# Optimum Integral Design of B0ApF with Correctors for the Updated Parameters (first look)

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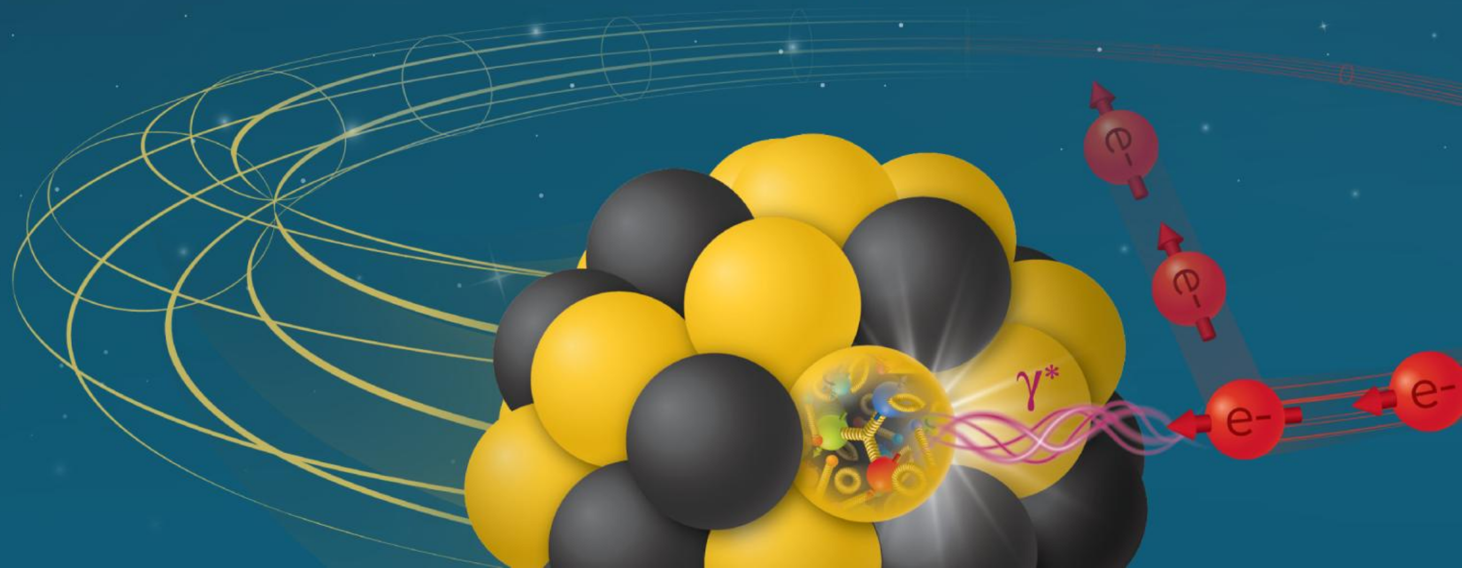
Electron-Ion Collider



# From Scott Berg (12/30/2025)

| | Baseline Acceptance | | Reduced Acceptance | |
|---|---|---|---|---|
| | Option 2 | Option 4a | Option 2 | Option 4a |
| Transverse Momentum Acceptance (GeV/c) | 1.23 | 1.23 | 1.11 | 1.11 |
| Neutral Cone Acceptance (mrad) | 4.0 | 4.0 | 3.6 | 3.6 |
| B0ApF Radius (mm) | 40 | ⇨ 39 | 36 | 35 |
| B0ApF Integrated Field (T·m) | 1.99 | ⇨ 1.56 | 1.99 | 1.56 |
| Q1ApF Entrance Radius (mm) | N/A | 42 | N/A | 38 |
| Q1ApF Exit Radius (mm) | 53 | 52 | 48 | 47 |
| Q1BpF Exit Radius (mm) | 78 | 78 | 71 | 71 |
| Q2pF Radius (mm) | 131 | 131 | 118 | 118 |
| B1pF/B1ApF Radius (mm) | 156 | 161 | 145 | 149 |
| B1pF/B1ApF Integrated Field (T·m) | 6.89 | 6.37 | 6.91 | 6.49 |
| Extra Space for B2pF (cm) | 9 | 56 | 11 | 48 |

on Collider IR SC Magnet Meeting December 30, 2025 J. Scott Berg

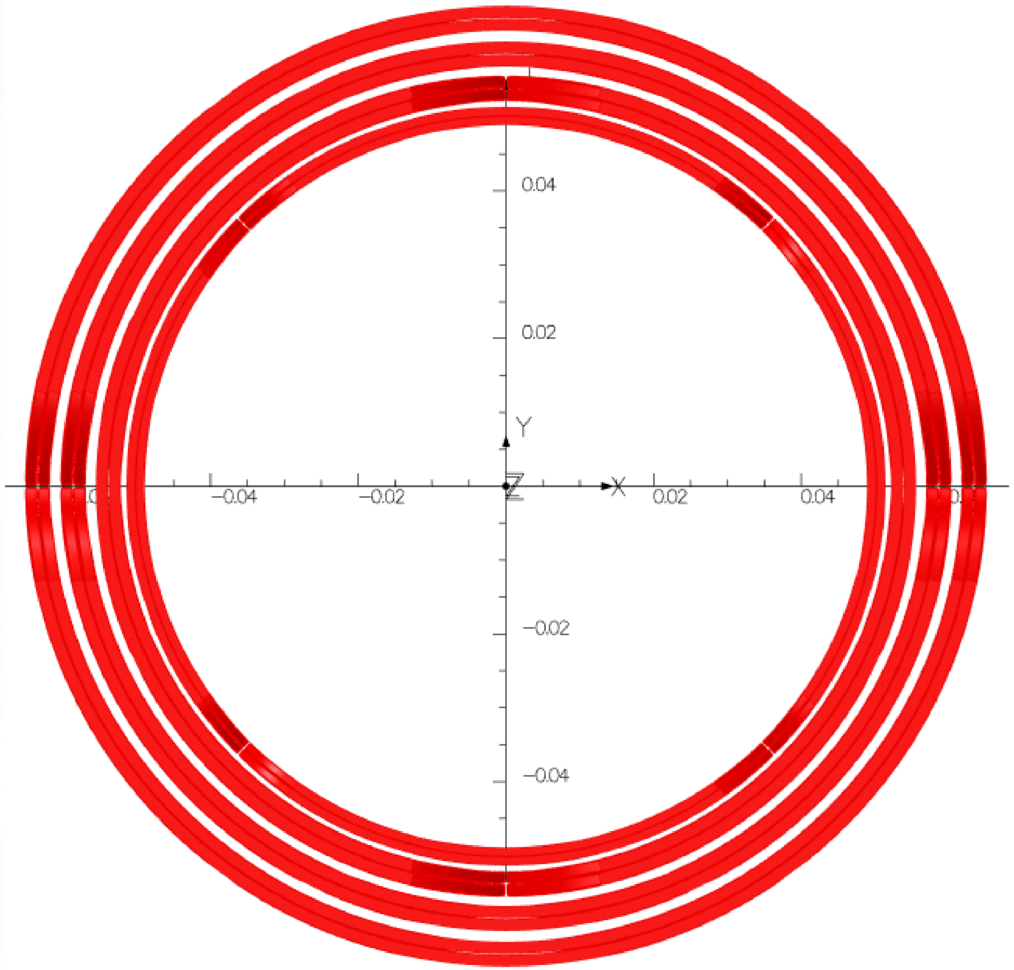
**Question:**
Can OID reduce the number of layers from serpentine?
**6 layers => 4 layers**

**This study is for 4-layer (2 coil set) OID:**
- **Coil L=0.765 m**
- **Coil id:115.36 mm**

**… AND for**
- **Coil id:105.96 mm (for aggressive case, corrector layers: 4>2)**

**Net reduction: 10 layers > 6 layers**

# Initial Parameters of the B0ApF Dipole and Correctors




| Magnet nc | Beam | Nominal I |
|---|---|---|
| B0ApF | Hadron | 1.56 T.m |
| B0ApF-SkQ | Hadron | 3 T |
| B0ApF-VC | Hadron | 0.5 T.m |

## Question:

**Can OID reduce number of winding layers as compared to that in the serpentine?**

## Results of initial investigation:

**✓ No. of layers in B0ApF reduced from 6 to 4,**
**No of layers in vertical corrector and skew quad might also get reduced from 2 each to 1 each. (OID allows single layer DW magnets).**

# Optimum Integral Design for Maximizing Integral Field

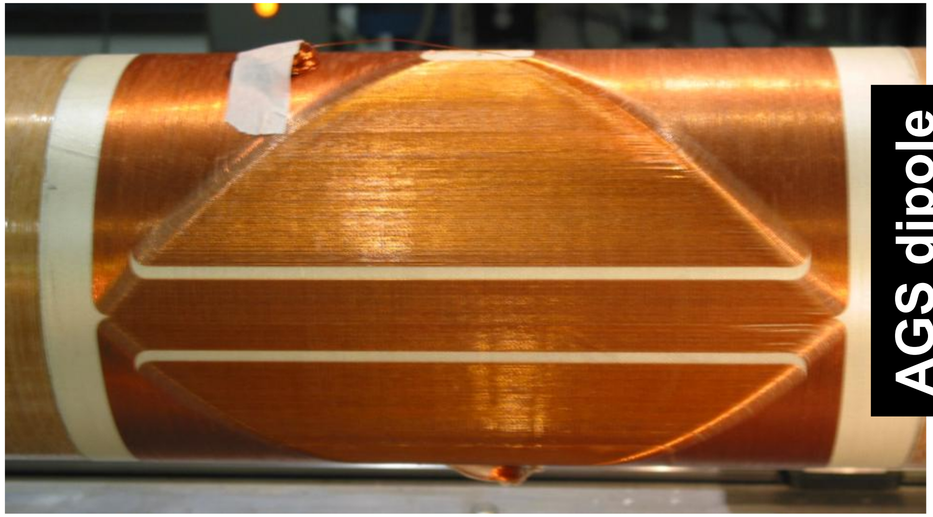
**Extend midplane turns to full coil length & optimize cross-section and ends together in a single step to obtain an overall cosine theta distribution in the integral sense:**

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

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

✓ **Loss due to ends essentially eliminated**

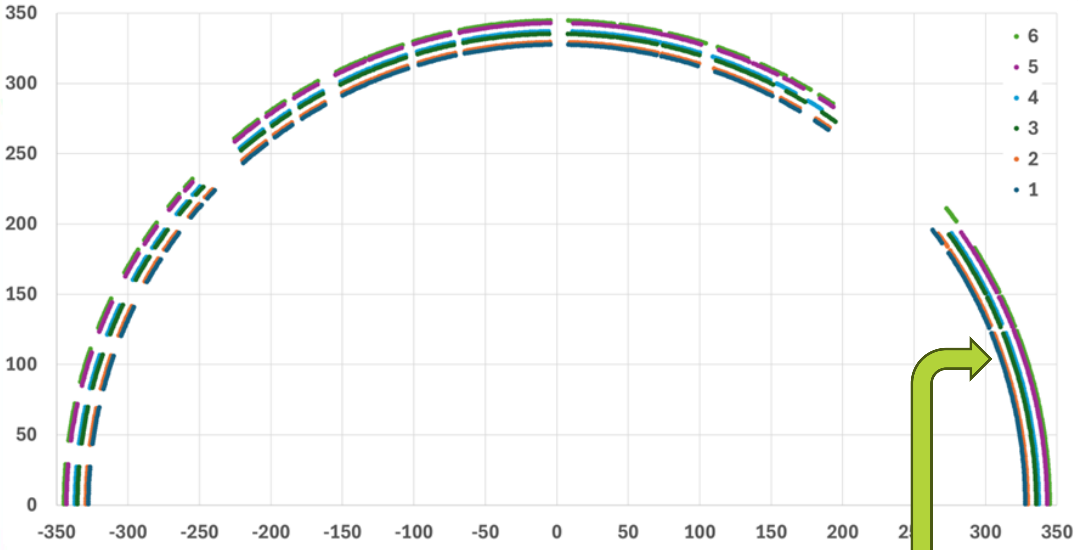
**Higher fill factor - both in the body and in the ends**

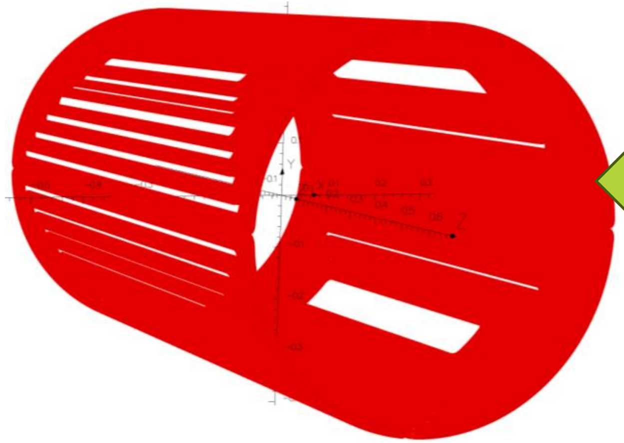


AGS dipole

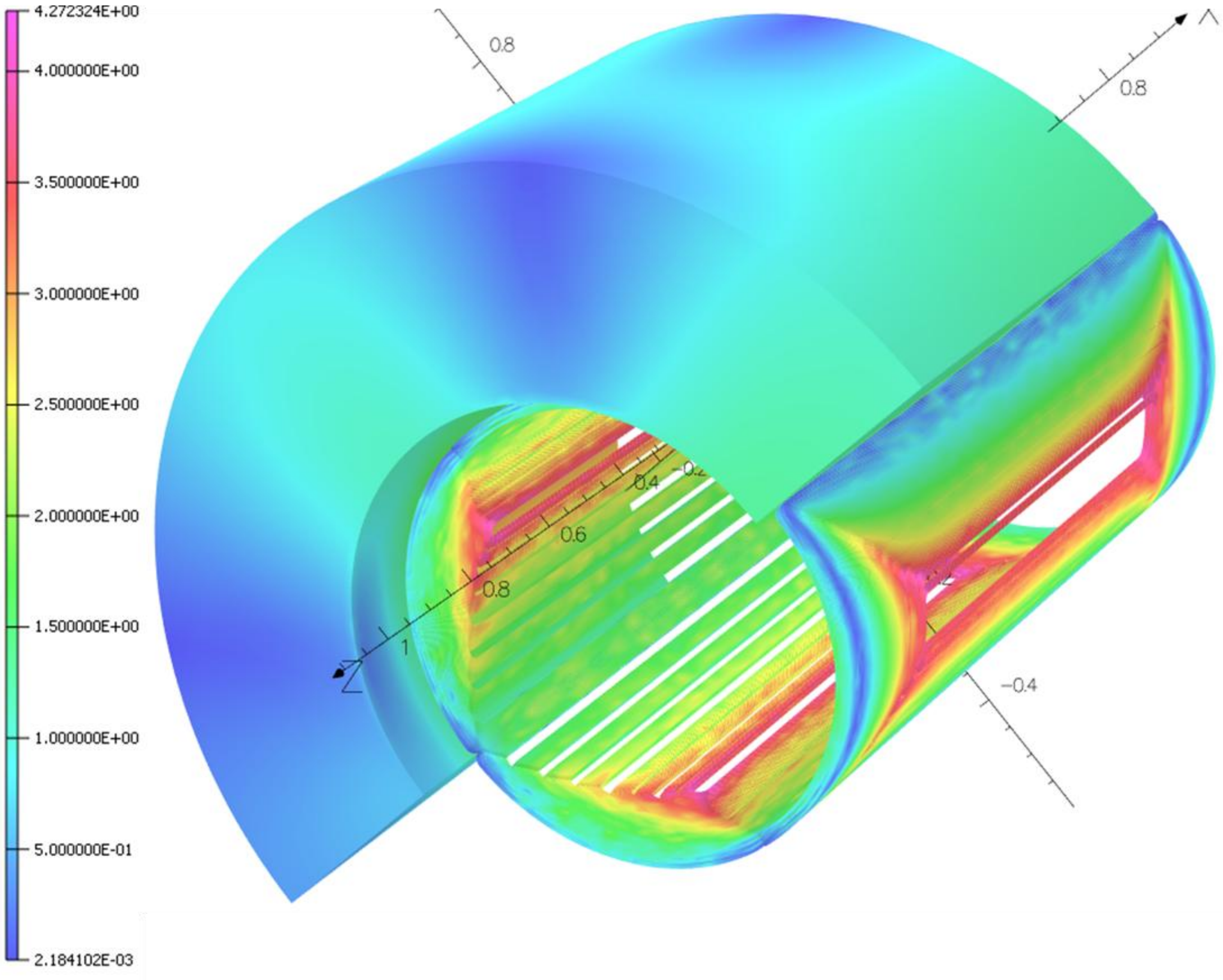
**A lot more turns are packed in the body since distribution doesn't have to be diluted to create a COS(θ) function. i.e., end helps create the COS(θ) distribution and also increase the field in the magnet body.**

# High fill factor in B0pF (helps increase the contribution to the field both from the body and from the the end)



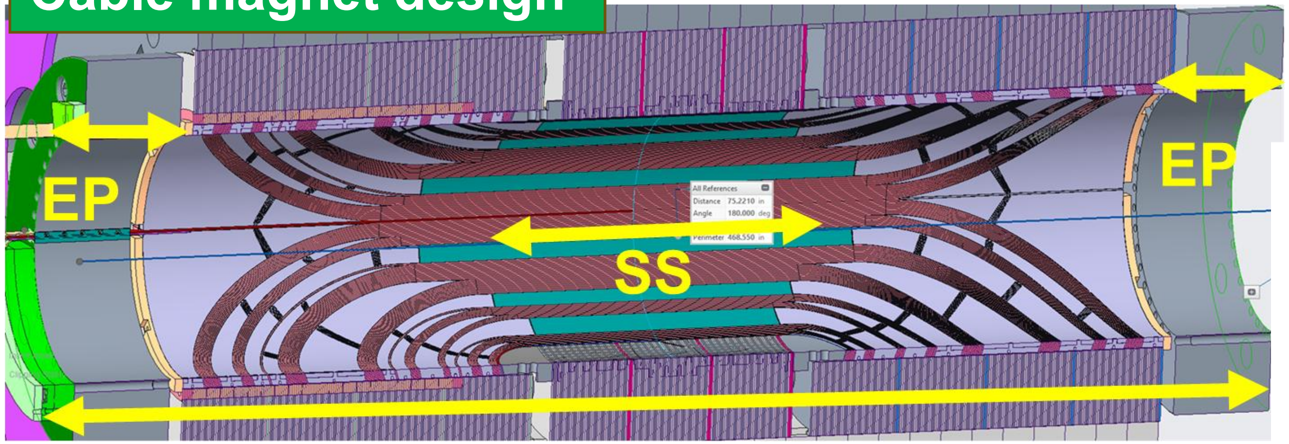



Note: How tightly packed turns are in this quadrant



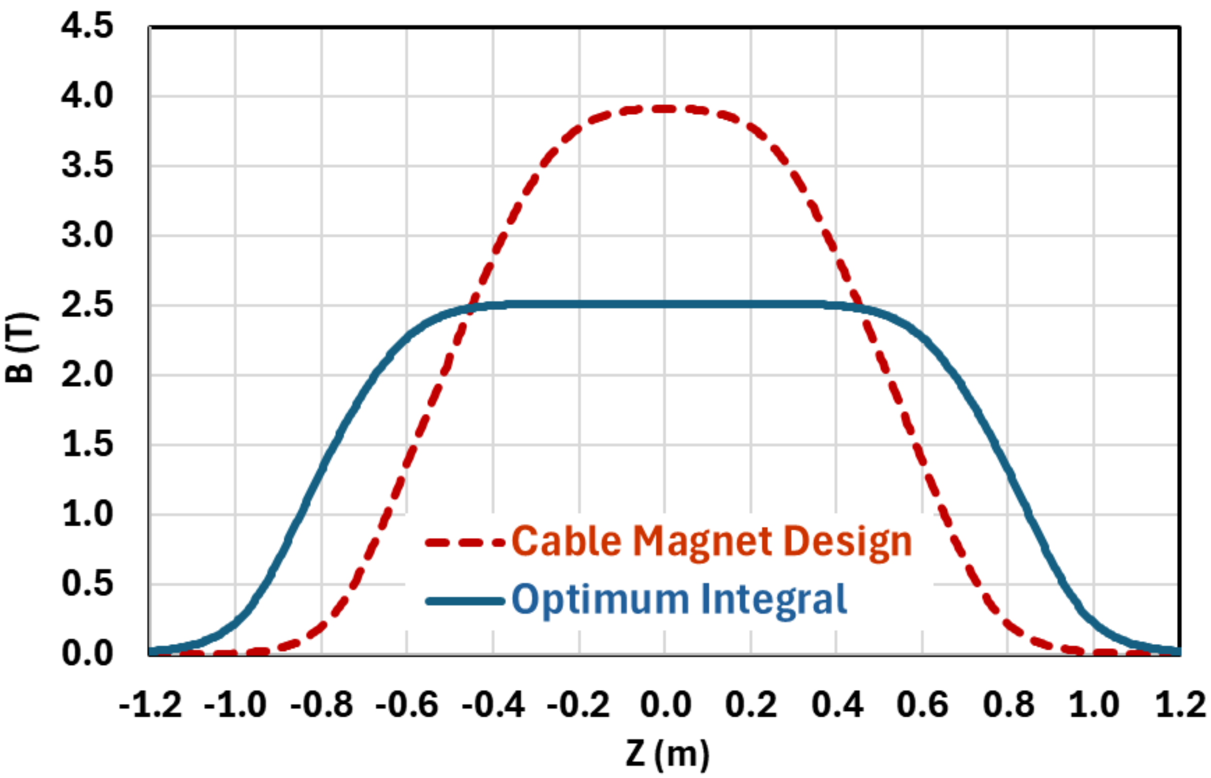
# An Earlier Examination of the Optimum Integral Design

Cable magnet design




Direct wind optimum integral design

A wider flap-top in Optimum Integral

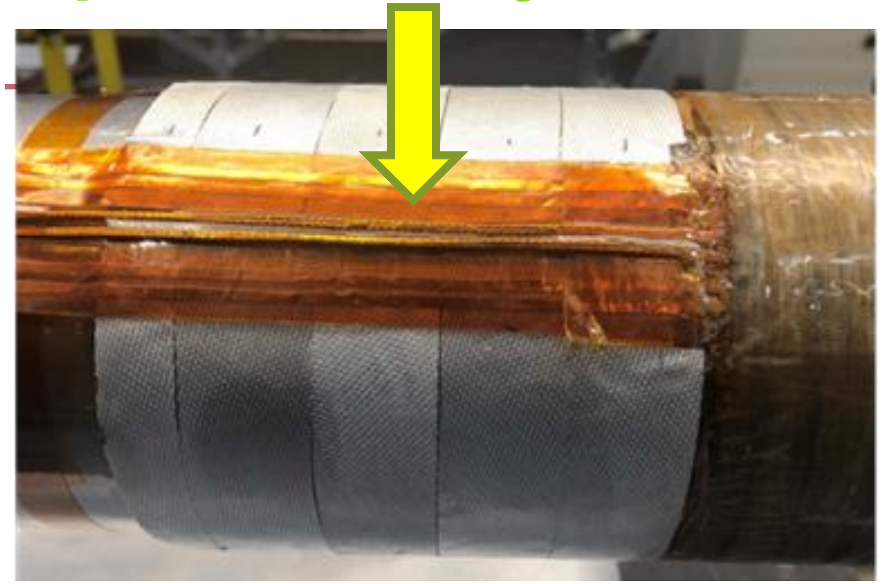


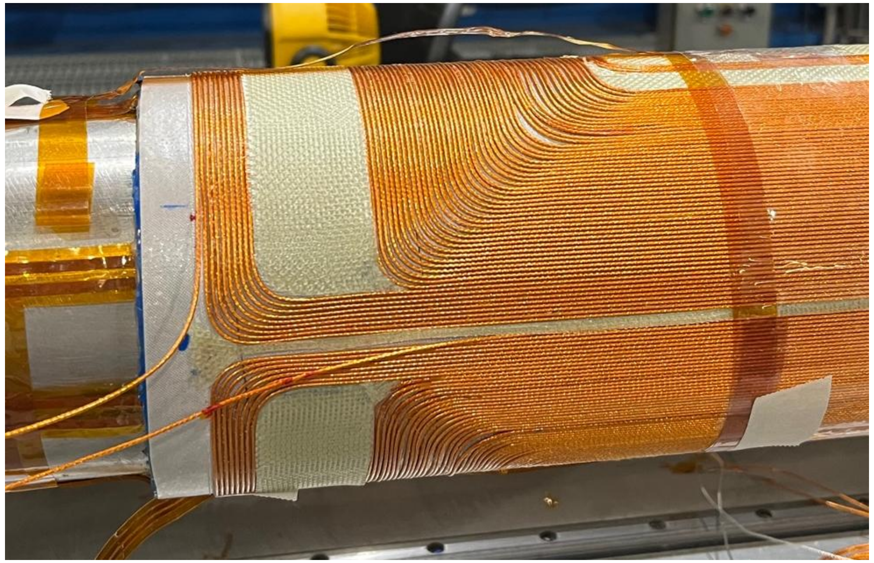

**Technical benefit: $B_o$ goes down from ~3.9 T to ~2.5 T; forces/stresses go down as $B^2$**

*Calculations for the cable magnet design from Mithlesh Kumar

# Design Choices to Eliminate Loss in Radial Space Used by Leads

- Baseline Optimum Integral Design" uses extra radial space for bringing leads out. This is done at the pole "over the coil".
- This has been used in the first two and in the last six layers of the PBL/BNL B0ApF.
- Extra use of radial extra space may be OK in some but may not be desired in others.
- A solution was implemented in four coils to avoid this loss which required a splice at the pole. Leads come out at midplane.
- Examination of other options is underway.
- One can perhaps also bring leads out after four layers to reduce use of radial space.





# Loss in Integral Field Due to Ends and Some Short EIC Magnets

- **Relative loss starts becoming important when the length of magnet is so small that the straight becomes comparable to the ends.**
- **Typical mechanical length of end: ~ 2 coil diameter each in dipole. Total ends in dipole: ~four diameter (~2 coil diameter in quad).**
- **Compare coil length (L) to coil i.d. (id) ratios. Relative loss will be significant when the ratio is <8 in dipoles and <4 in quadrupoles.**

## Coil length to coil diameter ratios in some EIC magnets:

- **B0ApF (*L* = 600 mm, i*d* = 114 mm): ~5.3**
- **B1ApF (*L* = 1600 mm, i*d* = 370 mm): ~4.3**
- **B1pF/B1ApF (L = 2250 mm, id = 363 mm): ~6.2**
- **B0pF/Q0eF (L=1200 mm, id = 656 mm): ~1.8 (refer to quad)**

**Reference guide**
**~8 in dipole**
**~4 in quads**

# Initial Design of B0ApF for Updated Parameters

## (same coil id as in the serpentine)

# Computed field harmonics in the 4-layer design

**First attempt to save 2 layers (reduce from 6 layers in serpentine to for 4 layers in OID)**

B0ApF-4lyr-L785-c4.X01

```
$FCNX VC2CB=.TRUE.,VC2CE=.TRUE.,MAGTYPE=2,
   LAYERS=4,RFEMM=80,R0MM=25.,
      RBENDMM=12,NBEND=10 &end
 3 3 0.785  1.6 52.98 1000 0.4 0.2
 3 3 0.785  1.6 54.71 1000 0.4 0.20
 3 3 0.785  1.6 57.68 1000 0.4 0.20
 3 3 0.785  1.6 59.41 1000 0.4 0.20
B2 0.  1.
B4 0.  2.
b6 0.  3.
b8 0.  4.
b10 0. 1.
b12 0. 1.
```

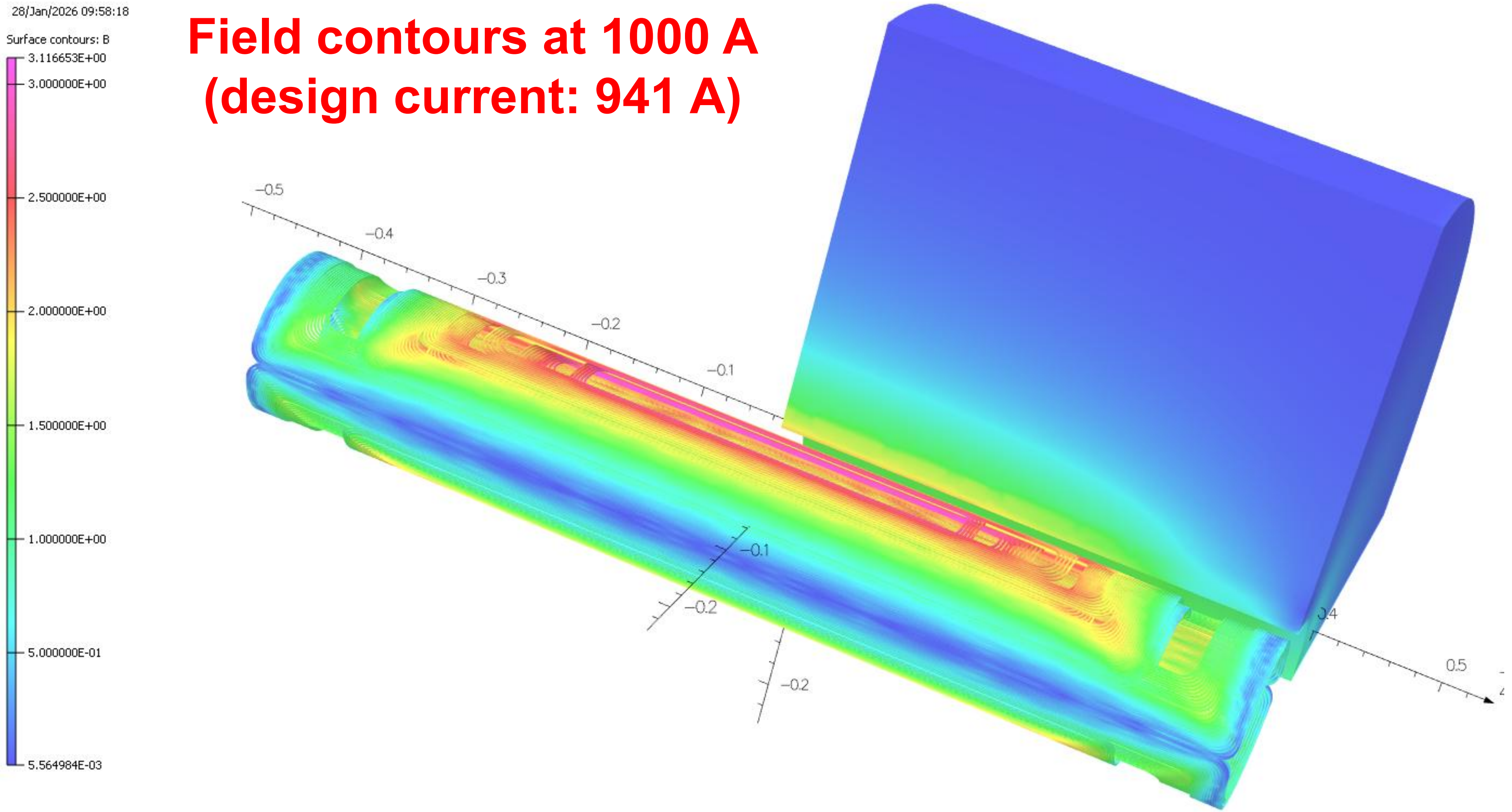
**Harmonics at r=25 mm <2 (spec@ @14 mm?)**

INTEGRATED FIELD HARMONICS :

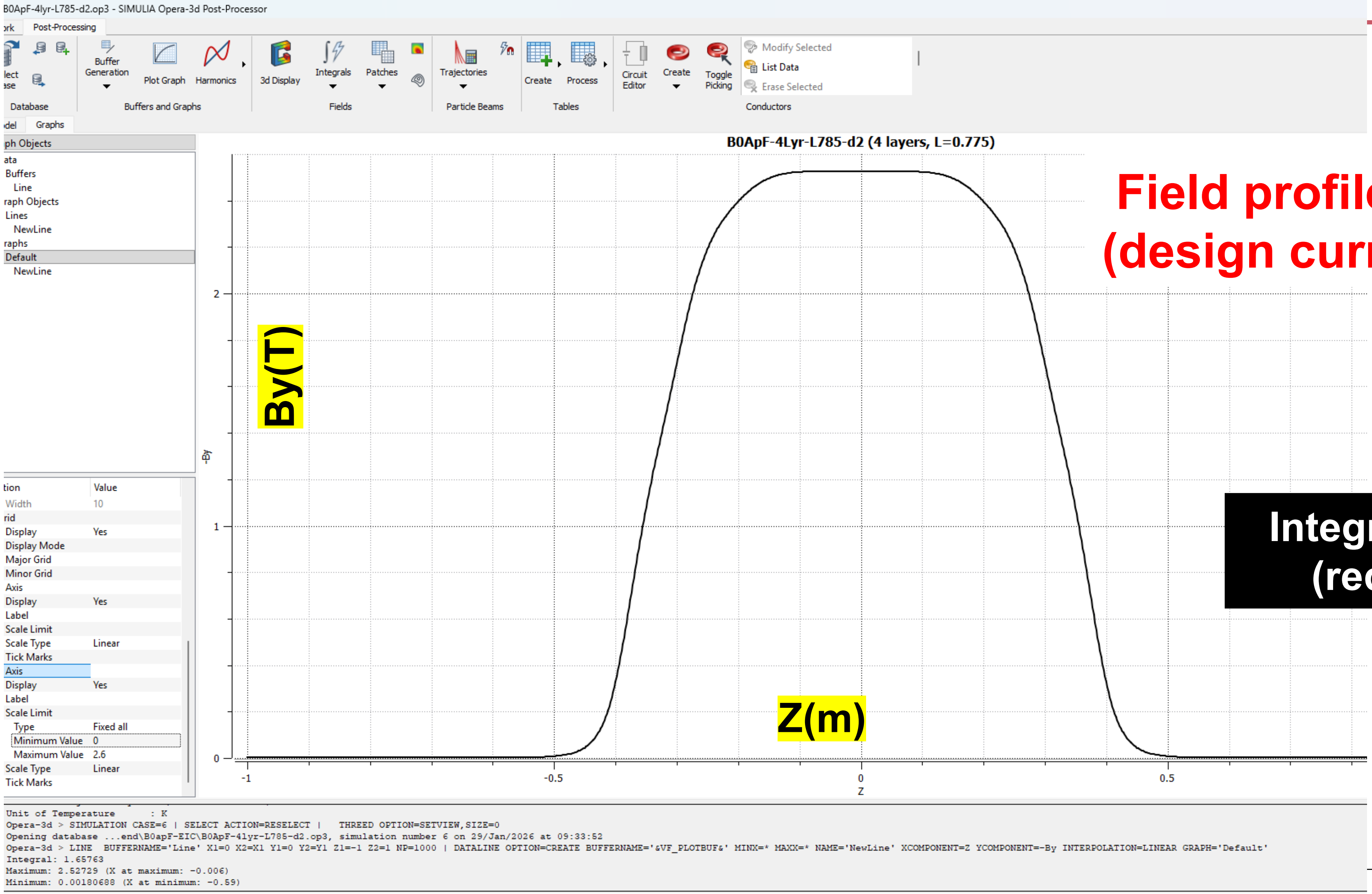
| No. | Bn(T.m) | bn*10^4(units) | bn(des) |
|---|---|---|---|
| 0 | 0.15408E+01 | 10000.0000 | 0.0000 |
| 2 | -0.22950E-04 | -0.1489 | 0.0000 |
| 4 | 0.93674E-04 | 0.6079 | 0.0000 |
| 6 | 0.27352E-03 | 1.7751 | 0.0000 |
| 8 | 0.13700E-04 | 0.0889 | 0.0000 |
| 10 | 0.54243E-05 | 0.0352 | 0.0000 |
| 12 | -0.37981E-05 | -0.0246 | 0.0000 |
| 14 | 0.60385E-06 | 0.0039 | 0.0000 |
| 16 | -0.12294E-06 | -0.0008 | 0.0000 |
| 18 | -0.12230E-07 | -0.0001 | 0.0000 |
| 20 | 0.60159E-08 | 0.0000 | 0.0000 |
| 22 | -0.35829E-09 | -0.0000 | 0.0000 |
| 24 | -0.21414E-10 | -0.0000 | 0.0000 |
| 26 | 0.28304E-10 | 0.0000 | 0.0000 |
| 28 | 0.47929E-11 | 0.0000 | 0.0000 |
| 30 | -0.24616E-11 | -0.0000 | 0.0000 |

- Old US definition: b2 is sextupole

# 4-layer Optimum Integral Design for B0ApF@1kA



# 4-layer Optimum Integral Design for B0ApF@1kA

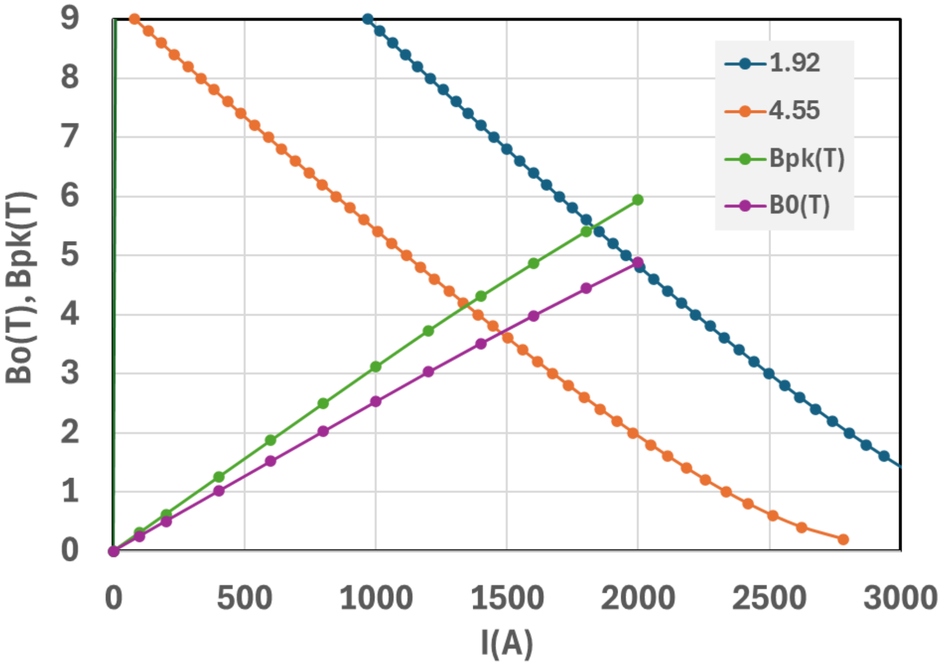


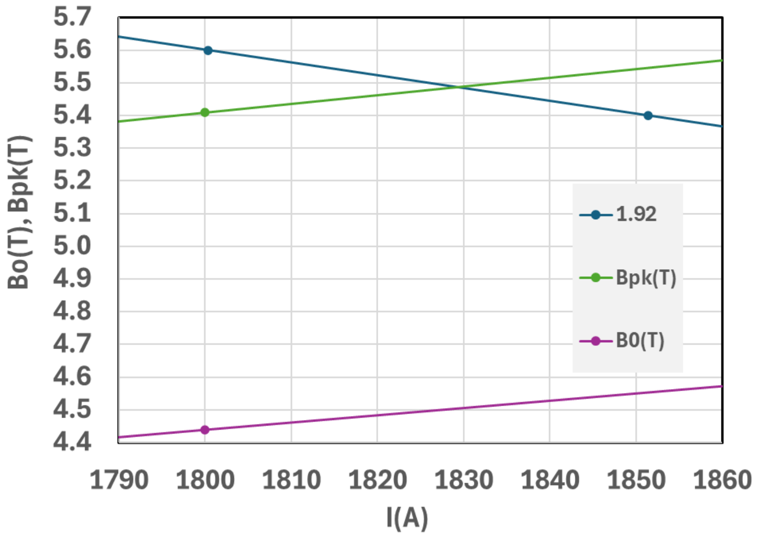

**Field profile at 1000 A (design current: 941 A)**

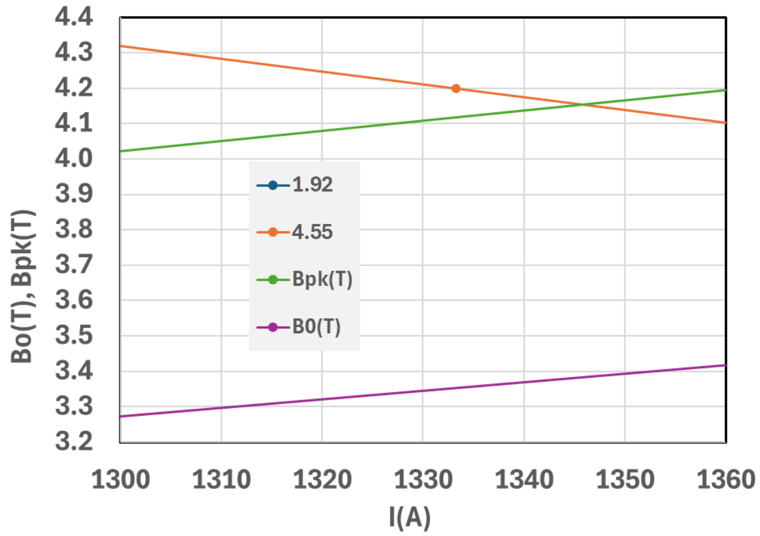
**Integral Field = 1.66 T.m (required: 1.56 T.m)**

# 4-layer optimum integral design B0ApF

| I(A) | B0(T) | Bpk(T) | Bint(T.m) |
|---|---|---|---|
| 0 | 0.000 | 0.000 | 0 |
| 100 | 0.253 | 0.312 | 0.166 |
| 200 | 0.506 | 0.624 | 0.332 |
| 400 | 1.011 | 1.248 | 0.663 |
| 600 | 1.517 | 1.871 | 0.995 |
| 800 | 2.022 | 2.495 | 1.326 |
| **1000** | **2.527** | **3.117** | **1.658** |
| 1200 | 3.028 | 3.728 | 1.987 |
| 1400 | 3.514 | 4.311 | 2.311 |
| **1600** | 3.983 | 4.867 | 2.625 |
| 1800 | 4.438 | 5.409 | 2.931 |
| 2000 | 4.881 | 5.940 | 3.230 |



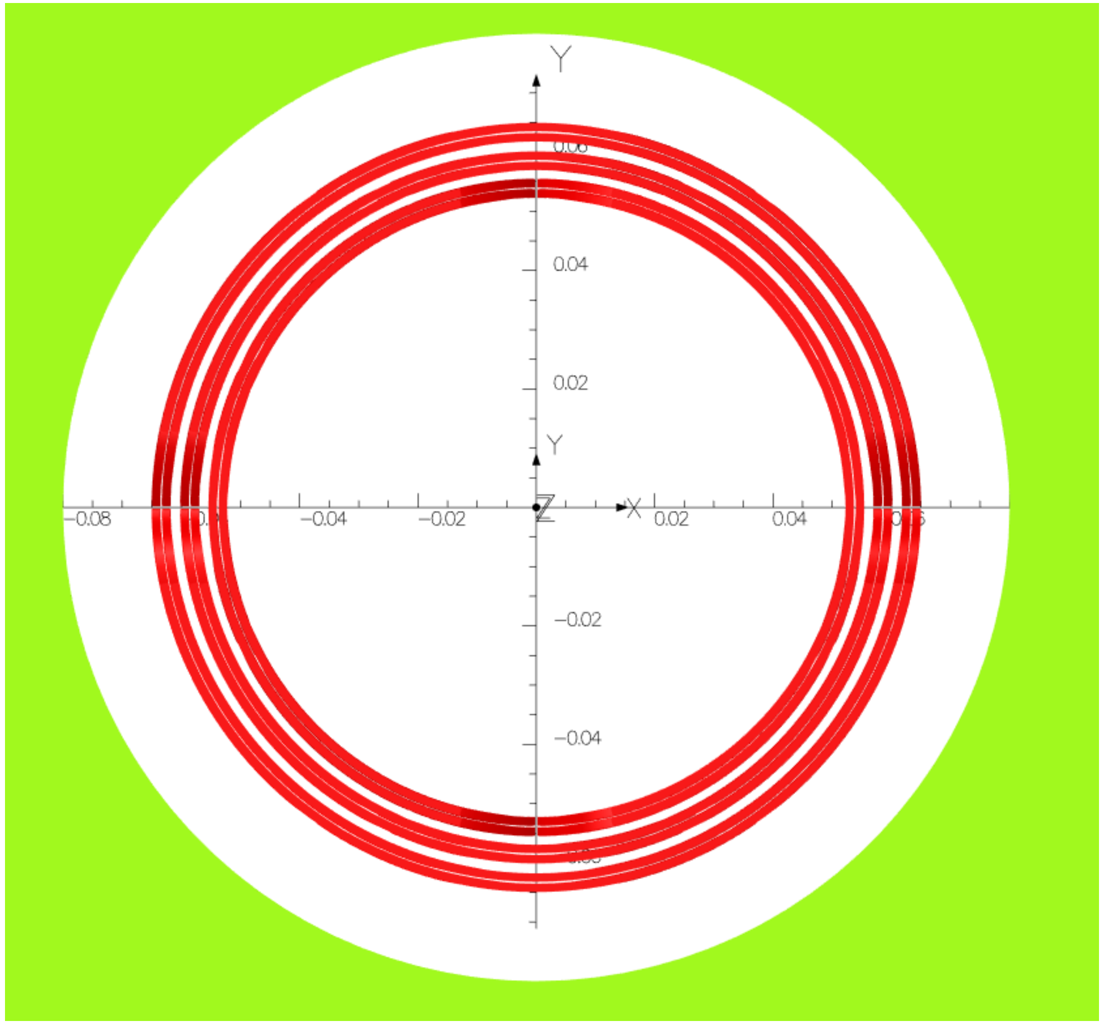

| Four Layer (2 Coil Set) OID | |
|---|---|
| I_baseline(A) | 941 |
| Iss (A), 1.92 K | 1830 |
| LoadLine Fraction, 1.92 K | 51% |
| Iss (A), 4.55 K | 1345 |
| LoadLine Fraction, 4.55 K | 70% |

**Peak field enhancement**
**Bpk/Bo=1.23 (23%)**

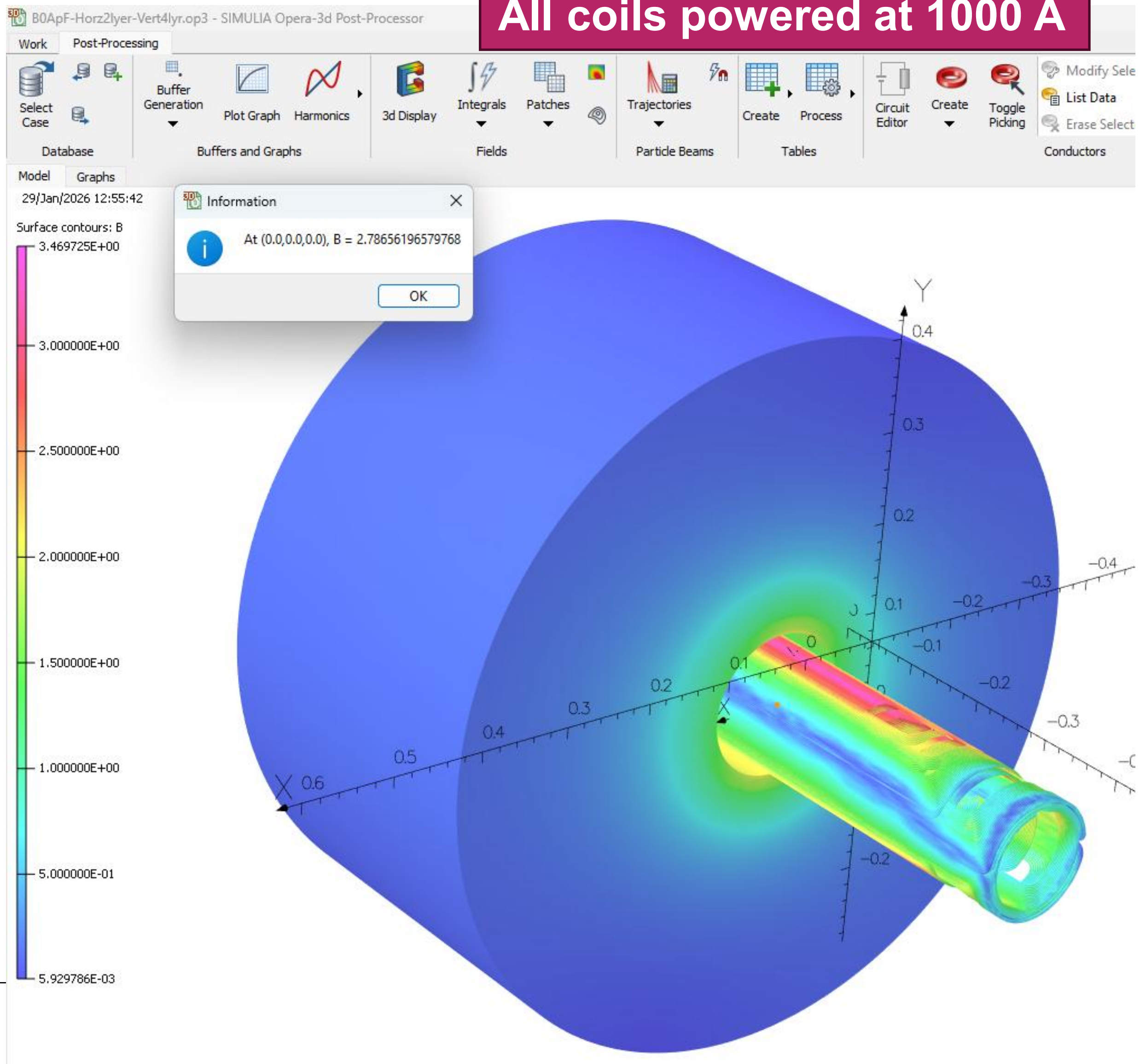
➢ **Promising results of a quick study, with a potential for even better outcome**

# Initial Model of Vertical Dipole (inside B0ApF)

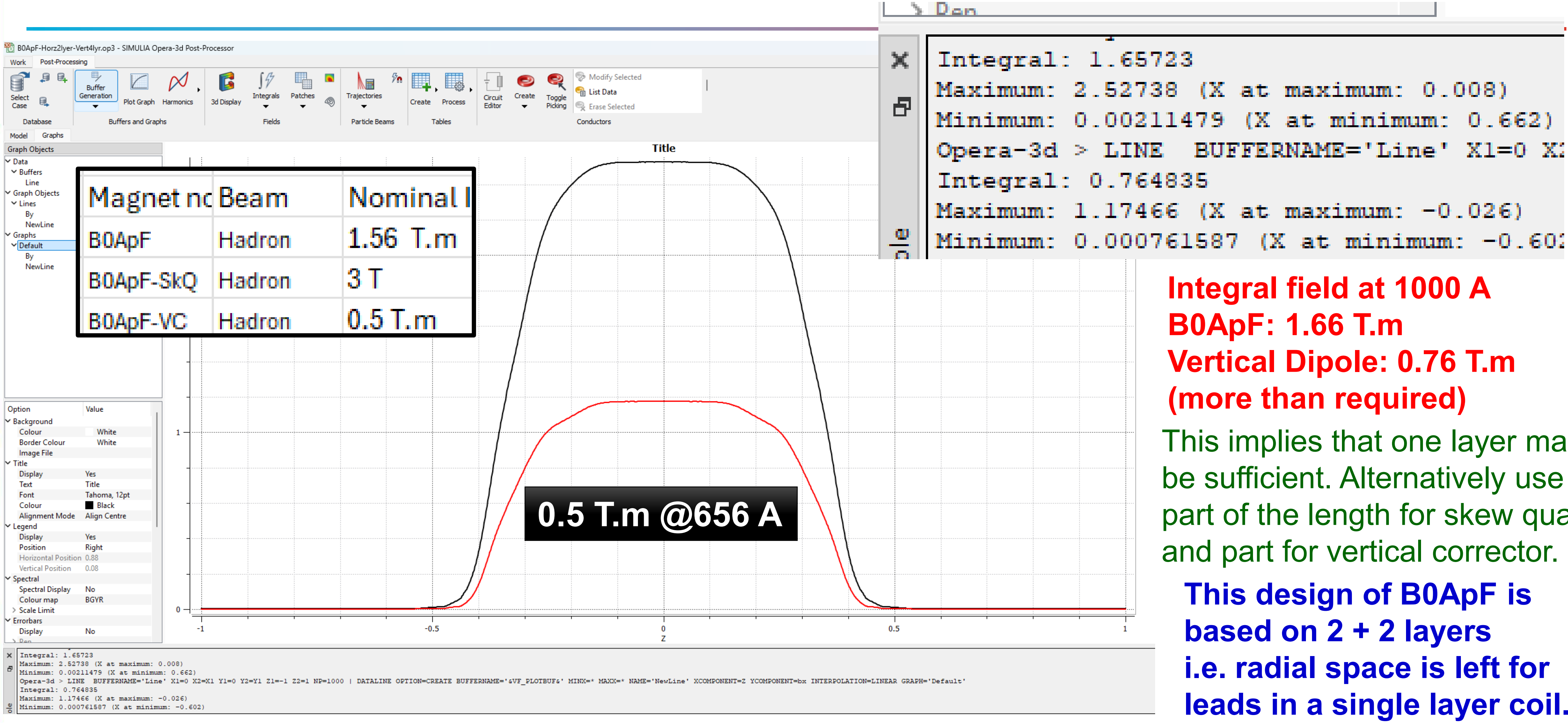
# 4 Layers for Horizontal Dipole (B0ApF), 2-layers for Vertical Corrector




**All coils powered at 1000 A**



# 4 Layers for Horizontal Dipole (B0ApF), 2-layers for Vertical Corrector




| Magnet nc | Beam | Nominal I |
|---|---|---|
| B0ApF | Hadron | 1.56 T.m |
| B0ApF-SkQ | Hadron | 3 T |
| B0ApF-VC | Hadron | 0.5 T.m |

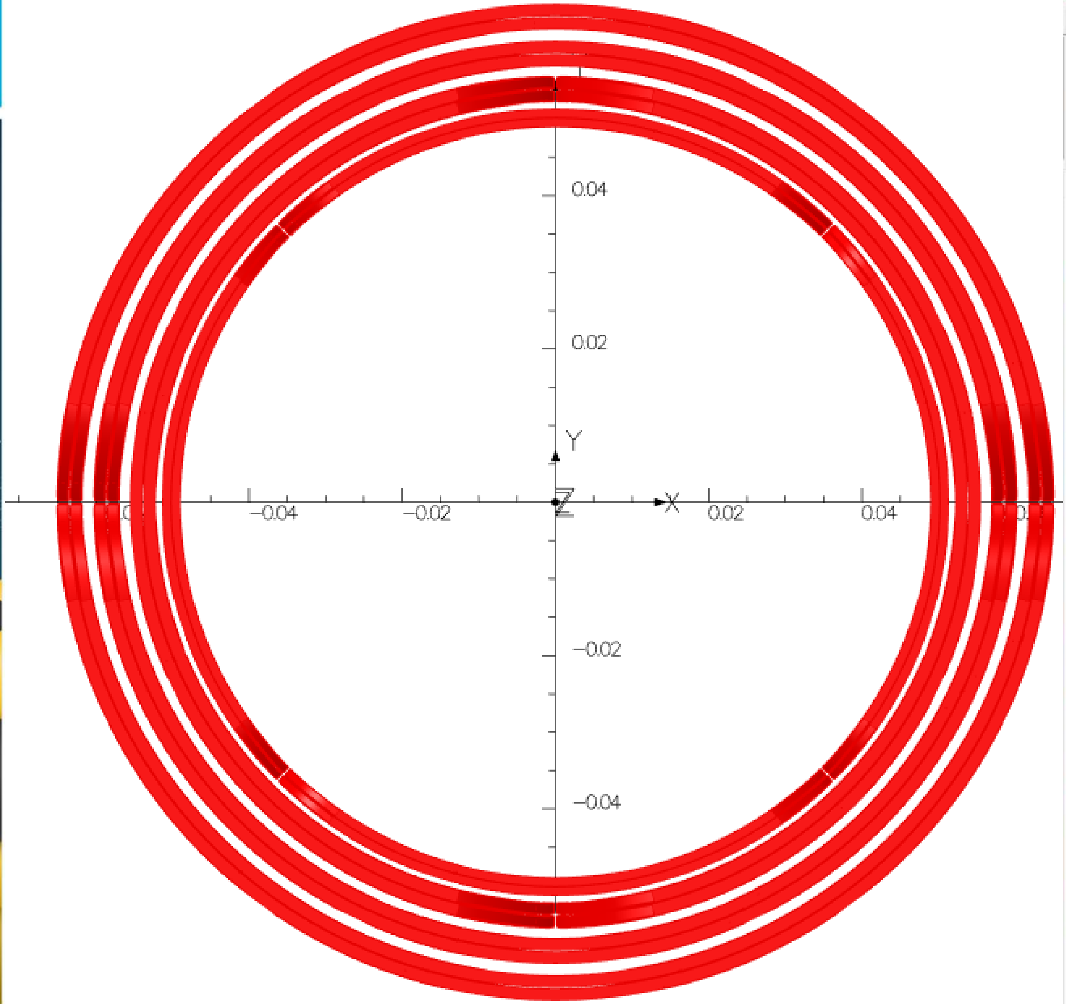
**Integral field at 1000 A**
**B0ApF: 1.66 T.m**
**Vertical Dipole: 0.76 T.m**
**(more than required)**

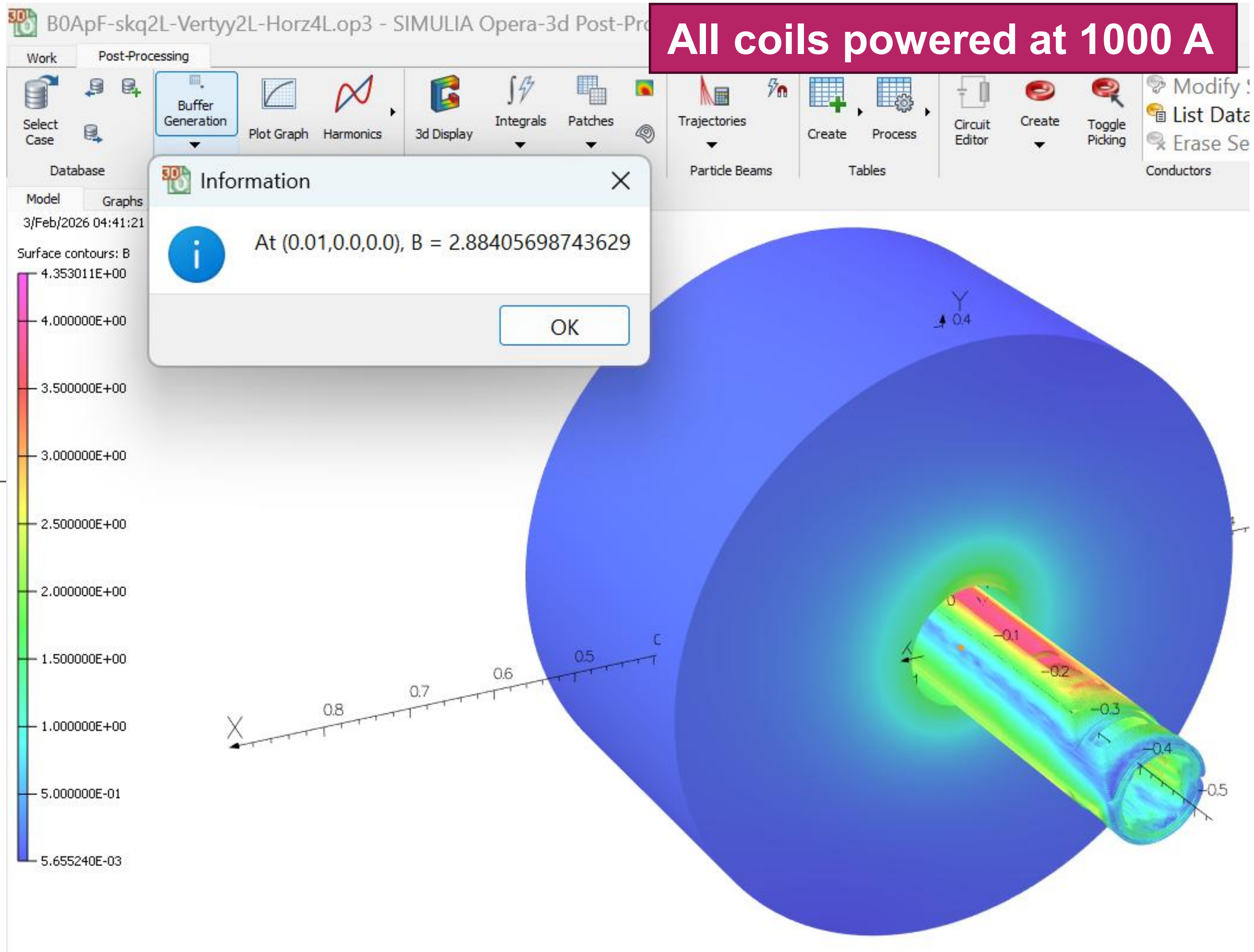
This implies that one layer may be sufficient. Alternatively use part of the length for skew quad and part for vertical corrector.

**This design of B0ApF is based on 2 + 2 layers i.e. radial space is left for leads in a single layer coil.**

# Initial Model of Skew Quad and Vertical Dipole inside B0ApF

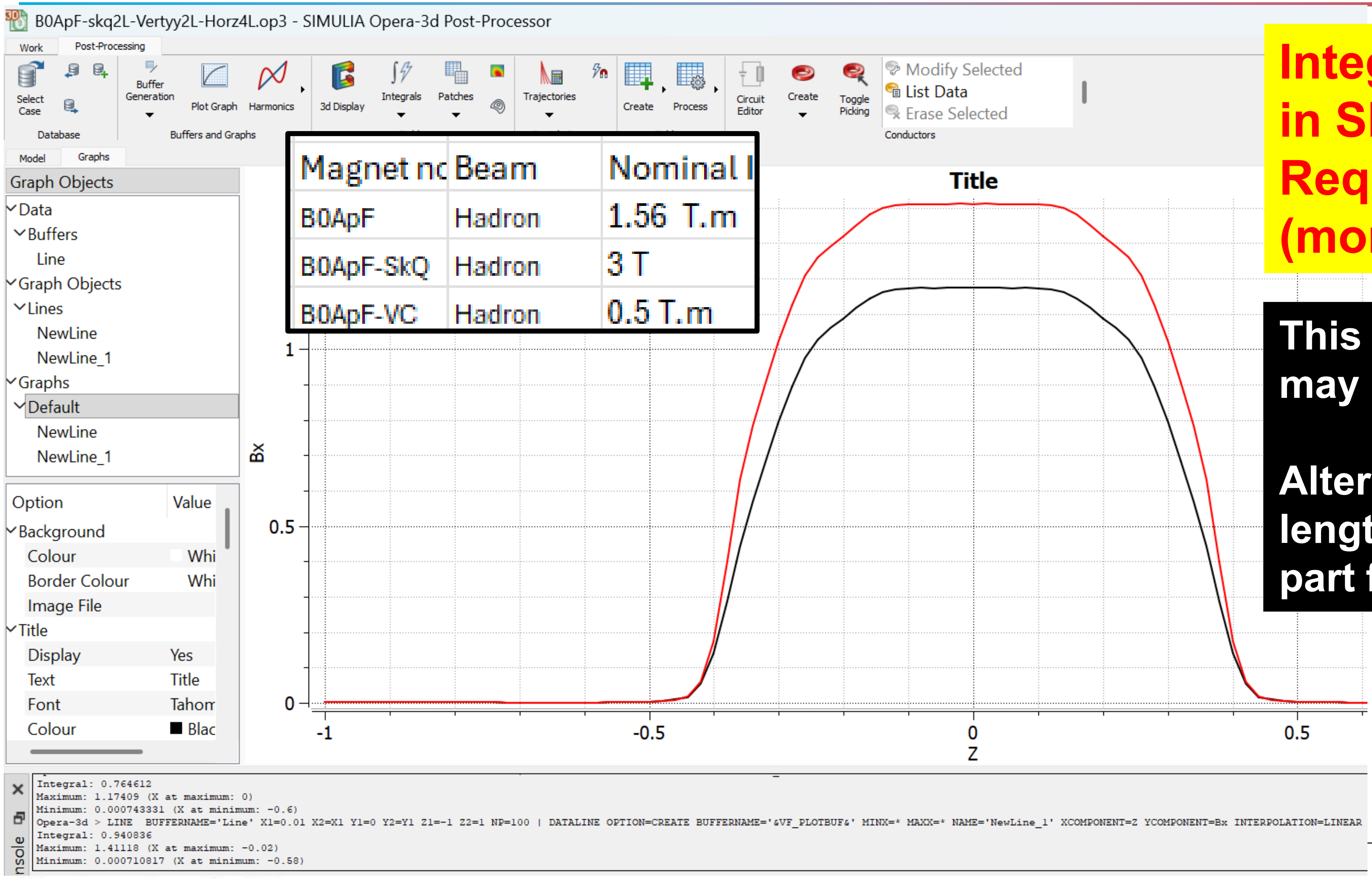
# 4-layer B0ApF with 2-layer Vertical Dipole & 2-layer Skew Quad inside




**All coils powered at 1000 A**

# 4-layer B0ApF with 2-layer Vertical Dipole & 2-layer Skew Quad inside



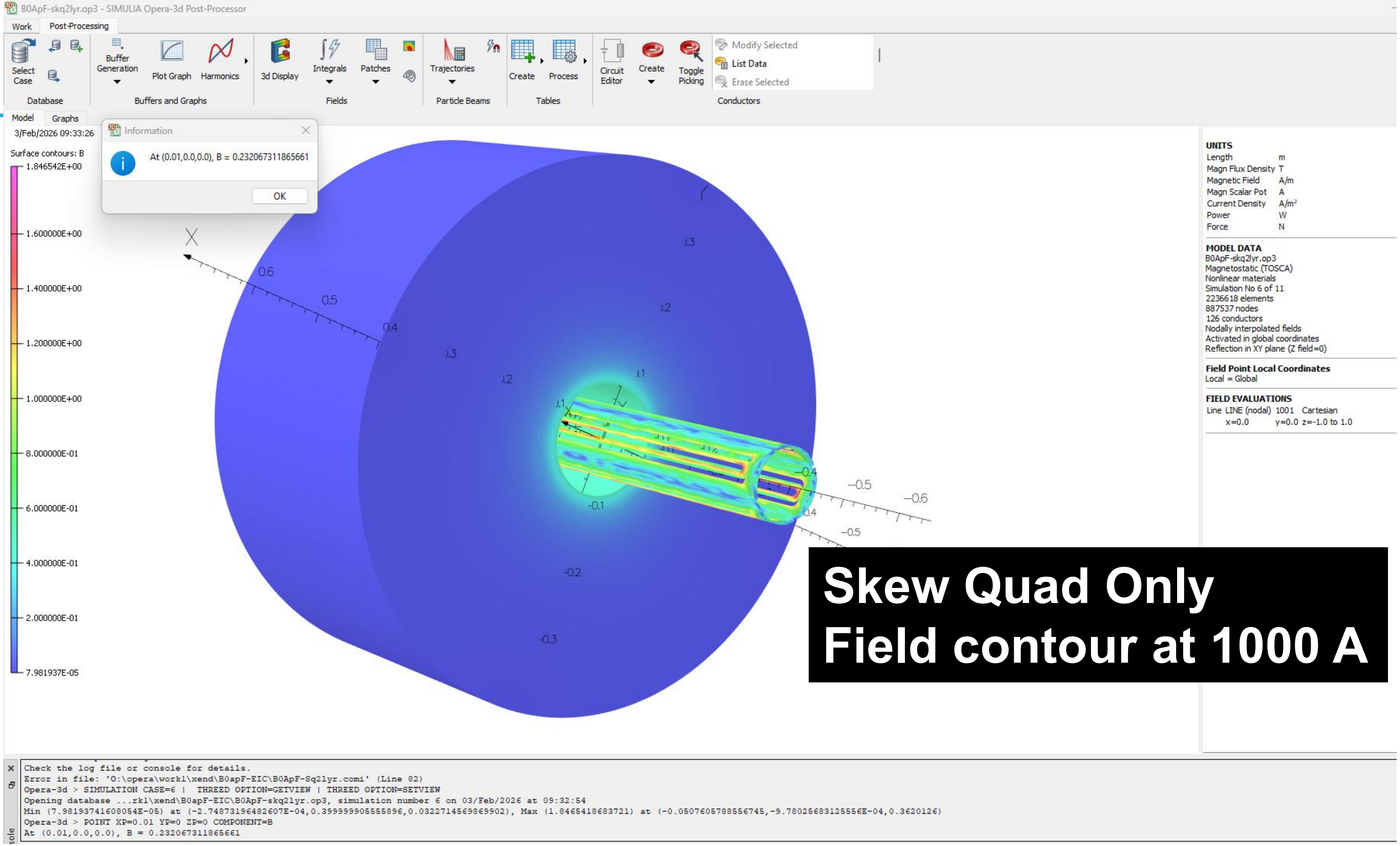

| Magnet nc | Beam | Nominal I |
|---|---|---|
| B0ApF | Hadron | 1.56 T.m |
| B0ApF-SkQ | Hadron | 3 T |
| B0ApF-VC | Hadron | 0.5 T.m |

**Integral field at 1000 A in Skew Quad: ~17 T**
**Required: 3 T @176 A**
**(more than required)**

**This implies that one layer may be sufficient.**

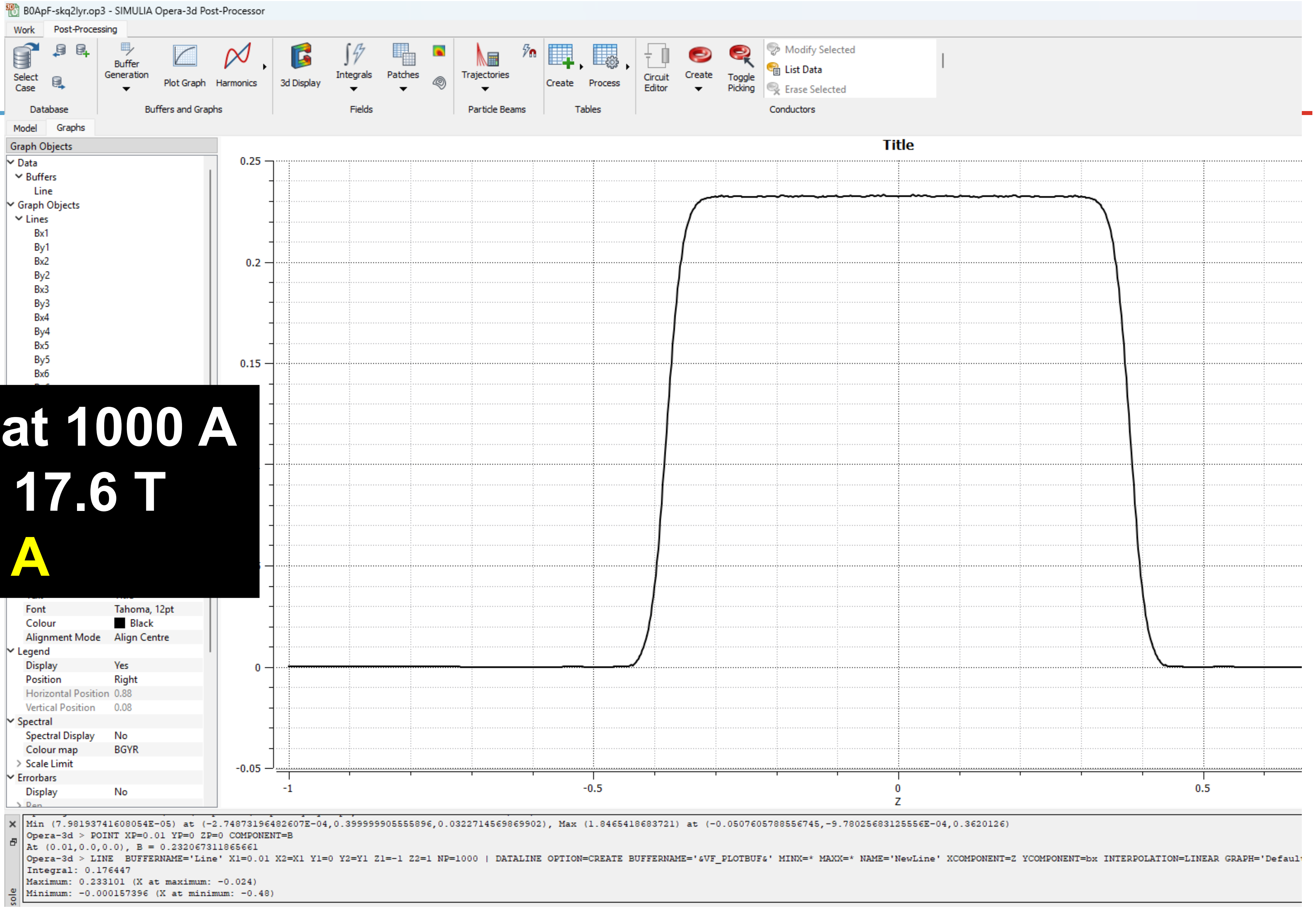
**Alternatively use part of the length for the skew quad and part for the vertical corrector.**

**This design of B0ApF is based on 2 + 2 layers i.e. radial space is left for leads in a single layer coil.**



B0ApF-skq2lyr.op3 - SIMULIA Opera-3d Post-Processor
Work
Post-Processing
Select Case
Database
Buffer Generation
Plot Graph
Harmonics
Buffers and Graphs
3d Display
Integrals
Patches
Fields
Trajectories
Particle Beams
Create
Process
Tables
Circuit Editor
Create
Toggle Picking
Modify Selected
List Data
Erase Selected
Conductors
Model
Graphs
3/Feb/2026 09:33:26
Surface contours: B
1.846542E+00
1.600000E+00
1.400000E+00
1.200000E+00
1.000000E+00
8.000000E-01
6.000000E-01
4.000000E-01
2.000000E-01
7.981937E-05
Information
At (0.01,0.0,0.0), B = 0.232067311865661
OK
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
B0ApF-skq2lyr.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 6 of 11
2236618 elements
887537 nodes
126 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Field Point Local Coordinates
Local = Global
FIELD EVALUATIONS
Line LINE (nodal) 1001 Cartesian
x=0.0 y=0.0 z=-1.0 to 1.0
Check the log file or console for details.
Error in file: 'O:\opera\work1\xend\B0apF-EIC\B0ApF-Sq2lyr.comi' (Line 82)
Opera-3d > SIMULATION CASE=6 | THREED OPTION=GETVIEW | THREED OPTION=SETVIEW
Opening database ...rk1\xend\B0apF-EIC\B0ApF-skq2lyr.op3, simulation number 6 on 03/Feb/2026 at 09:32:54
Min (7.98193741608054E-05) at (-2.74873196482607E-04,0.399999905555896,0.0322714569869902), Max (1.8465418683721) at (-0.0507605788556745,-9.78025683125556E-04,0.3620126)
Opera-3d > POINT XP=0.01 YP=0 ZP=0 COMPONENT=B
At (0.01,0.0,0.0), B = 0.232067311865661
Skew Quad Only
Field contour at 1000 A

| Magnet nc | Beam | Nominal I |
|---|---|---|
| B0ApF | Hadron | 1.56 T.m |
| B0ApF-SkQ | Hadron | 3 T |
| B0ApF-VC | Hadron | 0.5 T.m |




**Integral Gradient at 1000 A**
**Skew Quad Only: 17.6 T**
**3 T @ 170 A**

**A little higher gradient because the yoke is not saturated.**

# SUMMARY

# Extra Slides

# Radial build-up

| | | B0APF Cold Mass Buildup (01-07-26) A | | | Base line radial built-up | Reduced aperture radial built-up |
|---|---|---|---|---|---|---|
| Support Tube Thickness | Kapton Thickness | Substrate Barrier | Main Conductor Diameter | Roving thickness | Machined G-10 Layer | Machined G-10 Layer |
| 0.312 | 0.003 | 0.005 | 0.063 | 0.008 | 0.030 | 0.030 |
| | | | 1.6002 | | | |
| Beamtube Thickness | Inner Helium Containment | | Corrector Conductor Dia. | | | |
| 0.06 | | | 0.043 | | | |
| | | | 1.0922 | | | |
| Coil Buildup Step | Radius (inches) | Diameter (inches) | Radius (mm) | Diameter (mm) | Center Conductor Radius (mm) | Center Conductor Radius (mm) |
| Clear Aperture | 1.536 | 3.071 | 39.00 | 78.00 | | |
| Beamtube Outer Surface | 1.5955 | 3.191 | 40.53 | 81.05 | | |
| 4mm Helium Space | | | | | | |
| Support Tube Inner Surface | 1.7535 | 3.507 | 44.54 | 89.1 | | |
| Support Tube Outer Surface (8mm wall) | 2.0655 | 4.131 | 52.46 | 104.93 | | |
| Kapton (66% overlap .001") | 2.0685 | 4.137 | 52.54 | 105.08 | | |
| **Skew Quad Corrector** | | | | | | |
| Substrate Barrier #1 | 2.0735 | 4.147 | 52.67 | 105.33 | | |
| Conductor Layer #1 | 2.1165 | 4.233 | 53.76 | 107.52 | **53.213** | **49.009** |
| Substrate Barrier #2 | 2.1215 | 4.243 | 53.89 | 107.77 | | |
| Conductor Layer #2 | 2.1645 | 4.329 | 54.98 | 109.96 | **54.432** | **50.229** |
| Kapton (66% overlap .001") | 2.1675 | 4.335 | 55.05 | 110.11 | | |
| 2 Layers Tension Roving | 2.1835 | | | | | |
| **Skew Dipole Corrector** | | | | | | |
| Substrate Barrier #1 | 2.1885 | 4.377 | 55.59 | 111.18 | | |
| Conductor Layer #1 | 2.2515 | 4.503 | 57.19 | 114.38 | **56.388** | **52.184** |
| Substrate Barrier #2 | 2.2565 | 4.513 | 57.32 | 114.63 | | |
| Conductor Layer #2 | 2.3195 | 4.639 | 58.92 | 117.83 | **58.115** | **53.912** |
| Kapton (66% overlap .001") | 2.3225 | 4.645 | 58.99 | 117.98 | | |
| 2 Layers Tension Roving | 2.3385 | 4.677 | 59.40 | 118.80 | | |
| Machine Round | 2.369 | 4.737 | 60.16 | 120.32 | | |
| **Main Dipole** | | | | | | |
| Substrate Barrier #1 | 2.374 | 4.747 | 60.29 | 120.57 | | |
| Conductor Layer #1 | 2.437 | 4.873 | 61.89 | 123.77 | **61.087** | **56.883** |
| Substrate Barrier #2 | 2.442 | 4.883 | 62.01 | 124.03 | | |
| Conductor Layer#2 | 2.505 | 5.009 | 63.61 | 127.23 | **62.814** | **58.611** |
| 3 Layers Tension Roving | 2.529 | 5.057 | 64.22 | 128.45 | | |
| Machine Round | 2.559 | 5.117 | 64.99 | 129.97 | | |
| Substrate Barrier #3 | 2.564 | 5.127 | 65.11 | 130.23 | | |
| Conductor Layer #3 | 2.627 | 5.253 | 66.71 | 133.43 | **65.913** | **61.709** |
| Substrate Barrier #4 | 2.632 | 5.263 | 66.84 | 133.68 | | |
| Conductor Layer #4 | 2.695 | 5.389 | 68.44 | 136.88 | **67.640** | **63.437** |
| 3 Layers Tension Roving | 2.7185 | 5.437 | 69.05 | 138.10 | | |
| Machine Round | 2.749 | 5.497 | 69.81 | 139.62 | | |
| Substrate Barrier #5 | 2.754 | 5.507 | 69.94 | 139.88 | | |
| Conductor Layer #5 | 2.817 | 5.633 | 71.54 | 143.08 | **70.739** | **66.535** |
| Substrate Barrier #6 | 2.822 | 5.643 | 71.67 | 143.33 | | |
| Conductor Layer #6 | 2.885 | 5.769 | 73.27 | 146.53 | **72.466** | **68.263** |
| 3 Layers Tension Roving | 2.909 | 5.817 | 73.88 | 147.75 | | |
| Machine Round | 2.939 | 5.877 | 74.64 | 149.28 | | |
| Substrate Barrier #7 | 2.944 | 5.887 | 74.76 | 149.53 | | |
| Conductor Layer #7 | 3.007 | 6.013 | 76.37 | 152.73 | **75.565** | **71.361** |
| Substrate Barrier #8 | 3.012 | 6.023 | 76.49 | 152.98 | | |
| Conductor Layer #8 | 3.075 | 6.149 | 78.09 | 156.18 | **77.292** | **73.089** |
| Kapton (66% overlap .001") | 3.078 | 6.155 | 78.17 | 156.34 | | |
| 3 Layers Tension Roving | 3.102 | 6.203 | 78.78 | 157.56 | | |