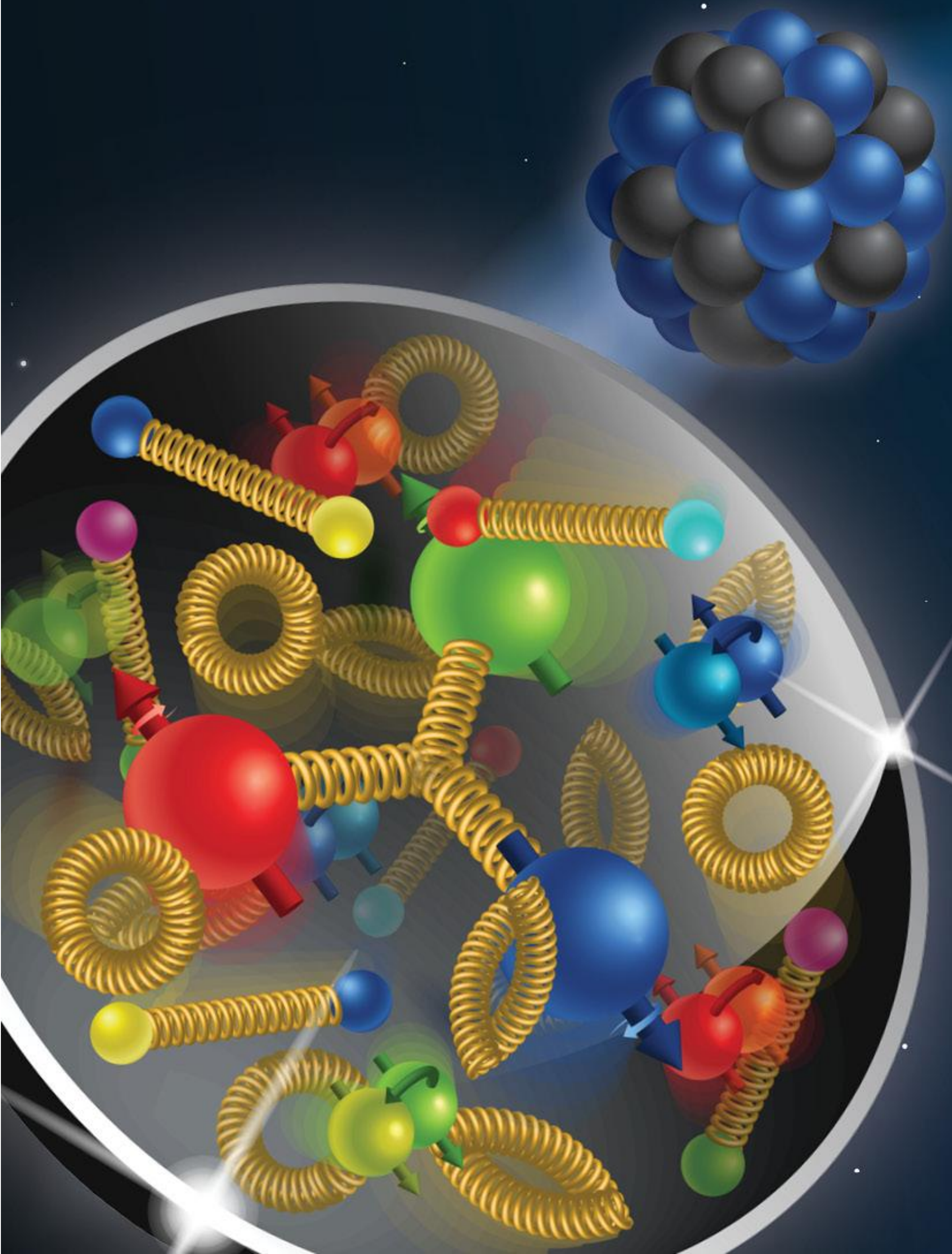


Optimum Integral Design (OID) for Risk Reduction in B0pF

Ramesh Gupta
(with input from Brett Parker and Vikas Teotia)

October 17, 2025

Electron-Ion Collider

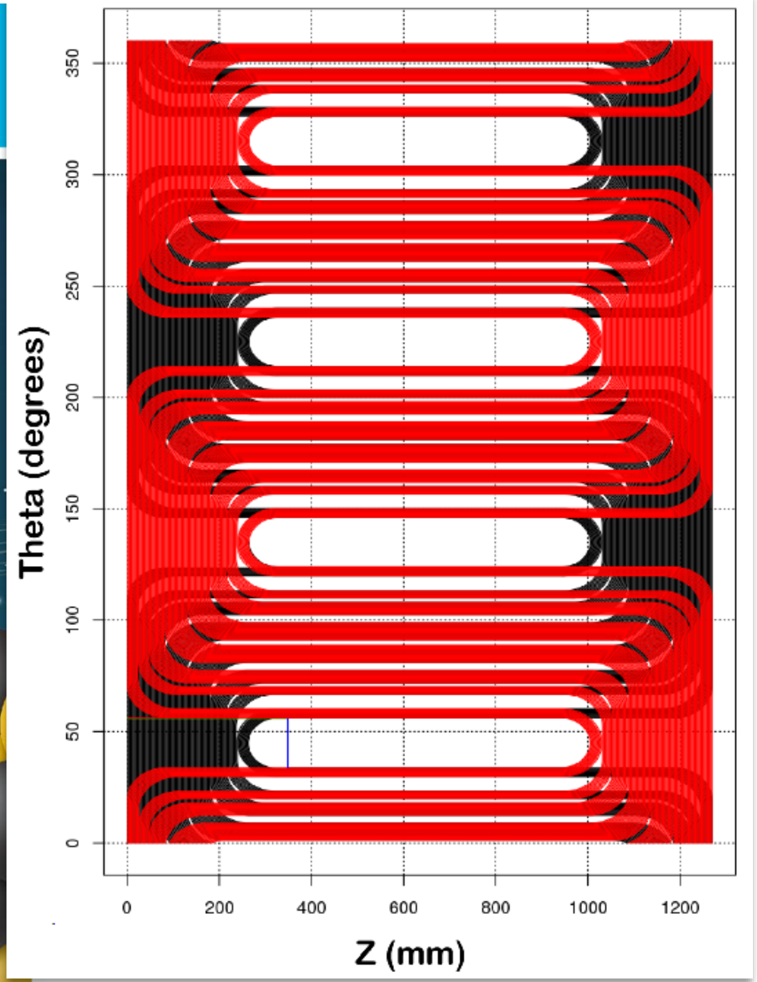
BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY | Office of Science

Highlights of Risk Reduction in B0pF

- A 6-layer combined function Optimum Integral Design (OID) operating at 889A, has been found to replace the current 10-layer (8 quad + 2 dipole) operating at 1143A.
- The only change is in the design of large aperture quad/dipole coils.
- The reduction in current from 1143 A to 889 A should help in quench protection as the required maximum voltage across the coil during energy extraction (one significant area of concern) should go down and the hot-spot temperature should get reduced.
- The design also increases operating margin from 43% to 70% at 1.92 K. It remains at 57% (21% at 4.2 K) even if the central superconducting wire in 6-around-1 cable is replaced by copper wire to improve further on the quench protection.
- In addition, the Lorentz forces on the individual turns also get reduced.
- To first order the layout of turns in the optimum integral design is the same as in the serpentine. A higher integral field comes due to differences in end region only. This difference makes a major impact on the magnets where the coil length to coil diameter ratio is small. This is the case in B0pF since the ratio is only ~1.8.

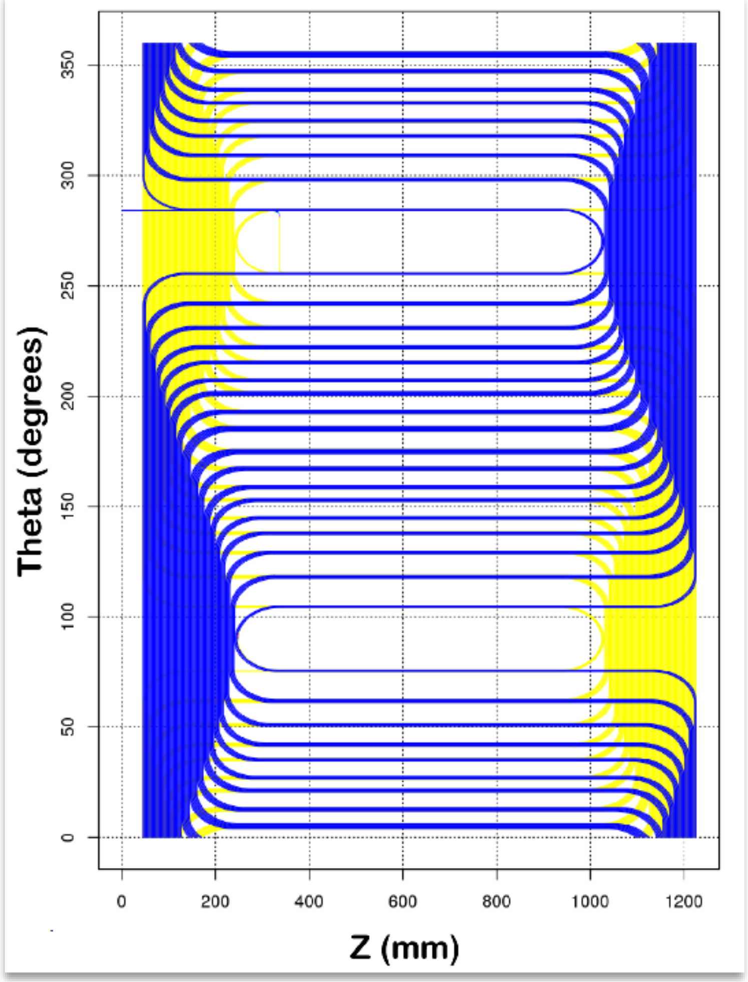
Serpentine Coil Design for B0pF (Brett Parker)

B0PF Quad Serpentine Coilset A



Three coil sets (6 layers) needed

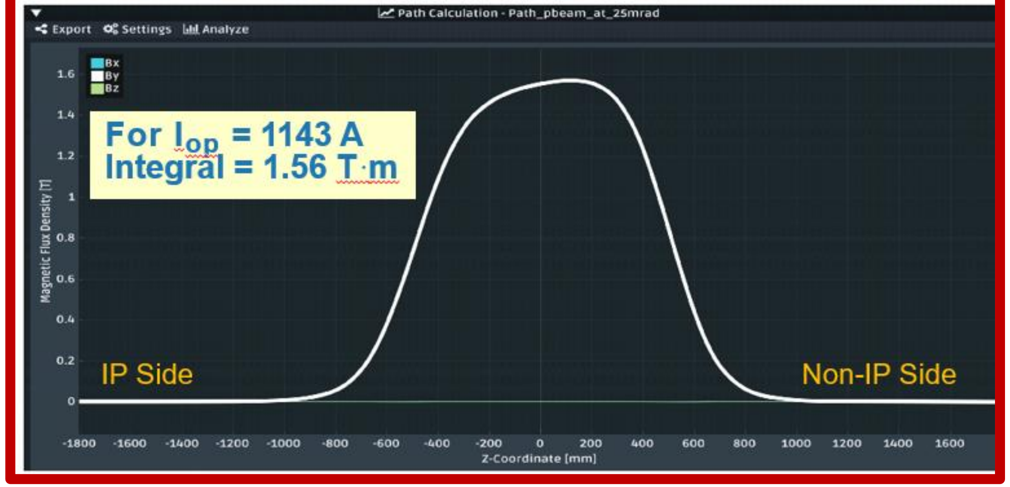
B0PF Dipole Serpentine Coilset



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

- Serpentine coil has several nice features and is a design of choice.
- Among other advantages, it offers a continuous winding pattern, which minimizes splices.

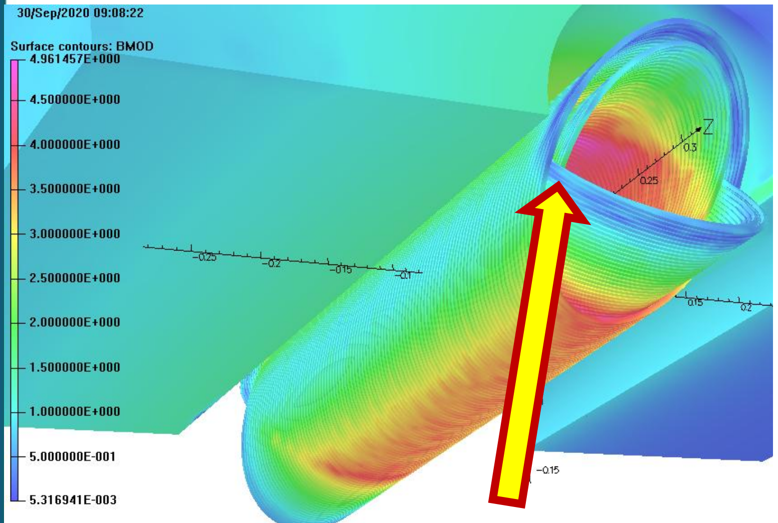
B0PF Field, By, at Hadron Beam Axis (25 mrad)



However, a small flat-top in B0pF means a significant loss in the field integral from the ends. Optimum Integral design should help here.

Optimum Integral Design – What and why efficient?

RHIC Cosine(θ) Coil Ends



Double helix

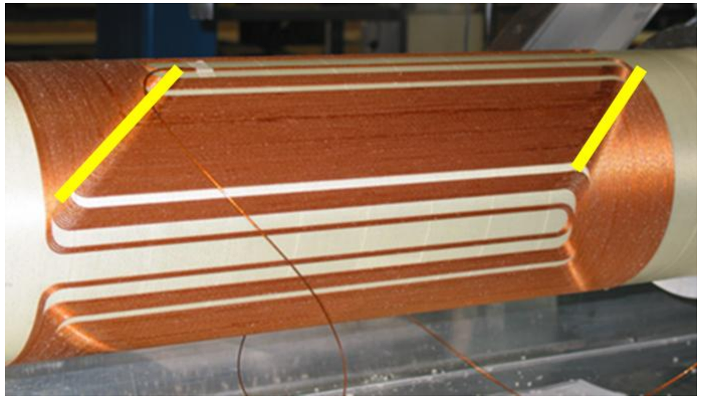
Midplane turns end here

Turns near the midplane contribute most to the field:

$$B \propto I \cos(\theta)$$

- **In most designs, length of the midplane turns gets reduced in the ends and so does the field/length from the turns.**
- **This relative loss in integral field due to ends becomes significant in short magnets.**

The Optimum Integral Design minimizes this loss by extending the midplane turns to almost the entire length of the coil winding.



Serpentine

Optimum Integral

Conventional Design Approach

- **It is a two-step process.**

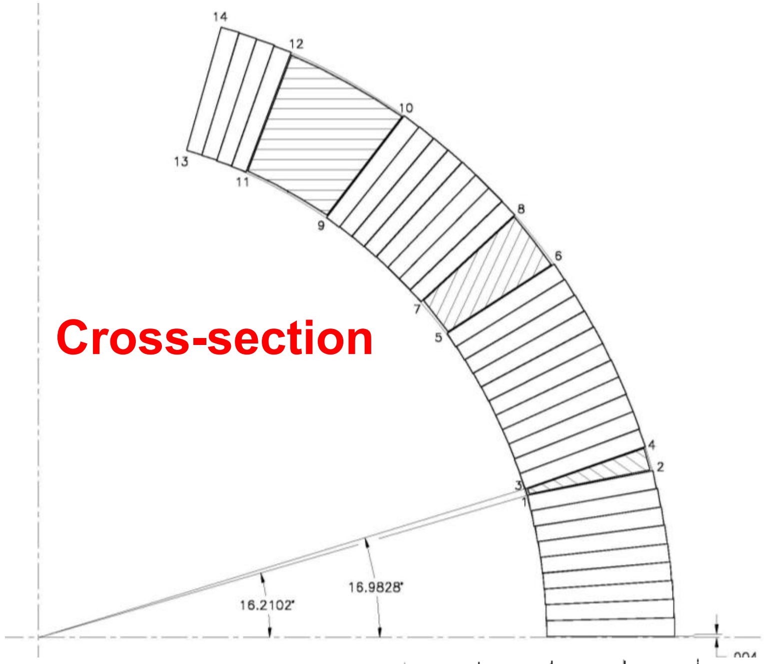
Step 1: Optimize coil cross-section to obtain "cosine theta like" distribution:

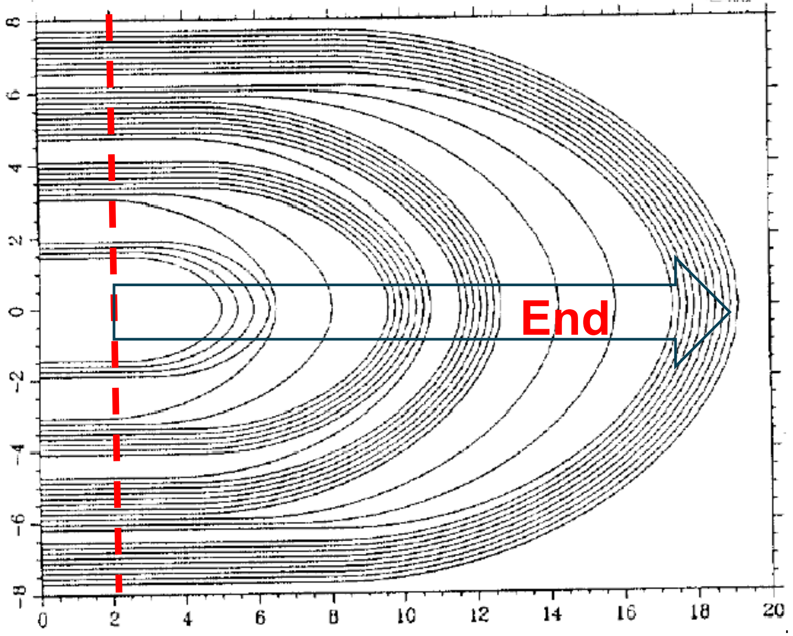
$$I(\theta) = I_o \cdot \cos(n\theta)$$

Step 2: Optimized ends for harmonics

(also, look for low peak fields in both cases)

Each step reduces the maximum integral field





Optimum Integral Design Approach

AGS dipole (2004)

(see, to 1st order, cosine theta like distribution in the length of turns)

- ➢ **Extend midplane turns to full coil length**

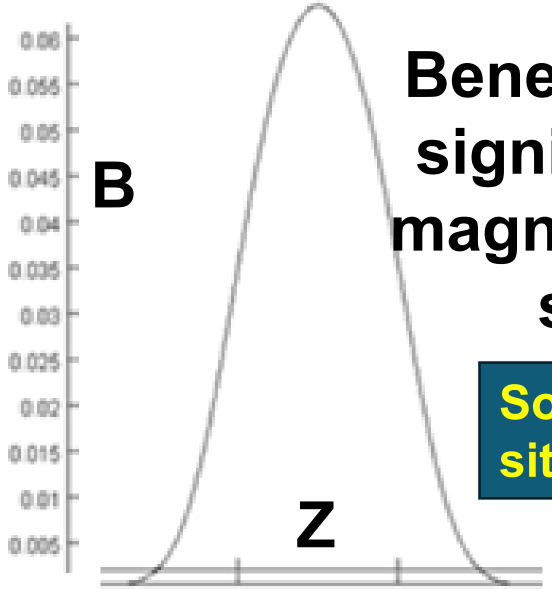
Then optimize cross-section & ends together in <u>a single step</u> to obtain an "overall cosine theta like" distribution in an integral sense:

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

End turns contribute maximum to the field, become a part of the integral optimization.

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

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



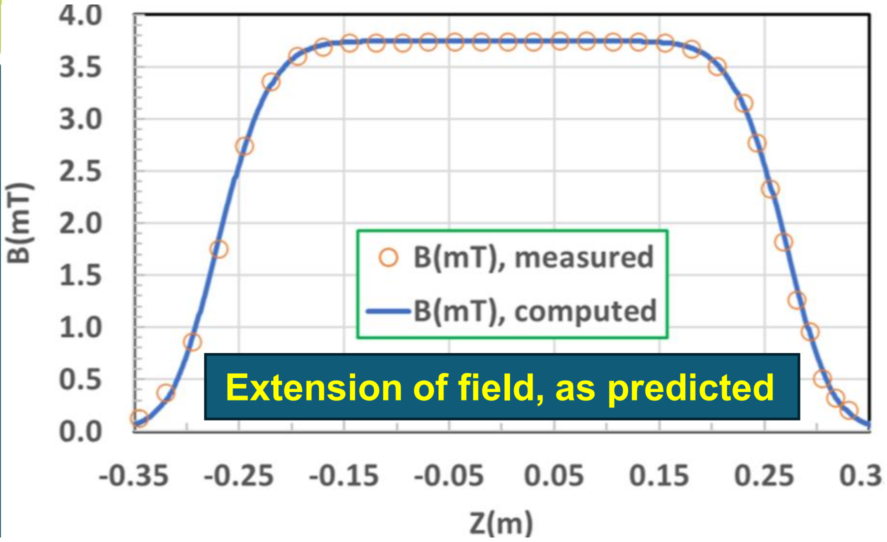
Benefits could be significant in any magnet with no to small flat-top

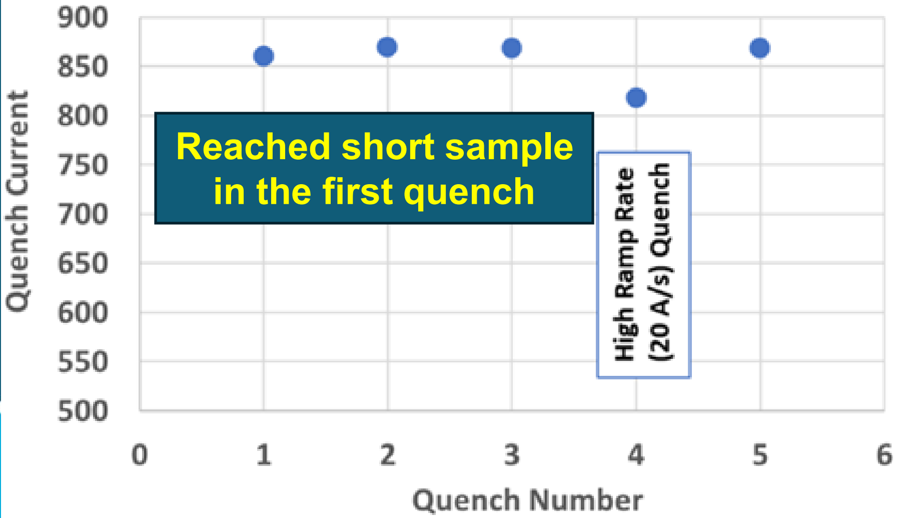
Somewhat similar situation in B0pF

Demonstration of the Optimum Integral Design with PBL/BNL STTR

Phase I: 2 layers, 114 mm

B_o = ~1.7 T, B_{pk} = ~2.2 T





A good field quality in a R&D coil

Optimum Integral Dipole 6-layer Design		
ITF (NO Fe)	1.860	mT.meter/A

Measured Integral Harmonics@31mm		
No.	bn	an
2	0.77	3.51
3	6.12	4.32
4	0.43	-0.98
5	0.93	0.50
6	0.20	-0.61
7	1.85	0.58
8	-0.02	0.22
9	-0.66	-0.19
10	0.02	-0.08
11	0.18	0.05
12	0.00	0.02

Some harmonics due to leads. Small harmonics can be tuned out in the next layers

Phase II: 12 layers

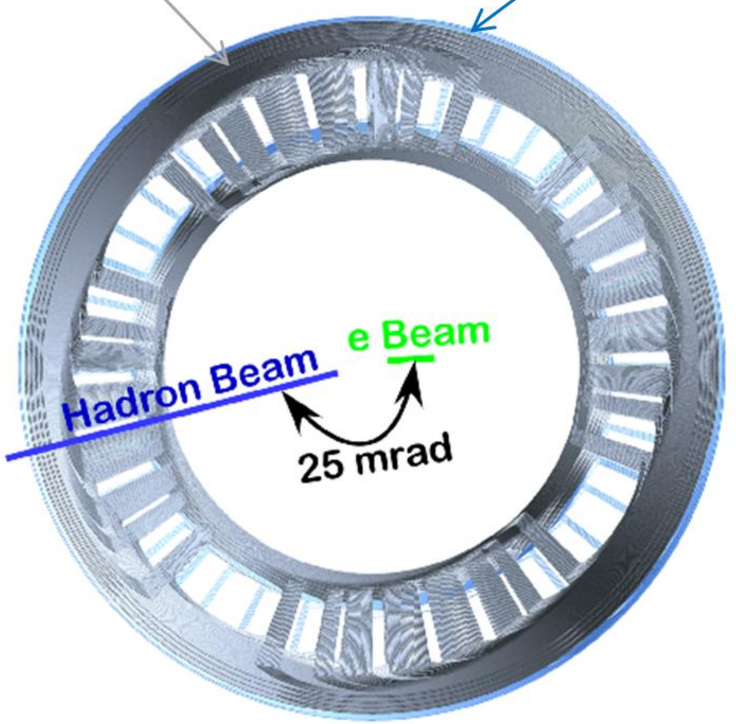
B_o = ~3.9 T, B_{pk} = ~4.3 T

(Margin: 10%@4.2K, >40%@1.92K)

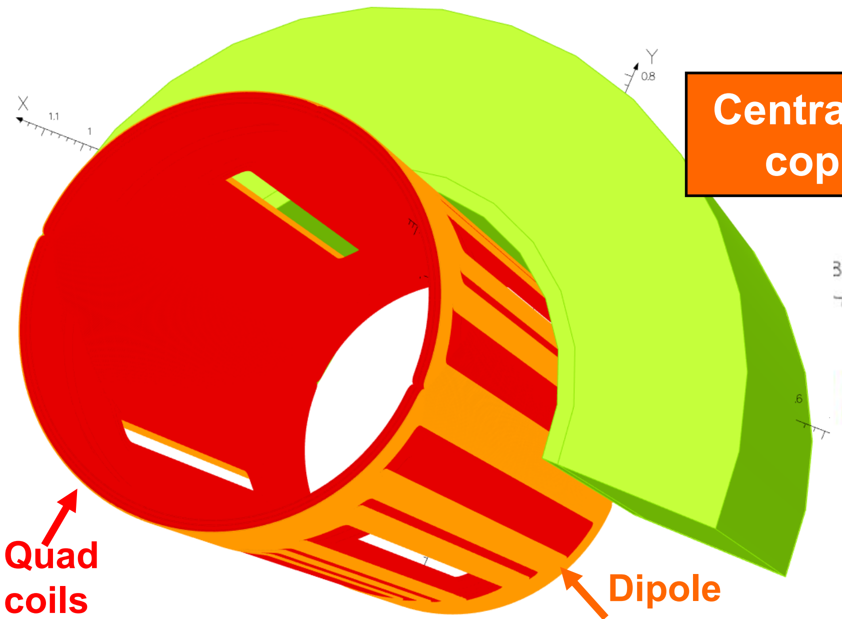
Magnet energized to ~2.9 T Higher current run limited by instrumentation/leads outside the magnet

B0pF Design Options

Current Design: Serpentine
10 Layers (8 Quad +2 Dipole)
I_{op} = 1143 A, Margin: 43%

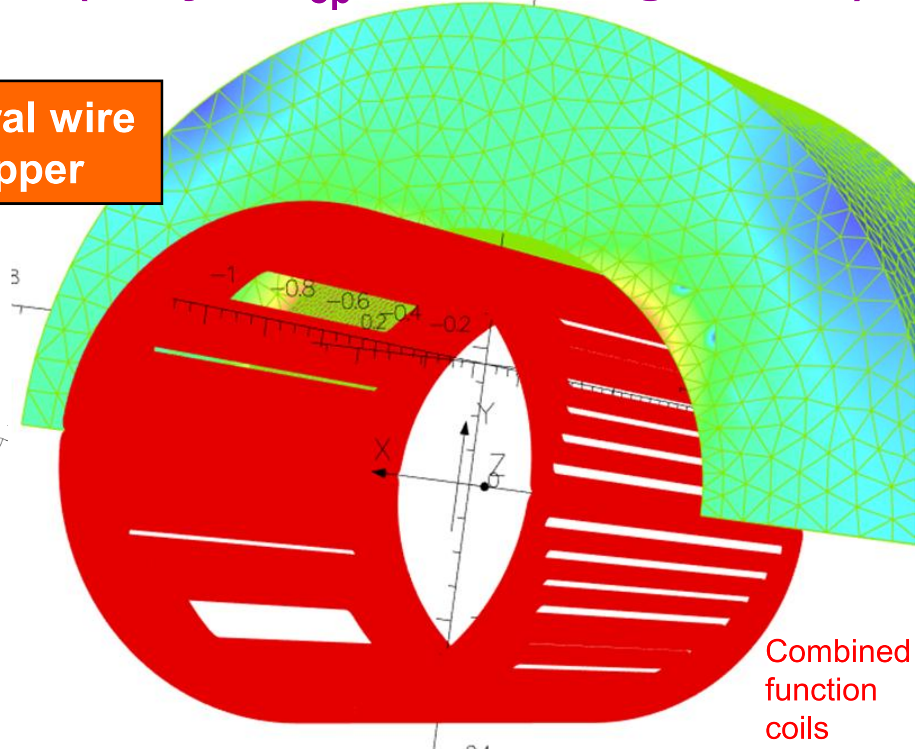


Option A: Optimum Integral
7 Layers (6 Quad +1 Dipole)
I_{op} = 840 A, Margin: 65%



Central wire copper

Option B: Optimum Integral
6 Combined Function Layers
Iop = 889 A, Margin: 57%
(8-layer: I_{op}=671A, Margin: 85%)



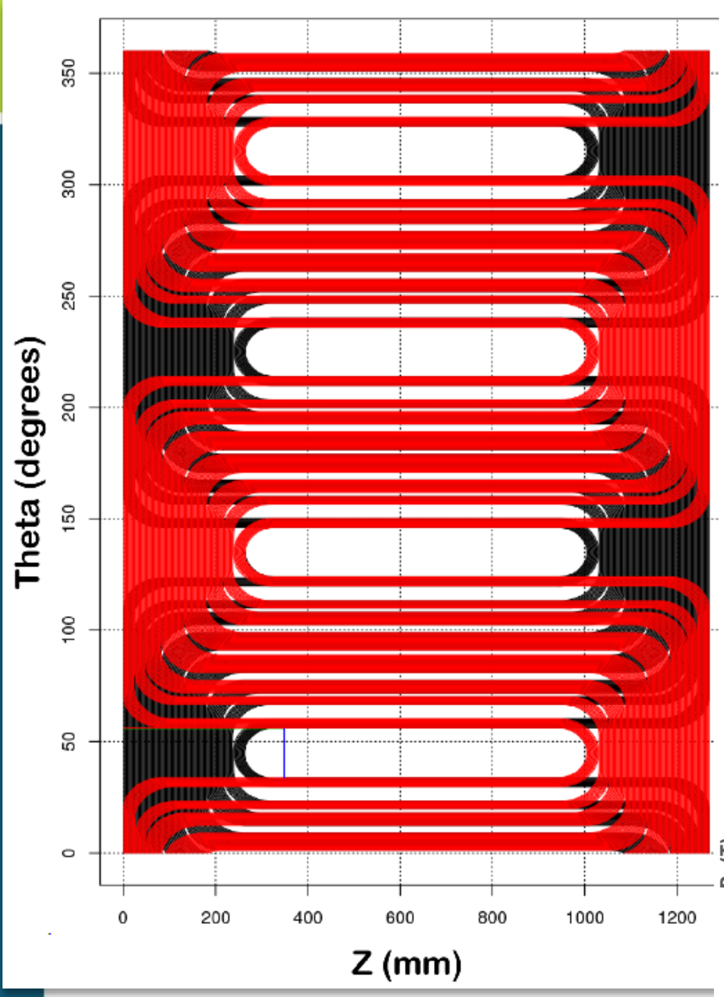
Combined function coils

Note: Both optimum integral designs have lower operating current and higher margin with fewer layers.

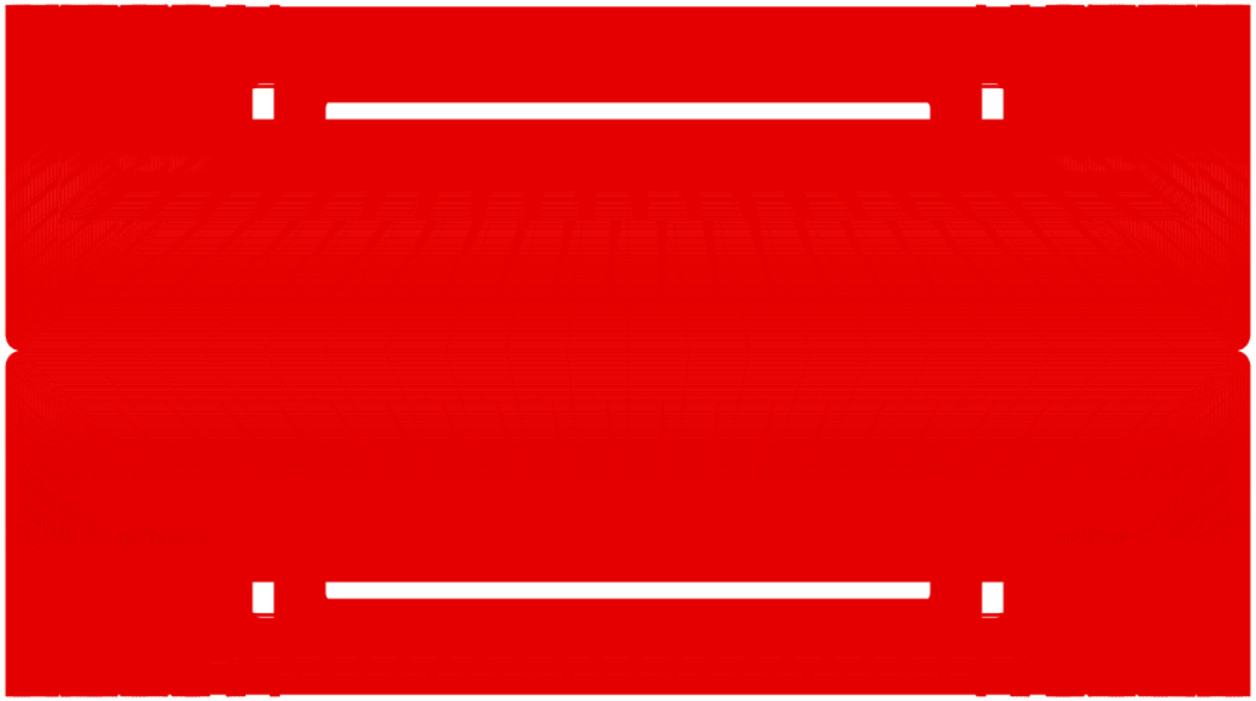
- **Option B will be presented in more details.**

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

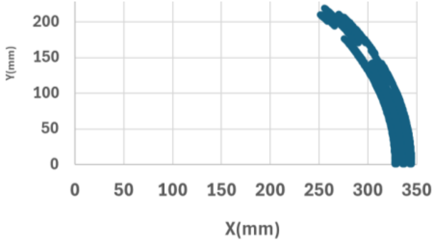
Serpentine Coil set A

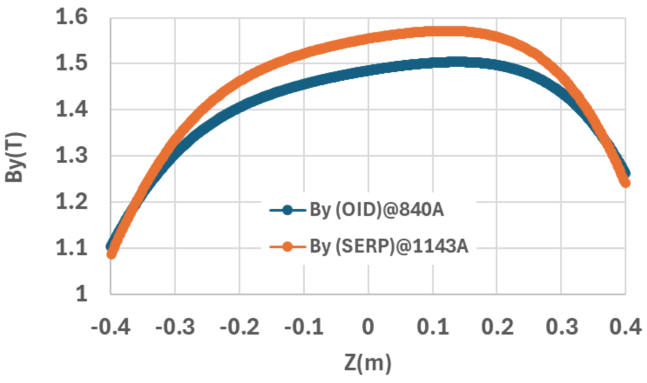


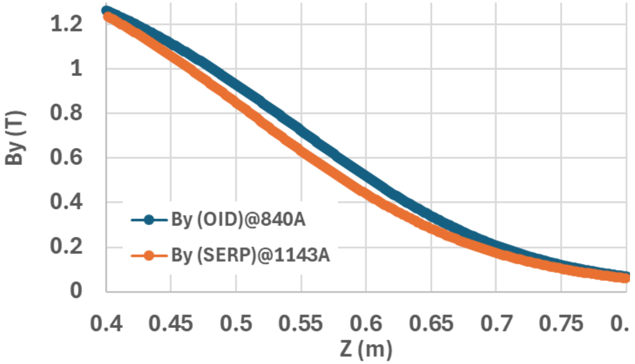
Optimum Integral Design Coil (6+1=7 layers)



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



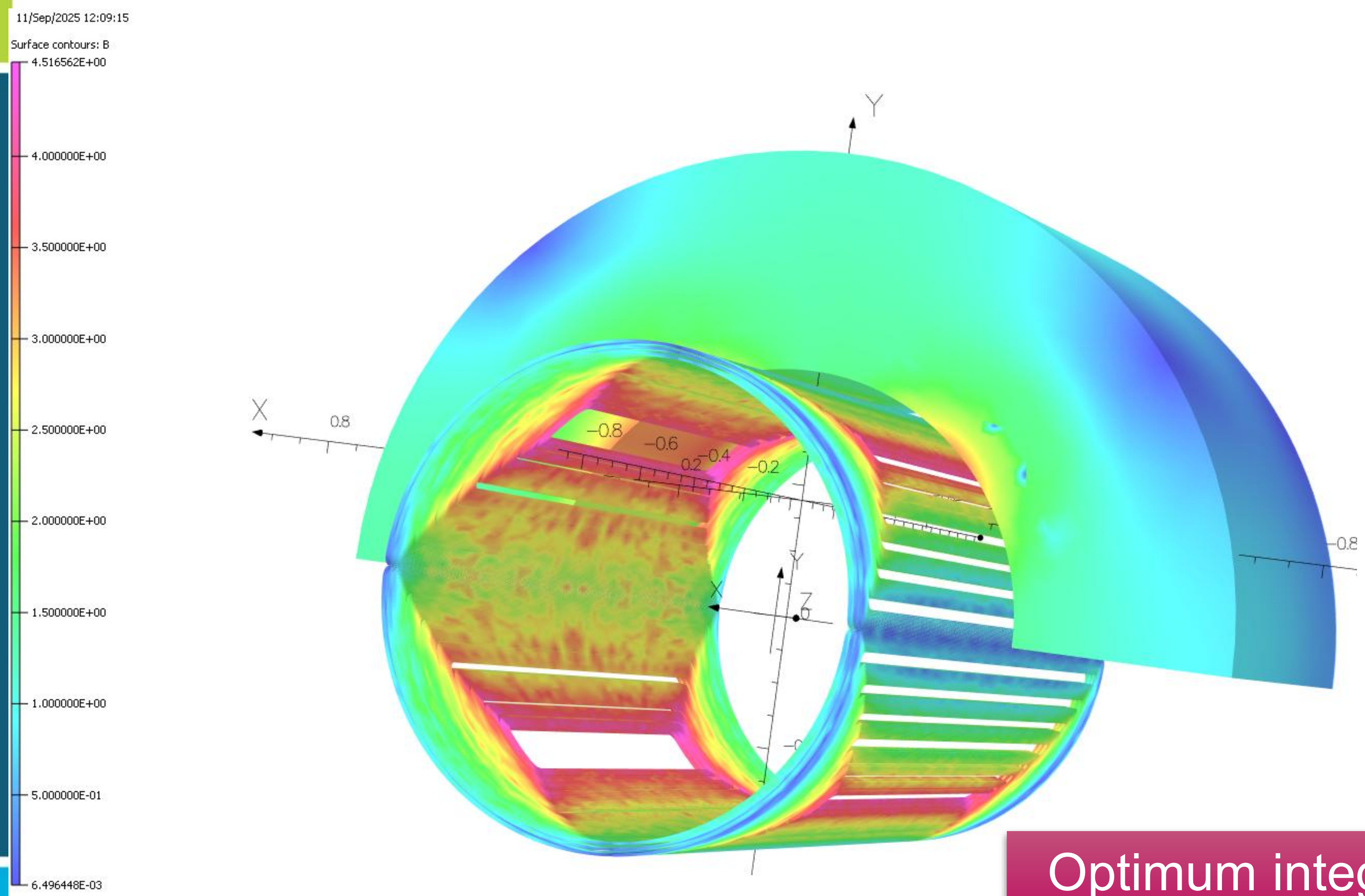




- Higher packing factor in the body.
- Ends contribute to the field and harmonic optimization.

✓ **In such short magnets, extended ends contribute to body field also**

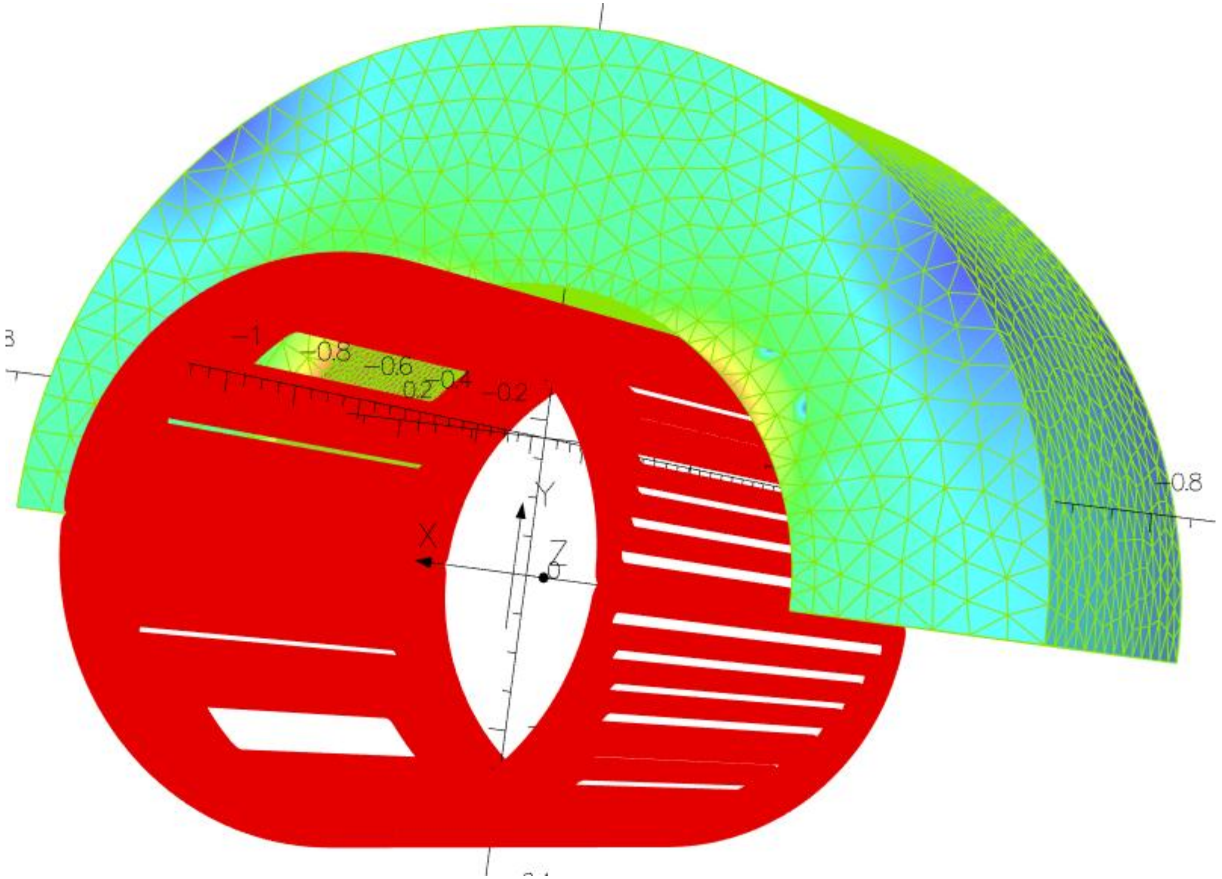
Model of the 1st Combined Function Optimum Integral Design (OID) for B0pF

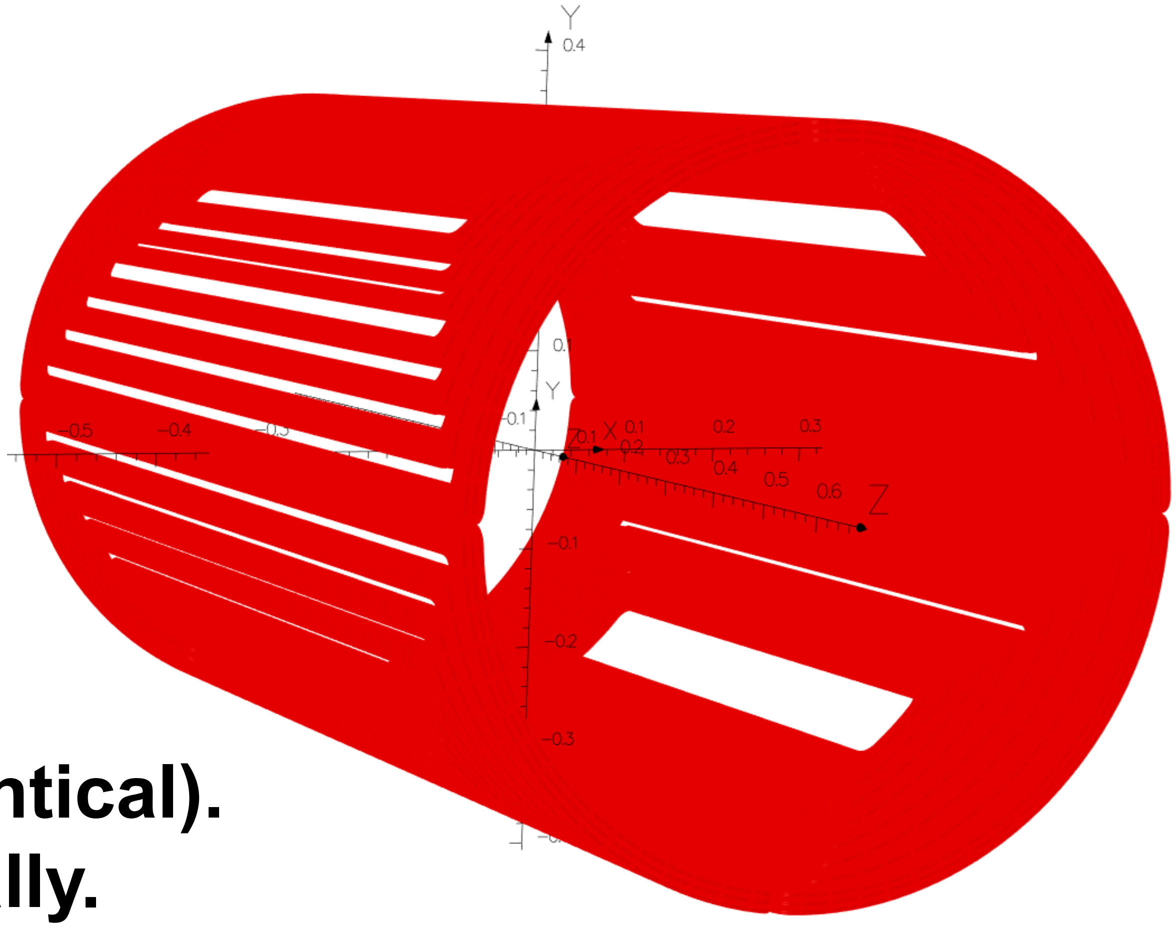


- **The main component is quadrupole, with a small dipole component added (in most combined function magnets, dipole is the main component, and a small quadrupole field gets added).**
- **Each layer is a combined function layer, and each is optimized Individually.**
- **One can add more layers later.**

Optimum integral design software was upgraded.
➢ A better solution possible with more upgrades.

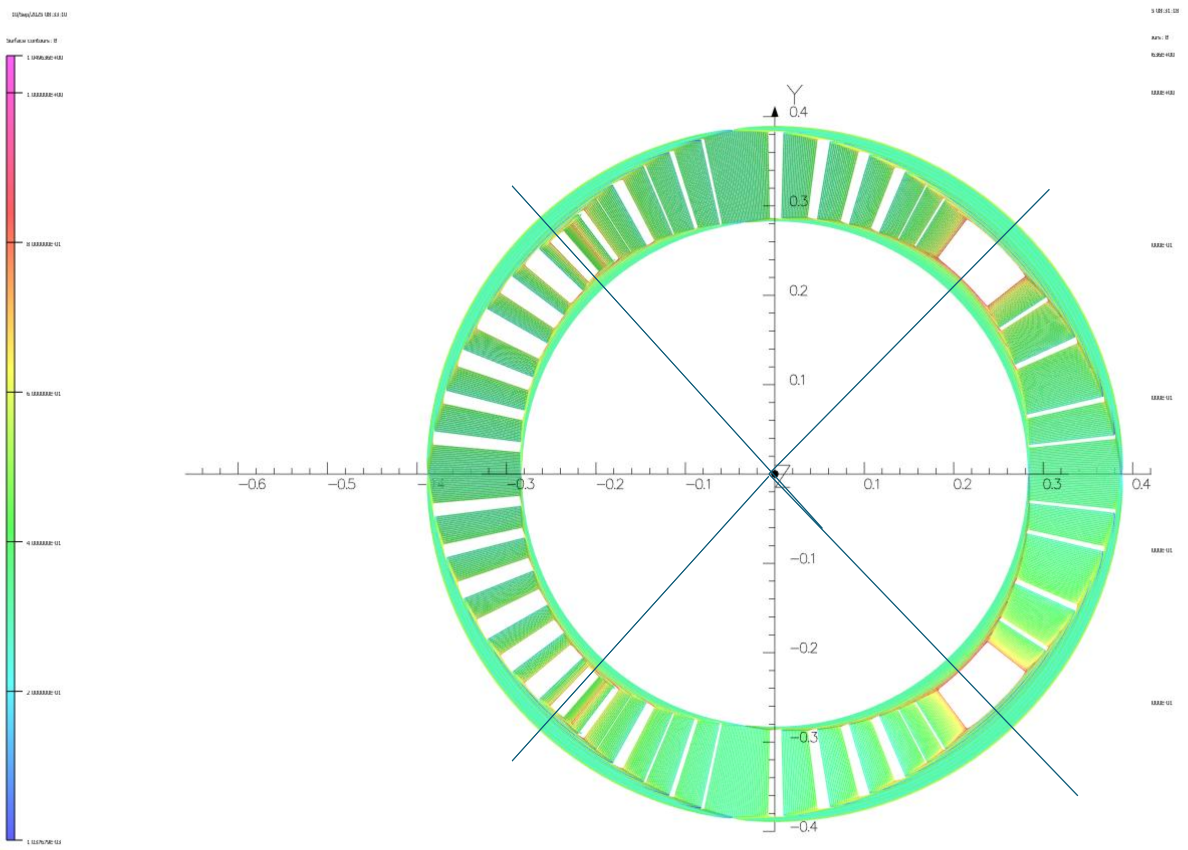
More views of the combined function designs (more turns on one side adding a dipole field)

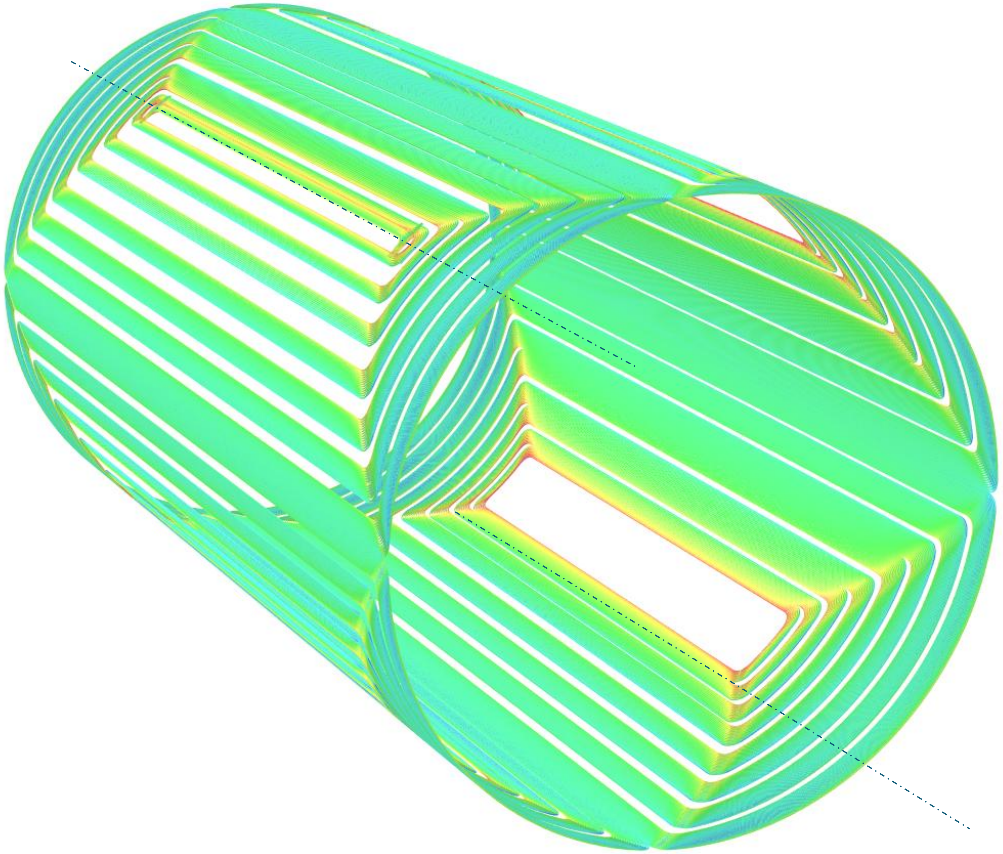




- All layers are similar (but not identical).
- Each layer is optimized individually.

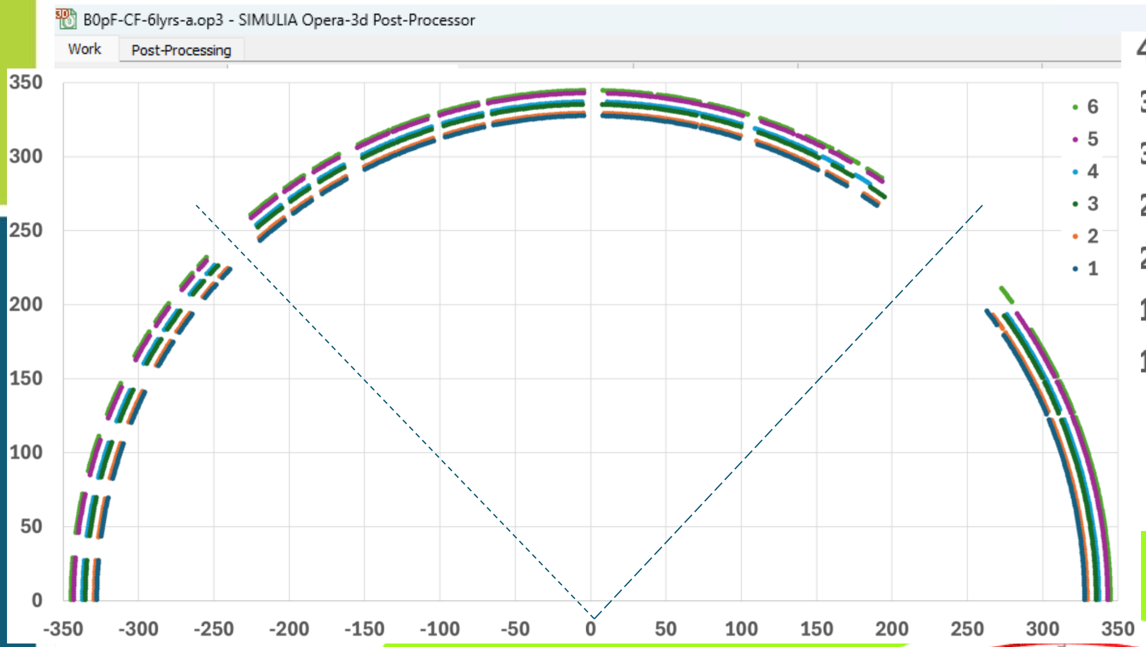
Poles are shifted from 45/135 degrees and vertical midplane from 90 degrees for efficient optimization of the combined function design



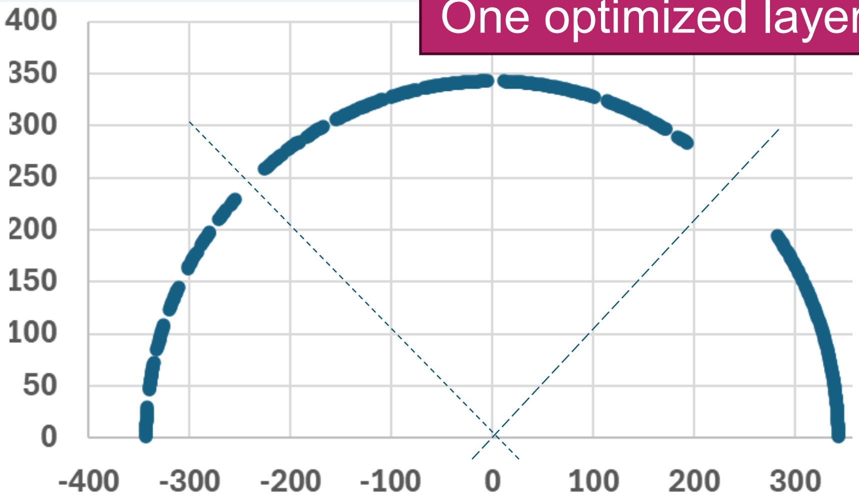


(note a primary quad coil configuration with dipole superimposed)

6-layer Combined Function Coil



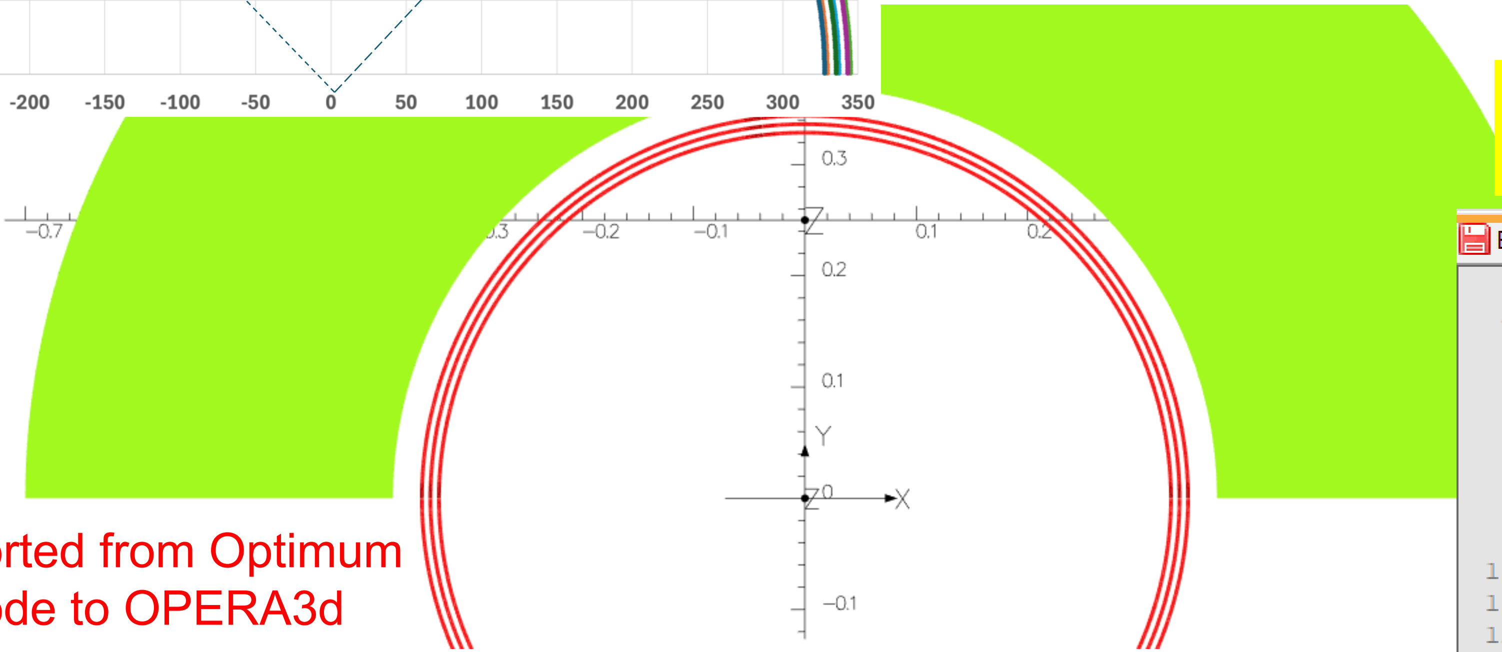
One optimized layer



INTEGRATED FIELD HARMONICS @50 mm

No.	Bn(T.m)	bn*10^4(units)
0	0.30777E-01	7421.3184
1	0.41471E-01	10000.0000
2	-0.68203E-07	-0.0164
3	-0.79736E-06	-0.1923
4	0.67121E-05	1.6185
5	-0.11534E-05	-0.2781
6	0.35714E-07	0.0086
7	0.44686E-08	0.0011
8	-0.29622E-08	-0.0007
9	0.20048E-09	0.0000
10	-0.52364E-10	-0.0000
11	0.40406E-11	0.0000
12	0.11720E-11	0.0000
13	-0.90136E-14	-0.0000
14	0.17211E-13	0.0000
15	0.11462E-14	0.0000
16	-0.50257E-15	-0.0000
17	-0.31427E-16	-0.0000
18	-0.93262E-17	-0.0000

Each layer has <2 units at 50 mm (sextupole mostly <0.2 unit)

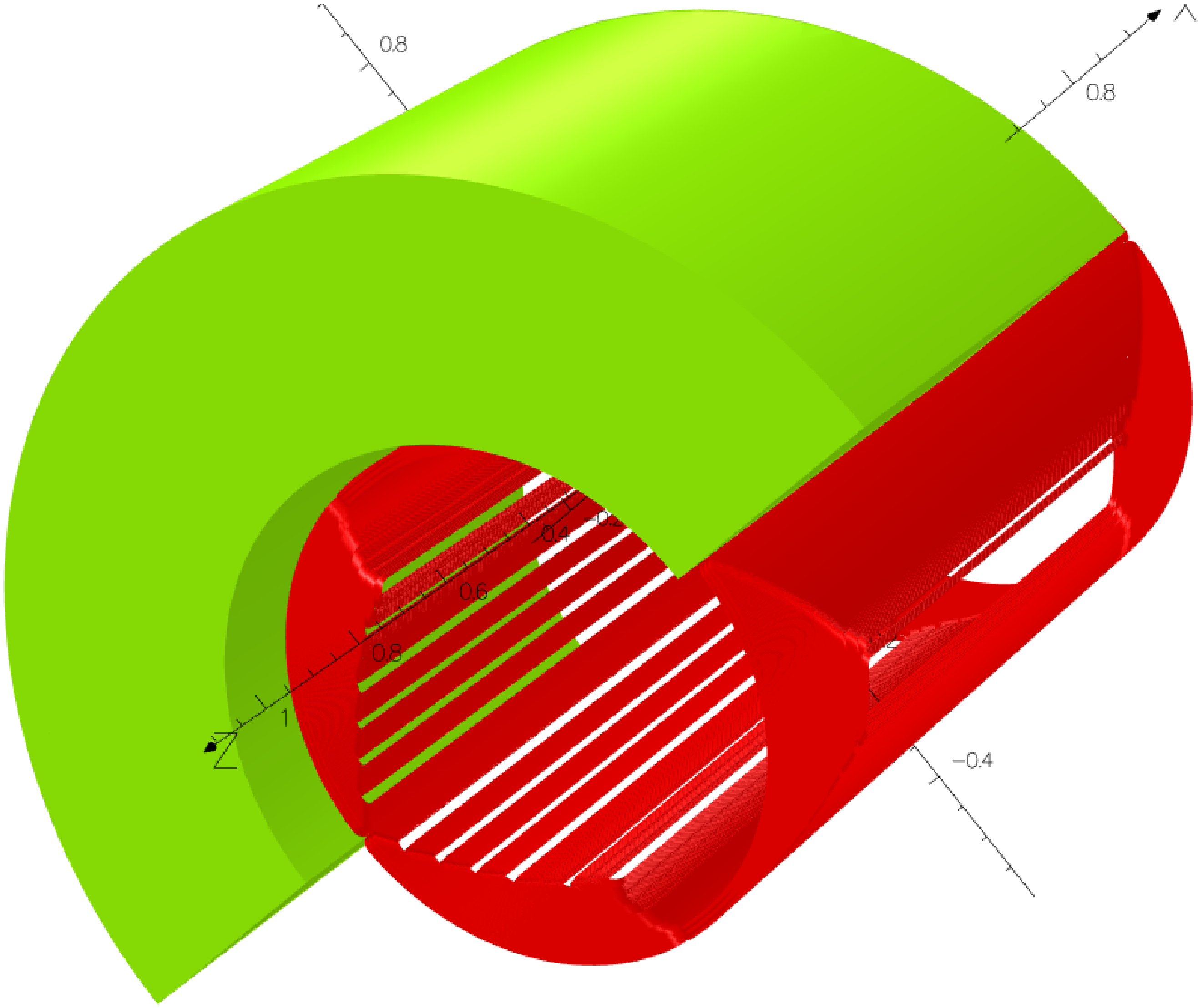


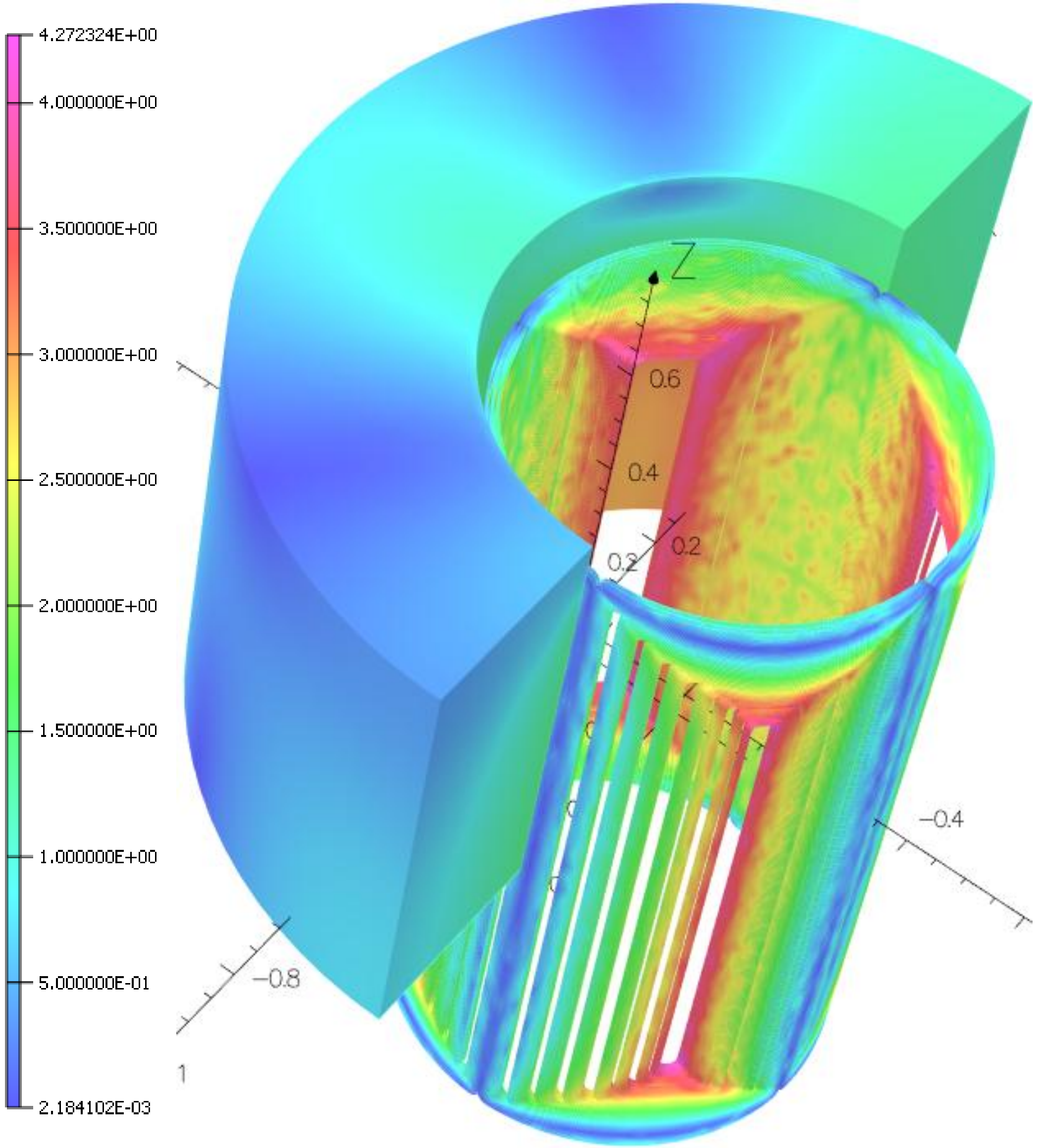
Coils imported from Optimum Integral code to OPERA3d

B0pF-CF-Layer5o.X01

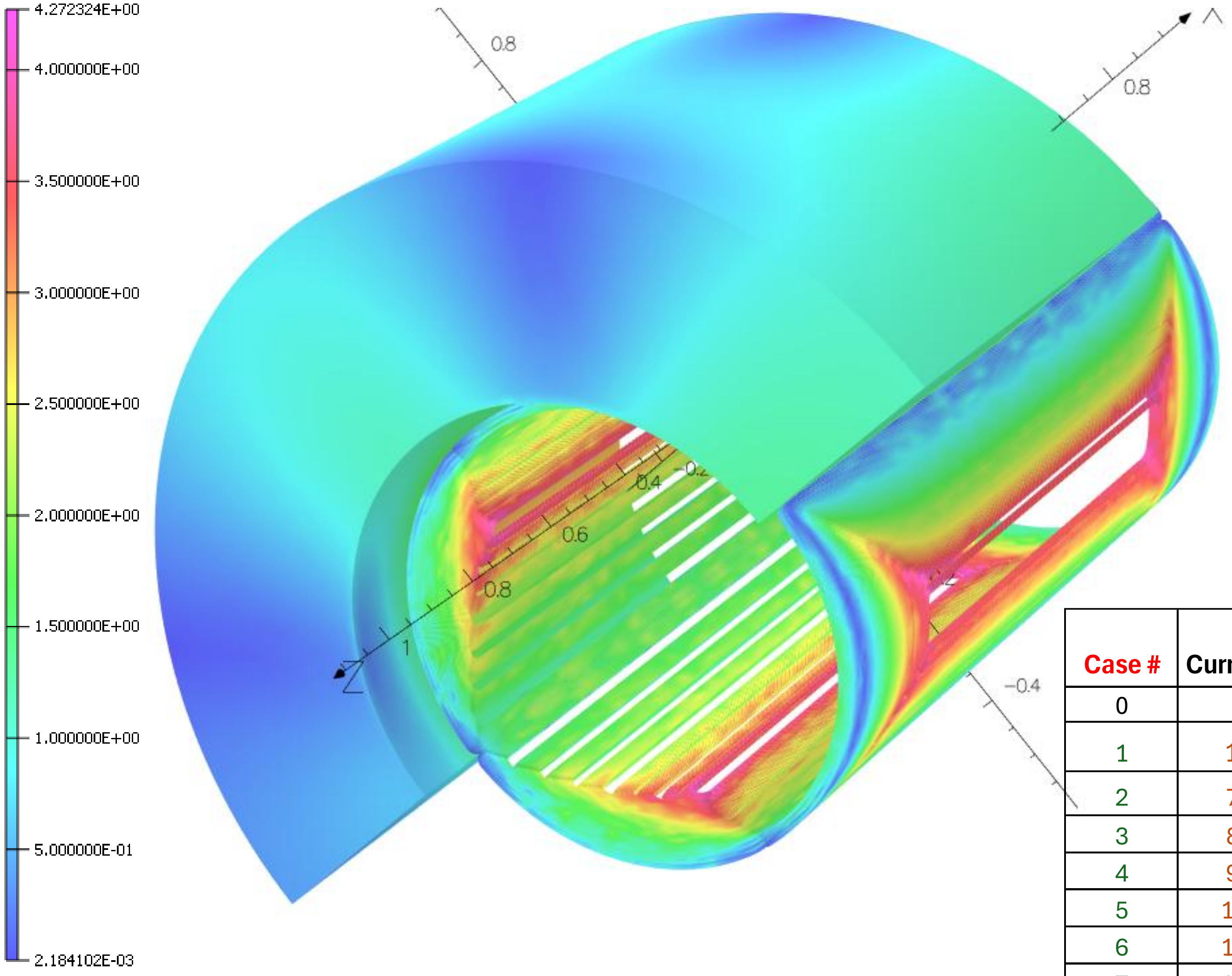
```
$FCNX VC2CB=.TRUE.,VC2CE=.TRUE.,MAGTYPE=5,
      LAYERS=4,RFEMM=400,R0MM=50.,
      RBENDMM=15,NBEND=10 &end
 8 8 1.25  1.778  343.10  1000 0.2 0.10
 -8 8 1.25  1.778  343.10  -1000 0.2 0.10
 8 8 1.25  1.778  343.10  -1000 0.2 0.10
 -8 8 1.25  1.778  343.10  1000 0.2 0.10
B0  7400.  1.
B2  0.  10.
B3  0.  10.
B4  0.  10.
B5  0.  4.
B6  0.  1.
B7  0.  1.
```

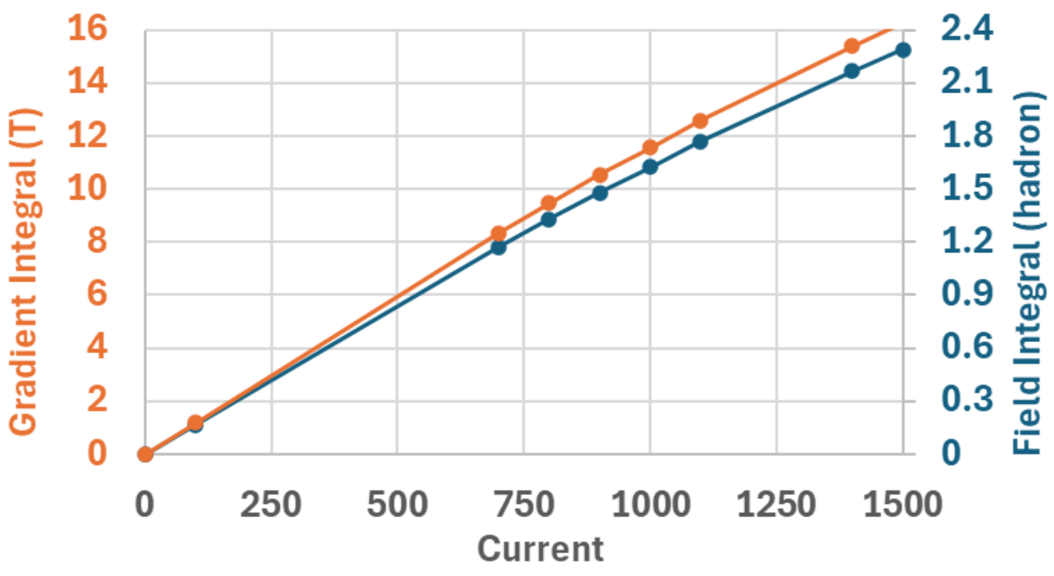
6-Layer Combined Function Coil Design for B0pF





6-Layer Combined Function Design for B0pF





Case #	Current(A)	B(x=0.126)	Bpk	Gint(T)	Bint(h)
0	0	0	0	0	0
1	100	0.168	0.494	1.123	0.1797
2	700	1.173	3.416	7.818	1.2508
3	800	1.330	3.849	8.864	1.4182
4	900	1.479	4.272	9.870	1.5793
5	1000	1.624	4.687	10.842	1.7347
6	1100	1.764	5.092	11.789	1.8862
7	1400	2.158	6.280	14.435	2.3096
8	1500	2.281	6.671	15.251	2.4401

6-layers-combined function

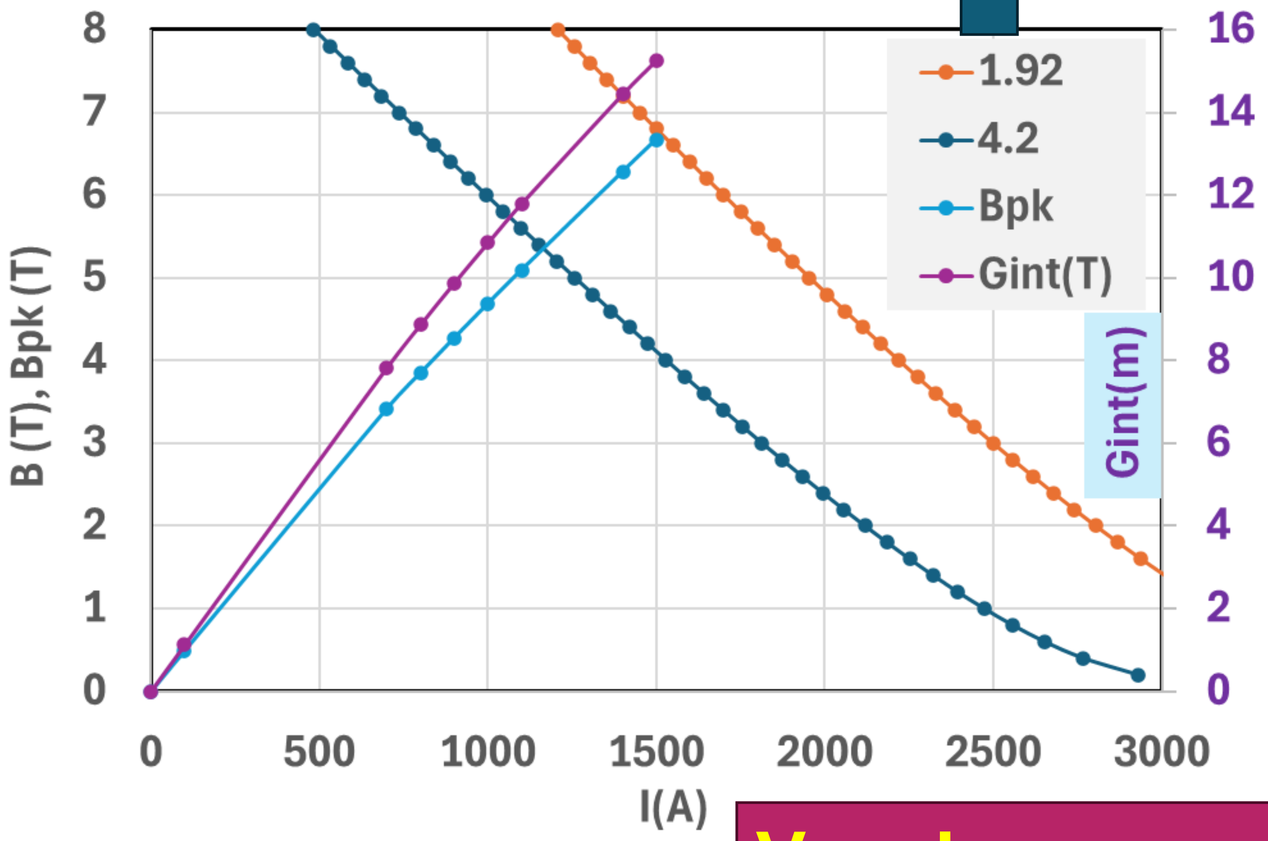
B0pF-CF-6lyrs-a.op3

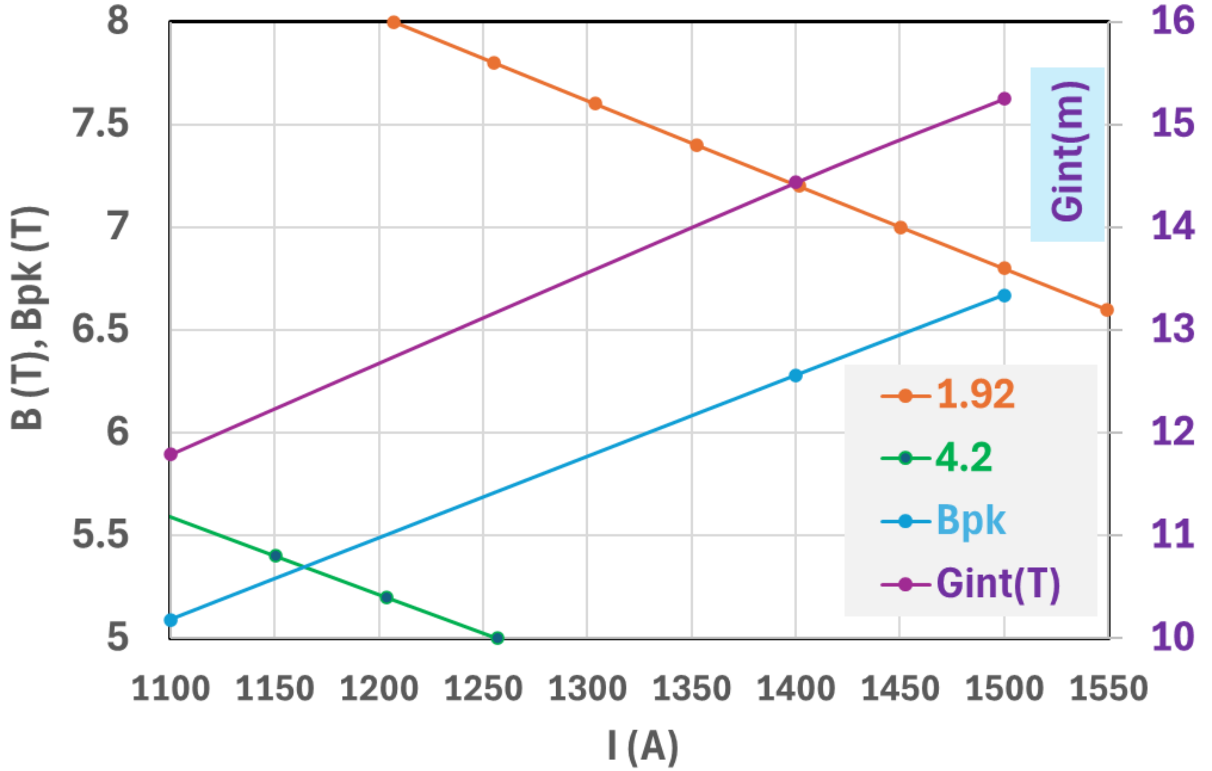
Design Values		Current (A)
Gint(T)	9.75	889
Bint(h)	1.56	889

Stored Energy at Design: ~0.84 MJ
Inductance: ~2.1 Henry

6-layer Optimum Integral Combined Function Design
(6 around 1, all super – design 1.92 K; testing 4.2 K)

Design Values		Current (A)
Gint(T)	9.75	889
Bint(h)	1.56	889





	Iss(A)	Margin(%)
All SC @1.92K	1520	71%
All SC @4.2K	1160	30%

Very large margin @1,92K; healthy margin @4.2K

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

- Starting design with a big margin (71%) allows some to be traded for quench protection (e.g., higher cu/sc – too late).
- However, making the center wire copper (instead of super) is expected to help. This will improve the quench back.
- It may also increase effective cu/sc ratio (from 1.75 to 2.21), depending on the current transfer between superconductor and copper wires. This would further reduce the hot spot temperature, beside improving stability against transients.
- The ramp rate reduction in I_c also gets eliminated.
- The penalty will be a reduction in the critical current of the cable which will be now 6/7 of what it was for all super wires.

➢ Question: Will that reduced margin be still sufficient?

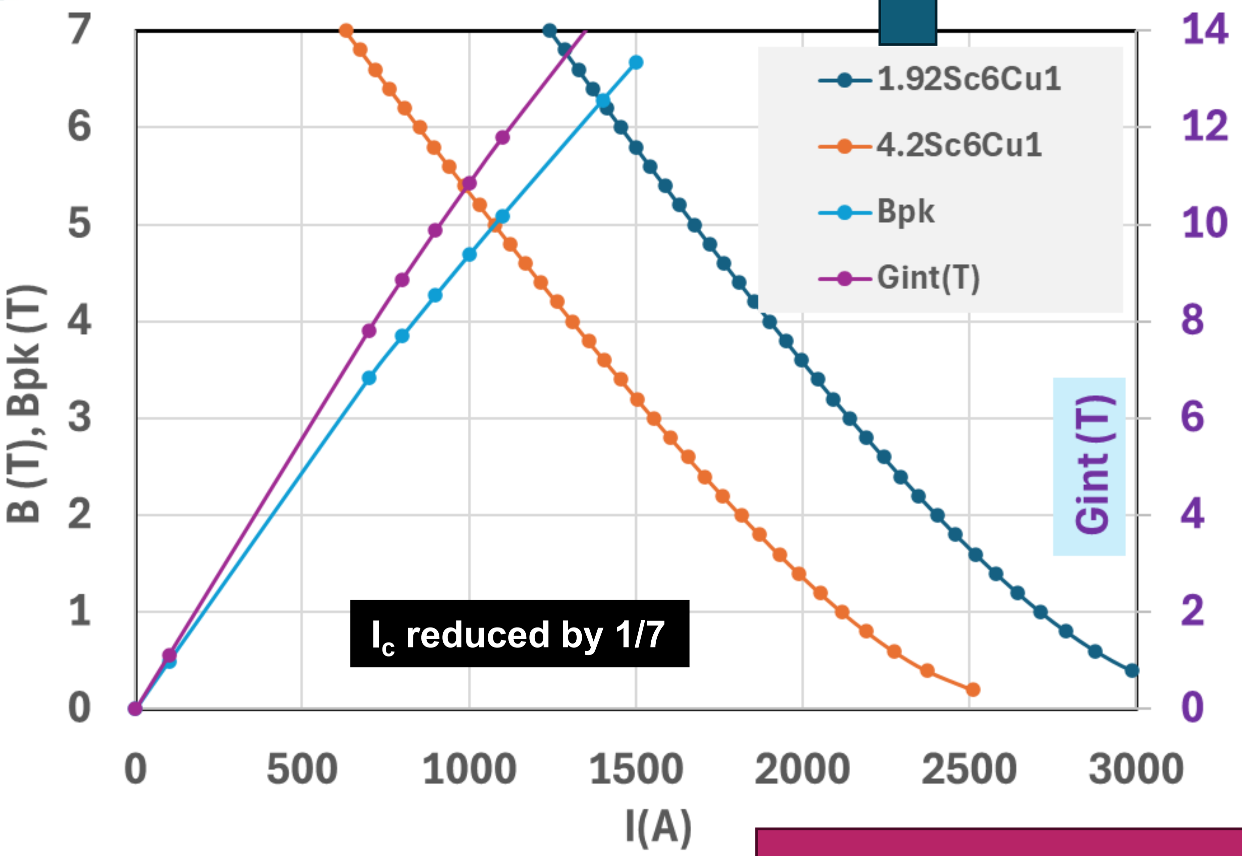
  ✓ Yes, it is (please see the next slide).

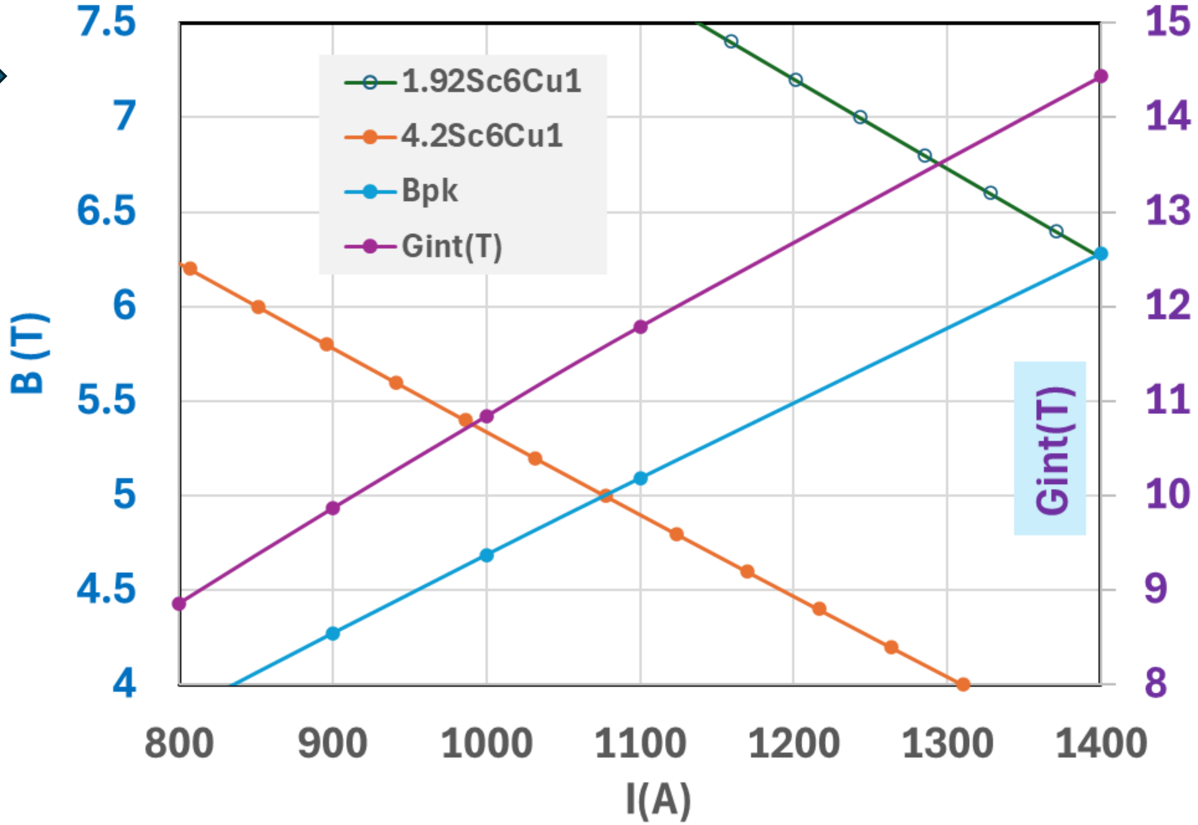
Effective Copper to Superconductor ratio in 6-around-1 copper

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@4.2K	1077	Amp
Jcu@Qnch	1272	A/mm^2
Iquench@1.92K	1520	Amp
Jcu@Qnch	1795	A/mm^2
Idesign	889	Amp
Jcu@design	1050	A/mm^2

6-layer Optimum Integral Combined Function Design
(6 super around 1 Cu wire – design 1.92 K; testing 4.2 K)

Design Values		Current (A)
Gint(T)	9.75	889
Bint(h)	1.56	889

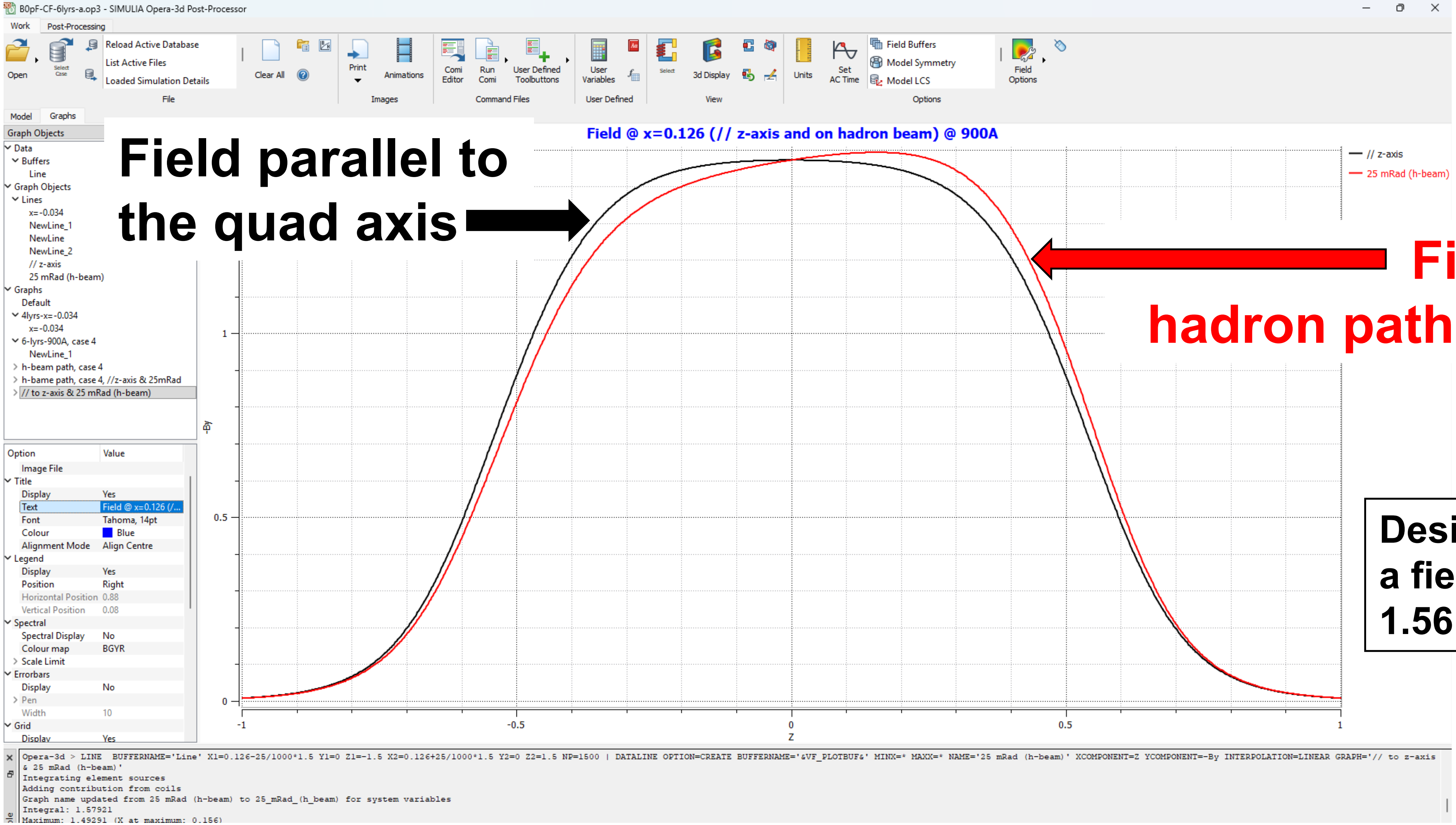




	Iss(A)	Margin(%)
SC6Cu1 @1.92K	1400	57%
SC6Cu1 @4.2K	1077	21%

Sill a healthy margins both at 1.92K and at 4.2K

Field along the hadron path (X=126 mm) @ 900 A

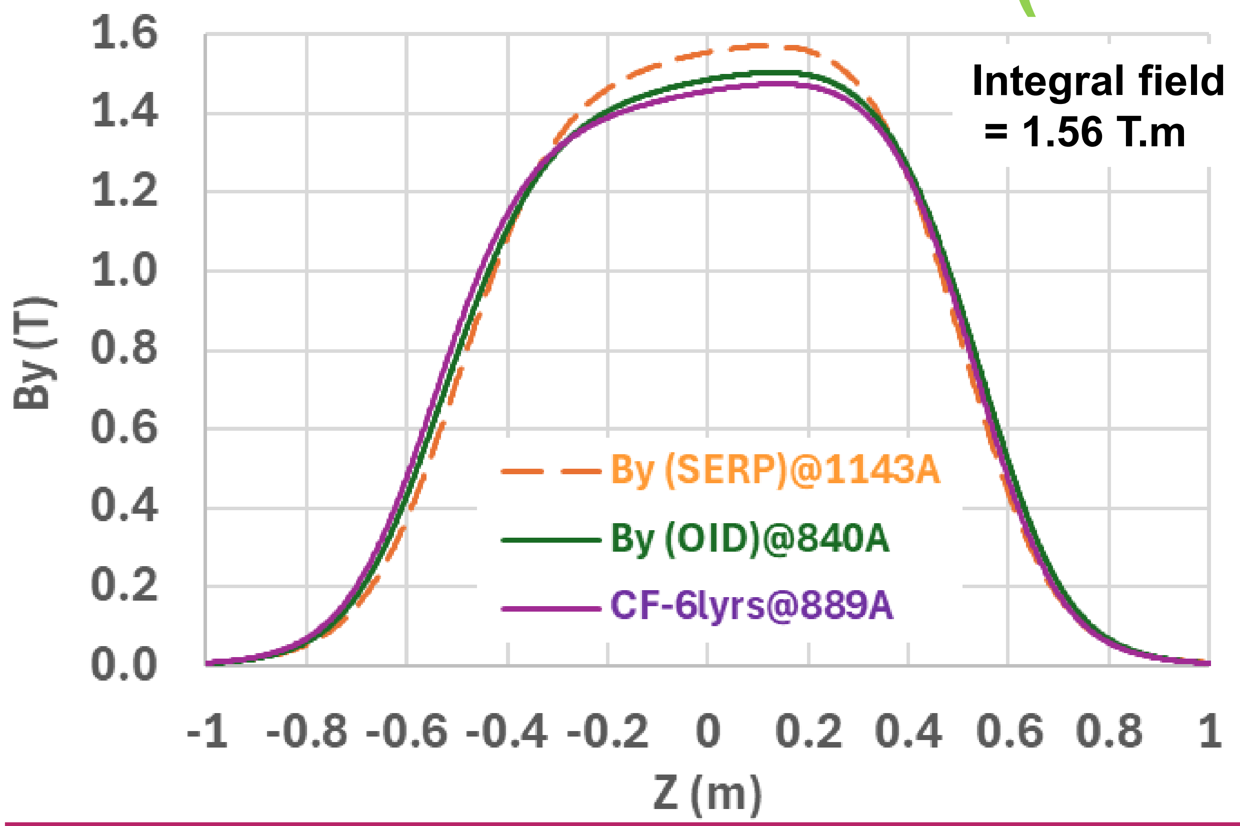


Field parallel to the quad axis

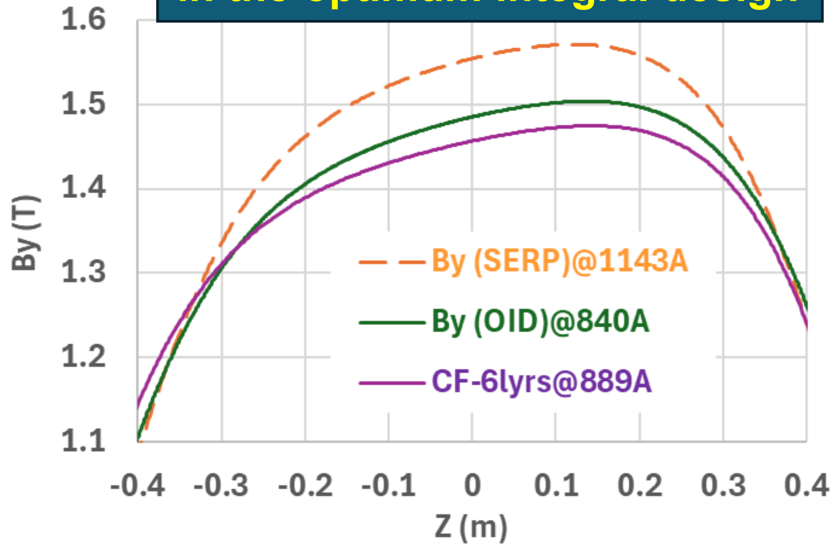
Field on the hadron path (25 mrad)

Design current for a field integral of 1.56 T.m: 889 Amp

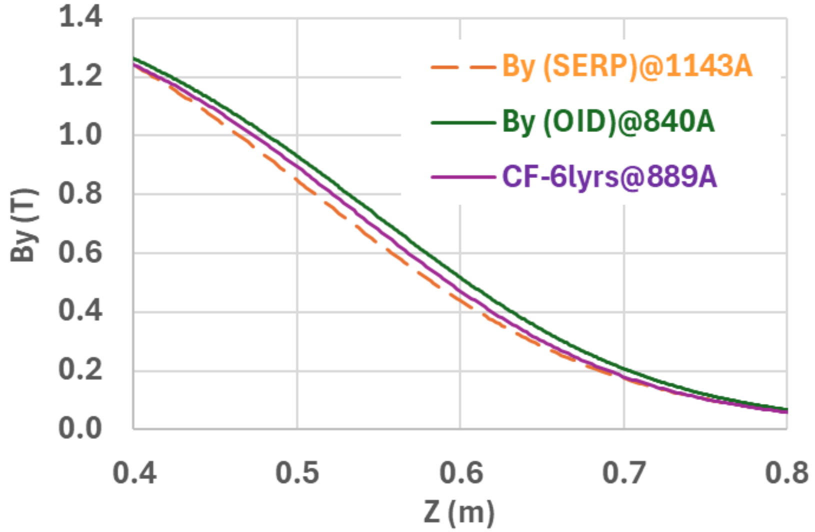
Field along the hadron path in Serpentine, OID (Quad+Dipole) and OID (Combined Function)



Note: A drop in the peak field in the optimum integral design



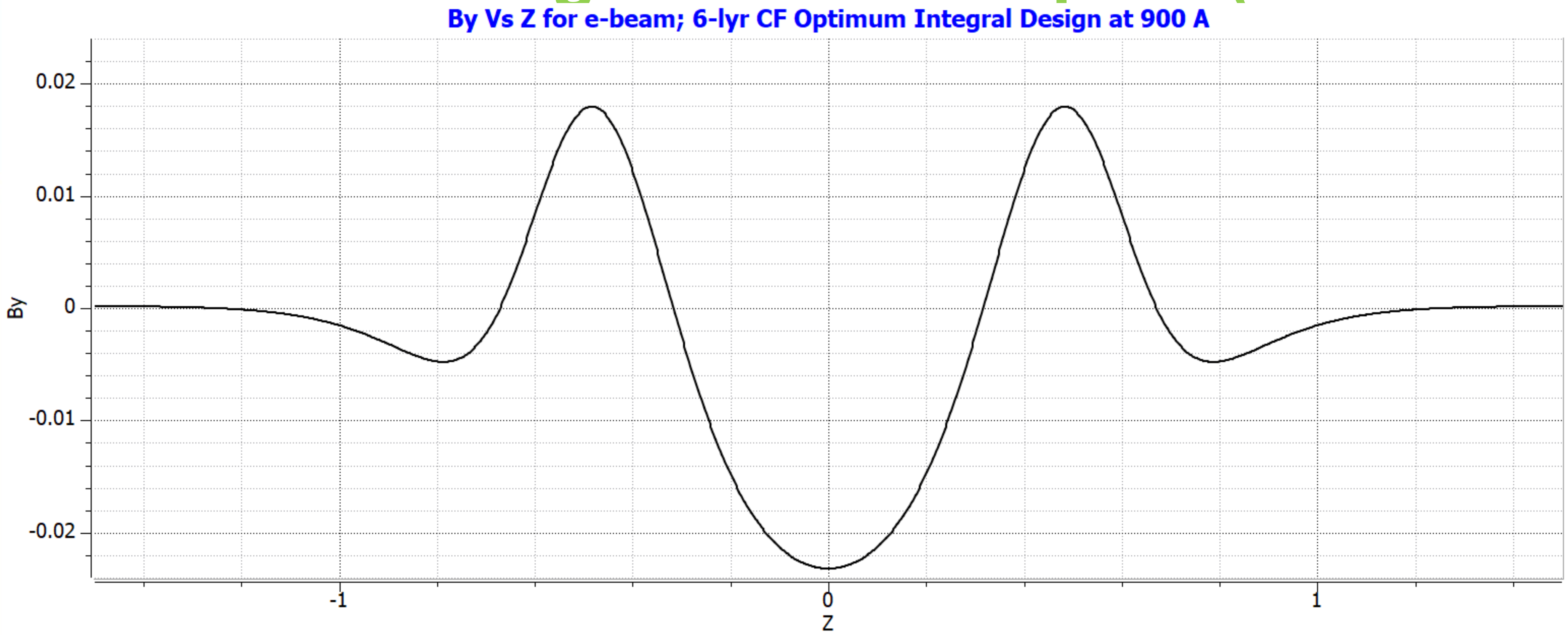
Expect a reduction in Lorentz forces due to a lower current and a lower field (IXB)



Note a fewer layers and a lower current in OID:

- **Serpentine design (8Q+2D): 10 layers @1143A**
- **OID separate coils (6Q+1D): 7 layers @840 A**
- **OID combined function (6CF): 6 layers @889 A**

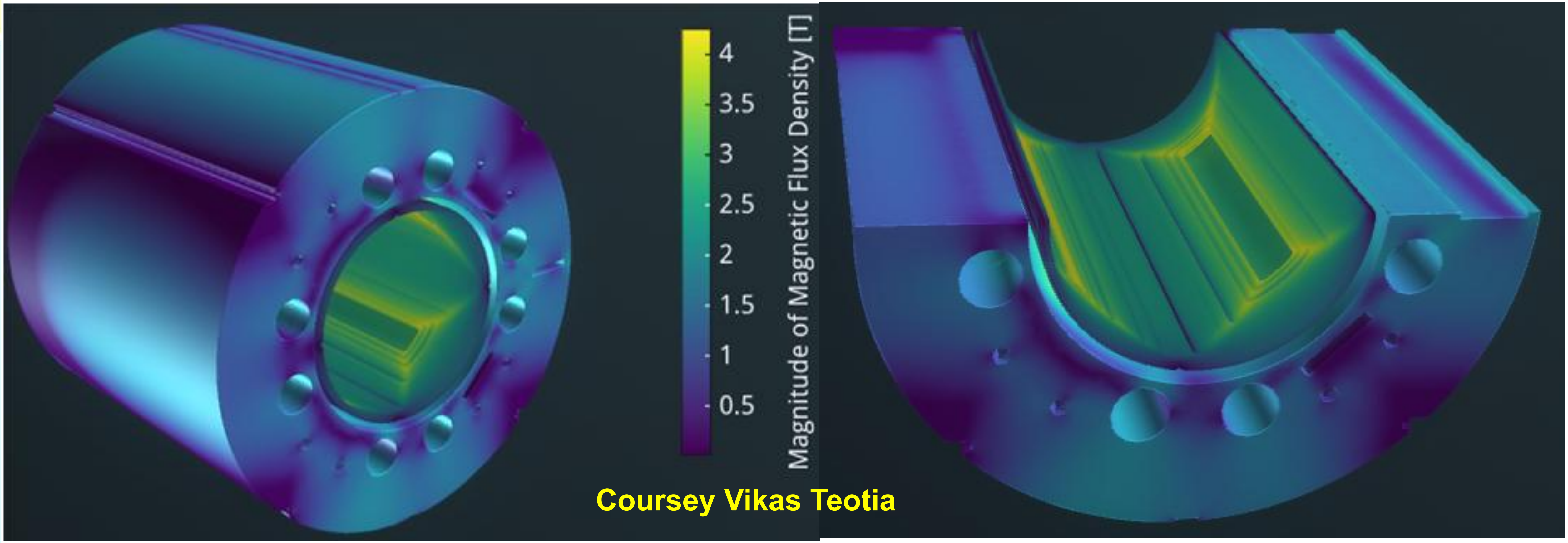
Field along the electron path (X=-34 mm)



Swing in B_y in the initial design is ~0.02 T (a factor of two more than in the serpentine design presented at PDR). This swing may be reduced by adjusting the body-end optimization, perhaps at the expenses of efficiency.

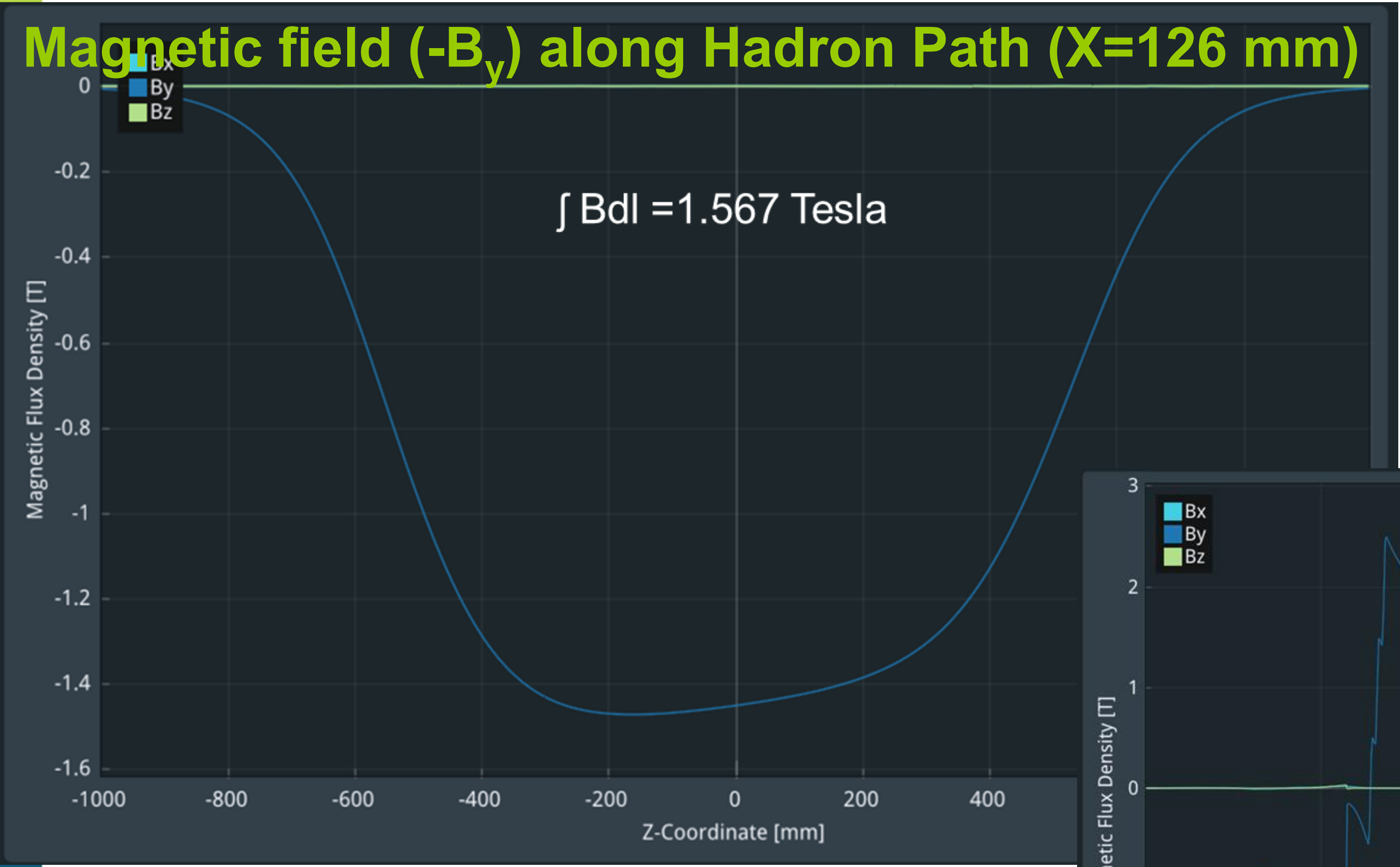
- **However, the merit of a hard 0.01 T specification still needs to be evaluated.**

RAT Model of the 6-layer Combined Function Optimum Integral Design for B0pF



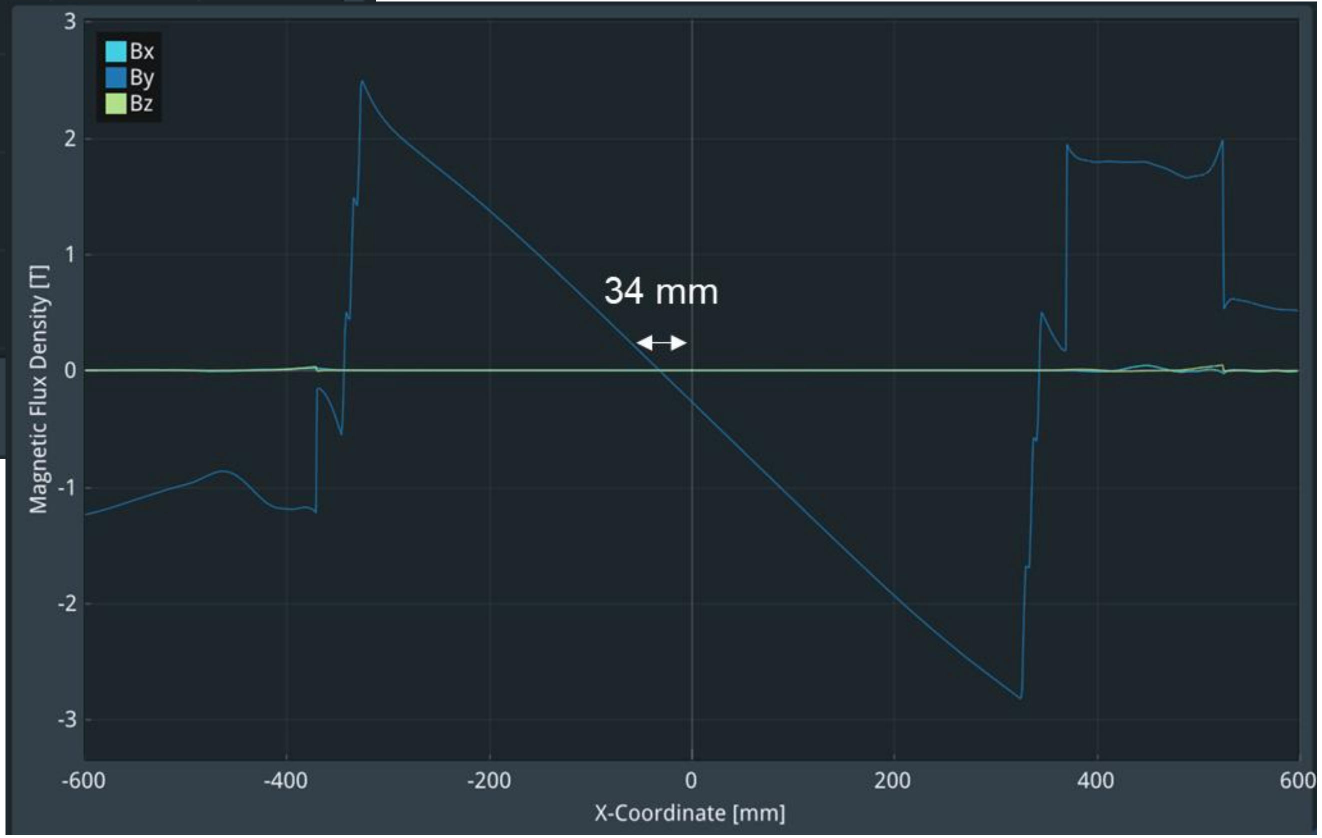
- **RAT is used to cross-check and confirm the design. Other codes OPERA3d and OptIntegral (custom code)**
- **RAT also creates inductance matrix which is used in the quench simulation codes.**

Magnetic field ($-B_y$) along Hadron Path (X=126 mm)



Good Agreement

Field profile on x-axis

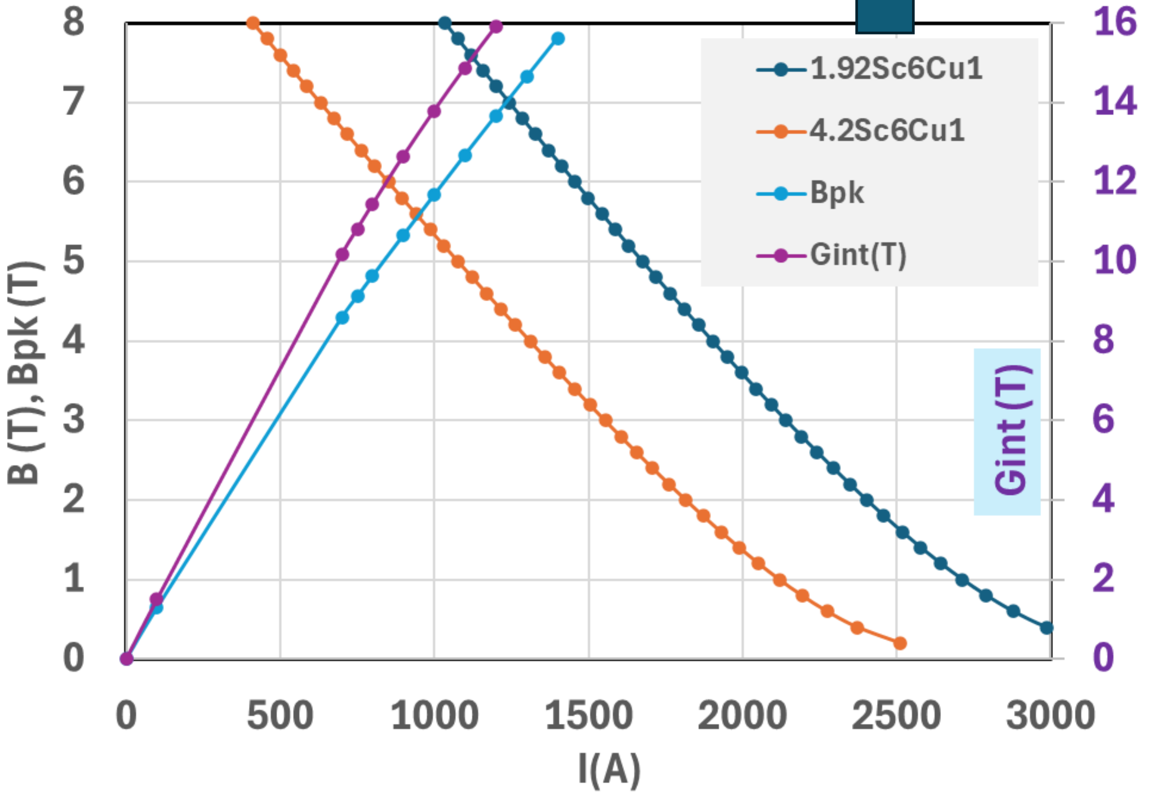


8-layer Optimum Integral Combined Function Option

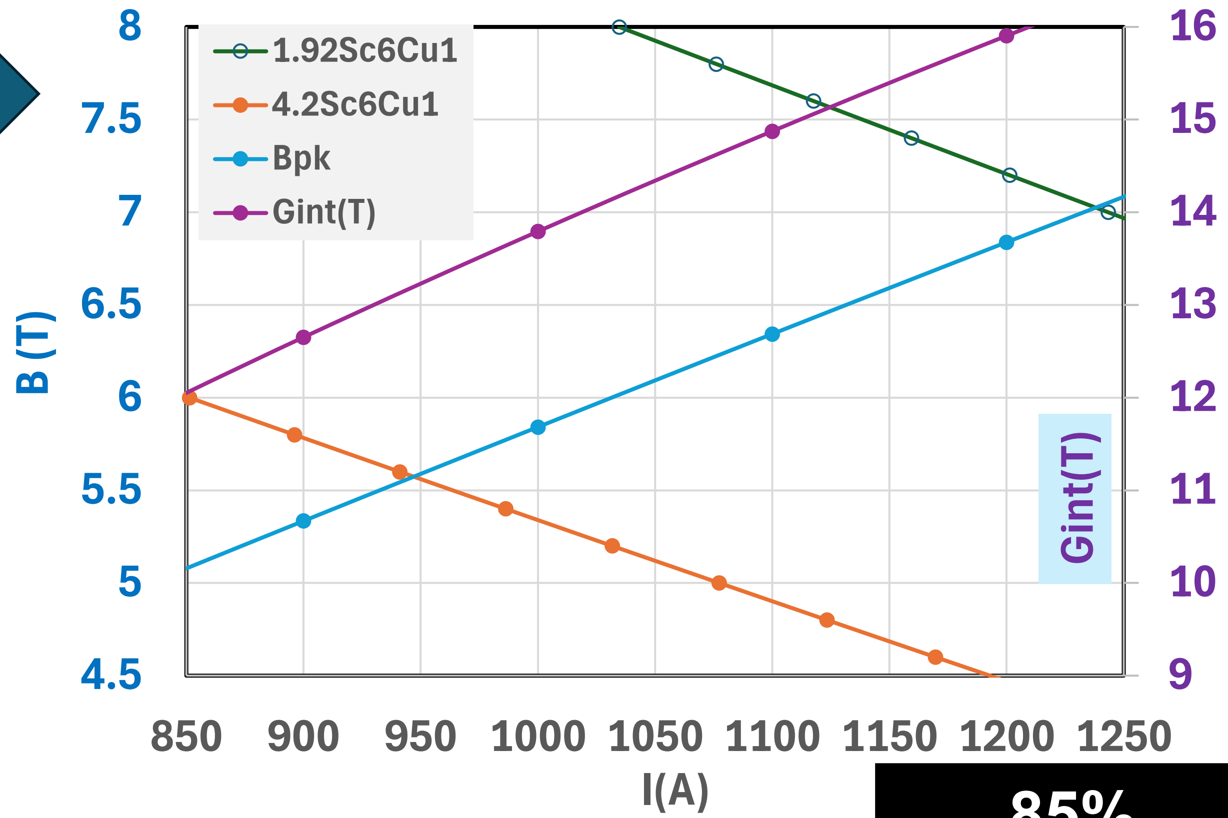
(Risk Mitigation – 2 more layers may be added, depending on the previous tests)

➢ **Current reduced; margin increased!**

Design Values		Current (A)
Gint(T)	9.75	671
Bint(h)	1.56	671



Central wire in 6-around-1 copper (rest 6 are super)



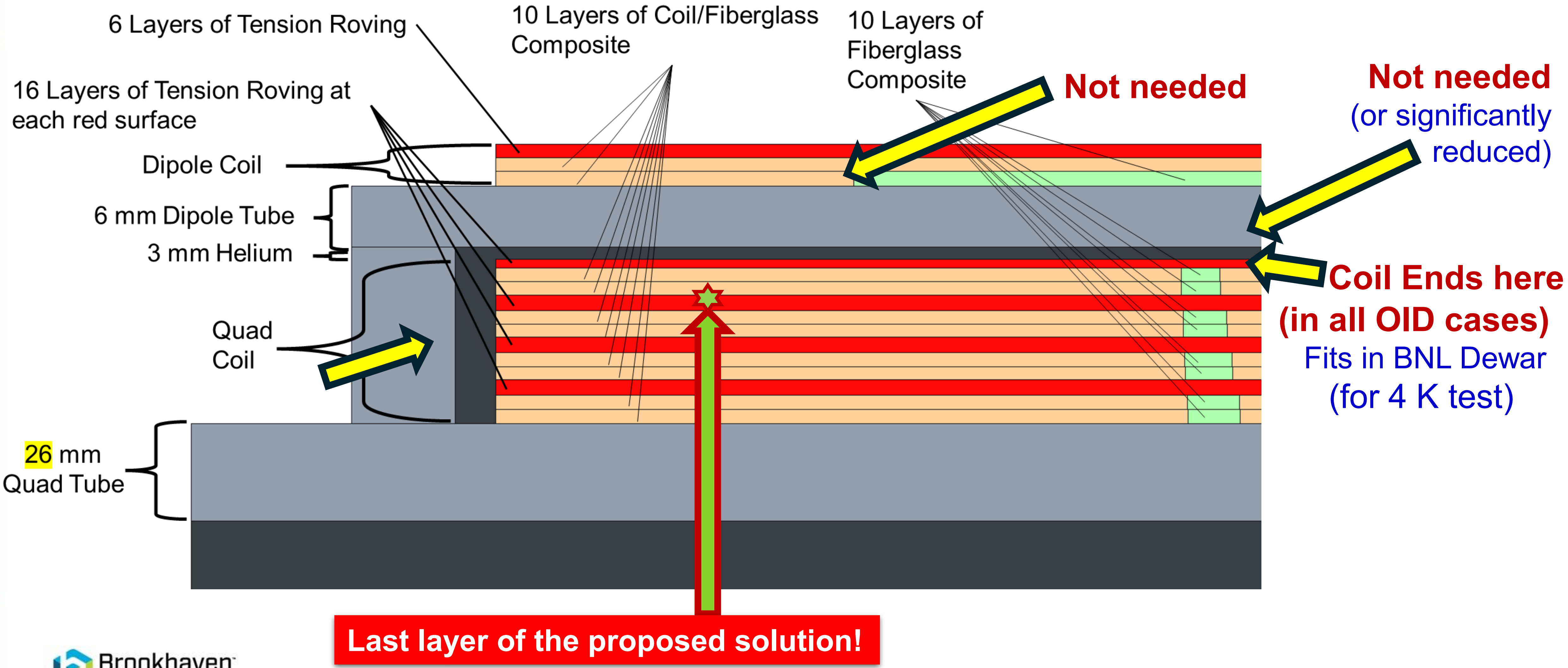
	Iss(A)	Margin(%)
SC6Cu1 @1.92K	1240	85%
SC6Cu1 @4.2K	948	41%

85% operational margin

➢ **Demonstrate performance at 4.2 K test in BNL Dewar with over 50% margin**

Possible Impact on the Coil Build-up

- In addition to the reduced current for QP, the coil build-up also gets reduced!



Other Studies

- Based on the initial studies, a 6-layer design seems to offer a good balance between the quench protection, margin and the number of layers.
- Several other variations were examined in both (a) separate function coils and (b) in combined function coils. These variations included 4-layer designs and 8-layer designs, as well as different number of copper wires in 6-around-1 cable.
- More iterations (including updating the code for more flexibility in the combined function design & feedback from quench analysis), should bring better optimization.
- More layers means lower current but higher inductance. We may be able to go for even higher dump resistor while still staying in the safe coil voltage limit.
- Model calculations just started with RAT. Initial results show a good agreement.
- Individual optimum integral coil will take longer to build. However, overall reduction in manufacturing the coil should be significant due to fewer layers.
- A few quick test windings should be carried out for better optimization, etc..

Summary and the Next Step (1)

- **Optimum Integral Design (OID) is significantly more efficient than the preferred serpentine coil for B0pF due to a small coil length to coil diameter ratio.**
- **A 6-layer design combined function optimum integral design meets the integral field requirements at ~889 A with over 70% margin.**
- **The large margin allows the central superconducting wire in the 6-around-1 cable to be replaced by the copper wire, while still maintaining a healthy margin of over 55% and over 20% at 4.2 K to validate the design.**
- **Lower current (1143 A => 889 A) should reduce voltage across the coil during energy extraction after quench and reduce the hot spot temperature.**
- **The proposed update in design should help mitigate some of the outstanding risks. Making the central wire copper would further help in quench protection.**

Summary and the Next Step (2)

- Incorporating the proposed update, changes only the large quadrupole and dipole coils. All other aspects of B0pF remain essentially the same.
- Since everything fits in the established envelop, most of the detailed designed work carried out so far should remain applicable.
- This update is in time and should not have any impact on the overall schedule. The strength of the direct wind technology is that the optimization in the EM design only changes the wiring file, with also no impact on the schedule.
- Next step will be to perform a detailed quench analysis and establish a more robust solution for the quench protection. There are several options.
- Mechanical analysis needs to be performed again. Since Lorent forces are lower, the winding tension should get reduced. This may possibly also reduce the thickness of the inner tube (?), which would reduce the coil inner radius.

Extra slides

Background

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

Brookhaven National Laboratory Magnet Division Optimum Integral Design for EIC -Ramesh Gupta Magnet Steering Group Meeting July 25, 2025 8

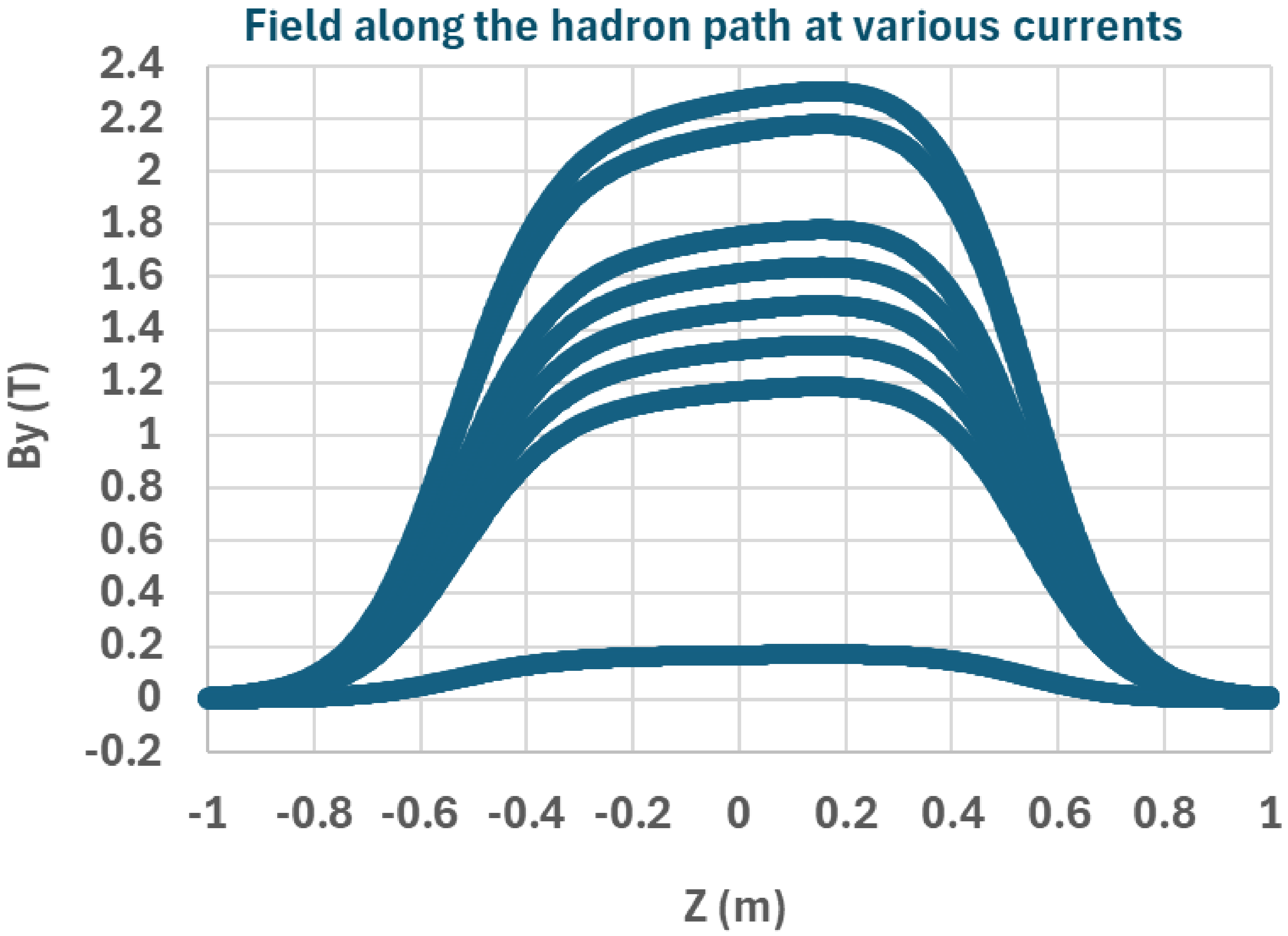
The slide presented in an earlier MSG encouraged us to evaluate the optimum integral design for B0pF.

However, to justify a change, the benefits must be significant, such as:

- ***Number of layers gets reduced and/or margin gets increased.***
- ***Quench protection becomes less challenging.***
- ***Stresses gets reduced significantly.***

Field Profile along the Hadron Path at Different Excitation

6-layer combined function design



Possible Impact on the Coil Build-up

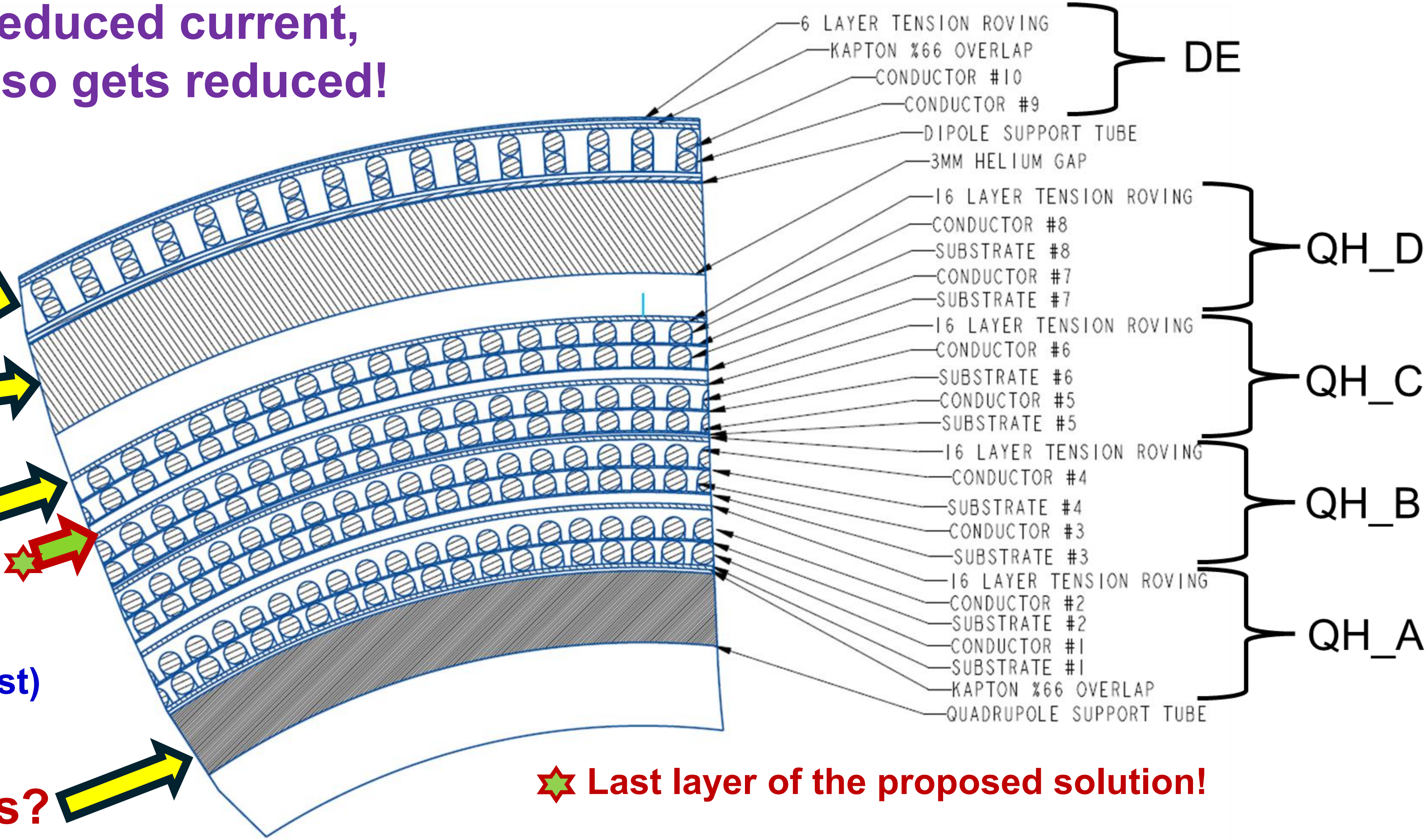
In addition to the reduced current, the coil build-up also gets reduced!

Not needed

Not needed
(or significantly reduced)

Coil Ends here
(in all OID cases)

Fits in BNL Dewar
(enough margin for 4 K test)



Reduced thickness?

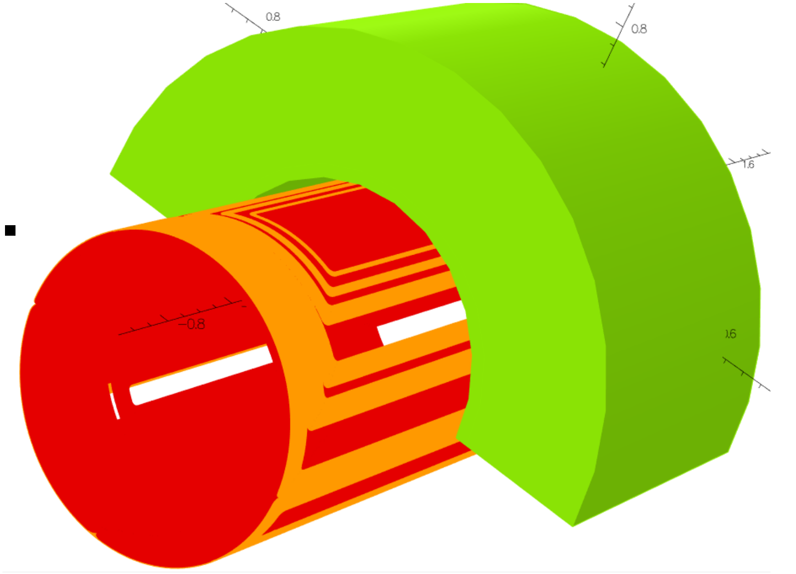
Last layer of the proposed solution!

(that will bring all layers inside, further improving the performance)

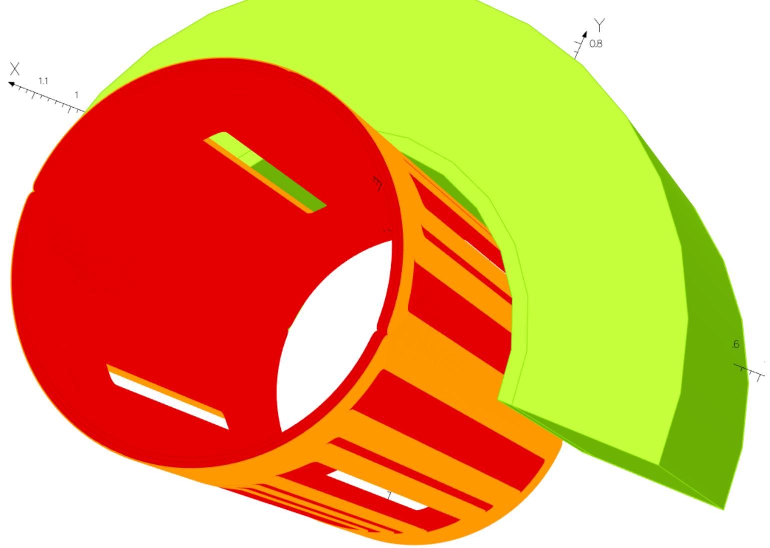
OPTION A – QUADRUPOLE IN SERIES WITH THE DIPOLE

Dipole Coil(s) Added to the Quad in B0PF

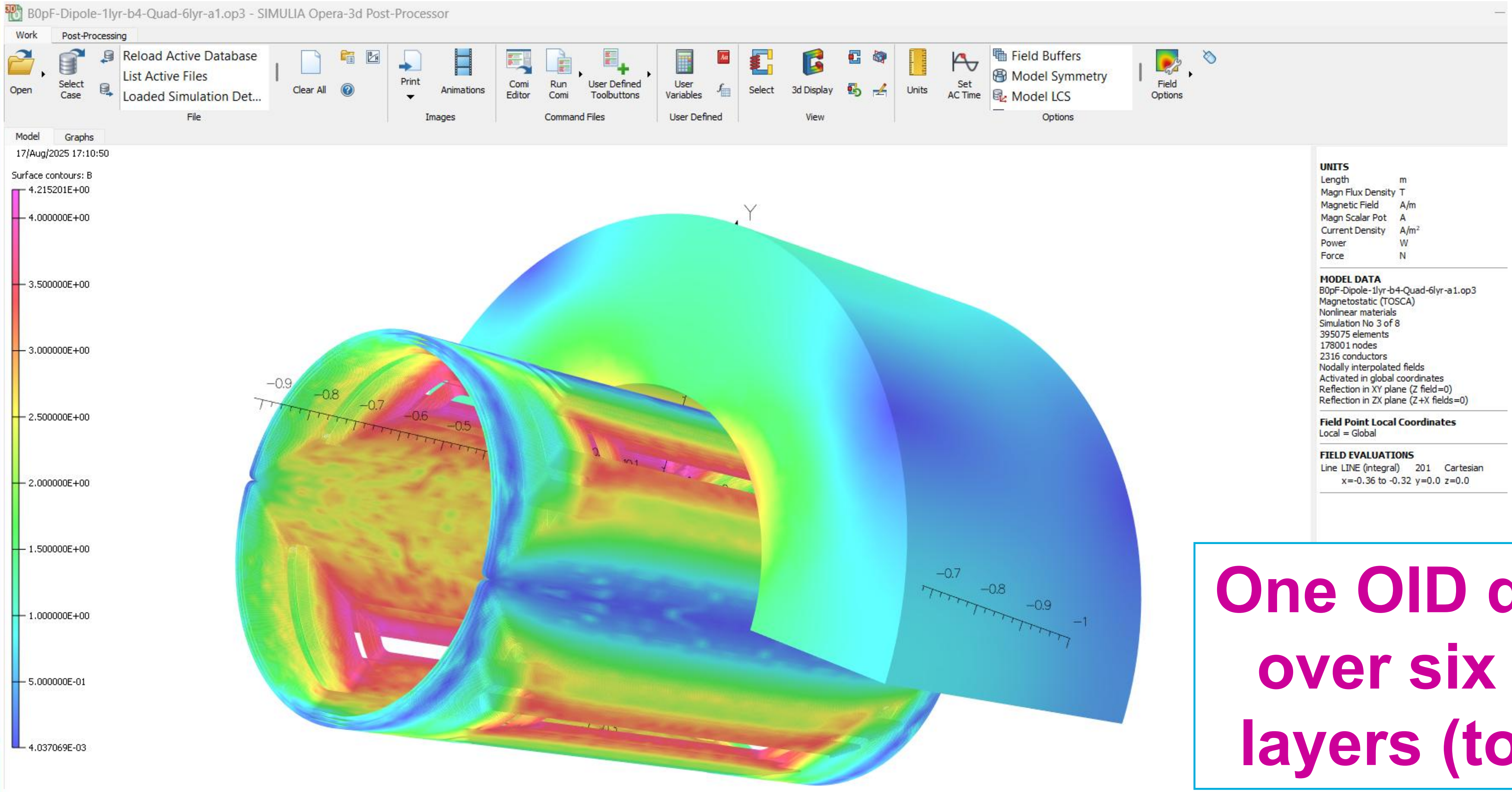
- **Dipole coil(s) runs in series with the quad and is made with the same cable as the quad coils.**
- **A single layer is enough (optimum integral design can have a single layer, as was in the optimum integral corrector in the AGS tunnel)**
- **Even a single layer design creates too much field, and 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

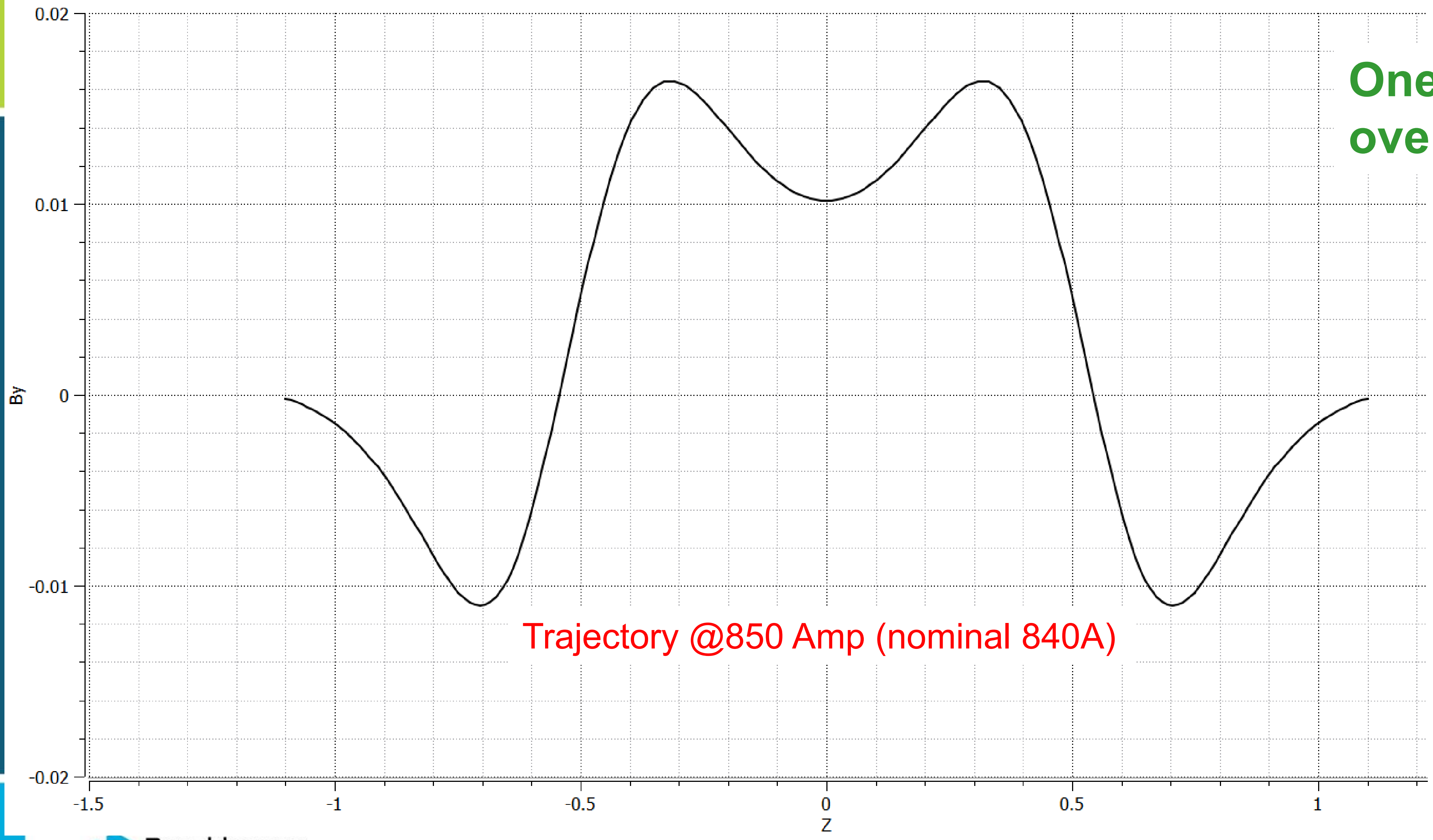


Model with field Superimposed at 850 A
(nominal current for desired integral is 840 A)



One OID dipole layer over six OID quad layers (total seven)

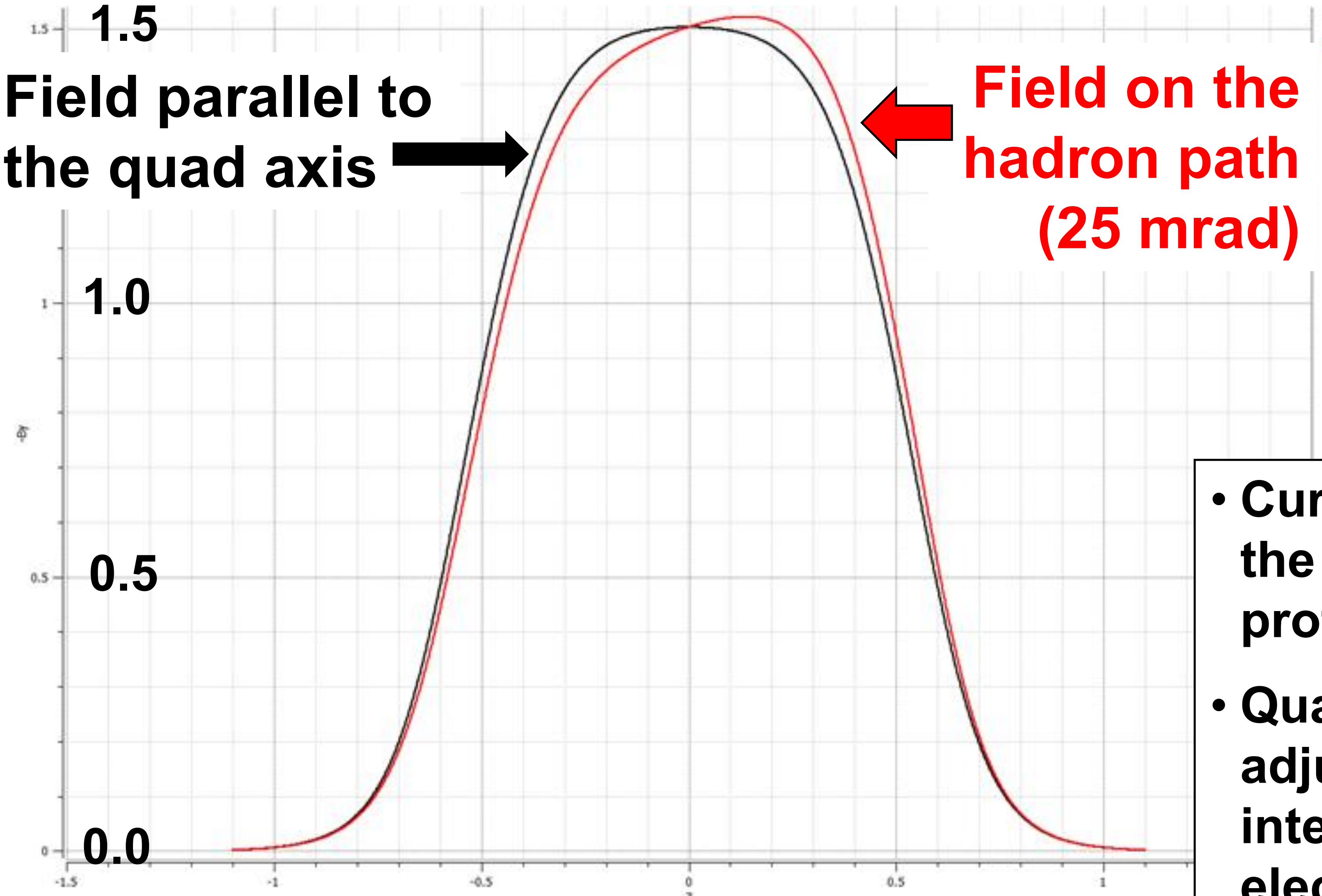
Field along the electron path (X=-34 mm)



One dipole layer over six quad layers

- **Integral field is almost zero.**
- **Oscillations in B_y, are already close to +/- 0.01 T, even without tuning.**
- **The design may be fine tuned, if necessary.**

Field along the hadron path (X=126 mm)



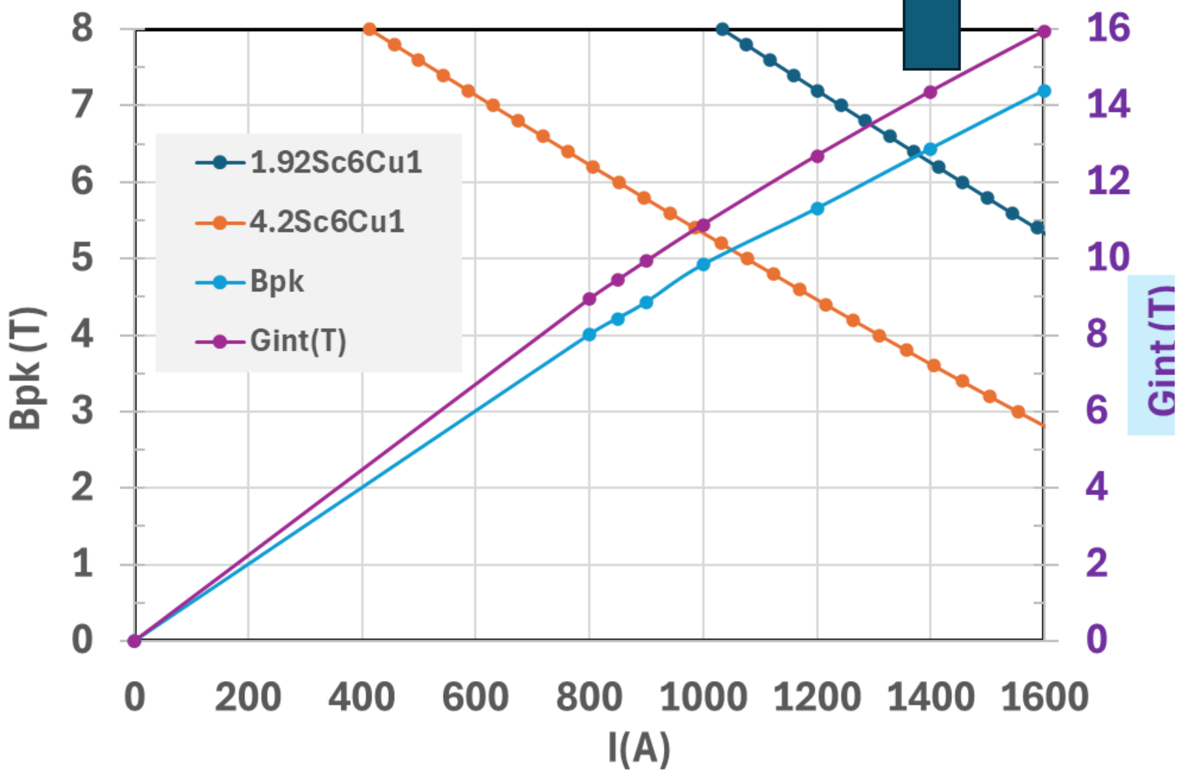
One dipole layer over six quad layers

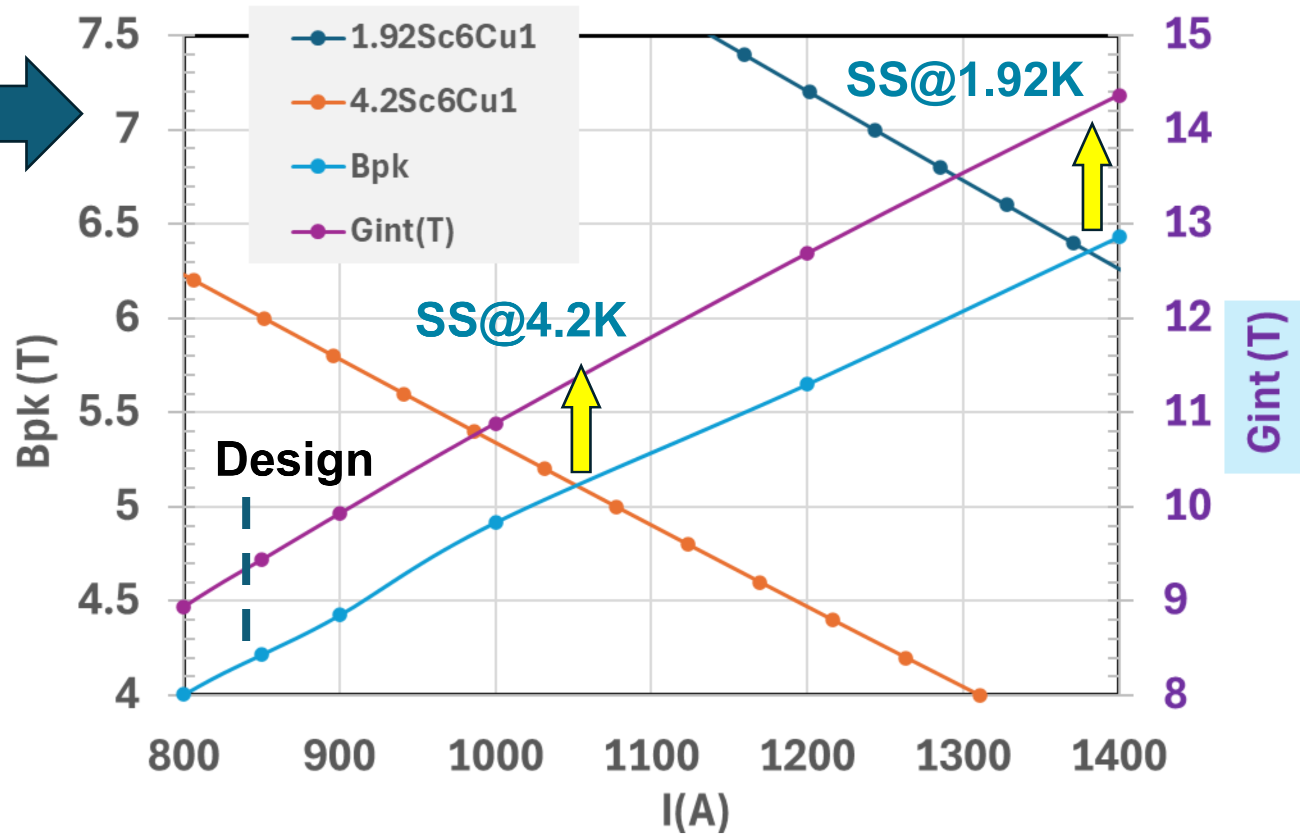
- Current in quad to make the integral 1.56 T.m for the proton beam is ~840 A.
- Quad to dipole ratio is adjusted to make field integral zero on the electron beam path

Trajectory @850 Amp (design current 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 @840 A instead of 1143 A

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

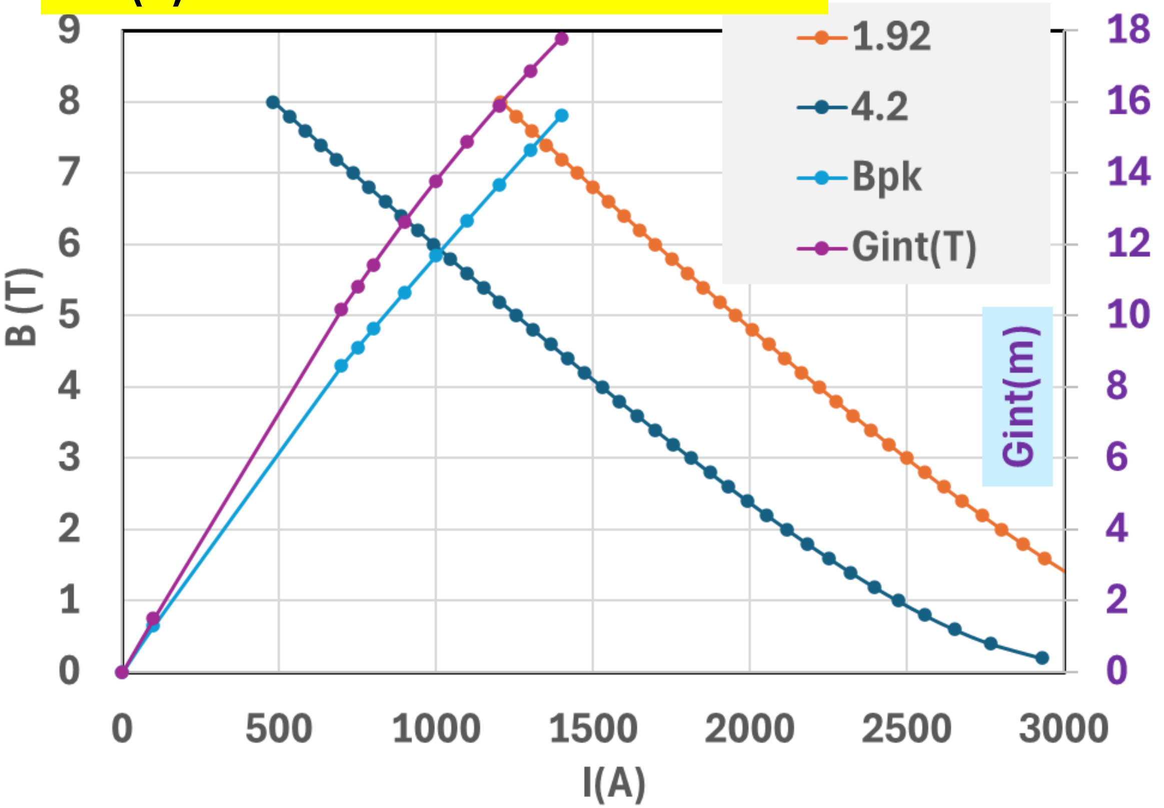
I_{ss} @4.2K: ~1050 Amp (~25% margin)
I_{ss} @1.92K: ~1390 Amp (~65% margin)
*****BOTH ARE HEALTY MARGINS*****

8-layer Optimum Integral Combined Function Option

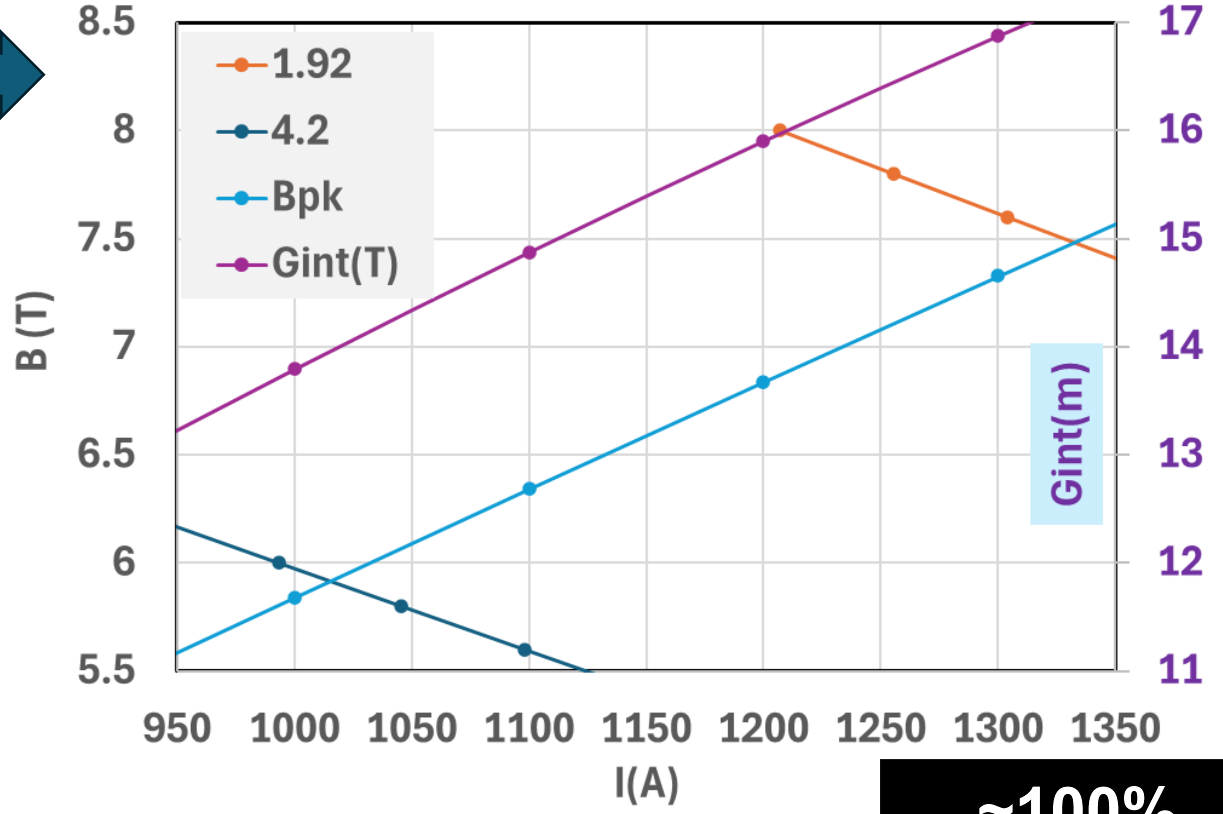
(Risk Mitigation – 2 more layers may be added, depending on the previous tests)

- Current reduced; margin increased!

Design Values		Current (A)
Gint(T)	9.75	671
Bint(h)	1.56	671



All seven wires in 6-around-1 superconducting



	Iss(A)	Margin(%)
All SC @1.92K	1330	98%
All SC @4.2K	1020	52%

~100% operational margin

- **Demonstrate performance at 4.2 K test in BNL Dewar with over 50% margin**