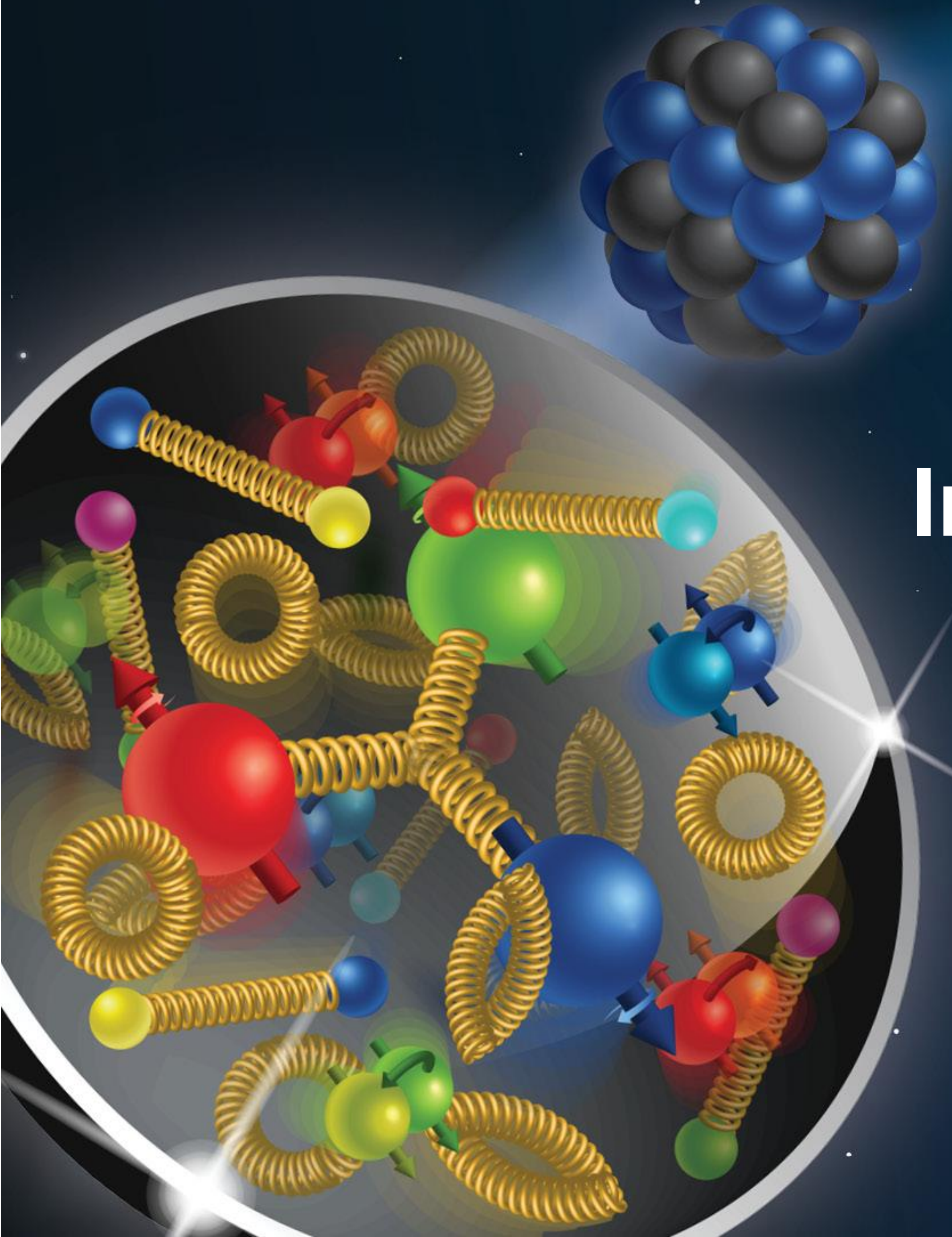

Investigation of the Optimum Integral Design for B0pF

Ramesh Gupta

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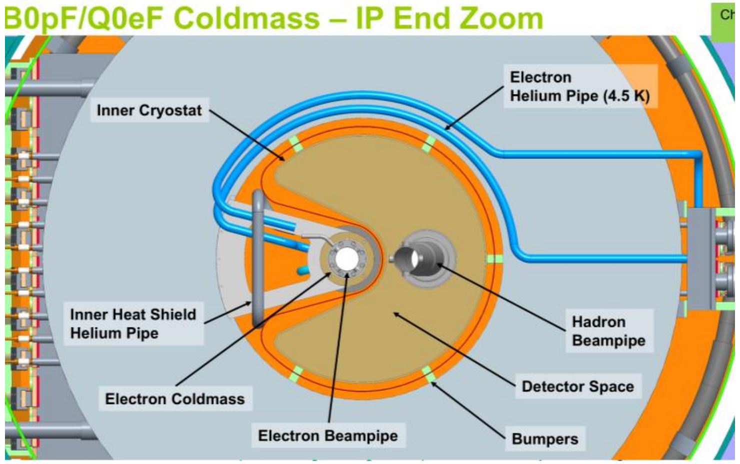
Electron-Ion Collider

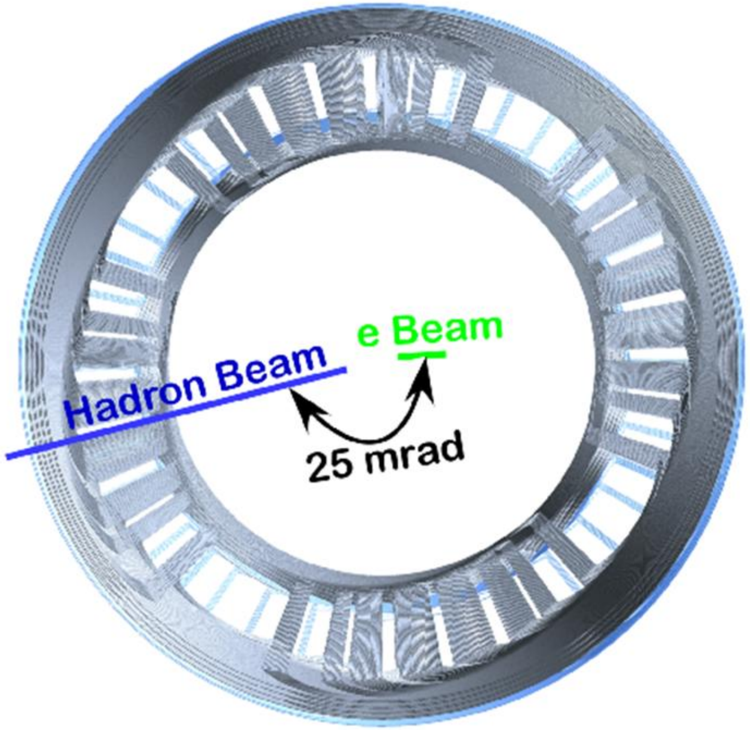
BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY Office of Science

Background

Courtesy Brett Parker

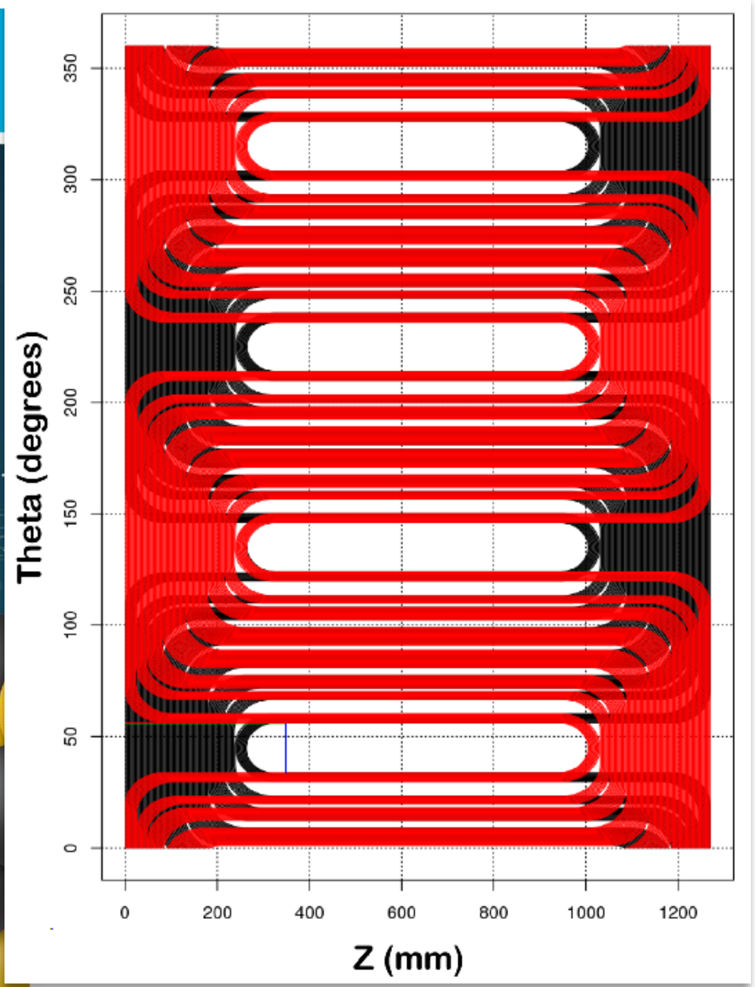
- B0pF is a complex multipurpose magnet - spectrometer for experimentalists, dipole for hadron and quad for “e” beams. Design must satisfy specific requirements for each of them.
- A PDR for this magnet has already been carried out. At this stage there must be a good reason for any major change.
- This investigation is for an alternate option in only one part of the design. Namely the large aperture quad/dipole coils, where MSG and review committee has raised concerns.
- Geometry of those coils is based on the serpentine design. We are examining the optimum integral design which minimizes the loss in magnetic length due to coil ends and therefore reduces the maximum field and current required.
- Brett Parker has carried out the EM design of the entire magnet. This study has been carried out with his guidance.





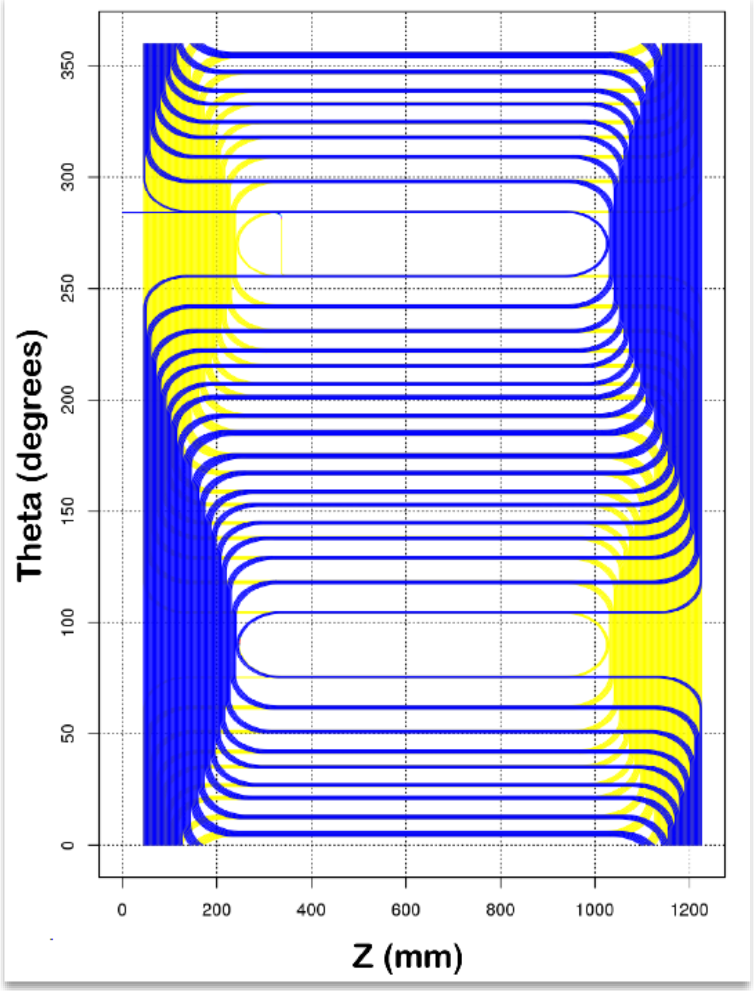
Serpentine Coil Design for B0pF (Brett Parker)

B0PF Quad Serpentine Coilset A



Three coil sets (6 layers) needed

B0PF Dipole Serpentine Coilset



One coil set (2 layers) needed
(body diluted and ends adjusted)

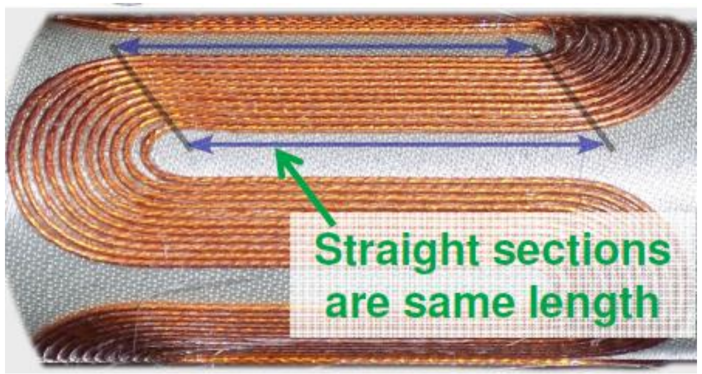
- Serpentine pattern has several nice features. It offers a continuous winding pattern which avoids splices between the poles.
- All turns have the same length. Thus, 3d harmonics same as 2d. Ends need not be optimized.
- However, as in other designs, ends don't generate much field.
- This loss in field due to Ends becomes important in short coils, particularly when length to diameter ratio is small. The ratio in the current design is ~1.9 for the quad and ~1.8 for the dipole.
- In such cases, optimum integral design, which minimizes this loss, is expected to make a large difference.

Optimum Integral Design for Short Magnets - Motivation

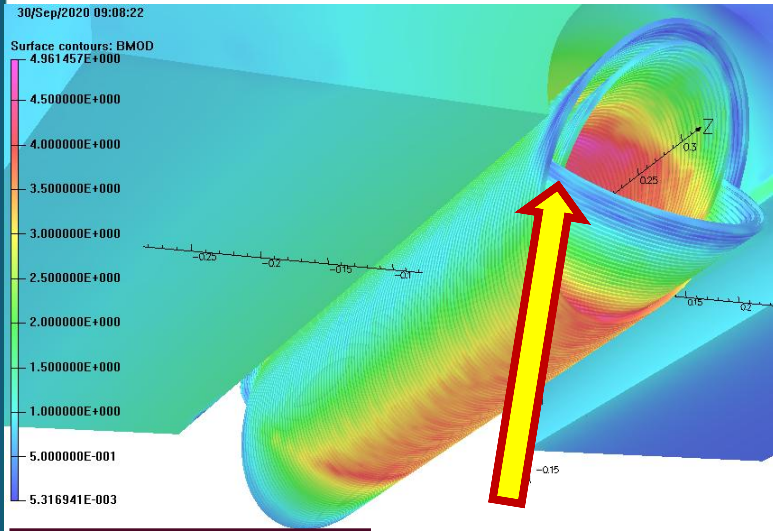
RHIC Cosine(θ) Coil Ends

Conventional End Designs:
- Conventional ends take large space (~2X coil ID in dipole)
- Field per unit length in ends is ~1/2 of that in the body.

=> A large loss in integral field in most designs for short magnets.



Serpentine



Double helix

Midplane turns end here

Optimum Integral Design:
- Midplane turns run almost full length of the coil in the ends.
- Turns near midplane contribute most to the field integral. They also determine the length of straight section. This implies almost no loss due to Ends.

Optimum Integral

Conventional Design Approach

A two-step process:

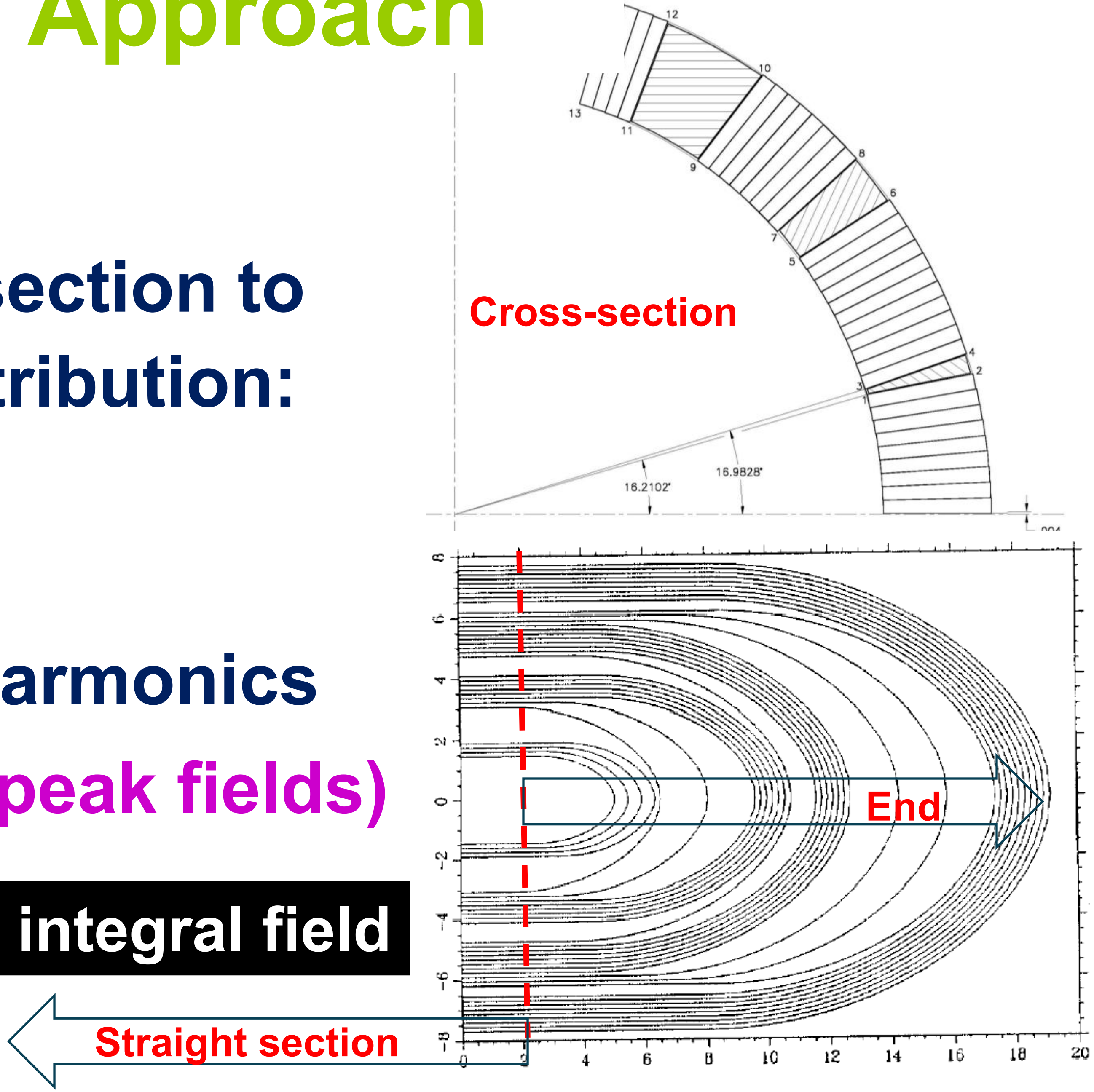
Step 1: Optimize coil cross-section to obtain cosine theta like distribution:

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

Step 2: Optimized ends for harmonics

(also, optimize both for low peak fields)

Each step reduces the maximum integral field



Optimum Integral Design Approach

Extend midplane turns to full coil length.

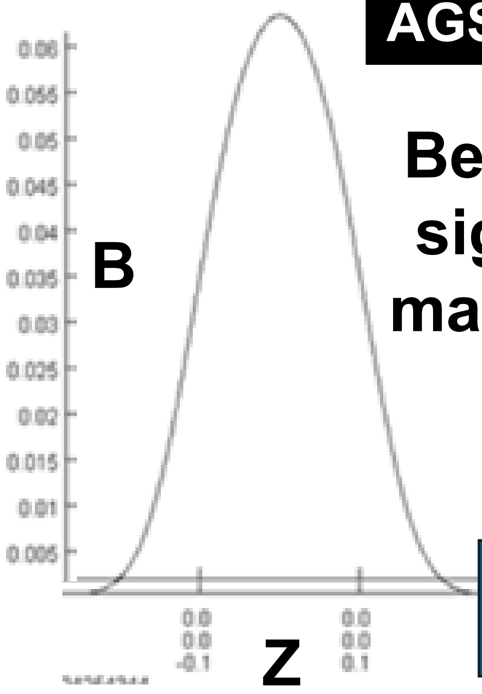
Then optimize cross-section & ends together in <u>a single step</u> to obtain an overall cosine theta distribution in an integral sense:

AGS dipole

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

Ends become part of the optimization and contribute fully to the integral field.

- ✓ **Loss due to ends essentially eliminated**



Benefits could be significant in any magnet with no to small flat-top

Somewhat similar situation in B0pF

https://wpw.bnl.gov/rgupta/optimum-integral/

Current B0PF Design and the Key Challenges

B0pF design has eight serpentine quadrupole layers (4 coil sets) running in series with two serpentine dipole layers (one coil set) to create a combined function design.

Following are the key features and the challenges with the current EM design:

- Desired integral field gradient: 9.75 T. Integral field should be zero on e-beam axis (x=-34 mm) with maximum field excursion <0.01 T along the e-beam path.
- Required integral field on the path of proton (hadron) beam (at x=+126 mm with a 25 mRad angle) to e-beam is ~1.56 T.m.
- Quench protection is a challenge. Both hot spot temperature and the required voltage across the coil is high during the energy dump.
- There are too many layers to fit in the present Dewar to test the entire coil.
- The design doesn't have sufficient margin for testing at the design field at 4.2 K.

Basic Design Features & Key Goals of the Optimum Integral Design

- The goal of this exercise is to examine the extend of these benefits and to see how far they can be used to reduce the challenges mentioned in the previous slide.
- Two sets of design (or options) are examined:
  a) reduced number of quad layers (four or six, instead of eight), running in series with a reduced number of dipole layers (one instead of two). Optimum integral design allows a single layer coil, as was the case for AGS corrector dipole.
  b) a combined function design with a total of six layers (instead of ten).

Reduction in the No. of layers from 10 to 7 or 6 or 5 allows coils with structure to fit in the SMD dewar for testing. It should also reduce the magnet cost and the schedule.

Note: The designs to be presented are initial investigations to see that the performance targets will be met. An optimized design can be completed well before the scheduled winding.

OPTION A – QUAD LAYERS IN SERIES WITH THE DIPOLE LAYER

Six Quad Layers (3 coil sets)

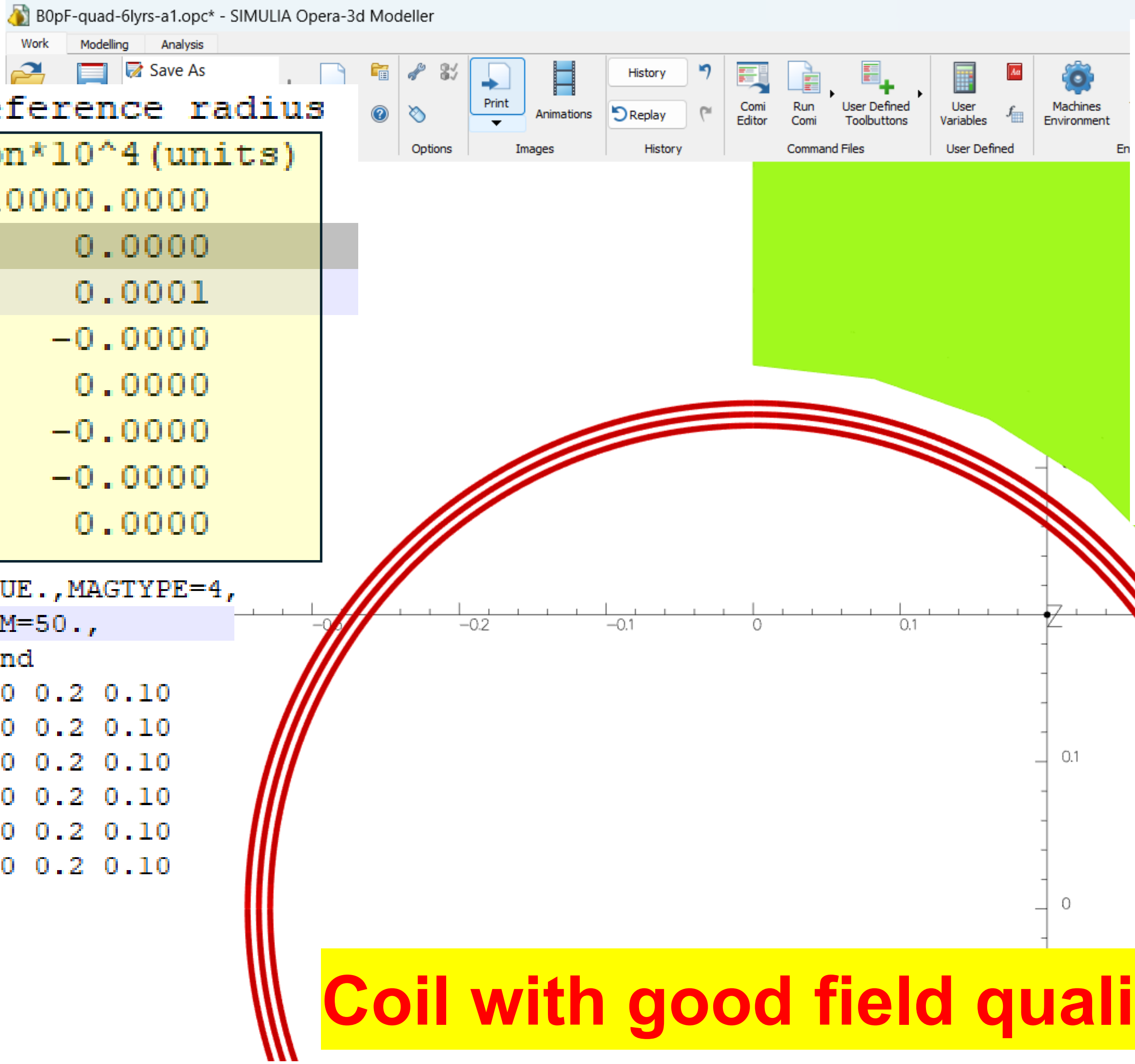
- **The current serpentine design has eight quad layers (4 coil sets)**

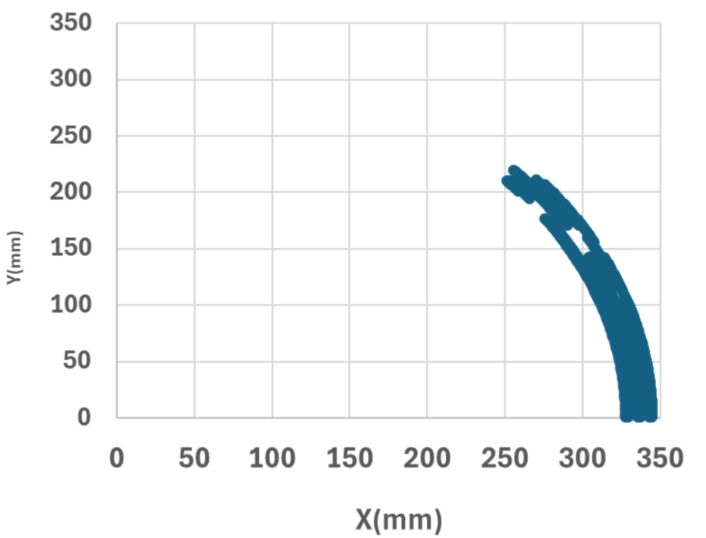
6-layer coil optimized with the optimum integral code

Harmonics at 50 mm reference radius

No.	Bn(T.m)	bn*10^4(units)
2	0.53402E+00	10000.0000
6	0.96962E-11	0.0000
10	0.35185E-08	0.0001
14	-0.16464E-11	-0.0000
18	0.55250E-15	0.0000
22	-0.11688E-19	-0.0000
26	-0.12945E-21	-0.0000
30	0.71922E-25	0.0000

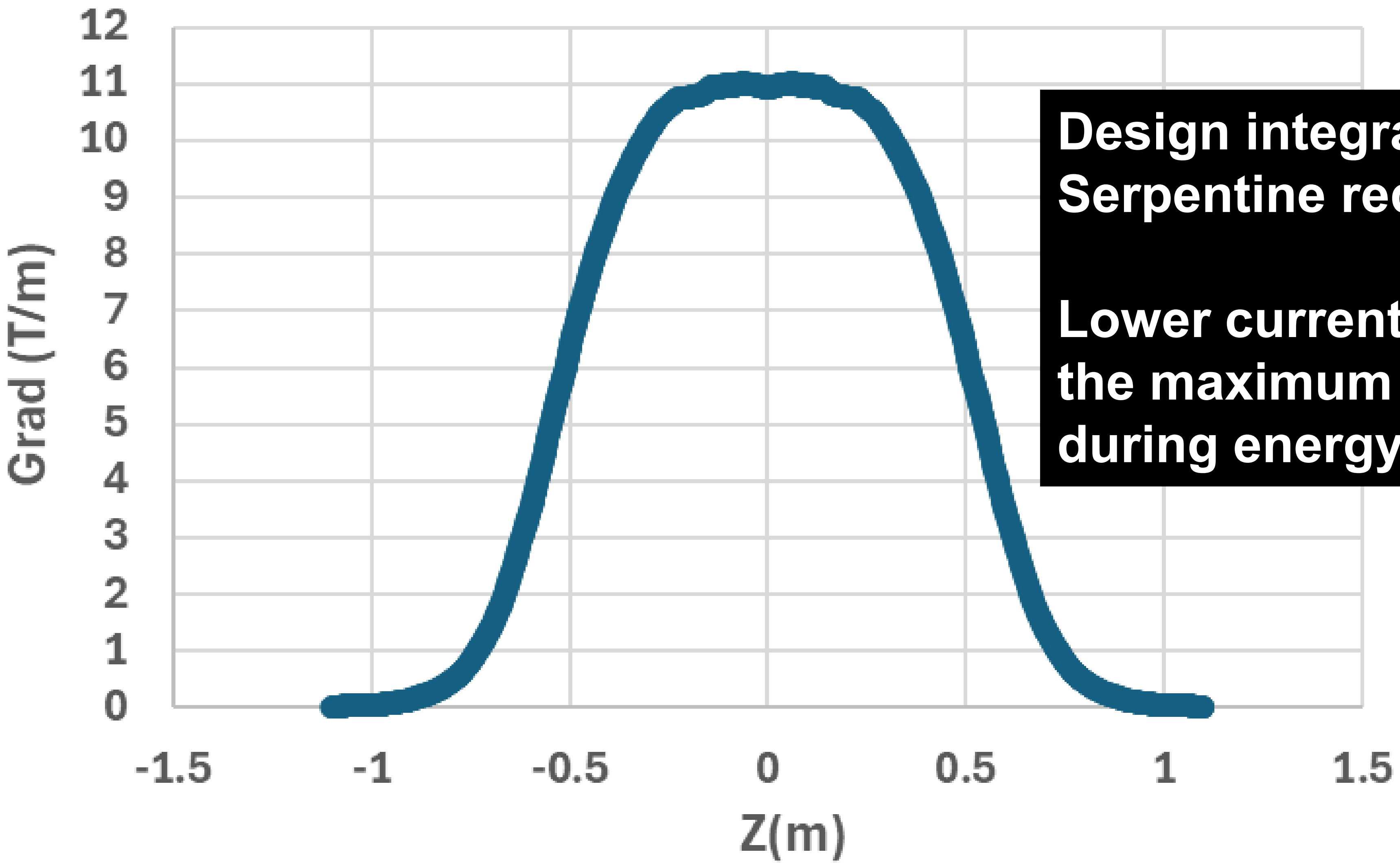
```
$FCNX VC2CB=.TRUE.,VC2CE=.TRUE.,MAGTYPE=4,
      LAYERS=6,RFEMM=400,ROMM=50.,
      RBENDMM=15,NBEND=10 &end
 3 3 1.25  1.778  327.76 1000 0.2 0.10
 3 3 1.25  1.778  329.49 1000 0.2 0.10
 3 3 1.25  1.778  335.43 1000 0.2 0.10
 3 3 1.25  1.778  337.16 1000 0.2 0.10
 3 3 1.25  1.778  343.10 1000 0.2 0.10
 3 3 1.25  1.778  344.83 1000 0.2 0.10
B5  0.  10.
B9  0.  3.
b13 0.  1.
b17 0.  1.
```





Coil with good field quality

Field Gradient along z-axis at 850 A in 6-layer Design

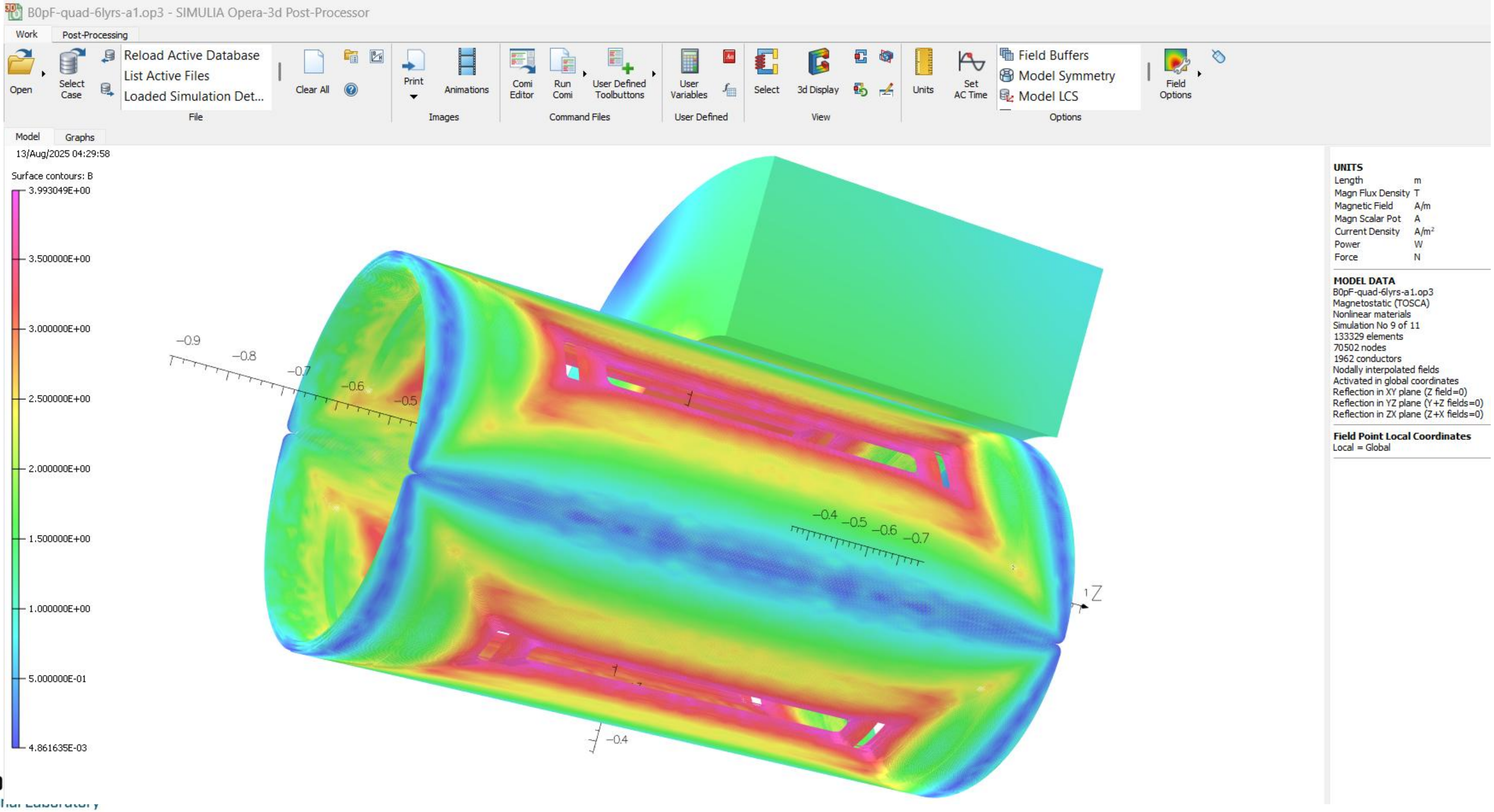


Design integral gradient 9.75T @827 A.
Serpentine required 8-layers @1143 A.

Lower current will significantly reduce the maximum voltage on the coil during energy extraction after quench.

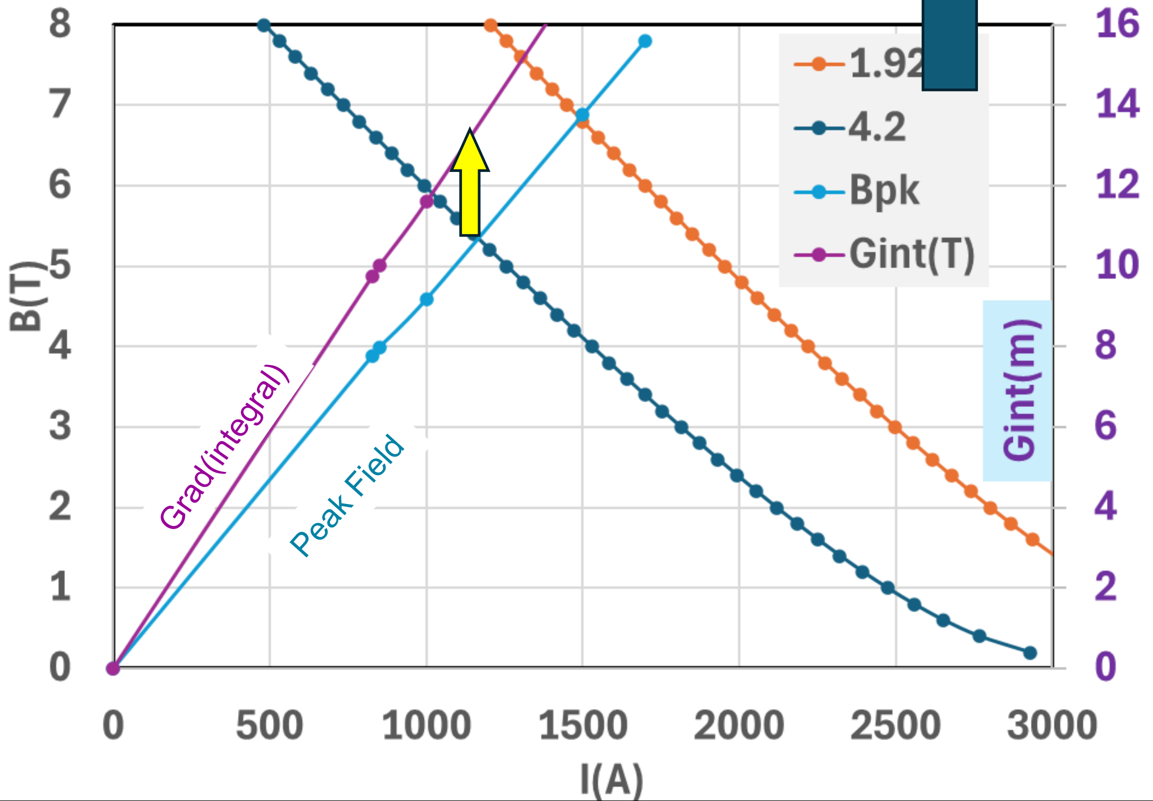
Note: Dipole field has not been added yet.

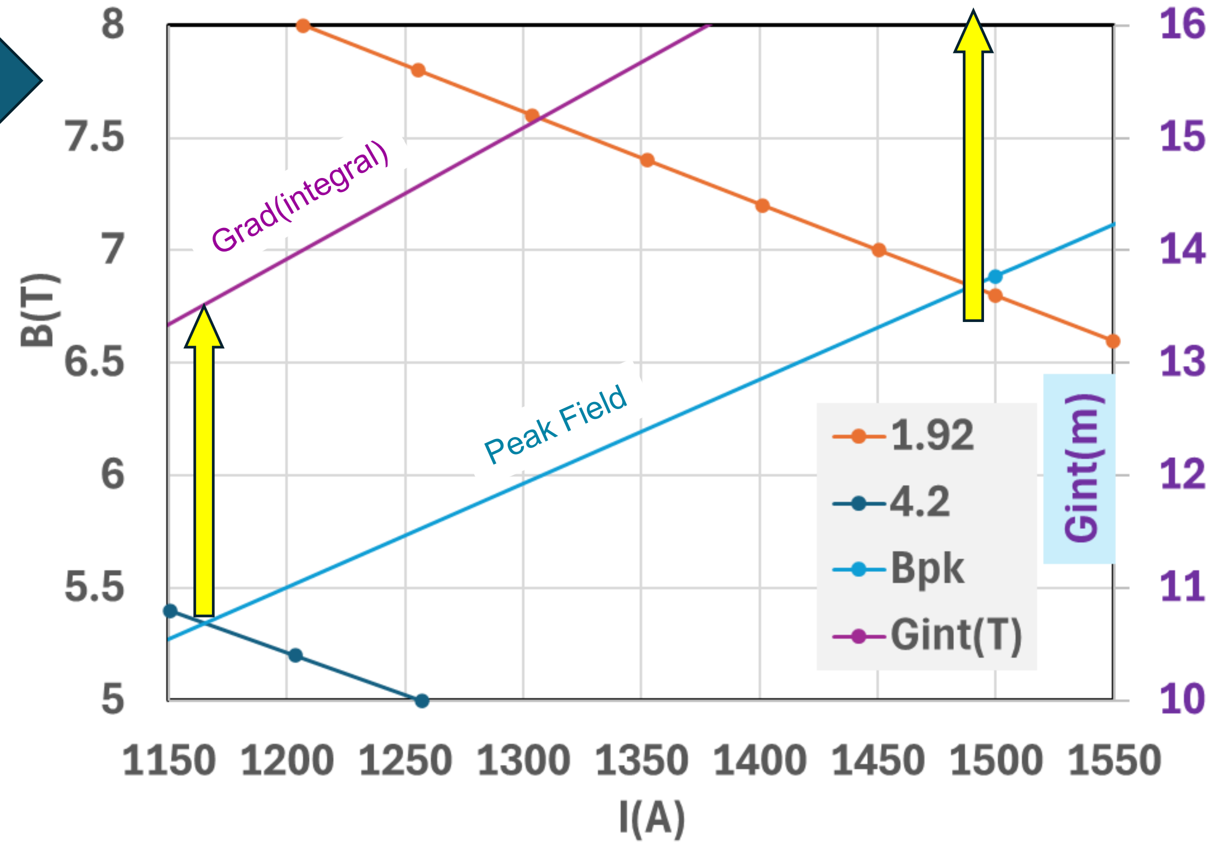
Field superimposed on coil and iron at 850 Amps



6-layer Optimum Integral Design for B0PF

(6-around-1 sc cable - 1.92 K for operation, 4.2 K for testing)





Large margins both at 1.92 K & 4.2 K

	Iss(A)	Margin(%)
All SC @1.92K	1490	80%
All SC @4.2K	1160	40%

Six superconductor around one copper in 6-around-1 cable (instead of all super)

- **Margin in the previous design is too excessive (80%). This will get dropped a bit when dipole is superimposed. We can tolerate further drop if that helps in quench protection.**
- **Making the center wire copper would help. It effectively increases the copper to super ratio (1.7 to 2.2). This should reduce the hot spot temperature and may prevent a quench.**
- **The penalty will be in reduction in the critical current of the cable which becomes 6/7 of that in all super wire case.**

➢ **Will the reduced margin be still sufficient?**

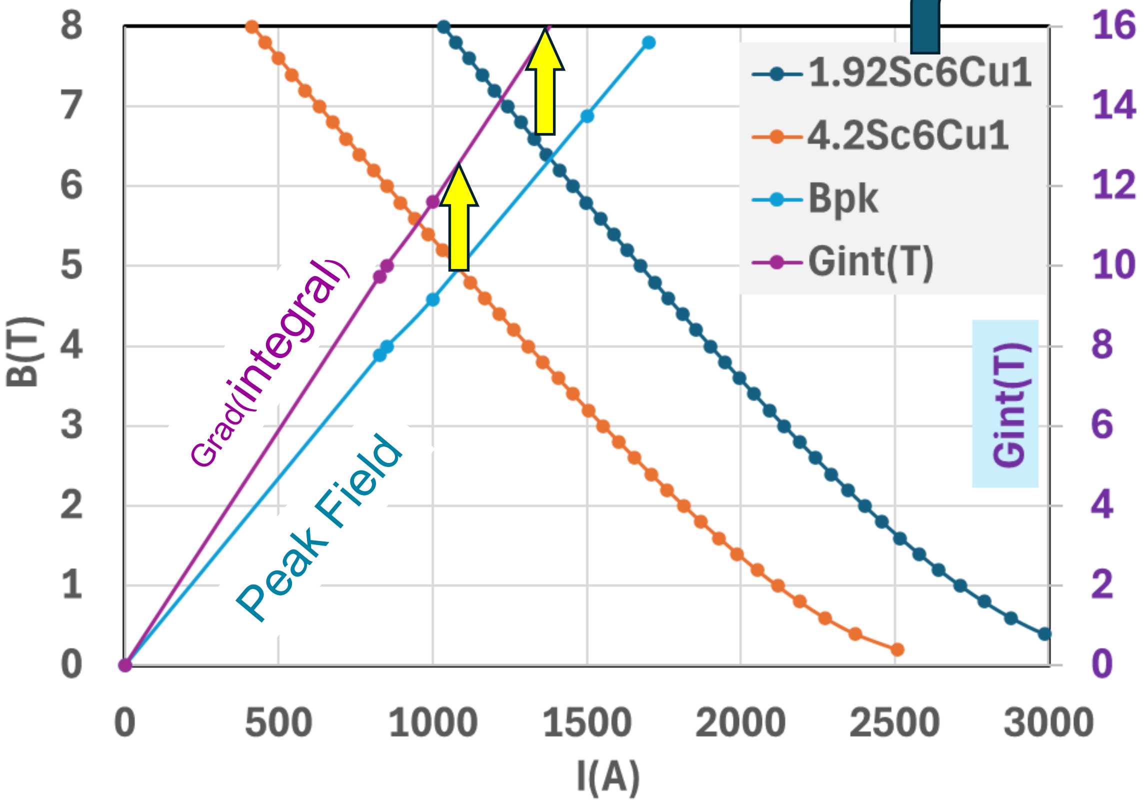
✓ **Yes, it is (see next slide).**

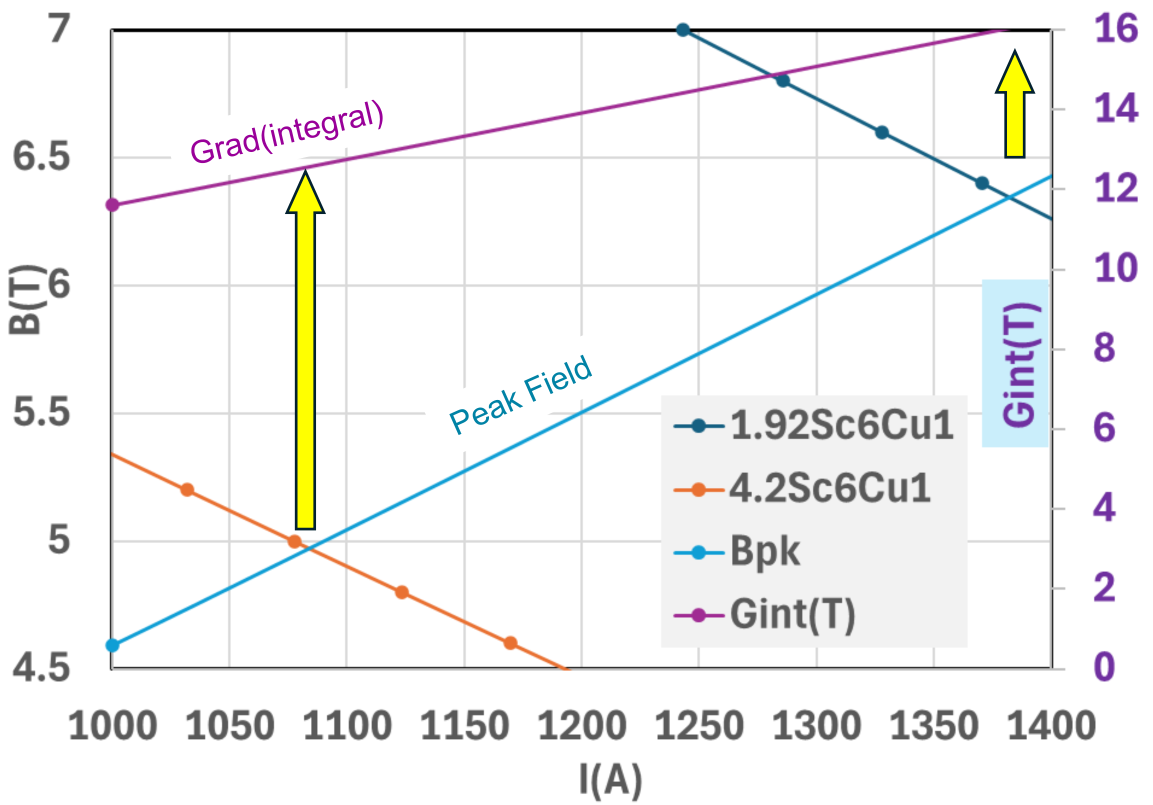
Effective Copper to Superconductor ratio in 6-around-1 copper

Cu/Sc from Brucker		
Original	Cu/Sc	1.75
Cu wires	1	
SC Wires	6	
Wire dia	0.473	mm
Wire area	0.176	mm^2
Super in wire	0.064	mm^2
Cu in Wire	0.112	mm^2
Cable Area	1.230	mm^2
Cu in Cable	0.847	mm^2
Super in cable	0.383	mm^2
Effective	**Cu/Sc**	**2.21**
Iquench	**1080**	Amp
Jcu@Qnch	**1276**	A/mm^2
Idesign	**827**	Amp
Jcu@design	**977**	A/mm^2

6-layer Optimum Integral Quad Coils with 1 Cu Wire

(6 super around 1 copper wire - 1.92 K and 4.2 K for testing)





Still healthy margins in 6sc-around-1cu case for both at 1.92 K and 4.2 K testing.

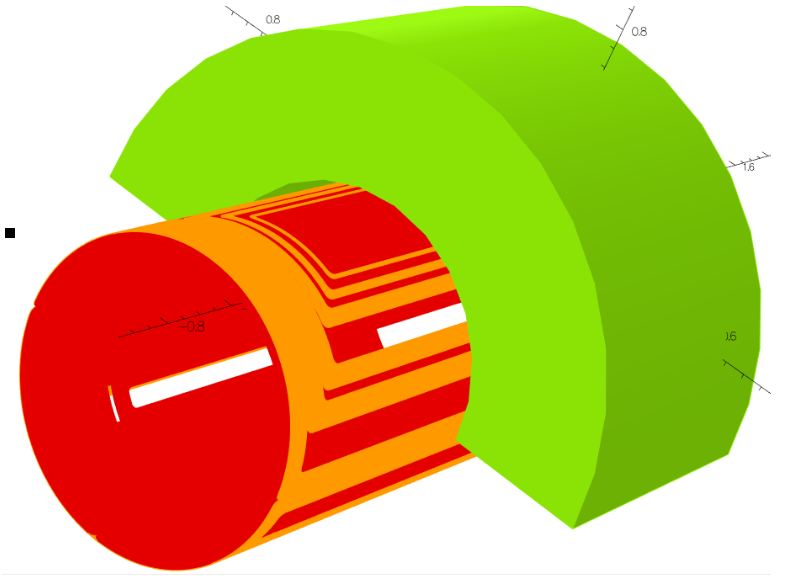
	Iss(A)	Margin(%)
SC6Cu1 @1.92K	1380	67%
SC6Cu1 @4.2K	1090	32%

Next Step : Add Dipole Coils

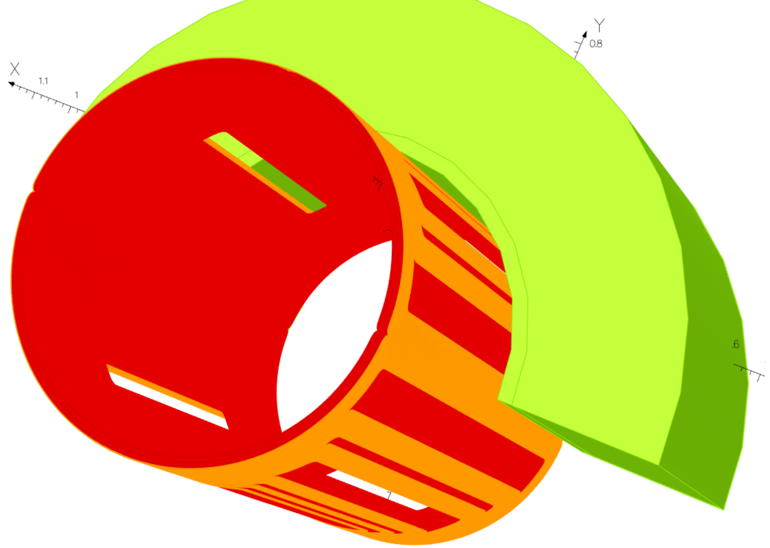
- Dipole coils are needed to make the integral field on the off-centered electron beam **zero** (x=-34 mm, instead of at x=0).
- An additional goal is to keep up-down variation in the vertical field (By) along the e-beam path to +/- <0.01 T.
- The integral field on the path of the hadron beam (x=126 mm with 25 mR angle to e-beam) must be ~1.56 T.m.
- Margins must be recomputed in the presence of the additional dipole coil(s) since it is expected to get reduced.

Dipole Coil(s) Added to the Quad in B0PF

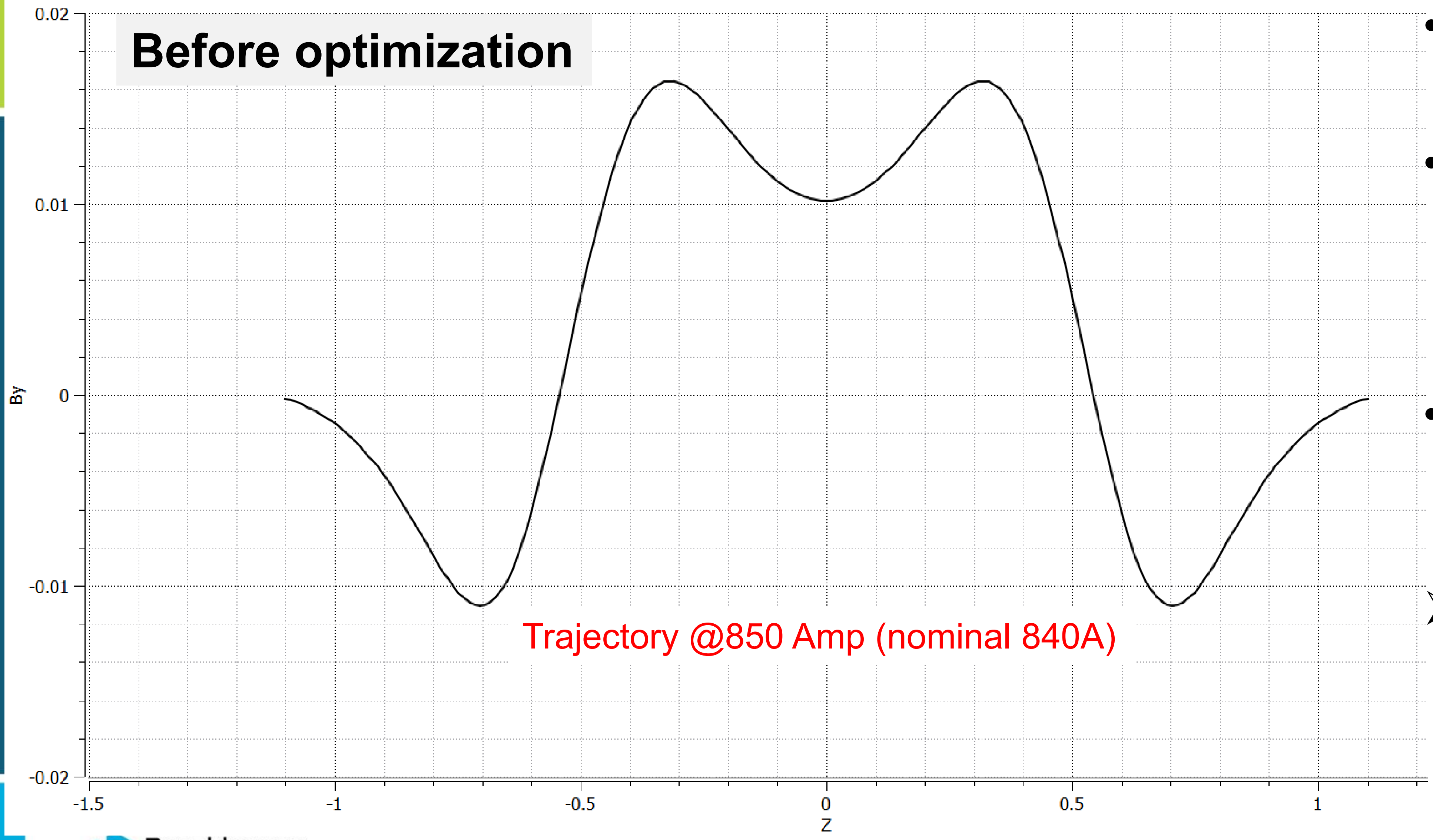
- Dipole coil(s) runs in series with the quad and is made with the same cable as the quad coils.
- A single layer is enough (optimum integral design can have a single layer, as was in the optimum integral corrector in the AGS tunnel)
- Even a single layer design creates too much field, and therefore more than ½ of the turns are removed to avoid over-correction.
- Turns are clubbed together in a few blocks (rather than increasing the spacing and then filling the gap) to save the construction time.



Dipole coil highlighted

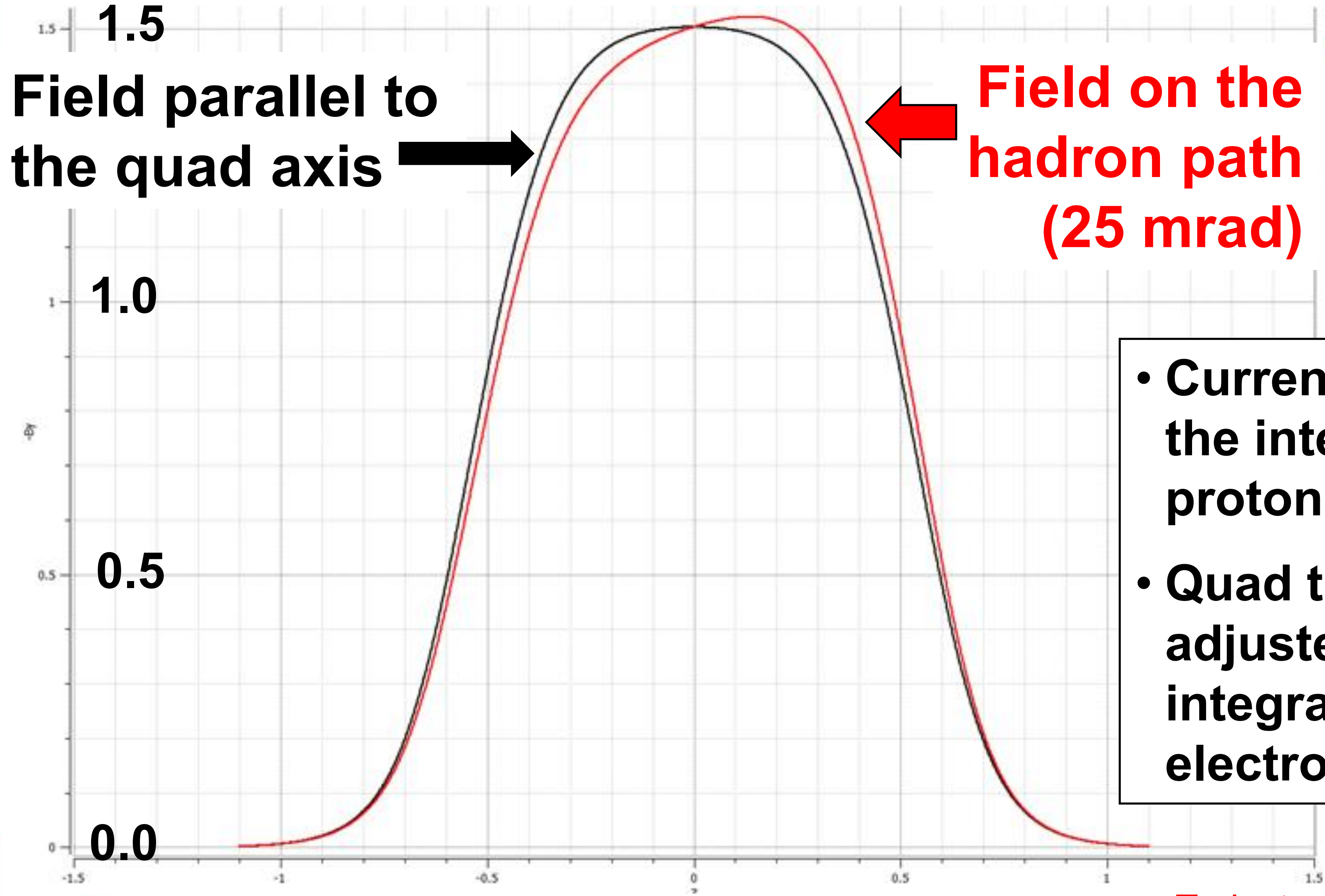


Field along the electron path (X=-34 mm)



- Integral field is almost zero.
- Oscillations in By, are already close to +/- 0.01 T, even without tuning.
- The design will be fine tuned in the next iteration.
  - ➢ Good enough for the proof-of-principle investigation

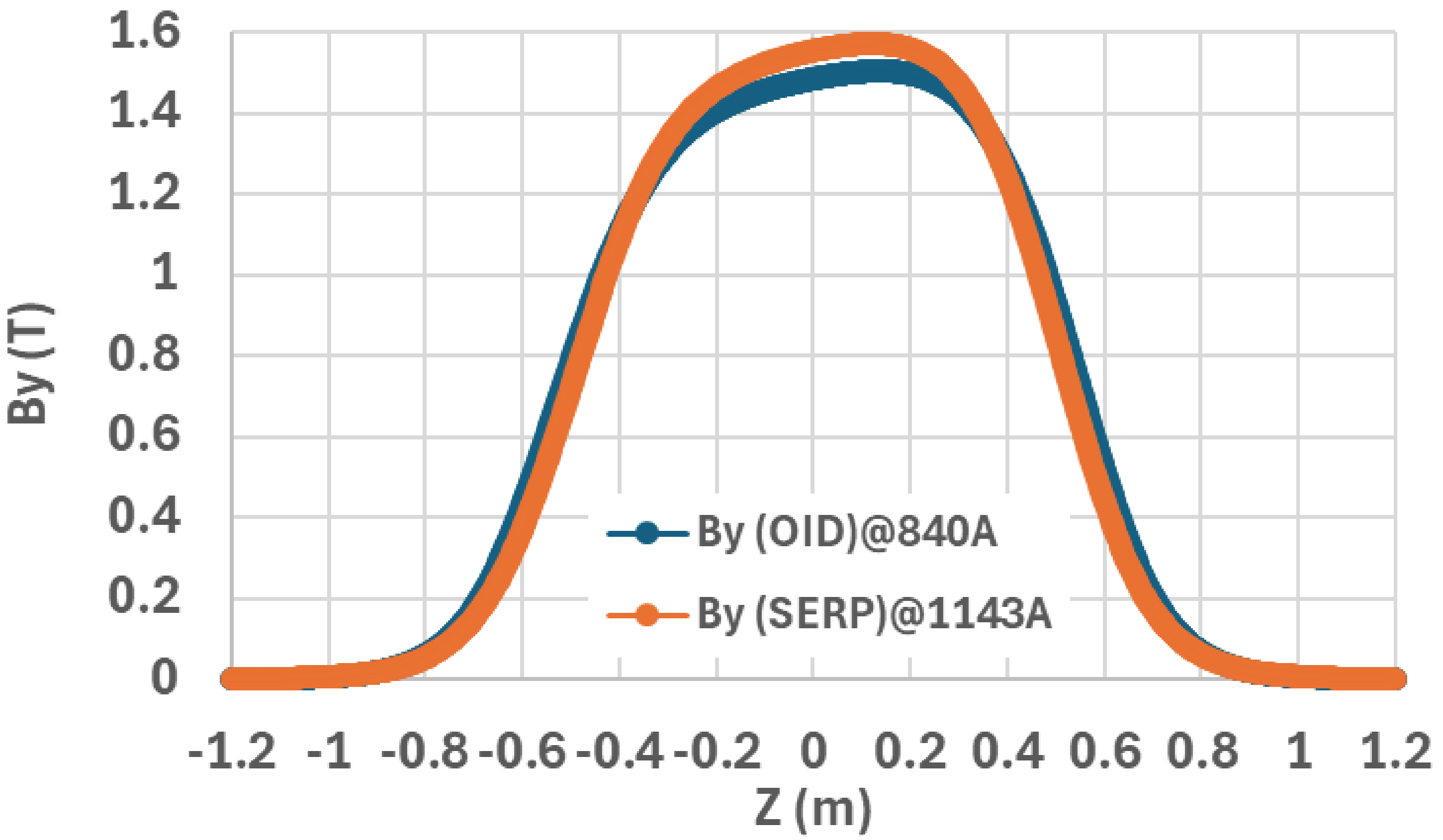
Field along the hadron path (X=126 mm)

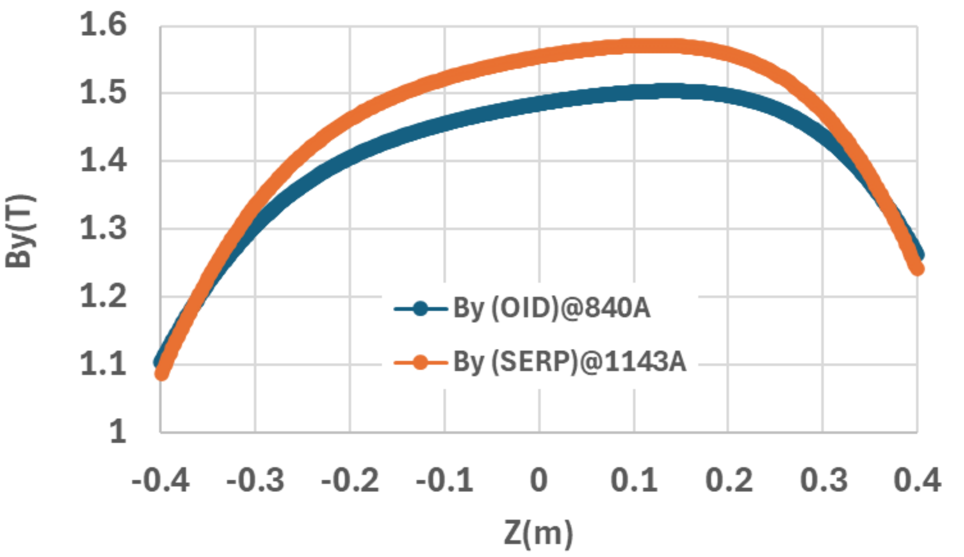


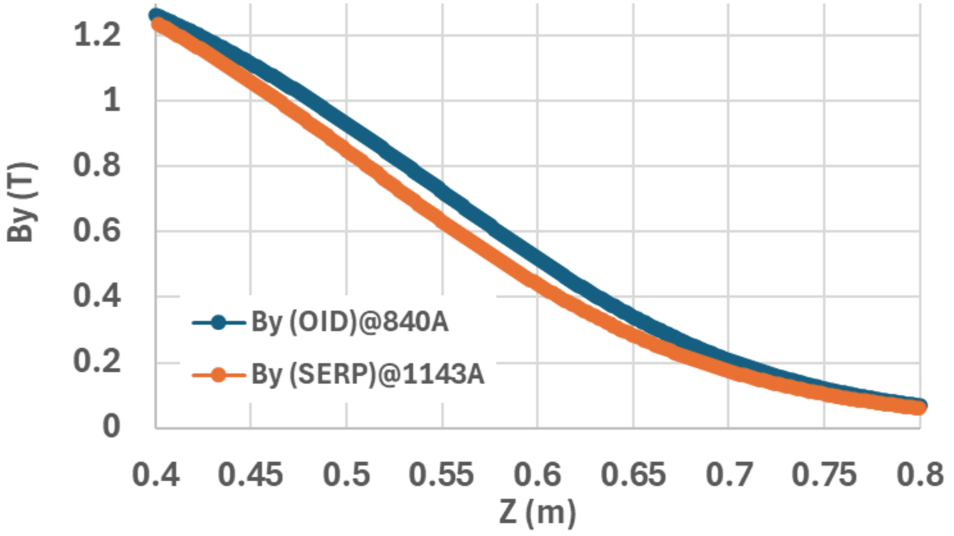
- Current in quad to make the integral 1.56 T.m for the proton beam is ~880 A.
- Quad to dipole ratio is adjusted to make field integral zero on the electron beam path

Trajectory @850 Amp (design current 840 A)

OID and Serpentine Designs for the Same Field Integral







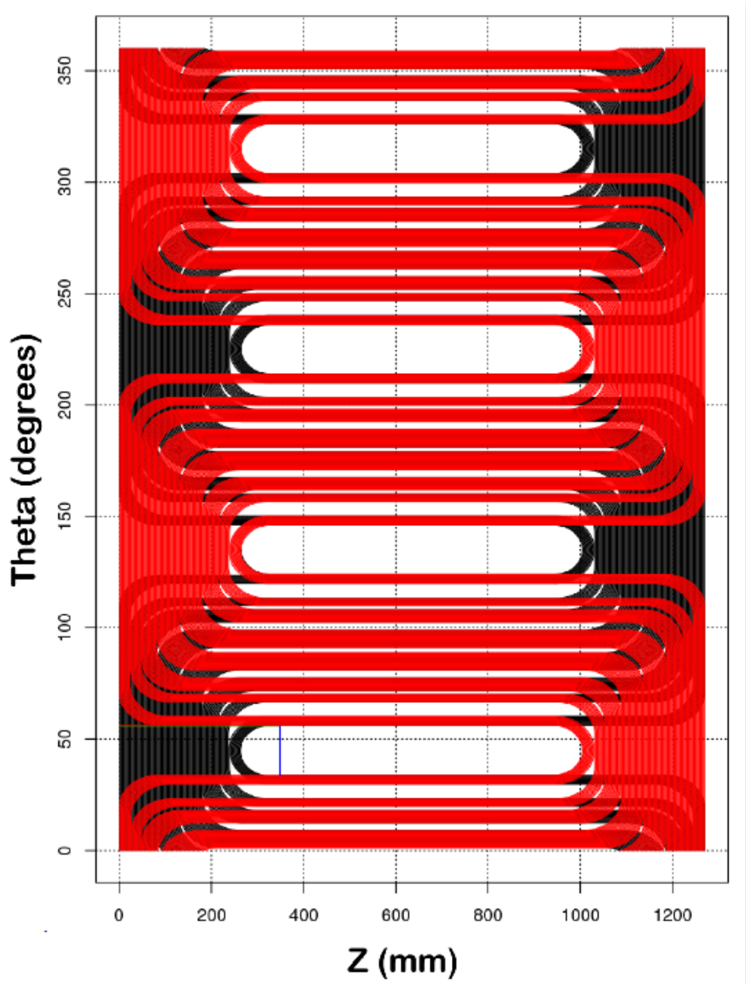
Lower number of layers and lower current.:

- **OID (6+1=7) layers @840 A;**
- **Serpentine design had (8+2=10) layers @1143A**

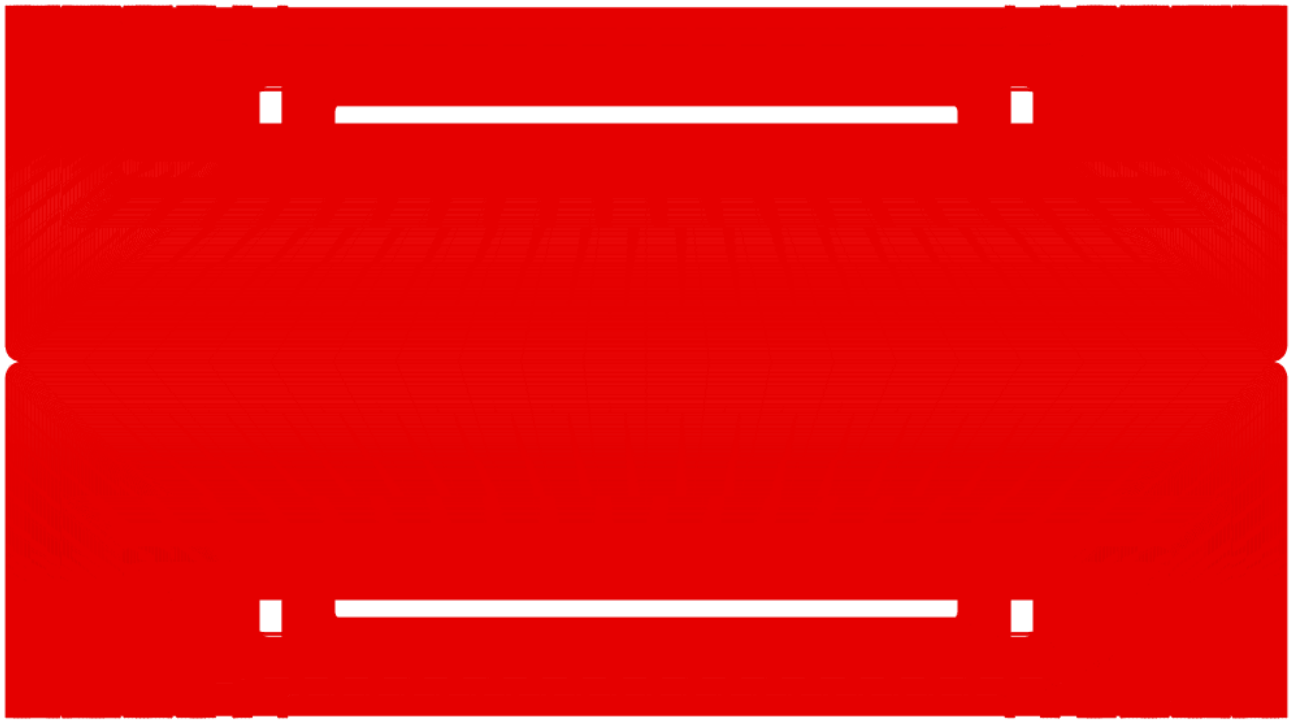
Integral field: 1.56 T.m

Why OID is so much more efficient over Serpentine in this case?

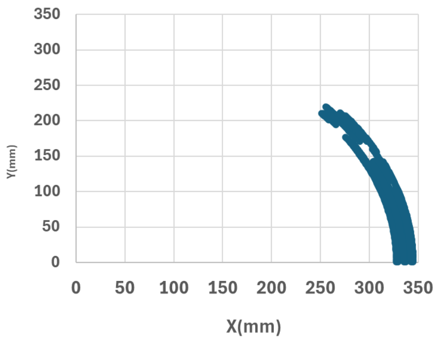
Serpentine Coil set A

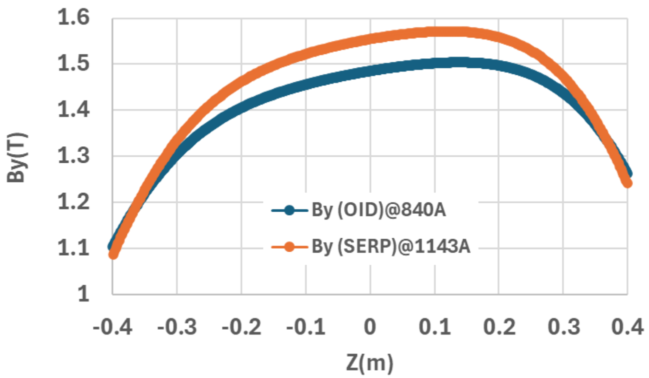


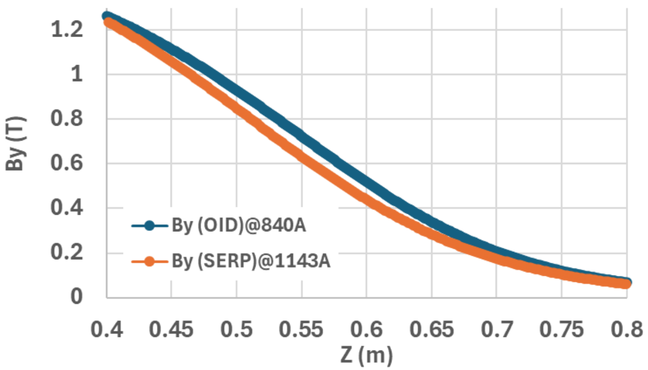
Optimum Integral Design Coil (6+1=7 layers)



Less layers, less current.
OID: 7 layers @840 A Vs.
Serpentine: ten @1143A

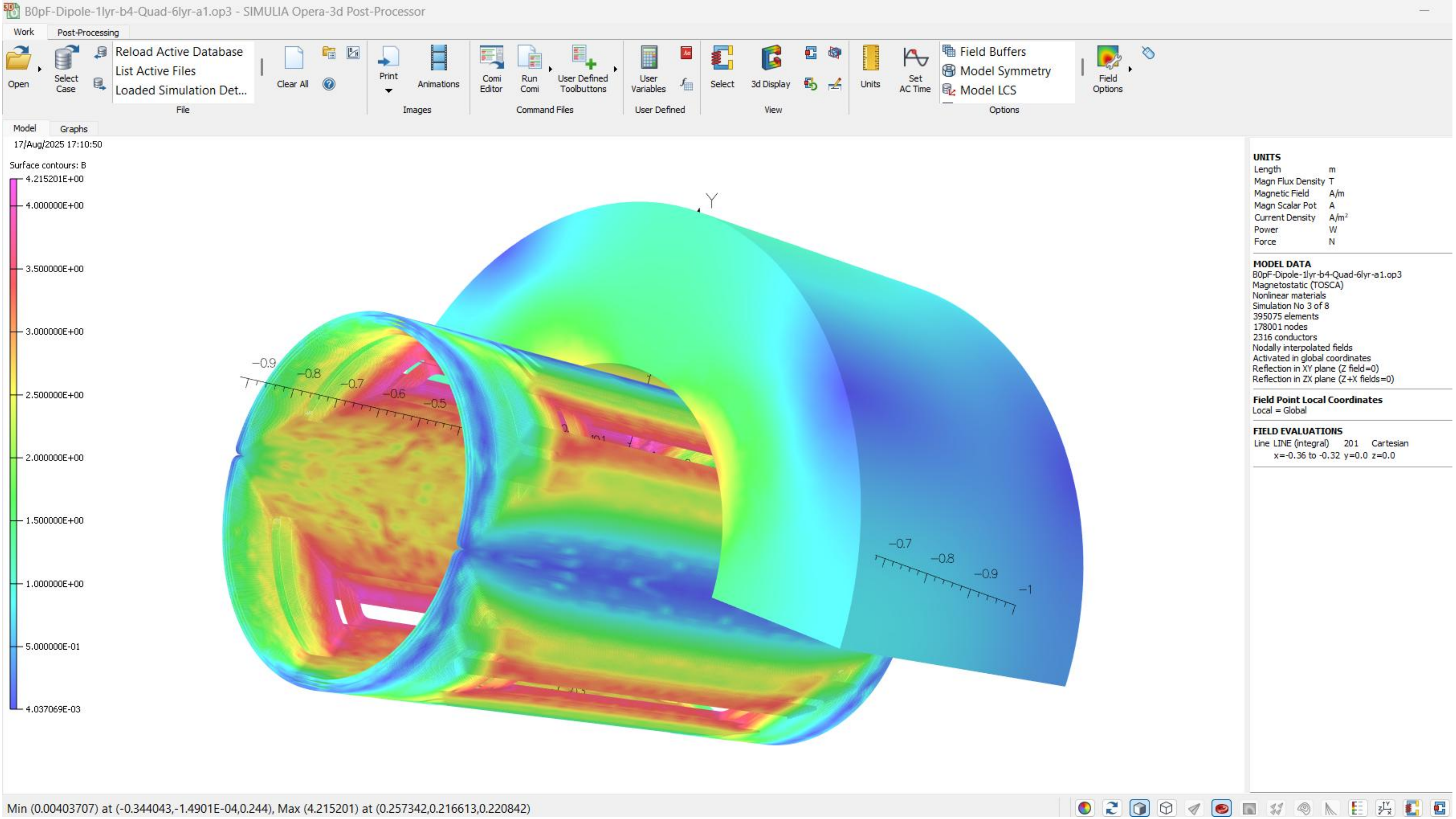






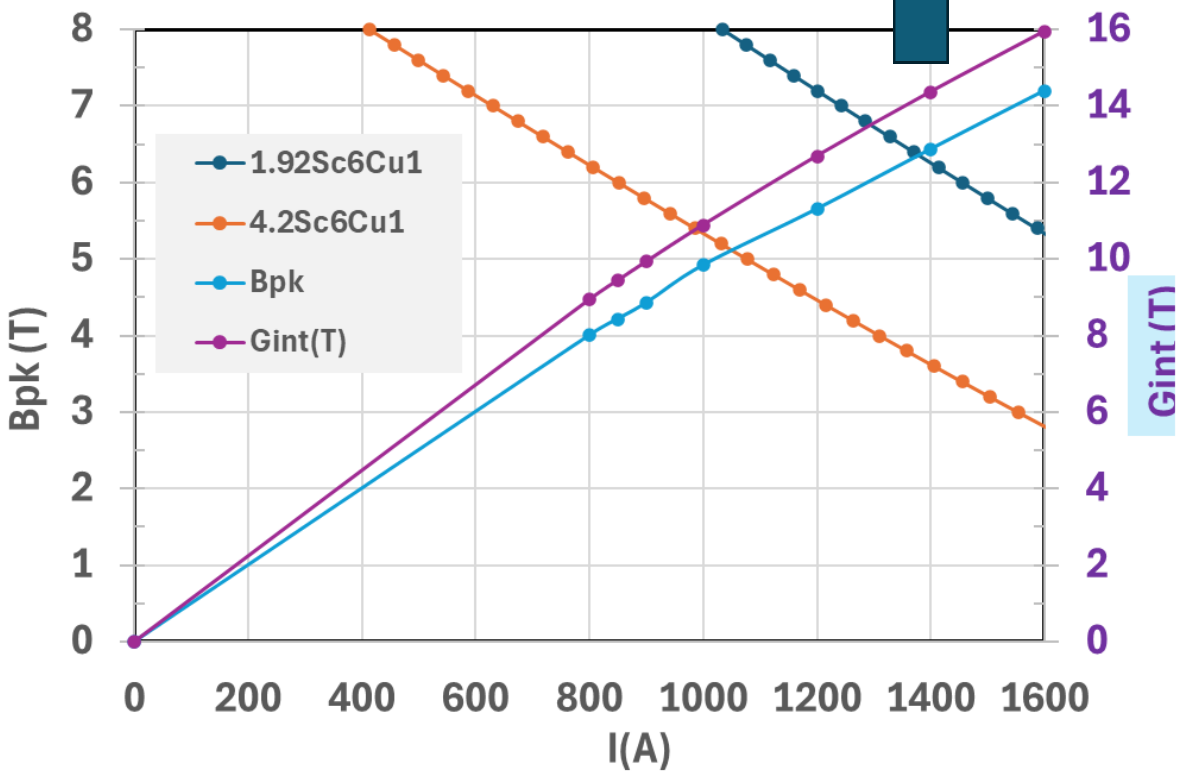
- Higher packing factor in the body.
- Both ends fully contributes to the field and harmonic optimization.
- In such short magnets, productive ends contribute to body field also

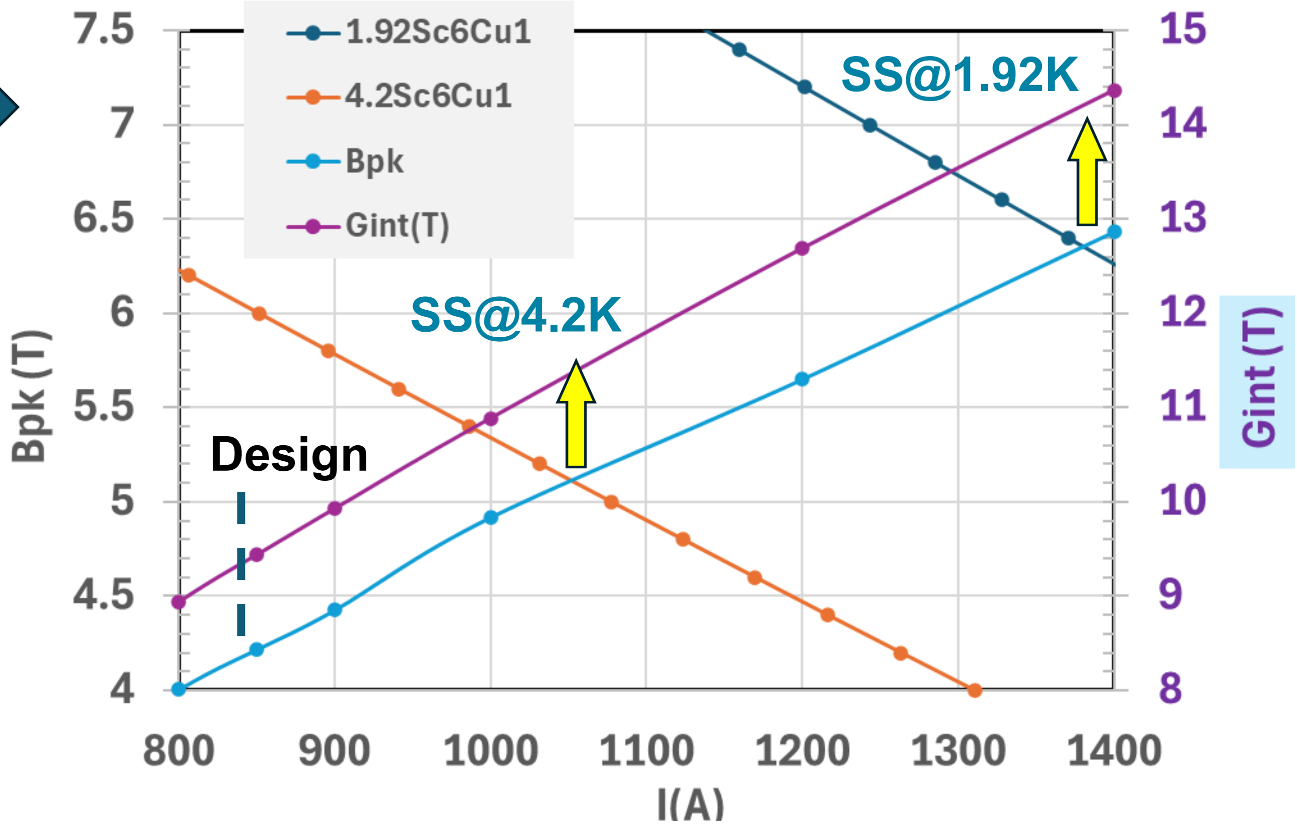
Model with field Superimposed at 850 A
(nominal current for desired integral is 840 A)



Optimum Integral Design B0pF Computed Performance
(6-layer quad in series with 1-layer dipole in 6sc around 1 cu)

- **Operating temperature in EIC: 1.92 K**
- **Initial testing temperature: ~4.2 K**





Design Integral Gradient: 9.75 T
Integral Field for Hadron: 1.56 T.m
Achieved @880 A instead of 1143 A

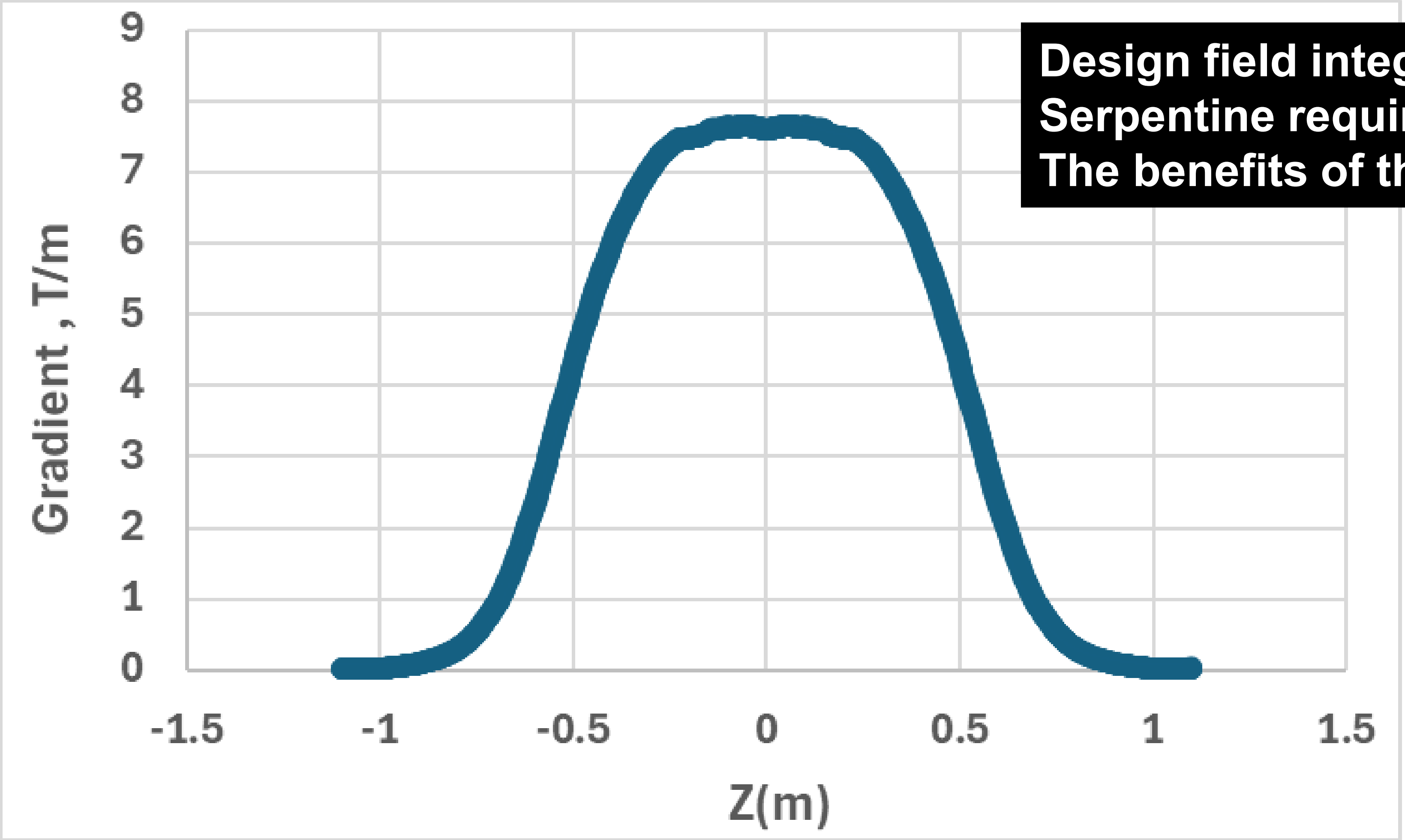
- **Nominal design current: ~840 Amp**

I_{ss} @4.2K: ~1050 Amp (~25% margin)
I_{ss} @1.92K: ~1390 Amp (~65% margin)
*****BOTH ARE HEALTY MARGINS*****

Four Layer (2 coil sets) Design

- **The current serpentine design has eight quad layers (4 coil sets)**

Field Gradient along z-axis in 4-layer Design



Design field integral @1220 A in 4-layer OID Serpentine required 8-layers @1143 A.
The benefits of the optimum integral design.

A 4-layer (2 coil set) design might work but will be too tight (not desirable) and will have issues with quench protection.

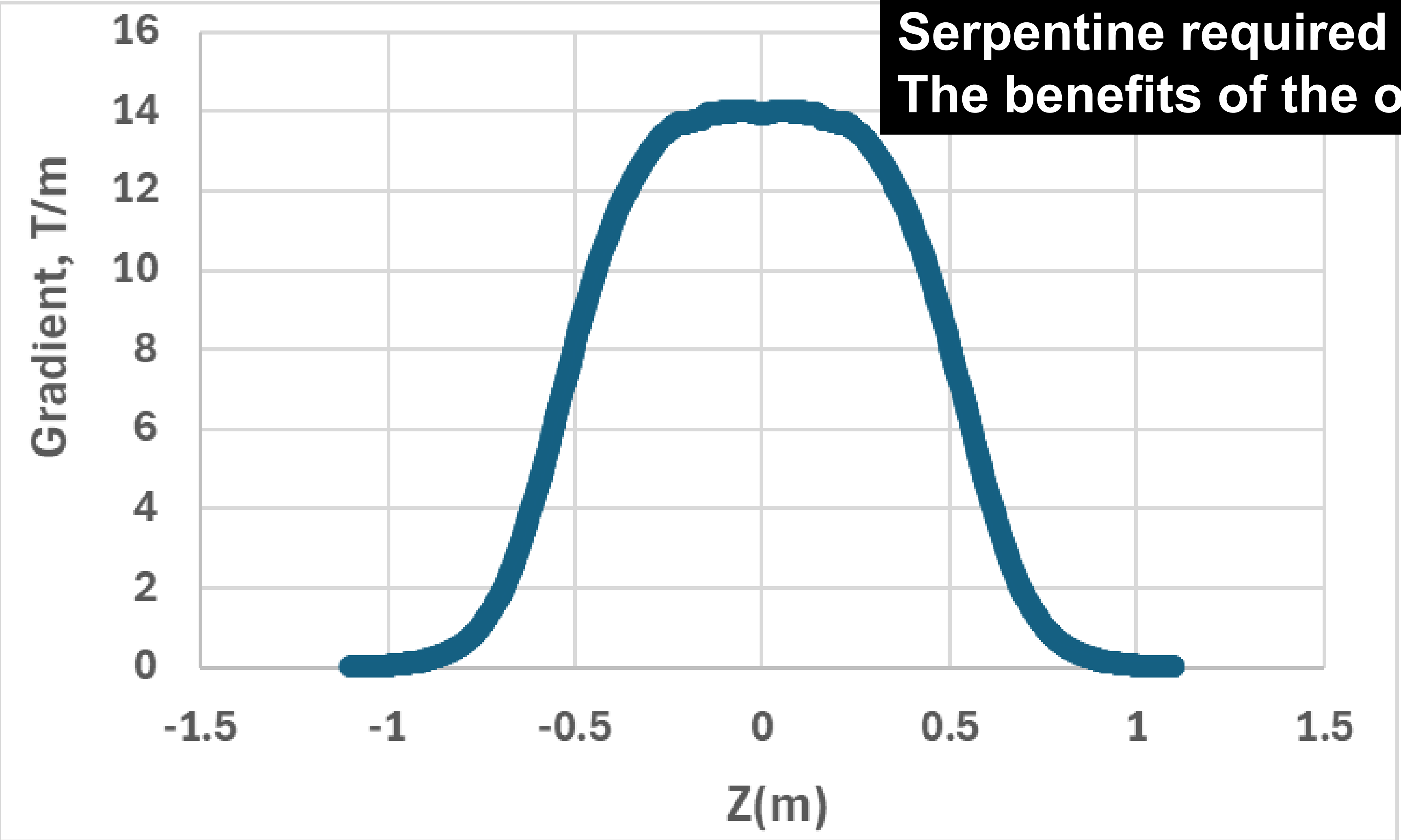
Eight Layer (4 coil sets) Design

➢ **The current serpentine design has eight quad layers (4 coil sets)**

This study is only for the sake of completeness as the expected performance will be an overkill.

Field Gradient along z-axis in 8-layer Design

Design field integral @660 A in 6-layer OID
Serpentine required 8-layers @1143 A.
The benefits of the optimum integral design.



Eight layer (4 coil set, same as in serpentine design) reduces current by a very large amount with a very large margin. This will be excessive.

As such, 6-layer quad and 1-layer dipole optimum integral design should be acceptable.

However, let's explore an enticing alternative.

- **Examine the combined function option (specially since the dipole component is relatively small).**

Required an update in the special software developed for the optimum integral design.

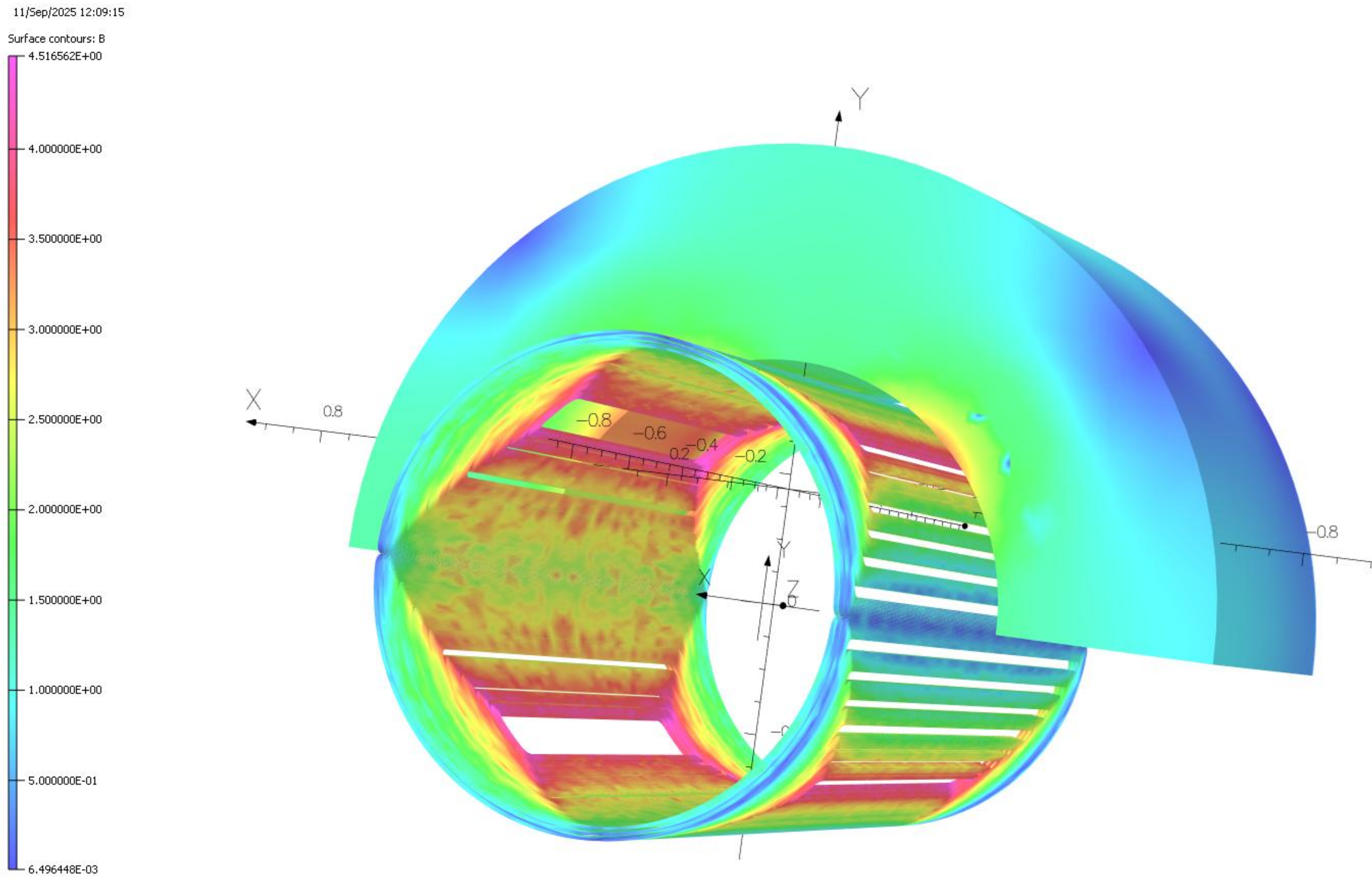
Model of the 1st Combined Function (CF) Optimum Integral Design (OID) for B0pF

Combined function OID may have either 8 layers or 6 layers layers (can be 7 also).

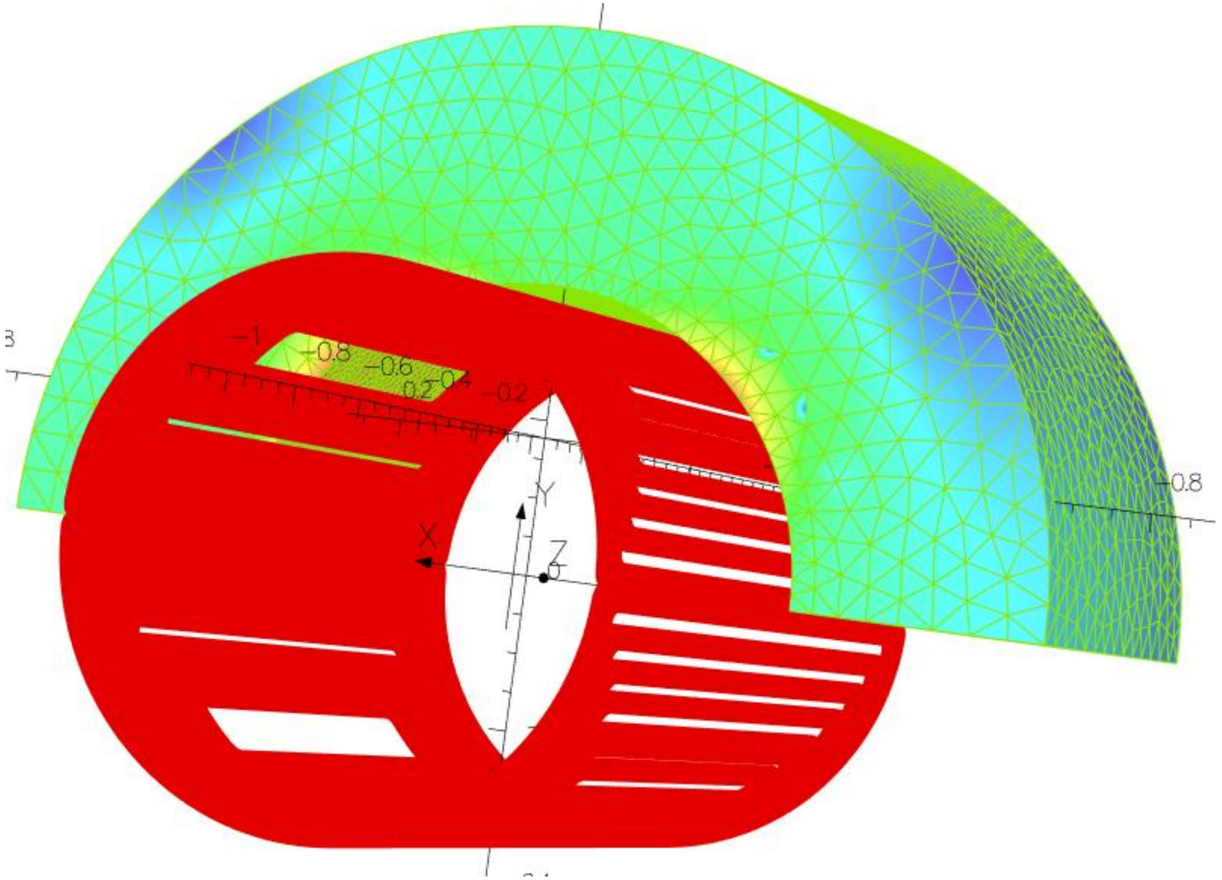
All layers are similar.

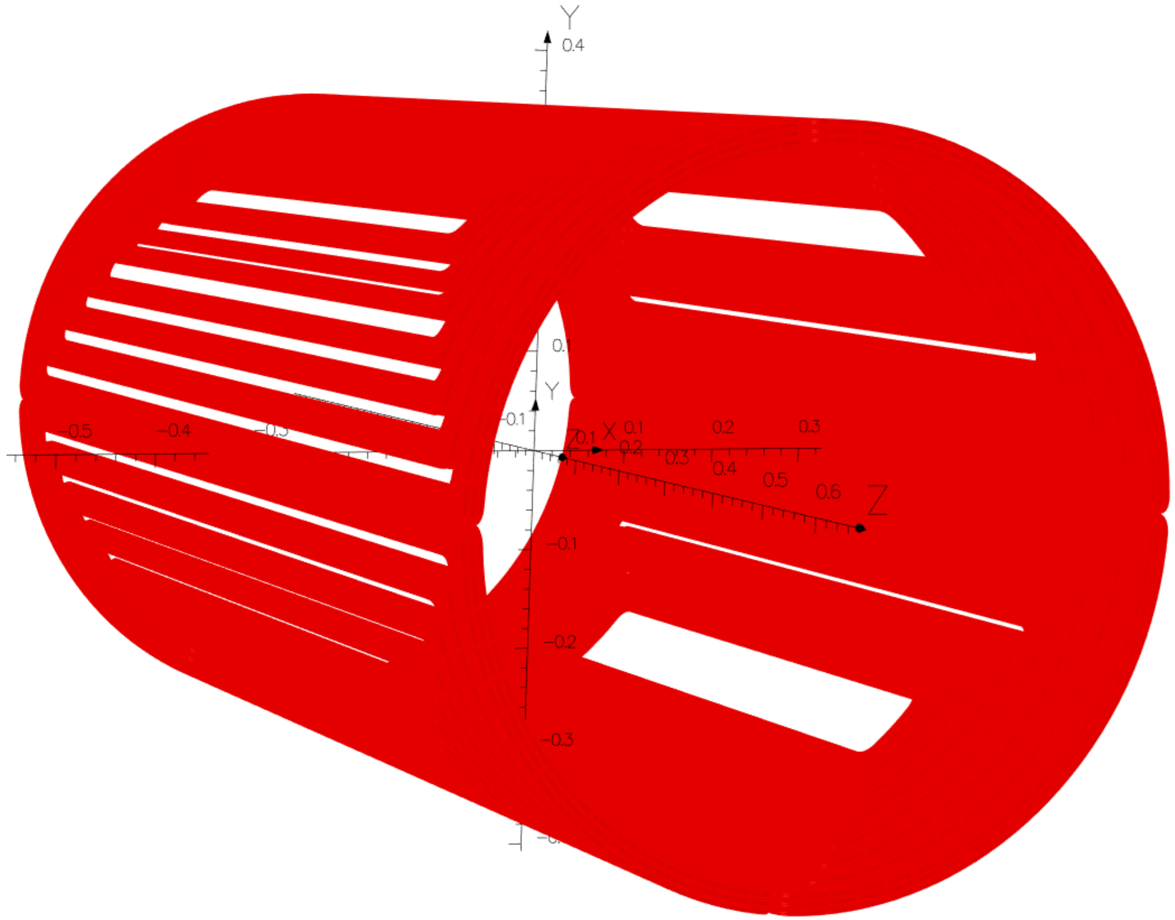
Each layer is optimized separately.

First investigation is limited to 6 layers only

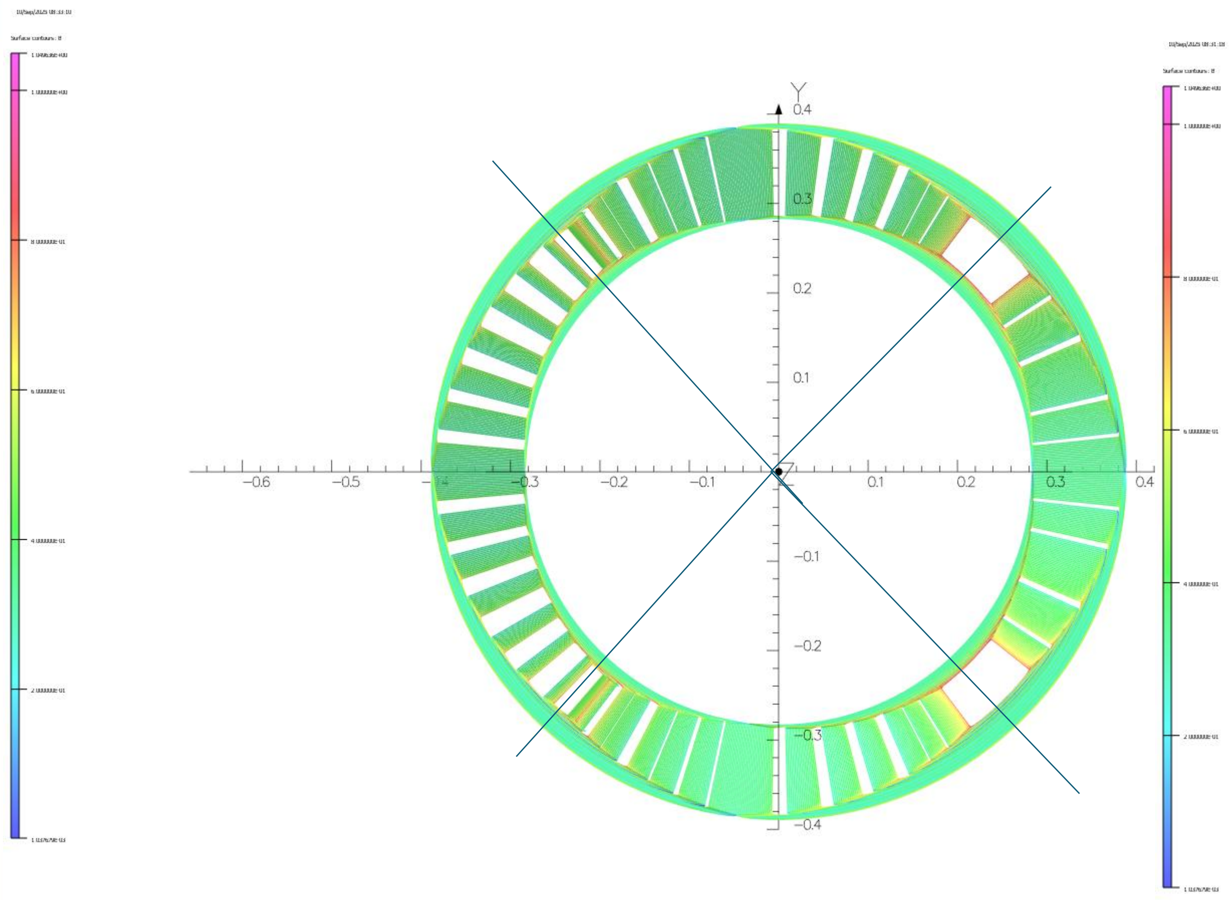


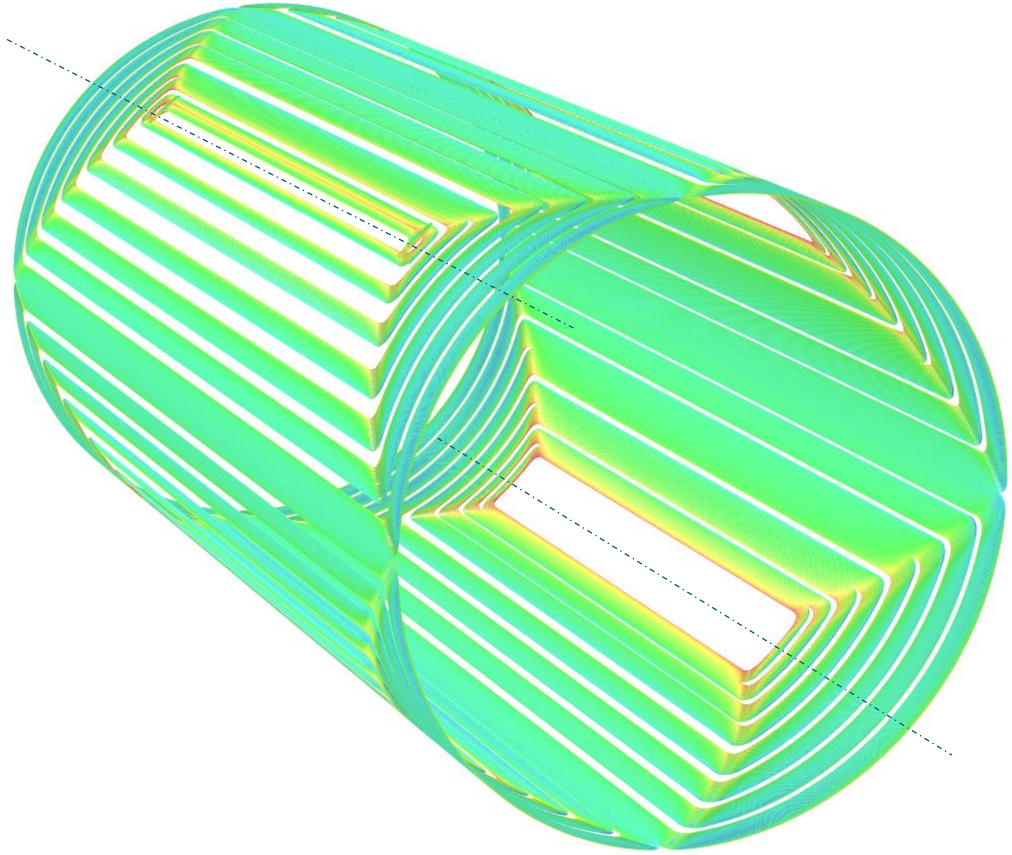
More views of the combined function designs



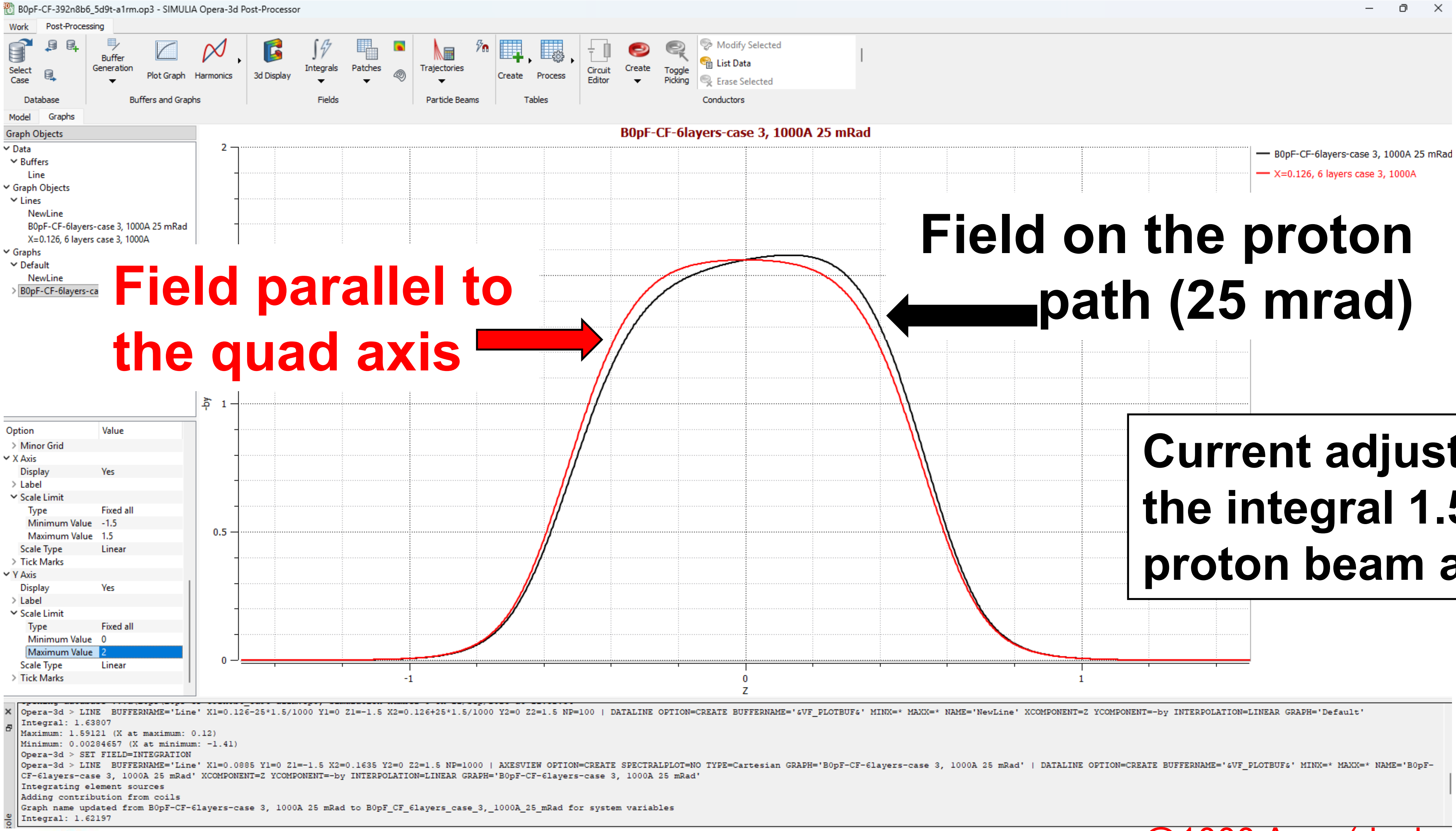


Poles shifted away from 45/90 degrees to optimize a combined function design efficiently





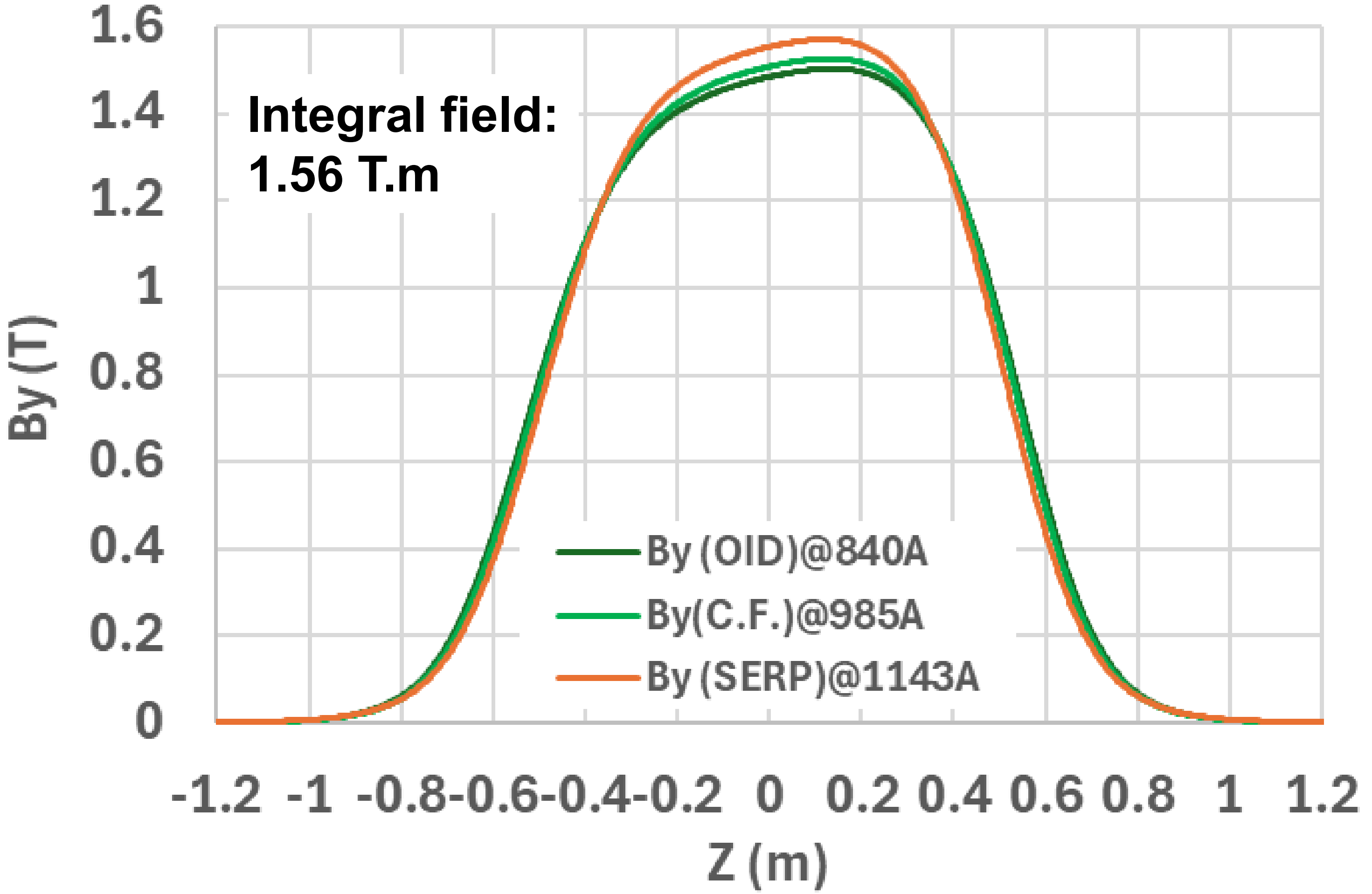
Field along the proton path (X=126 mm)

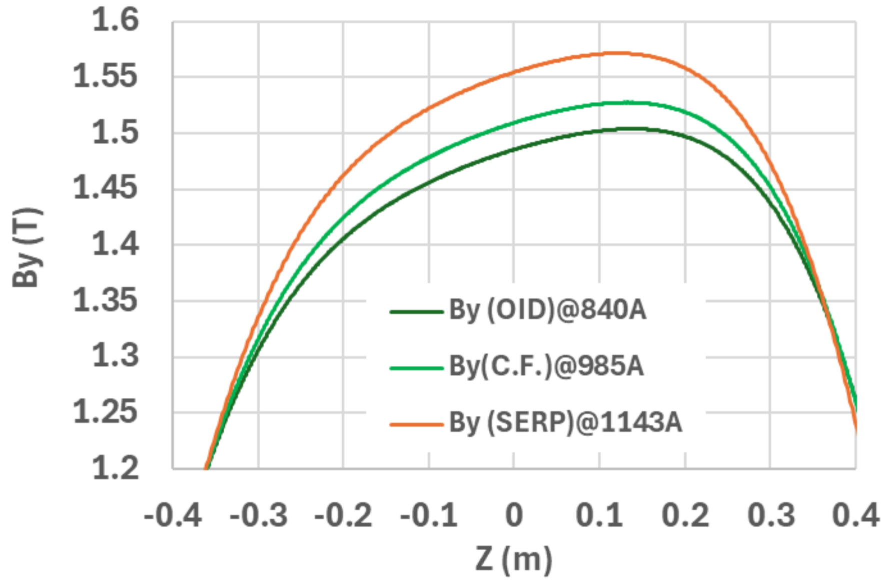


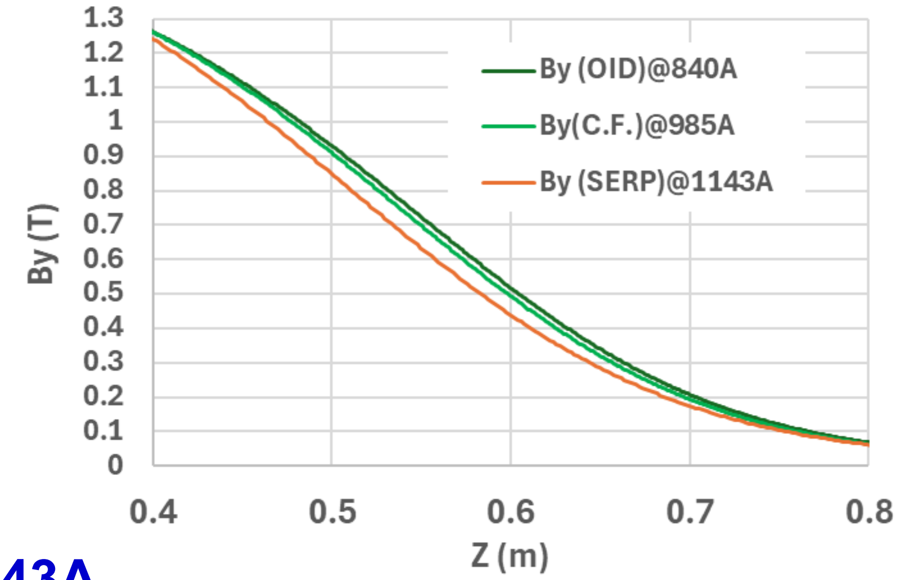
Current adjusted to make the integral 1.56 T.m for the proton beam at x=126 mm

@1000 Amp (design current 950 A)

Serpentine, OID (Quad+Dipole) and OID (Combined Function)



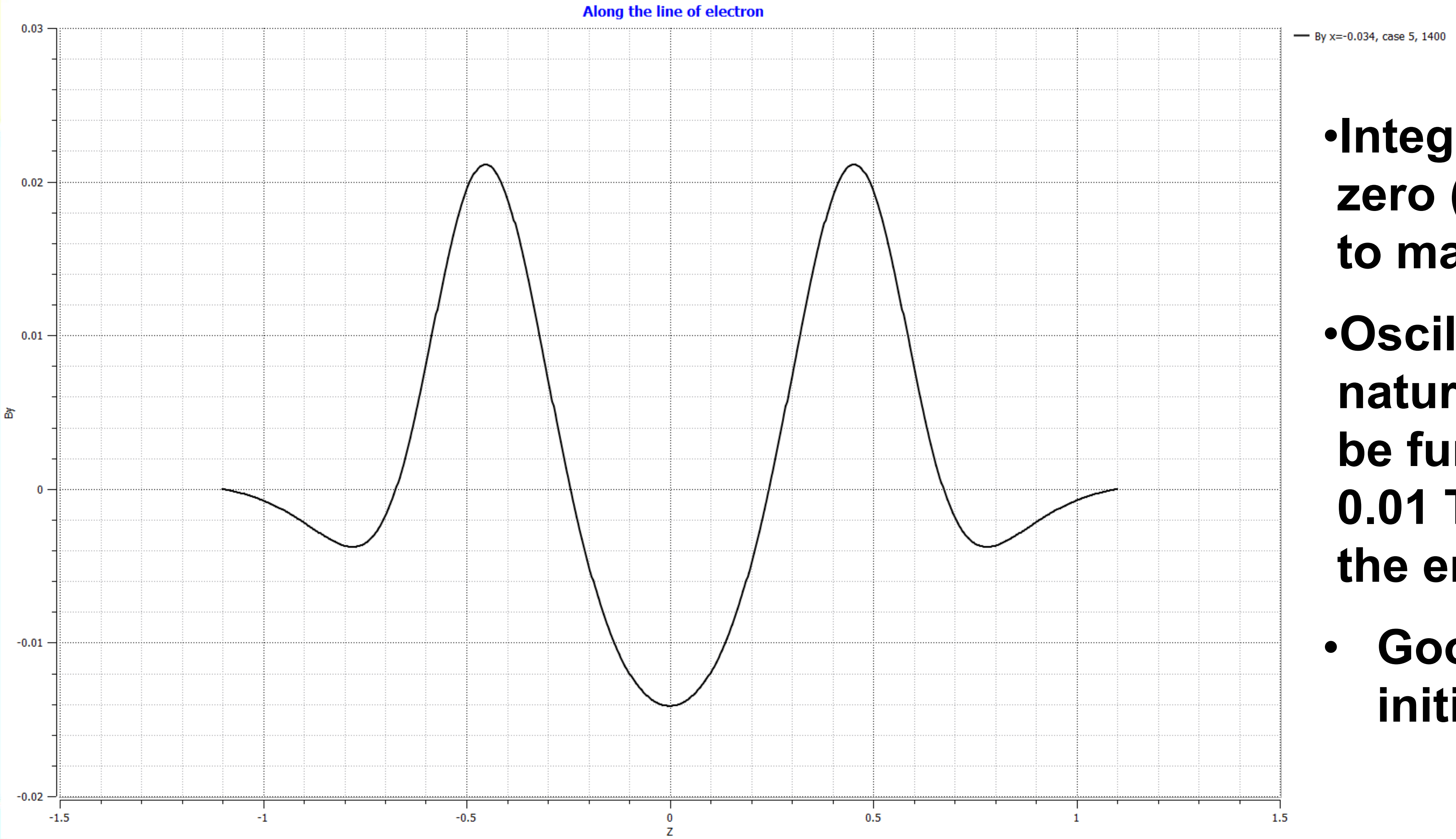




Lower number of layers and lower current:

- **OID (6Q+1D) 7 layers @840 A**
- **OID (Combined Function) 6 layers at 985 A**
- **Serpentine design had (8Q+2D) 10 layers @1143A**

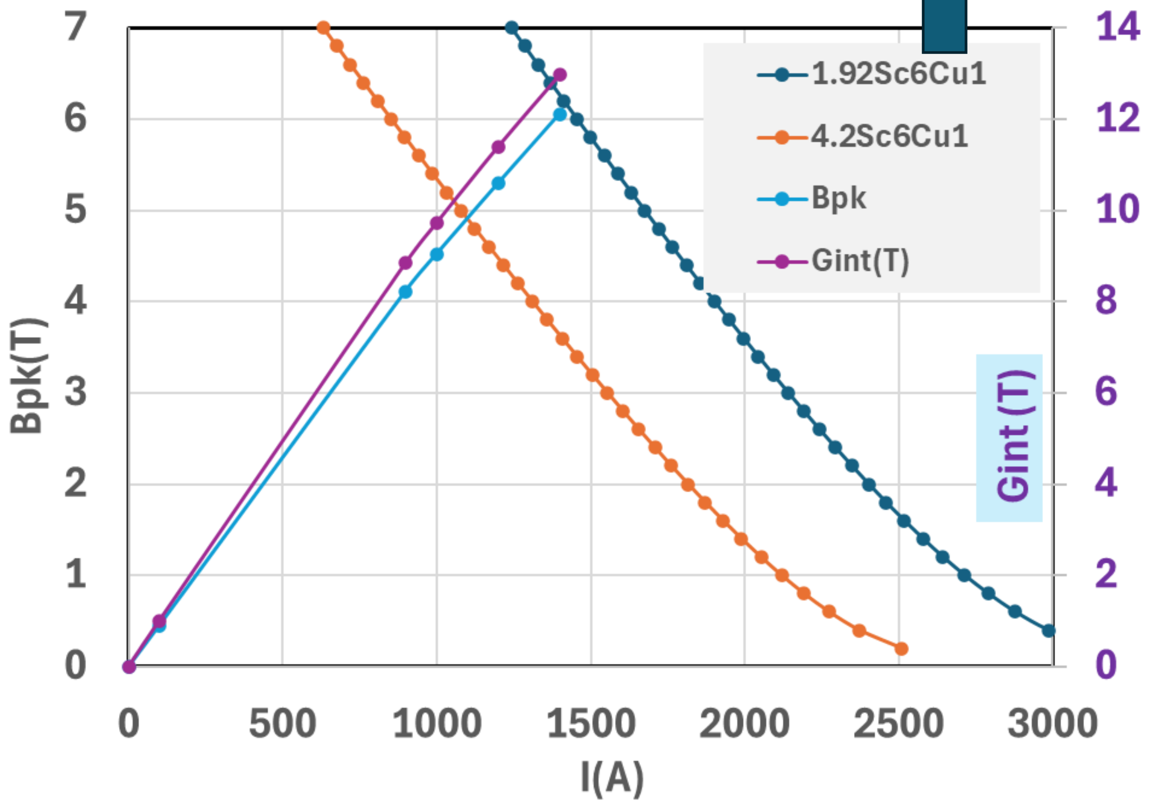
Field along the electron path (X=-34 mm)

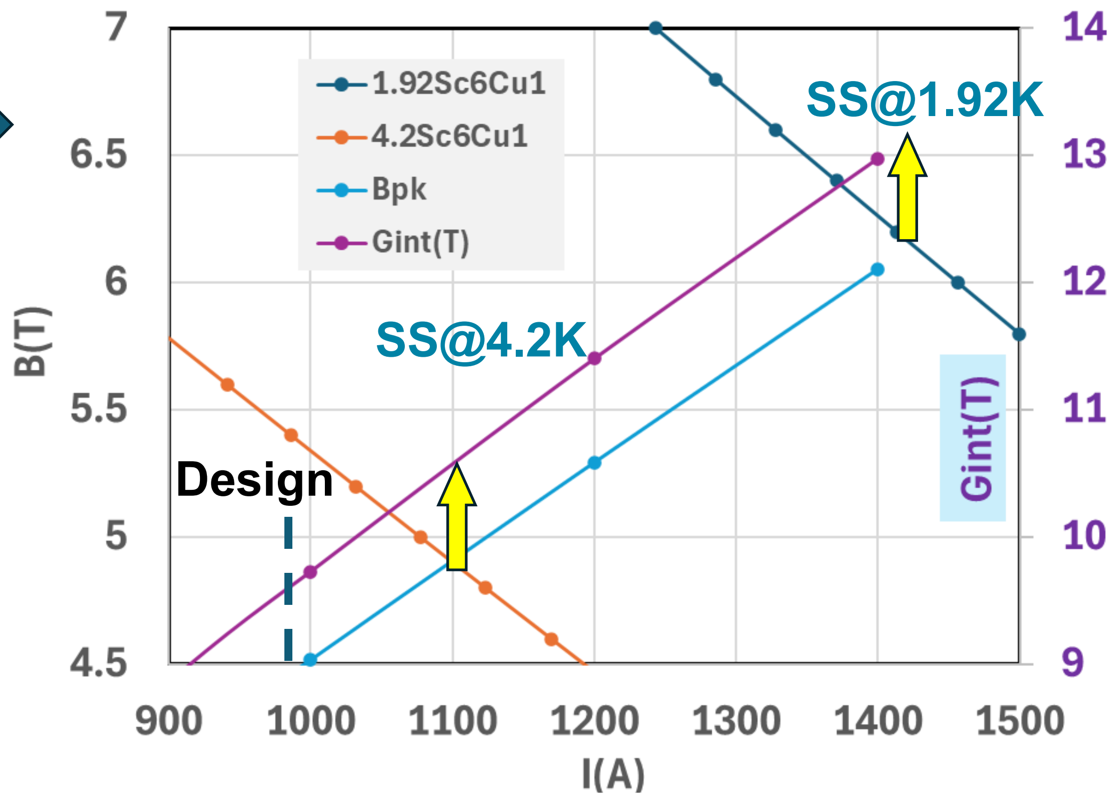


- Integral field is nearly zero (can be fine tuned to make it exactly 0)
- Oscillation in By is naturally ~0.02 T (may be further reduced to 0.01 T by optimizing the ends).
- Good enough for initial investigation

Optimum Integral Design B0pF Computed Performance
(6 individually optimized combined function layers, 6sc around 1 cu)

- Operating temperature in EIC: 1.92 K
- Initial testing temperature: ~4.2 K





- Nominal design current: ~985 Amp

I_{ss} @4.2K: ~1100 Amp (~12% margin)

I_{ss} @1.92K: ~1420 Amp (~44% margin)

May be OK. But worthwhile examining 7-layer and 8-layer designs also

Summary and the Next Step (1)

- **Preliminary optimum integral design has 6 layers of quad and one layer of dipole. It satisfies all the requirement while operating at 840 A rather than 1143 A in the current design.**
- **Lower current will reduce the voltage developed across coils while extracting the energy after the quench.**
- **Moreover, the center wire is made of copper (6 super around 1 Cu rather than all 7 super) to help quench protection by taking advantage of the quench back.**
- **This also increases Cu/Sc ratio to 2.2 to reduce current density in copper after quench at the design current, which was already smaller in this optimum integral design (840 A instead of 1143 A), to reduce hot spot temperature and provide better thermal stability against quench.**

Summary and the Next Step (2)

- It can fit in our Dewar for 4.2 K testing while still having a comfortable margin (25% margin at 4.2 and 65% at 1.92 K with 6 Sc around 1 Cu).
- Optimum integral design allows a combined function design (rather than quad and dipole in series). A 6-layer design may work but 7-layer and 8-layer designs should be examined for overall optimization (quench protection, etc.).
- Other aspects should be further evaluated, including winding and/or splicing options.
- Initial outcome of the exercise looks promising. However, the electro-magnetic design, etc., must be analyzed independently (e.g. with RAT). In parallel more optimized versions can be found.
- Next step will be to perform mechanical and quench analysis to evaluate the level of gains.

Extra slides

Background

The inset slide must force one to at least have a quick look at the optimum integral design for B0pF (reference for length to id ratio: <4 in quad; it's 1.8 here). However, to change from the serpentine design to anything else at this stage, the benefits must be significant, such as (at least one or two from the list below):

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, id = 114 mm): ~5.3
- B1ApF (L = 1600 mm, id = 370 mm): ~4.3
- B1pF/B1ApF (L = 2500 mm, id = 363 mm): ~6.9
- B0pF/Q0eF (L=1200 mm, id = 656 mm): ~1.8 (refer to quad)

Reference guide
~8 in dipole
~4 in quads

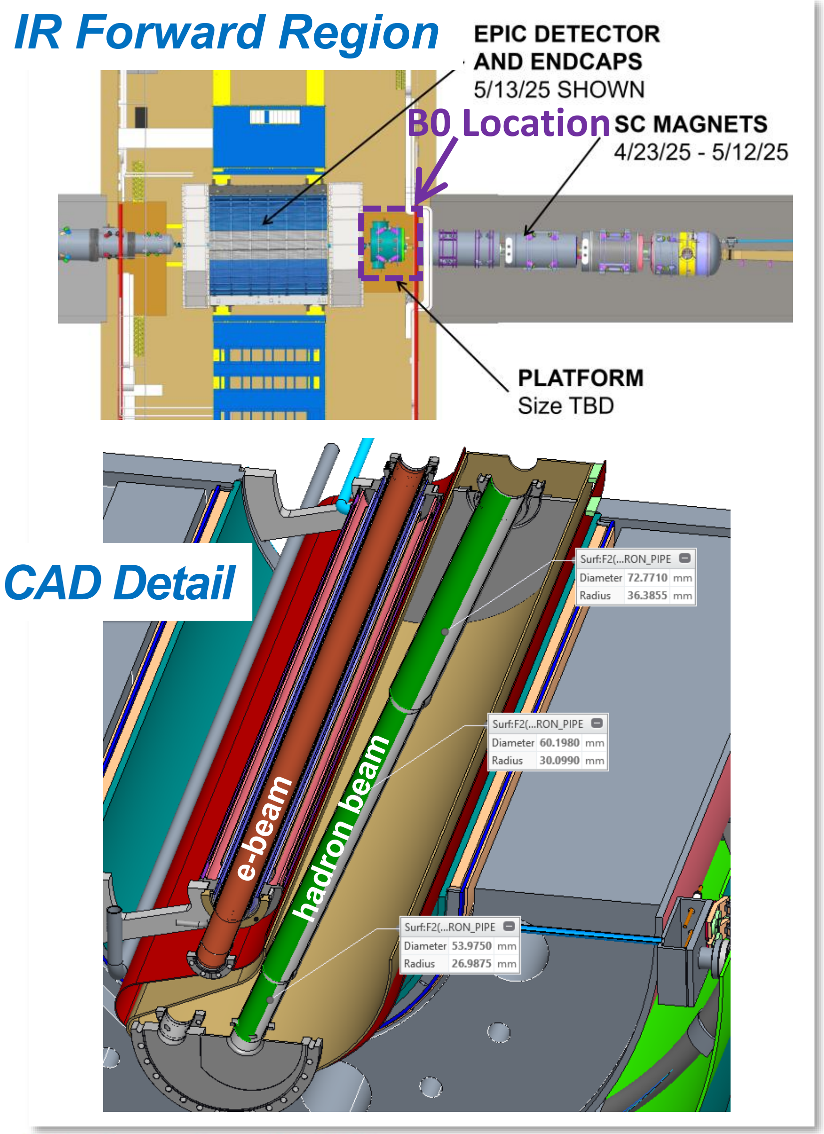
- ***6 layers instead of 8 layers so that it can be tested in our Dewar at 4K (beside cutting cost and schedule).***
- ***The magnet achieves the design field integral at 4.2 K (with a good margin) to demonstrate the design.***
- ***Quench protection becomes significantly less challenging.***
- ***Max. field gradient (Lorentz forces) gets reduced significantly.***

Following slides are from <2 days of work using the same cable as in serpentine. First look is promising!

Scope

Courtesy Brett Parker

Charge #1-2,4-5



- B0PF–Q0EF magnet combination are the closest magnets to the detector on the forward side.
- B0PF provides spectrometer field functionality for the experiment along with the baseline defocusing gradient for the first electron quadrupole, Q0EF.
- The Q0EF integrated gradient is independently adjustable from B0PF thanks to additional coils.
- A large B0PF coil radius is needed to accommodate both the warm space for detector elements and the superconducting Q0EF gradient tuning coil with its cold mass structure.

The purpose of this presentation is to communicate the baseline B0PF–Q0EF electromagnetic design highlighting how critical requirements are met and work for the future.

Requirements

Courtesy Brett Parker

Charge #1-2

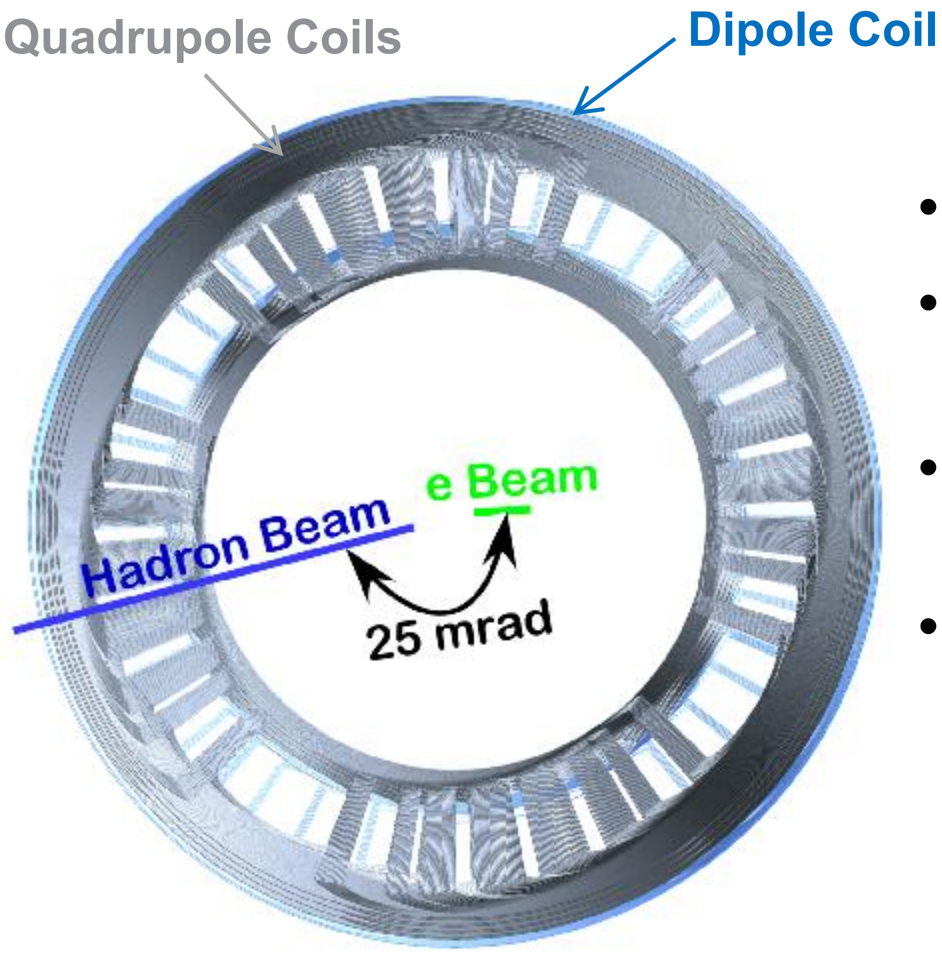
- Hadron and electron beams have 25 mrad relative angle and small separation at B0 spectrometer.
- Still, we need 1.56 T·m dipole strength for hadrons over a warm detector region for the experiment.
- The B0PF hadron dipole field is kept constant during collisions, independent of the hadron beam energy (for its spectrometer functionality).
- But must give quadrupole focusing for e-beam with zero dipole integral field (dipole small as practical†).
- And the e-beam focusing shall be independently adjustable for different e-energies (5 to 18 GeV).

†B0 is on incoming electron side with rapidly changing beta-functions (large beam divergence); thus, synrad generated here can impact the central detector.

Design

Courtesy Brett Parker

Charge #1-2,4-5



- Use quadrupole coils to provide electron focusing.
- Along with a dipole coil, powered in series, to zero out the field at the e-beam axis.
- Result is a combined function magnet which then provides the desired deflection of the hadron beam.
- The operating current is set to give 1.56 T·m for the hadrons which then yields an integrated gradient very close to what is needed at the middle, 10 GeV, e-beam energy.