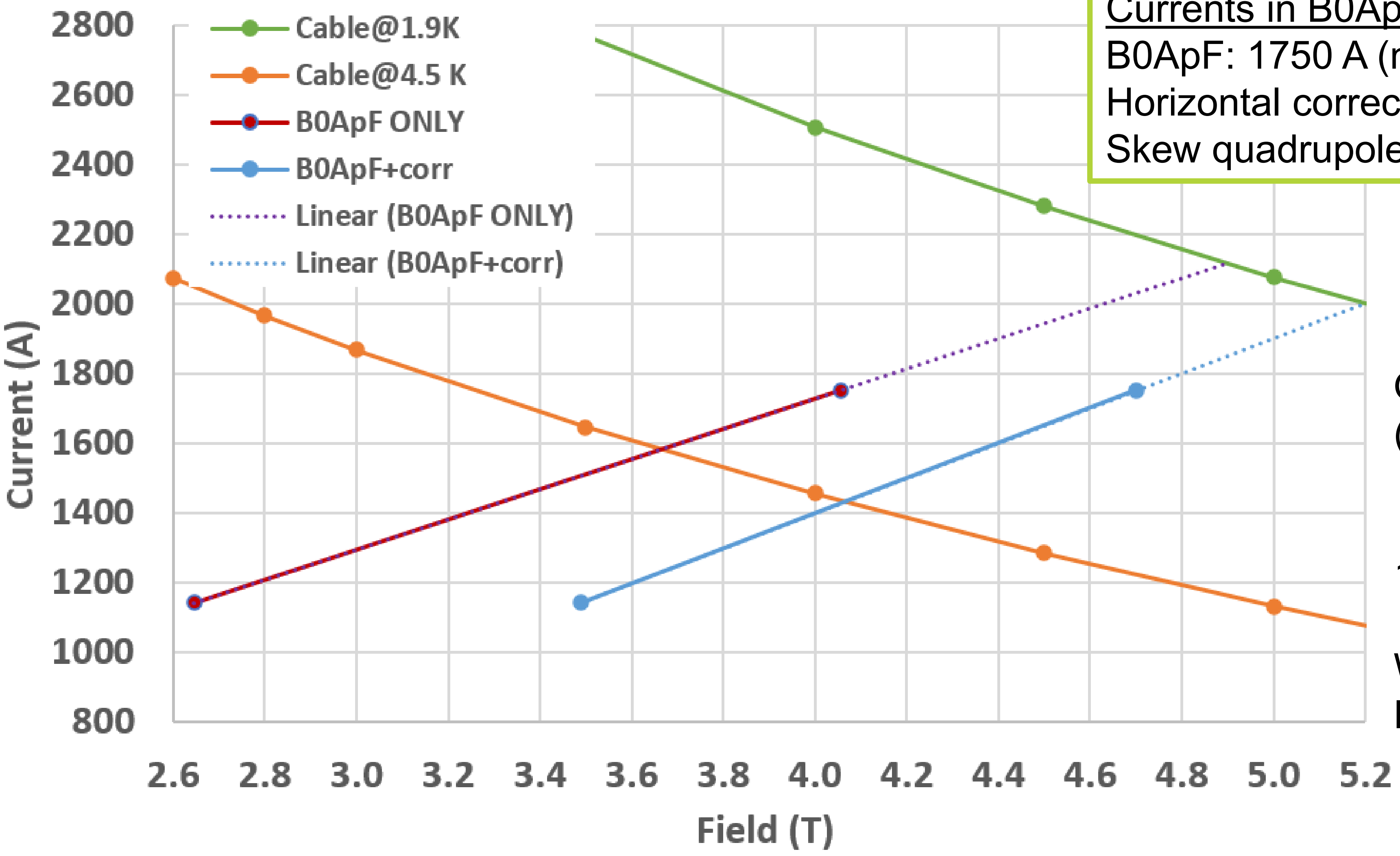




Skew Quad Only

<u>Currents in B0ApF package for margin calculation</u>:
B0ApF: 1140 A
Horizontal corrector: 1210 A
Skew quadrupole (one layer): 1320 A (nominal 860 A)

Margin Calculations for B0ApF



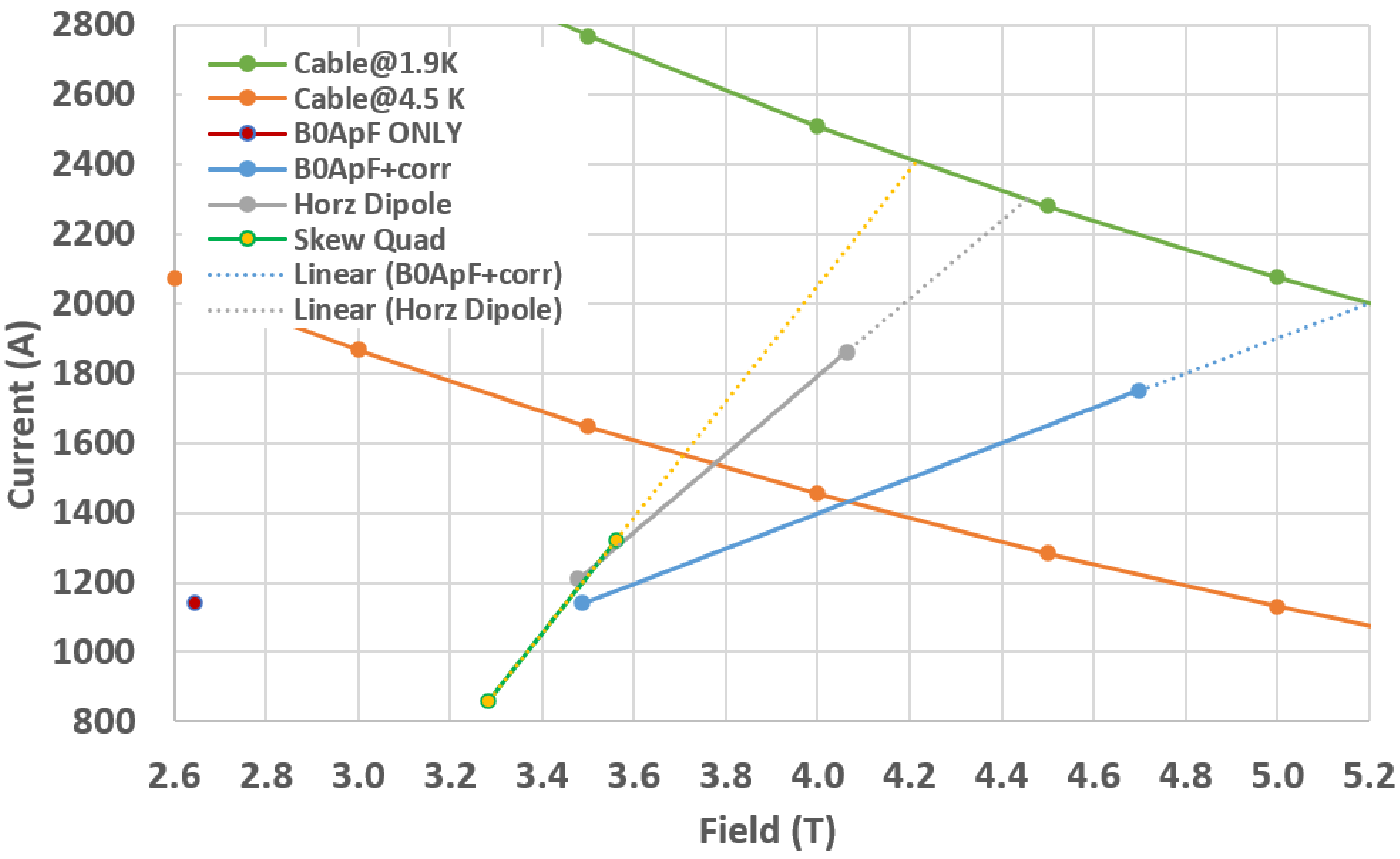
<u>Currents in B0ApF package for margin calculation</u>:
B0ApF: 1750 A (nominal 1140 A)
Horizontal corrector: 1210 A
Skew quadrupole: 860 A (single layer coil)

Quench current for B0ApF: ~2000A (with correctors at nominal current)

1140A/2000A = 0.57

We are at 57% of the load line
Requirement: 65% (we exceed that)

Margin Calculations for B0ApF and the Corrector Package



B0ApF: 1140A/2000A = 0.57

Horizontal Corr: 1210A/2300A = 0.53

Skew Quad: 860A/2400A = 0.36

<57% of the load line in all cases

Requirement: 65% (we exceed that)

Cross-talk calculations

Impact of B0ApF and corrector field on the electron

Calculating Small Fields in OPERA3d with High Accuracy

Accuracy of field calculations in OPERA3d (particularly when the fields are very small) requires a good understanding of the modelling and calculation methods used (including potential type, see right).

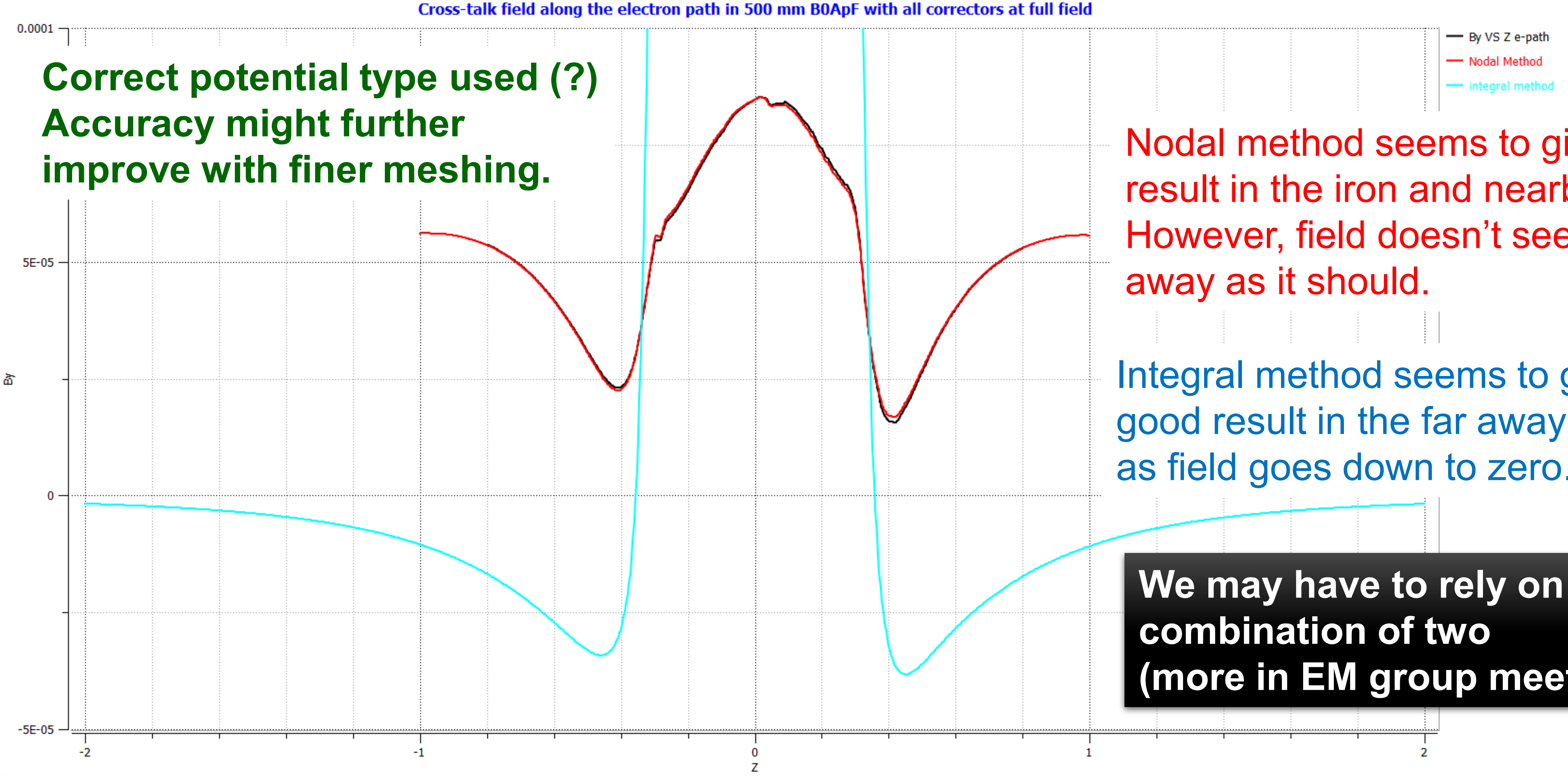
In early days, everything had to be set manually – a laborious process, but we were forced to learn.

Now, it is automated which balances the compute requirements and accuracy in most cases, but not all.

Emmanuele Ravaioli (LBL) has been using appropriate potential type and geting good results. Some update on the mix use of calculation methods for even better.

Model Description	Potential Type	Field Recovery	
		from mesh	from coils
Homogeneous Field: Conductor field >> Iron field			
Close to the iron	Reduced	Nodal	Integral
Far from the iron	Any	Integral	Integral
Homogeneous Field: Conductor Field almost = Iron Field			
Homogeneous conductor field	Any	Nodal	Integral
Inhomogeneous conductor field	Total	Nodal	Integral
If total cannot be used	Reduced	Nodal	Integral
Homogeneous Field: Conductor Field almost = –Iron Field			
Homogeneous conductor field	Total	Nodal	Any
Inhomogeneous conductor field	Total	Nodal	Any
If total cannot be used	Reduced	Nodal	Integral
Homogeneous Field: Conductor Field << Iron Field			
All situations	Any	Nodal	Integral
Peak Field on Conductor	Reduced	Nodal	Integral
Inhomogeneous Field			
Conductor Field >> Iron field	Reduced	Nodal	Integral
Conductor Field << Iron field	Any	Nodal	Integral
Far from iron	Any	Integral	Integral
Conductor Field almost = Iron field	Any	Nodal	Integral
Conductor Field almost = –Iron field	Total	Nodal	Integral

Field along the electron path when B0ApF and correctors are at full strength (model seems to produce small field through out)



Correct potential type used (?)
Accuracy might further improve with finer meshing.

Nodal method seems to give good result in the iron and nearby region. However, field doesn't seem to fall far away as it should.

Integral method seems to give good result in the far away region, as field goes down to zero.

We may have to rely on the combination of two (more in EM group meeting)

Summary

- First Phase of the magnetic and overall design of 500 mm long B0ApF and corrector coil is done. It seems to satisfy the basic requirements.
- Mechanical and quench protection calculations can now start.
- More field quality optimization, including field harmonics along the electron path (done but not processed yet) and harmonics for B0ApF and correctors as a function of current needs to be examined.