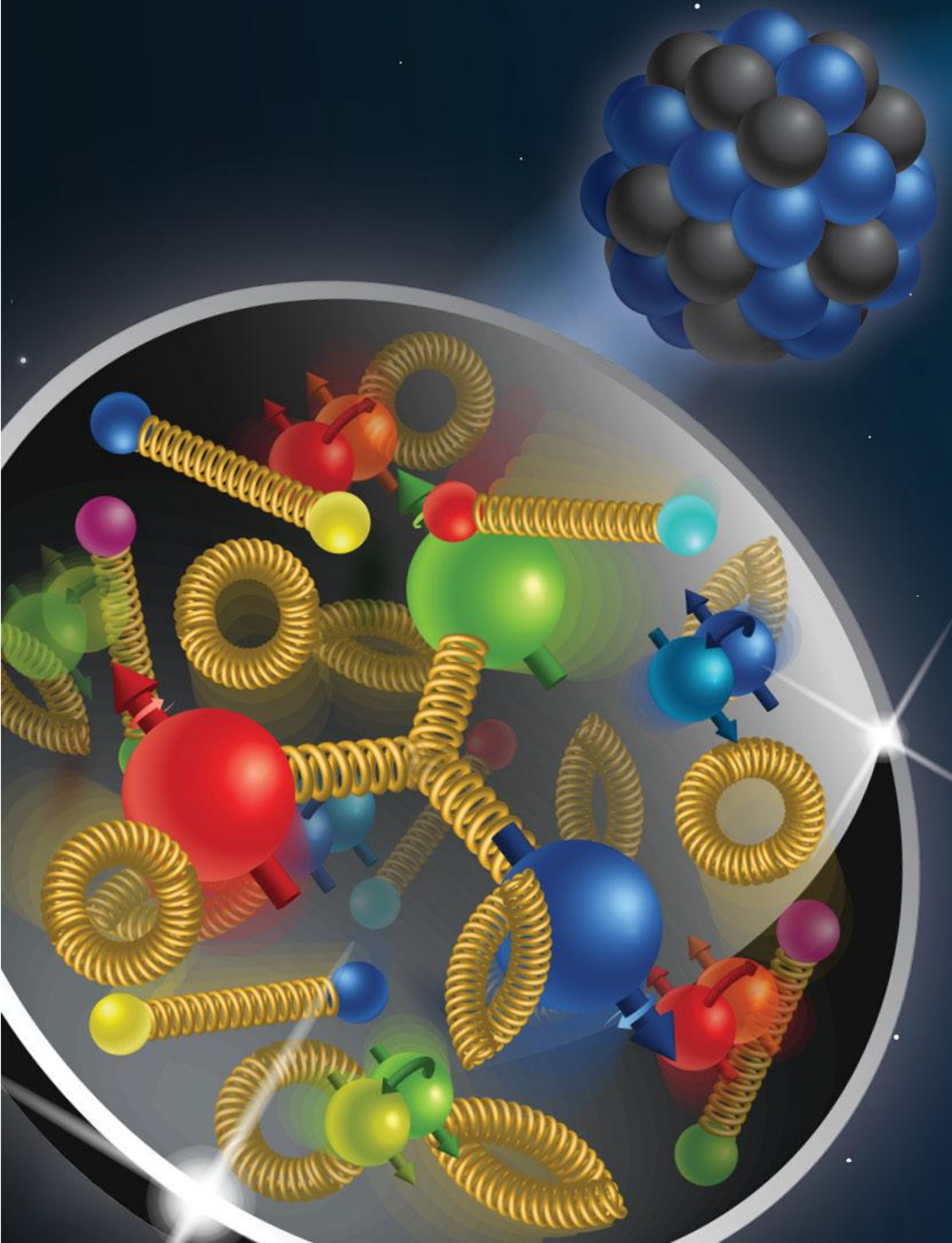

First Look at the Optimum Integral Design for B0pF

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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

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- ***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!

Self-imposed Designs goals for the 1st examination

- The preferred design is 6-layer (three coil sets), even though 4-layer and 8-layer designs were also examined. All designs are normalized for an integral field gradient of 9.75 T.
- Only one case each was optimized and only for a good field quality. More work should reduce the peak field for higher margin.
- The current baseline serpentine design operates at 1.92 K. It uses the 6-around-1 cable with all seven wires being superconducting.
- Variations examined for the optimum integral design: (a) 1.92 K Vs. 4.2 K, and (b) 7 superconductors Vs. 6 super around 1 copper.

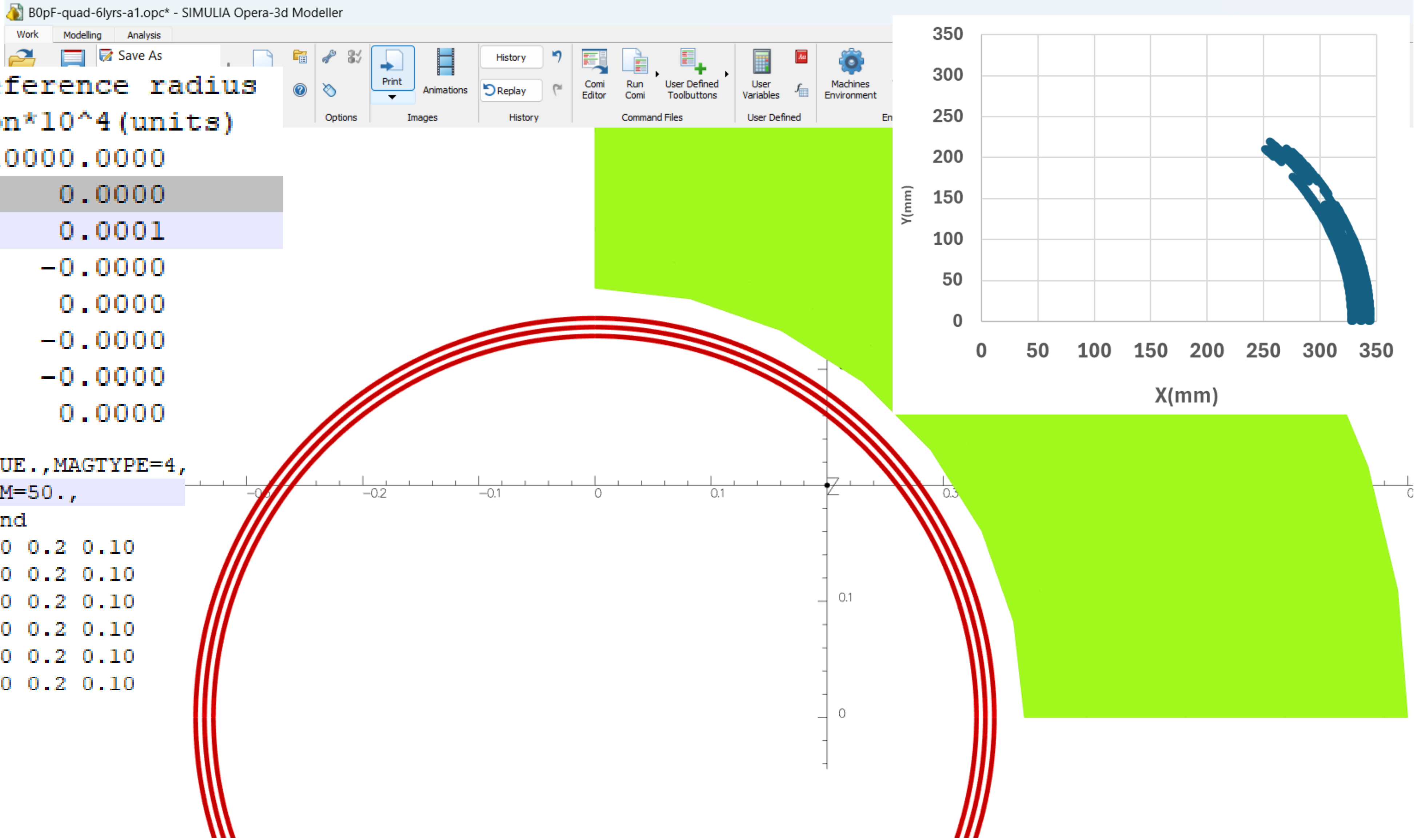
Six Layer (3 coil sets) Design

6-layer coil optimized with the optimum integral code

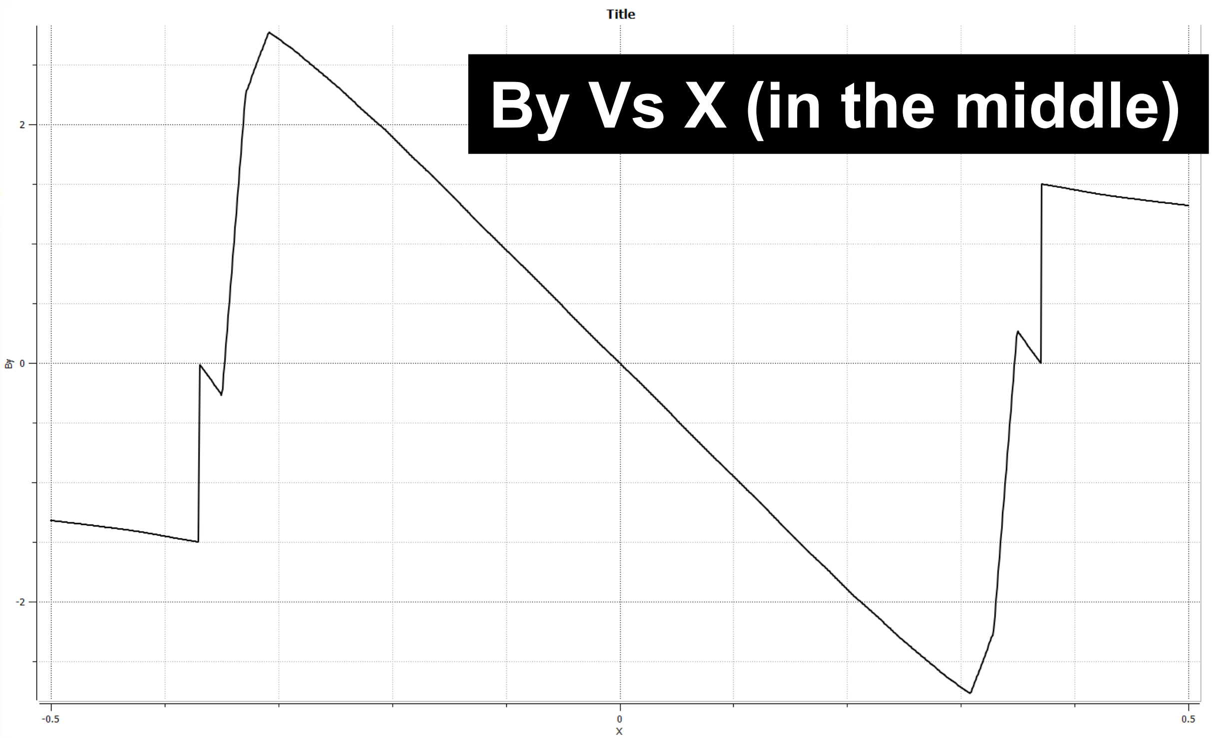
Harmonics at 50 mm reference radius

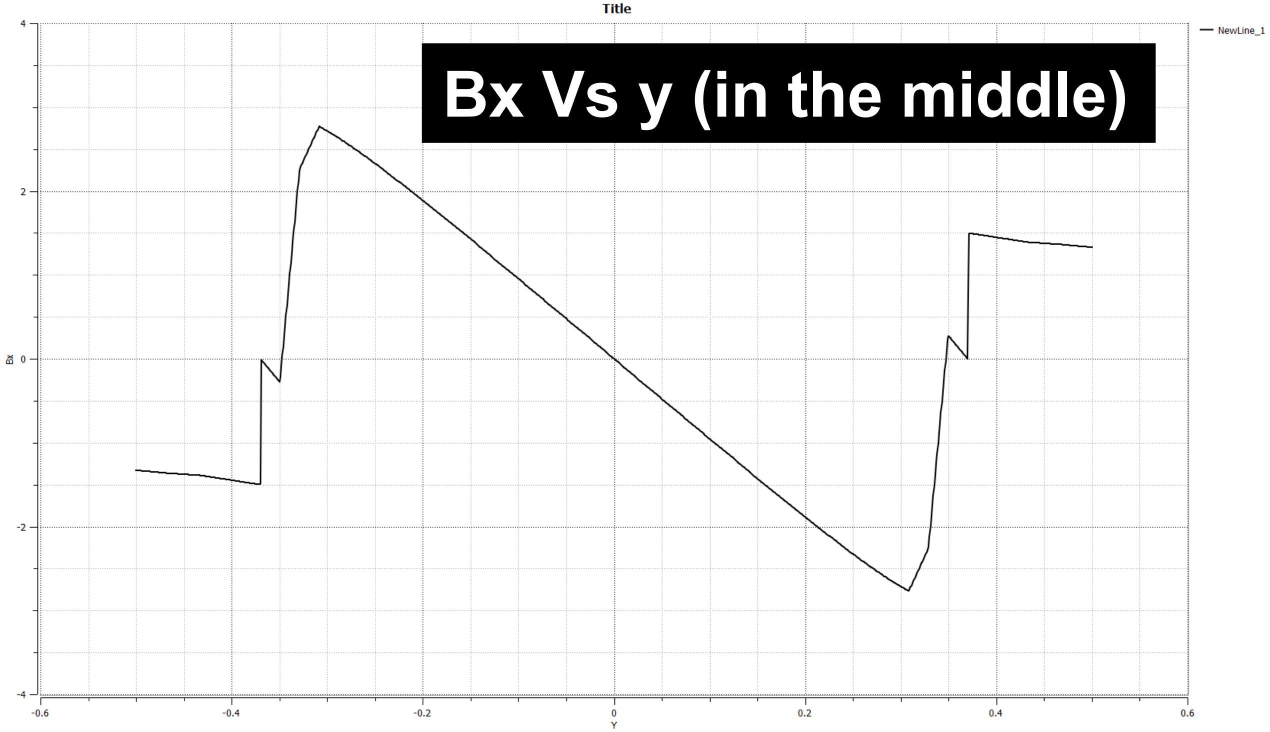
No.	Bn(T.m)	bn*10^4(units)
2	0.53402E+00	10000.0000
6	0.96962E-11	0.0000
10	0.35185E-08	0.0001
14	-0.16464E-11	-0.0000
18	0.55250E-15	0.0000
22	-0.11688E-19	-0.0000
26	-0.12945E-21	-0.0000
30	0.71922E-25	0.0000

```
$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.
```

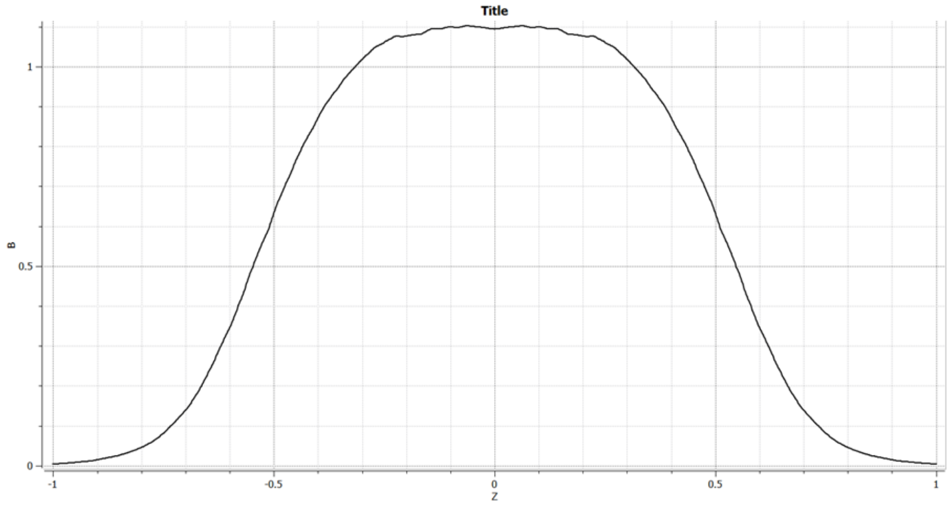


Field along x-axis, y-axis & parallel to z-axis (x=0.1m)

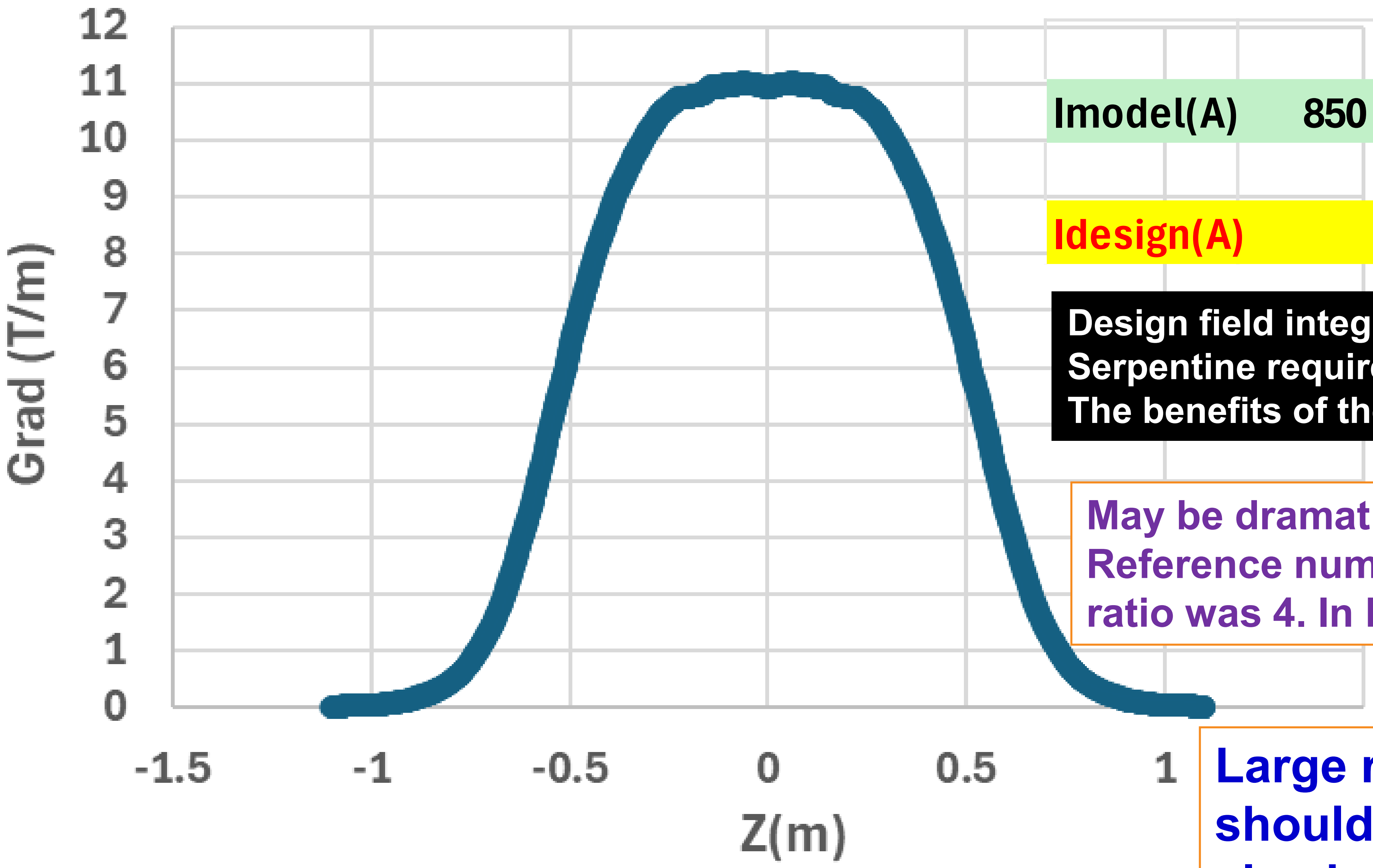




B Vs Z at X=0.1,y=0.



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



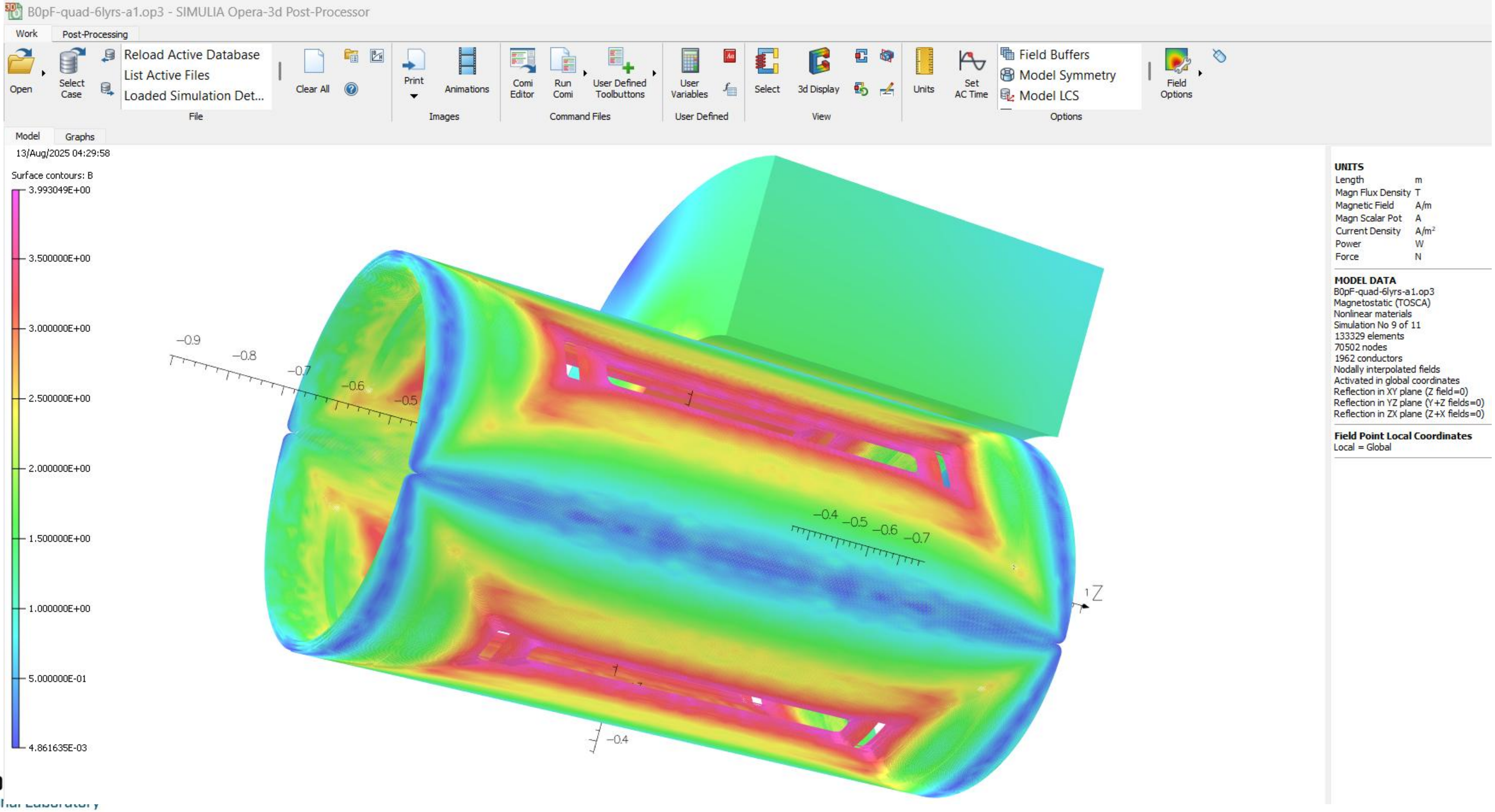
		Quad Integral field (T	
Imodel(A)	850		
		9.5	9.754
Idesign(A)		805	827

Design field integral @827 A in 6-layer OID
Serpentine required 8-layers @1143 A.
The benefits of the optimum integral design.

May be dramatic but not surprising.
Reference number for length to diameter ratio was 4. In B0pF we have 1.8.

Large reduction in current should help mechanically & also in quench protection

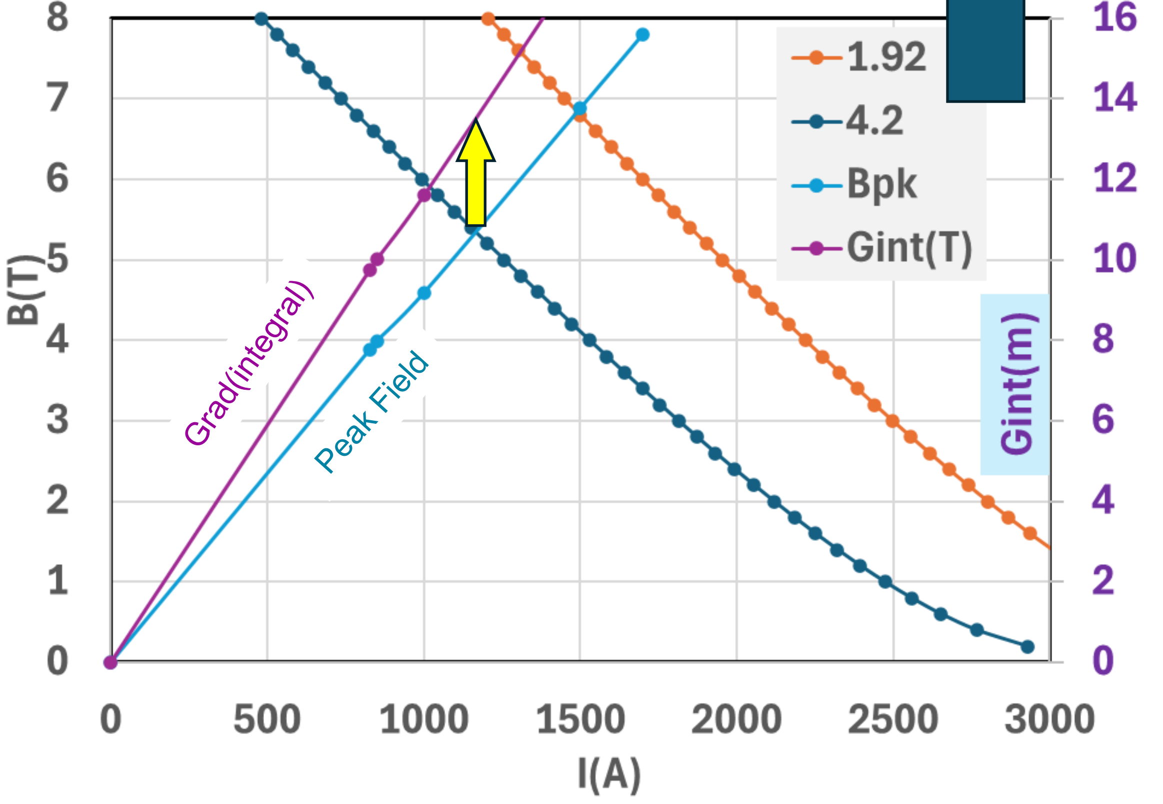
Field superimposed on coil and iron at 850 Amps

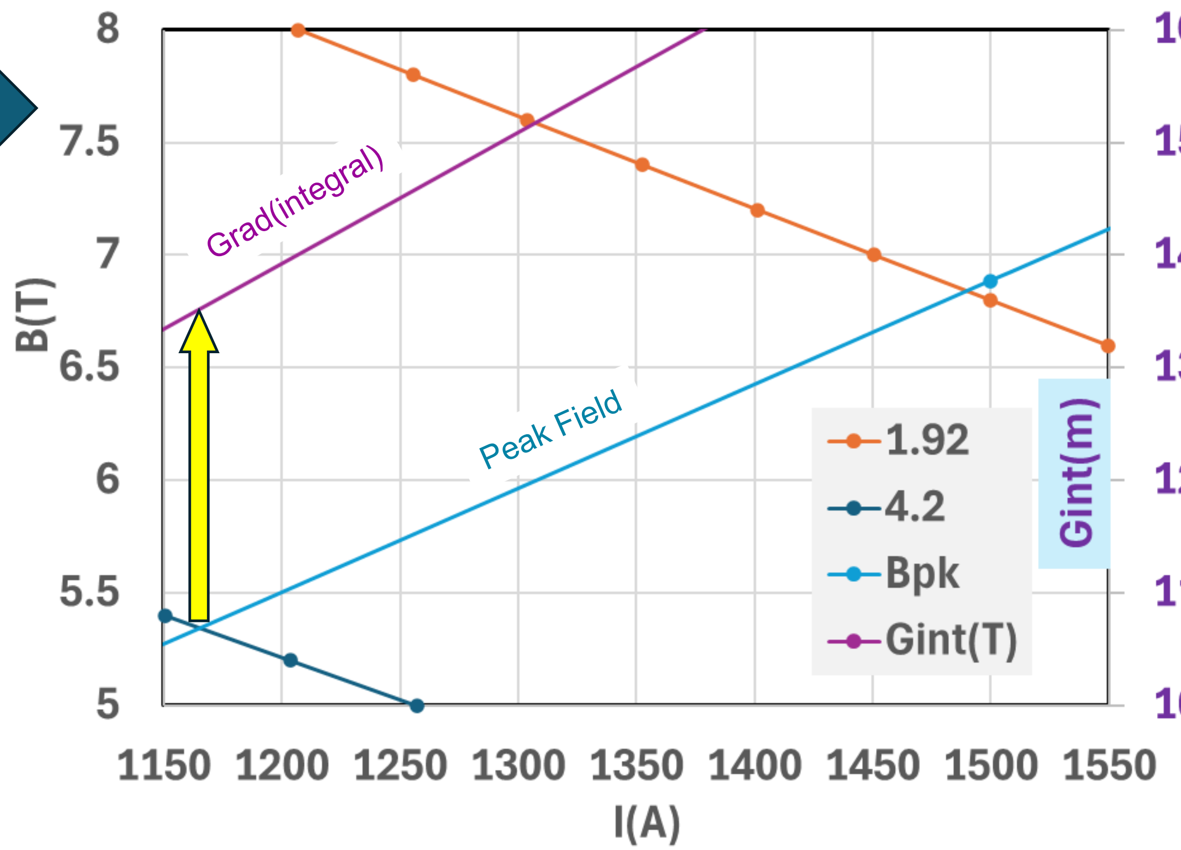


6-layer Optimum Integral Design for B0PF

(all seven wires superconductor - 1.92 K Vs 4.2 K for testing)

		Quad Integral field (T	
Imodel(A)	850		
		9.5	9.754
Idesign(A)		805	827





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

Large margins both at 1.92 K & 4.2 K

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

- Center wire in 6-around-1 cable is not transposed.
- This creates issues at high ramp rates as the center wire tries to resist the change. At very high ramp rates, the current can even be in a direction opposite to the transport current. That will reduce the quench current of the magnet.
- It, however, should also help in quench protection due to the “quench back” effect. The center wire can be copper.
- Making the center wire Cu effectively increases the copper to superconductor ratio. That will not only help in quench protection but may even prevent a quench.
- The penalty to pay is in reduction in the critical current of the cable which becomes 6/7 of that in all super wire case.

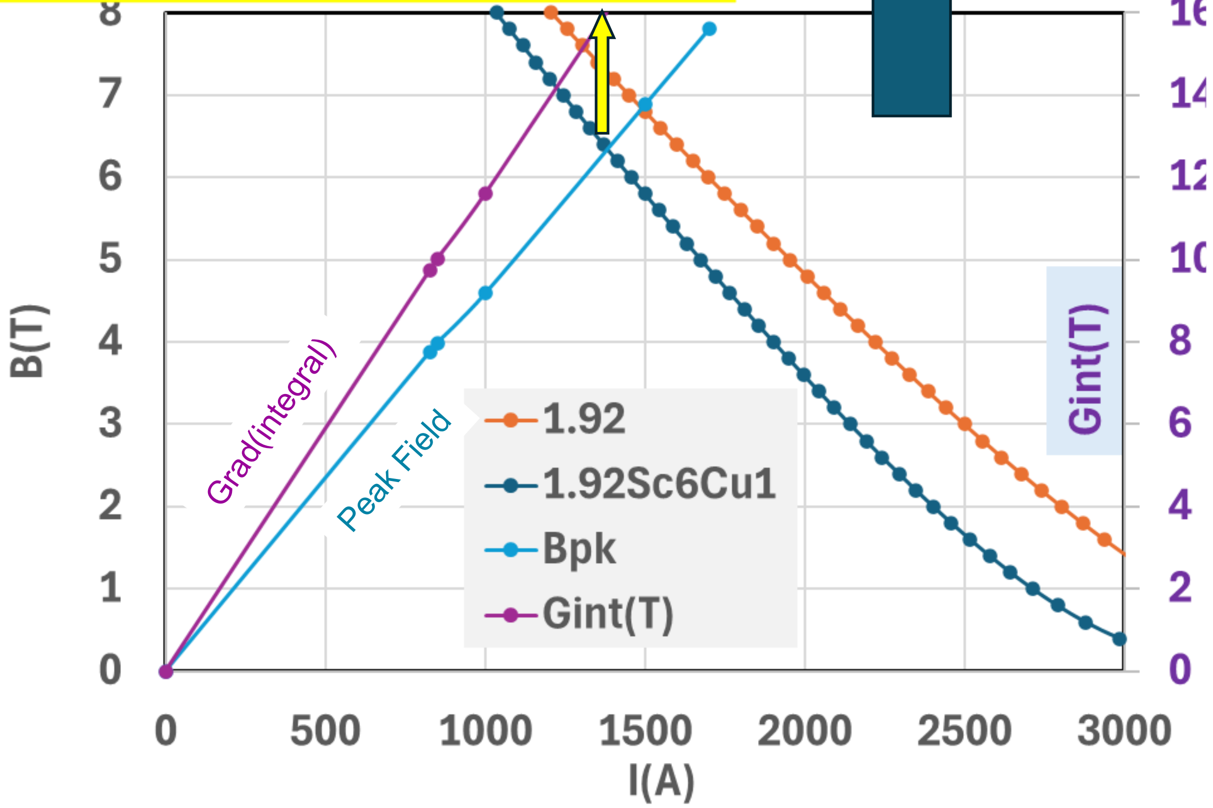
Effective Copper to Superconductor ratio in 6-around-1 copper

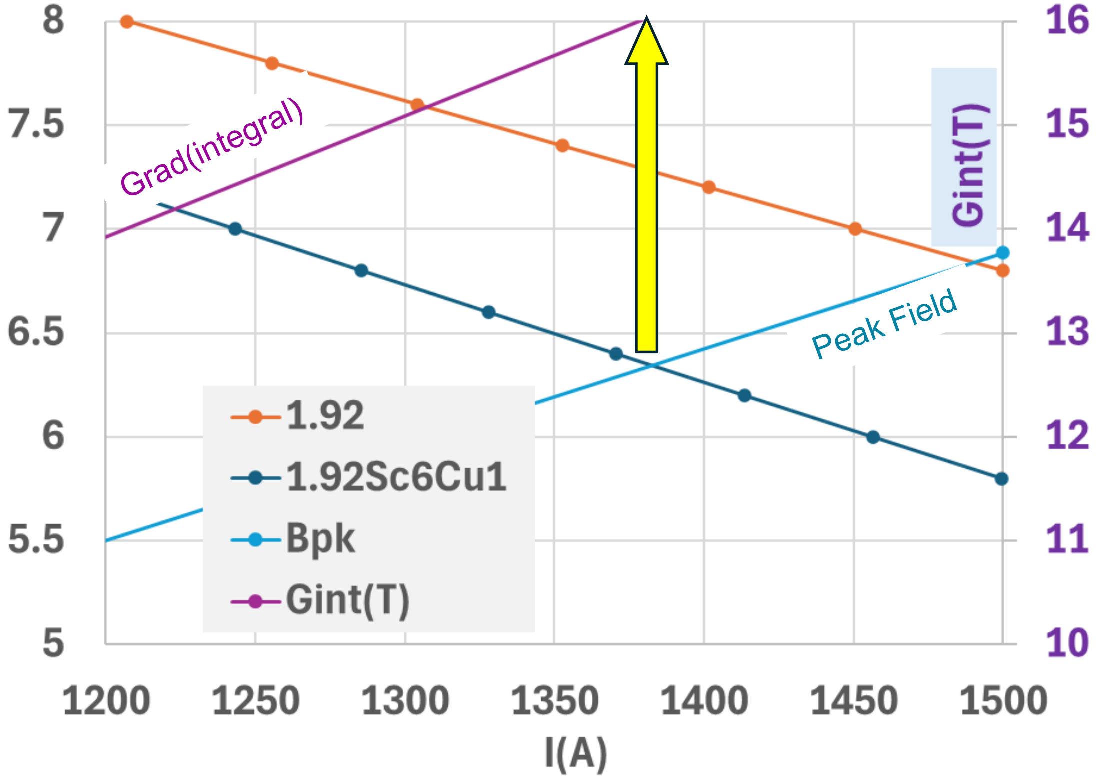
Cu/Sc from Brucker		
Original	Cu/Sc	1.75
Cu wires	1	
SC Wires	6	
Wire dia	0.473	mm
Wire area	0.176	mm^2
Super in wire	0.064	mm^2
Cu in Wire	0.112	mm^2
Cable Area	1.230	mm^2
Cu in Cable	0.847	mm^2
Super in cable	0.383	mm^2
Effective	**Cu/Sc**	**2.21**
Iquench	**1080**	Amp
Jcu@Qnch	**1276**	A/mm^2
Idesign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

6-layer Optimum Integral Design for B0PF

(all seven super Vs. central copper in 6-around-1 at 1.92K)

		Quad Integral field (T	
Imodel(A)	850		
		9.5	9.754
Idesign(A)		805	827





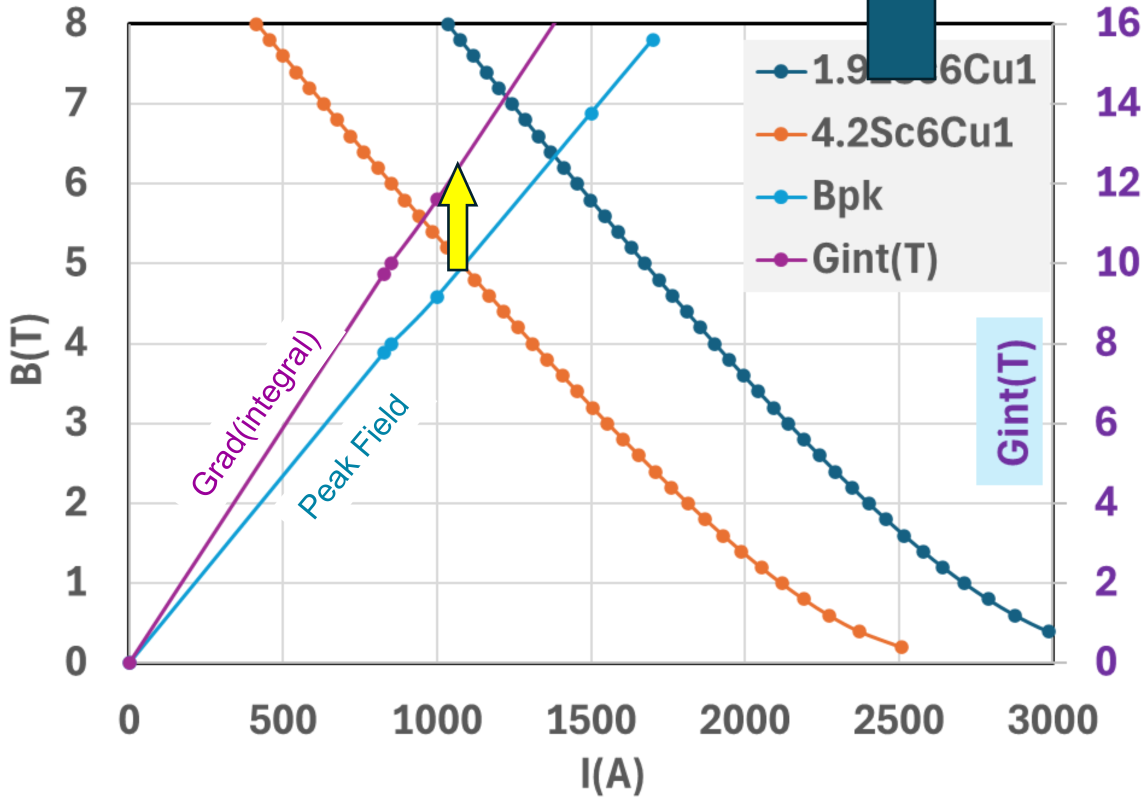
	Iss(A)	Margin(%)
All SC @1.92K	1490	80%
Sc6Cu1@1.92K	1380	67%

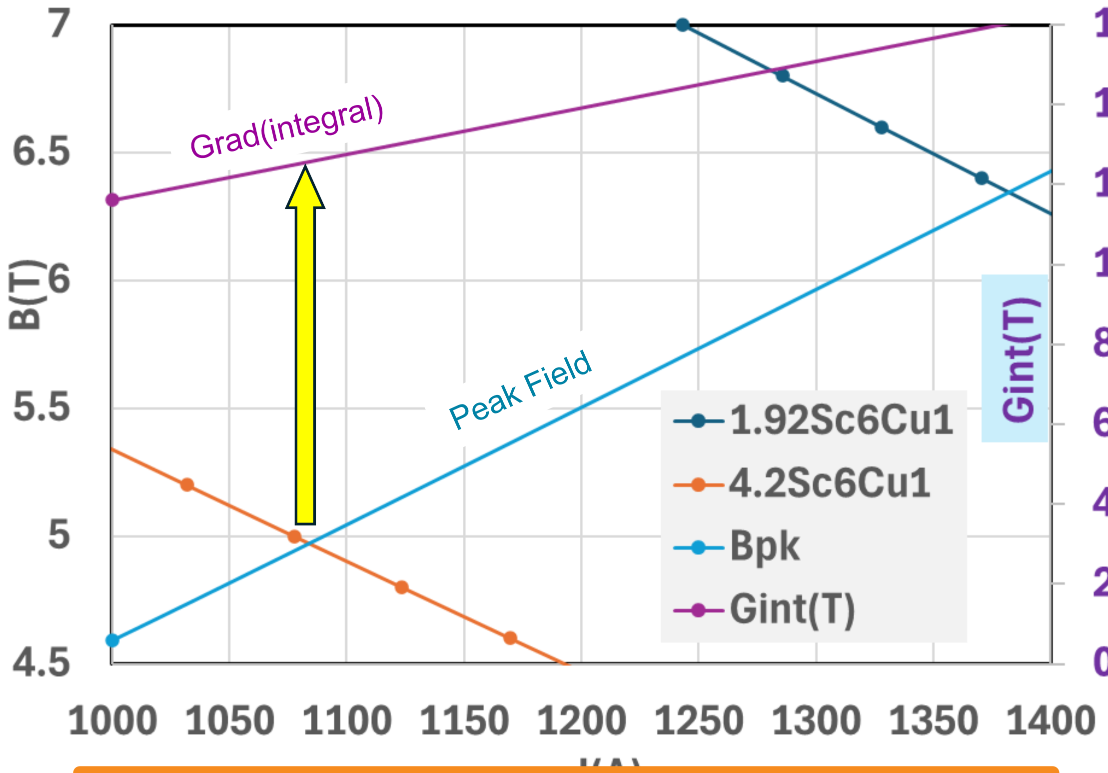
Large margins in both cases at 1.92 K

6-layer Optimum Integral Design for B0PF

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

		Quad Integral field (T	
Imodel(A)	850		
		9.5	9.754
Idesign(A)		805	827



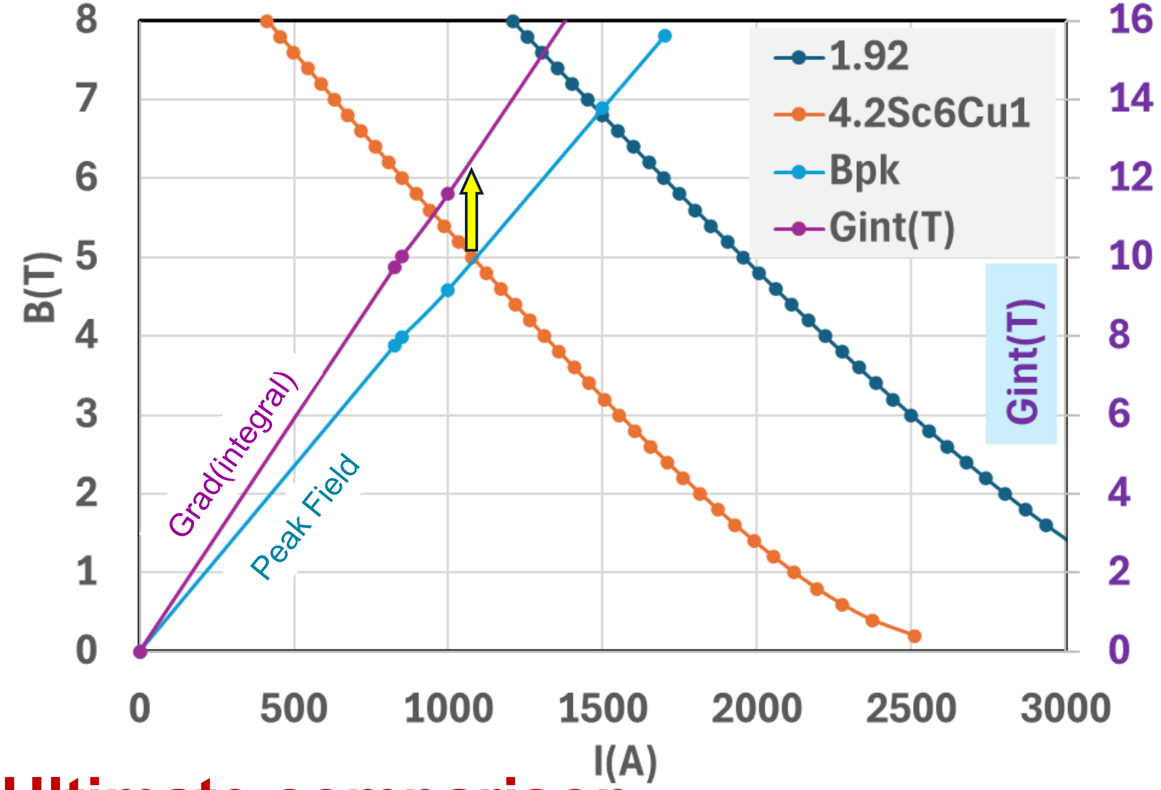


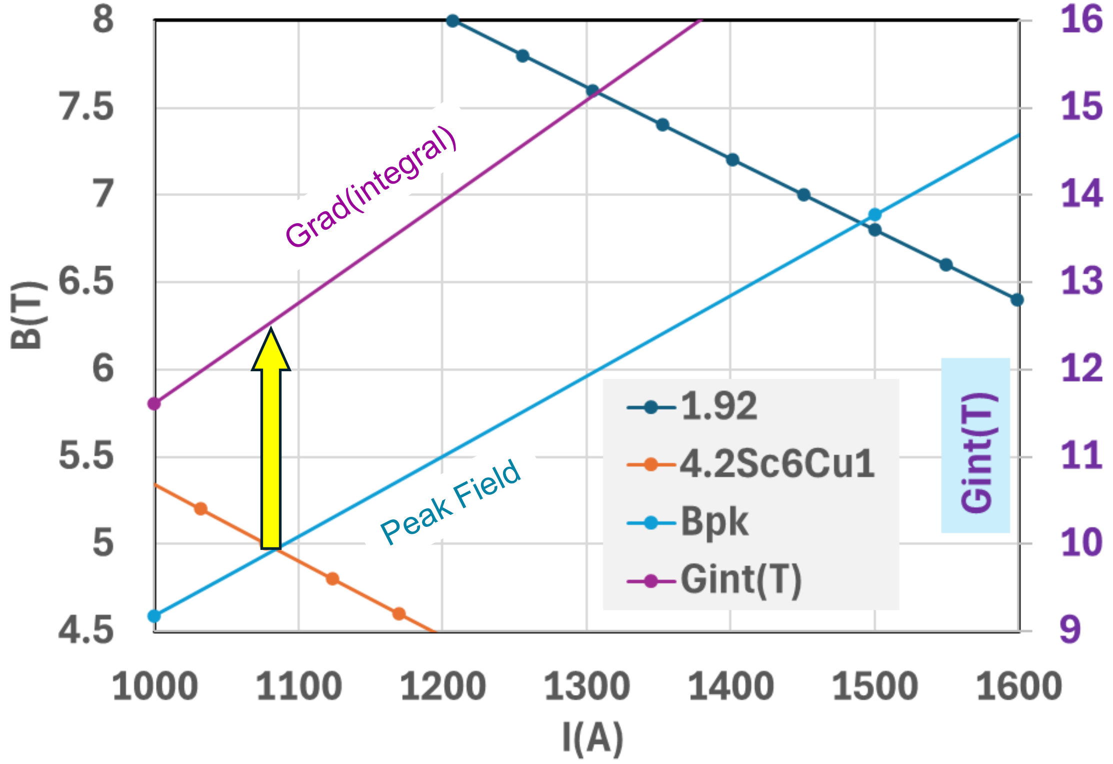
	Iss(A)	Margin(%)
SC6Cu1 @1.92K	1380	67%
SC6Cu1 @4.2K	1090	32%

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

6-layer Optimum Integral Design for B0PF

(all seven super at 1.92 K Vs six super and one cu at 4.2 K)





Ultimate comparison

(for reference present serpentine design has 8 layers, 1143 A and 43% margin at 1.92 K for all seven super)

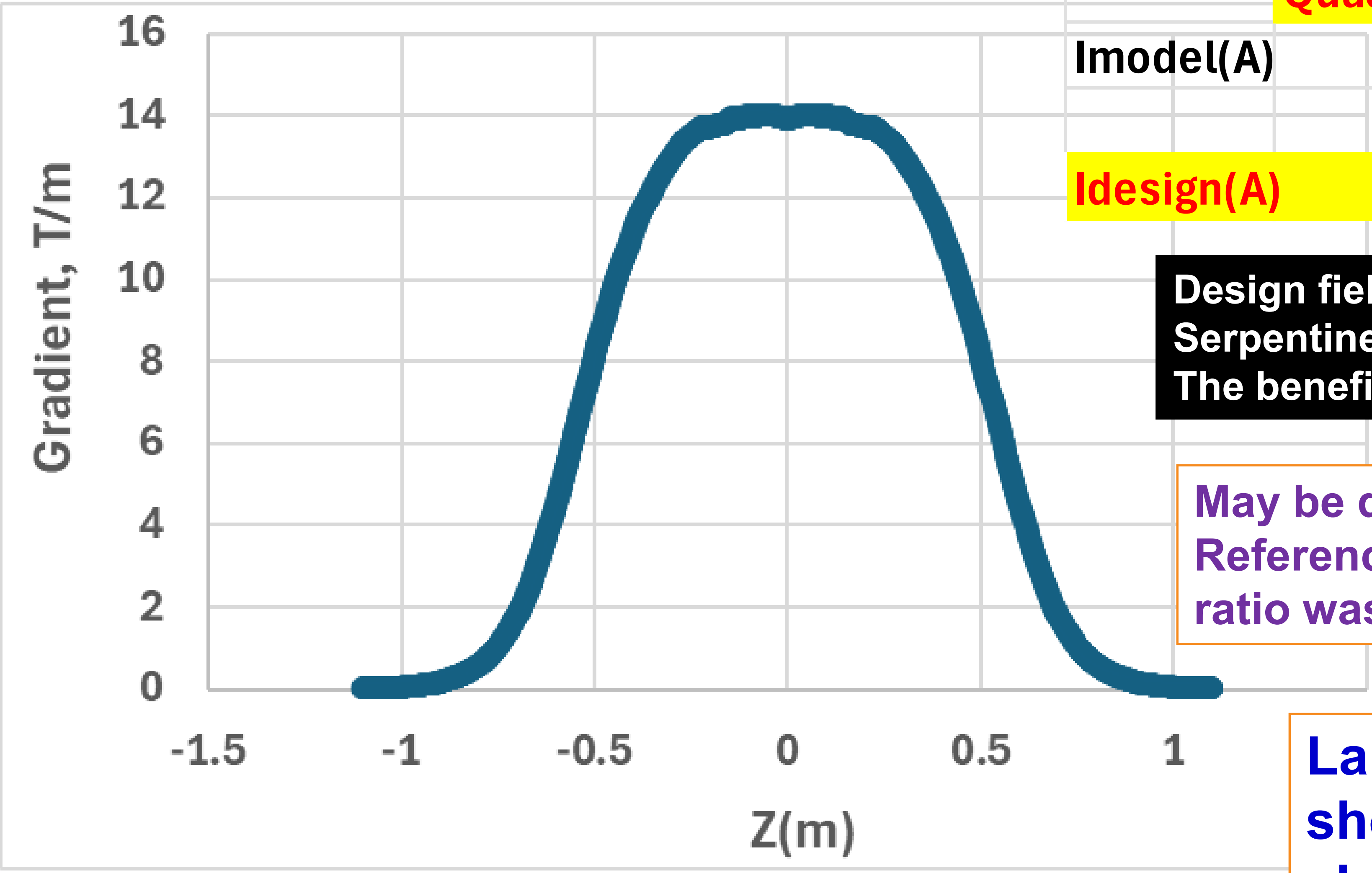
Still heathy margins despite granting all wishes!

➢ **Design current 827 A**

	Iss(A)	Margin(%)
All SC @1.92K	1490	80%
SC6Cu1 @4.2K	1090	32%

Eight Layer (4 coil sets) Design

Field Gradient along z-axis at 850 A in 8-layer Design



	Quad Integral field (T)			
Imodel(A)	1000			
			9.5	9.754
Idesign(A)			640	657

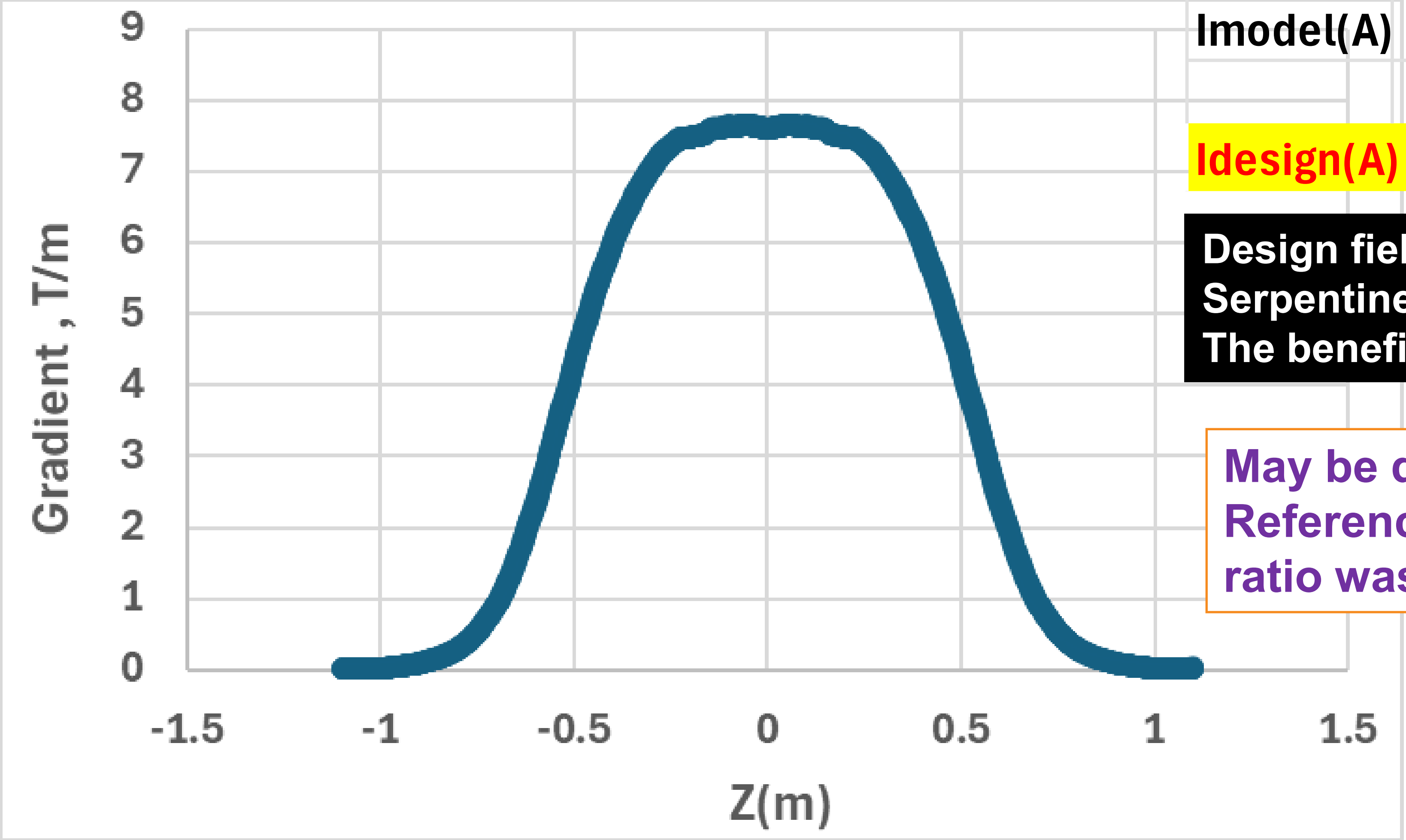
Design field integral @640 A in 6-layer OID Serpentine required 8-layers @1143 A. The benefits of the optimum integral design.

May be dramatic but not surprising. Reference number for length to diameter ratio was 4. In B0pF we have 1.8.

Large reduction in current should help mechanically & also in quench protection

Four Layer (2 coil sets) Design

Field Gradient along z-axis at 850 A in 4-layer Design



	Quad Integral field		
Imodel(A)	1000		
		9.5	9.754
Idesign(A)		1187	1219

Design field integral @1187 A in 4-layer OID
Serpentine required 8-layers @1143 A.
The benefits of the optimum integral design.

May be dramatic but not surprising. Reference number for length to diameter ratio was 4. In B0pF we have 1.8.

Note: A large reduction in the number of layers

Summary and the Next Step (1)

- Let us compare the two options. The current serpentine design has eight quad and two dipole layers. Even quad doesn't fit in the Dewar.
- It has a nominal operating current of 1143 A. It has a margin of 43% at 1.92 K when all wires in 6-around-1 are superconducting wire, same as always.
- A quench protection solution has been found for the serpentine design with ten sets of leads and dump registers. It, however, is in challenging territory.
- Initial optimum integral design has 6 layers in quad. It can fit in our Dewar for 4.2 K testing for a computed short sample that has a comfortable 32% margin.
- Moreover, the center wire is made of copper 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 (827 A instead of 1143 A).

Summary and the Next Step (2)

- **Lower maximum gradient means lower Lorentz forces, which should make the design less challenging. We may be able to reduce the thickness of inner tube.**
- **Initial outcome looks very promising. However, the electro-magnetic design, etc., must be analyzed independently (e.g. Vikas with RAT). In parallel a more optimized version can be found. This should be a few days activity only.**
- **Then a quick 1st order quench analysis of this design should be performed.**
- **Optimum integral design can conveniently allow a combined function design (rather than quad and dipole in series) – hopefully still in a 6-layer design.**
- **As attractive as that option maybe, evaluation of that may wait a bit for now. However, if that works, we will need only 6 sets of leads and dump resistors (instead of 10) and should offer a better technical and strategic option, in addition to all above.**