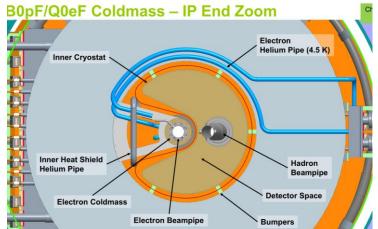


Background

- 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.



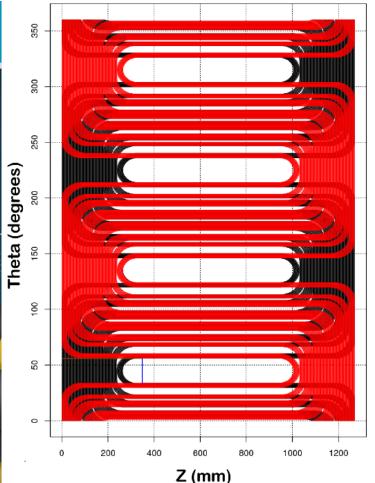






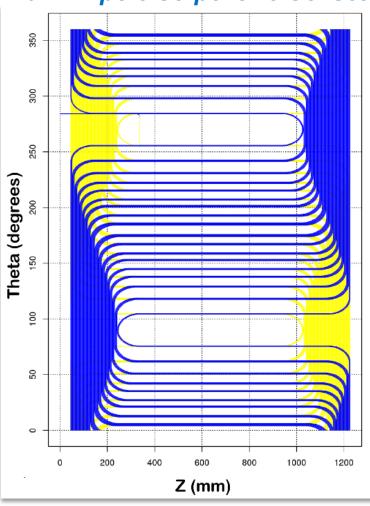
Serpentine Coil Design for B0pF (Brett Parker)

B0PF Quad Serpentine Coilset A



Three coil sets (6 layers) needed

B0PF Dipole Serpentine Coilset

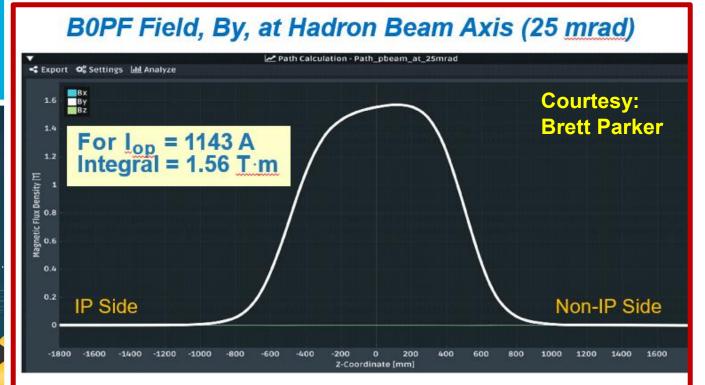


One coil set (2 layers) needed (body diluted and ends adjusted)

- Serpentine pattern has several nice features.
- It offers a continuous winding pattern which avoids splices between the poles.
- All turns have the same length.
 Ends are NOT separately optimized. A 2-d optimized is also a 3-d optimized design.
- While ends don't have a negative impact, they don't help in the overall design as well.
- Design also forces two layers of inefficient dipole coils.

Electron-Ion Collider

Coil Ends and Integral Field



Hadron beam passes through combined function field at 25 mrad angle; thus, field profile is not symmetric about longitudinal center.

With 326. mm inner coil radius and 1.27 m coil pattern length, the effective magnetic length is 1.00 m (central field 1.56 T).

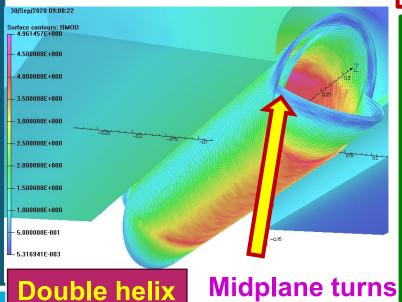
Is conventional harmonic definition even valid in such cases (valid only for 2-d or integral fields)?

- No long section of 2-d field in B0pF (an attraction of the serpentine coils).
- When the coil length to coil diameter ratio is small, such as here, loss in field due to ends becomes important.
- In serpentine design, as in the most other designs (cosine theta, canted cosine theta, etc.), ends/unit length contribute lower to the field integral.
- In such cases, the optimum integral design, which minimizes the loss in integral field due to ends, is expected to make a significant difference.
- In addition, the optimum integral design efficiently optimizes a combined function design, which can further reduce the # of layers.

Optimum Integral Design for Short Magnets - Motivation



RHIC Cosine(θ) Coil Ends

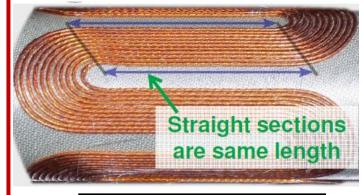


Brookhaven^{*}

Magnet Division

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

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

end here

Conventional Design Approach

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, optimize both for low peak fields)

Each step reduces the maximum integral field



Straight section Straight section

Cross-section

Optimum Integral Design Approach

Extend midplane turns to full coil length.

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

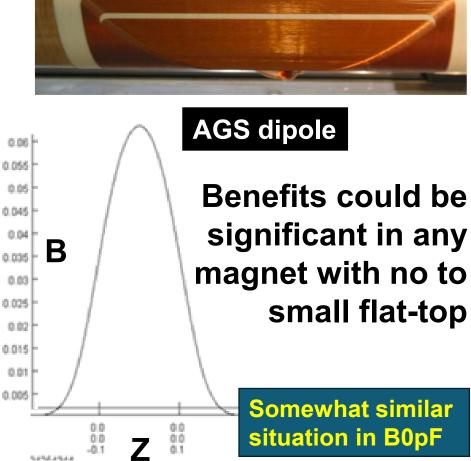
$$I(\theta) \cdot L(\theta) = I_o \cdot L_i(\theta) \propto I_o \cdot L_o \cdot \cos(n\theta)$$

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

✓ Loss due to ends essentially eliminated

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





October 5, 2025

B0PF Current 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 main challenges in the current design:

- Desired integral field gradient: 9.75 T. Integral field should be zero on e-beam axis (x=-34 mm) with the desired field excursion along the e-beam path <0.01 T.
- 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 extraction after quench.
- There are too many layers to fit in the present Dewar to test the entire coil at 4.2 K; and not enough margin at 1.92 K for mechanical testing of structure at 4.2 K.



Basic Design Features & Key Goals of the Optimum Integral Design

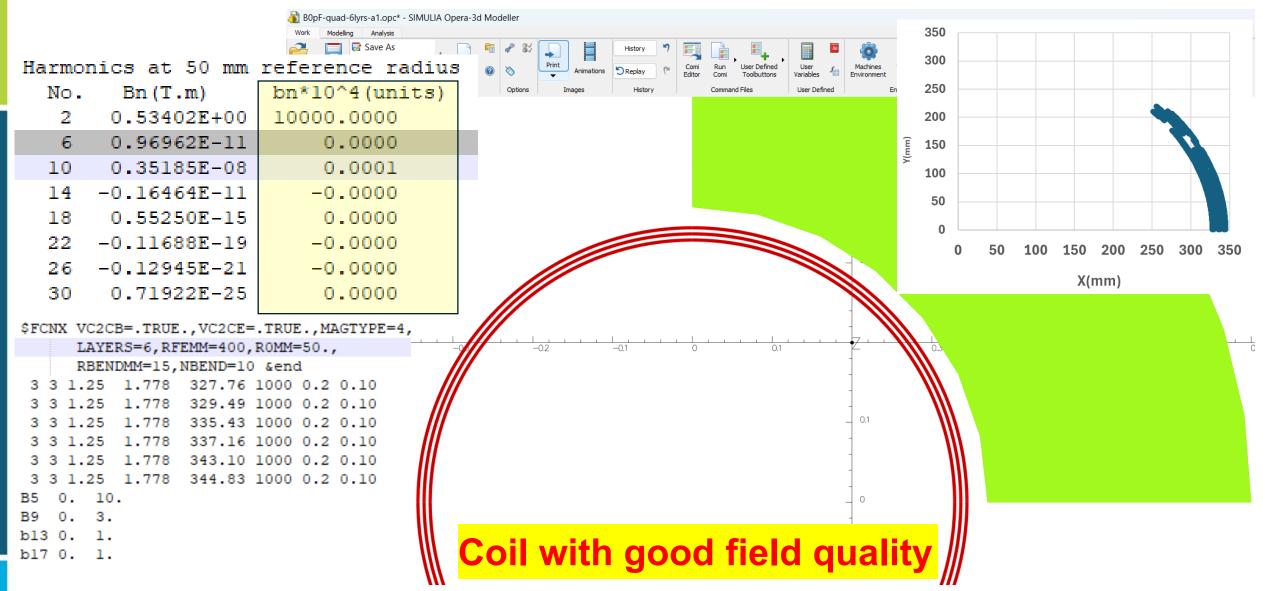
- The primary goal here is to examine the benefits of the optimum integral design and to evaluate how much do they reduce the challenges mentioned in the last slide.
- Two sets of designs are examined (with the following targets):
 - a) reduced number of layers: six quad layers (instead of eight) and one dipole layer (instead of two optimum integral design allows a single layer coil, as was the case for AGS corrector dipole), both coils in series; and a reduced current.
 - b) a combined function design with a total of six layers.
- 1. Reducing # of layers allows coils with structure to fit in the SMD dewar for testing.
- 2. Reducing # of layers should help in cost and the schedule.
- 3. Reducing design current should help in quench protection and in magnet structure.
 - > Designs to be presented today are iterated versions of the previous designs.
- > More optimization can be easily carried out before the scheduled winding.



OPTION A – QUADRUPOLE IN SERIES WITH THE DIPOLE



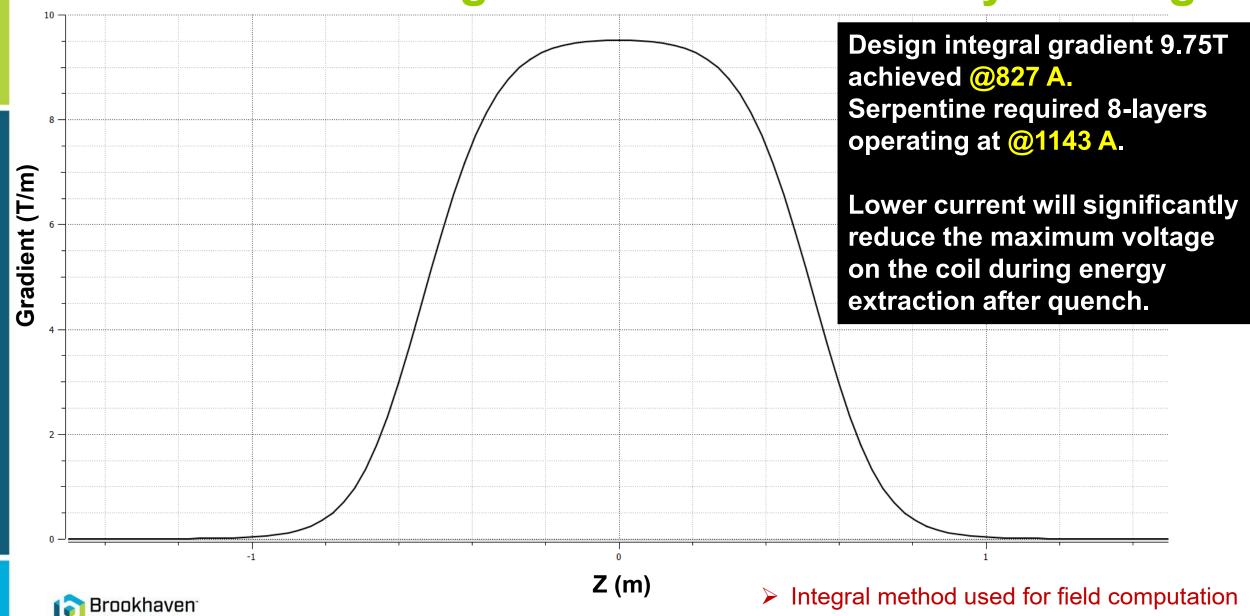
6-layer coil optimized with the optimum integral code





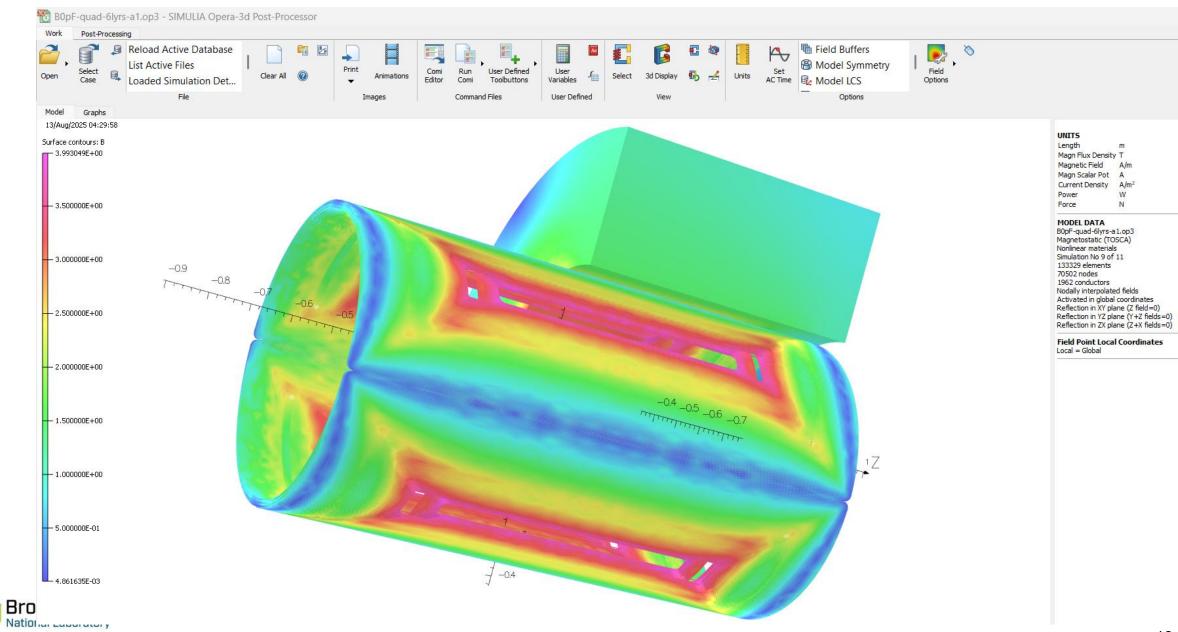
October 5, 2025

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



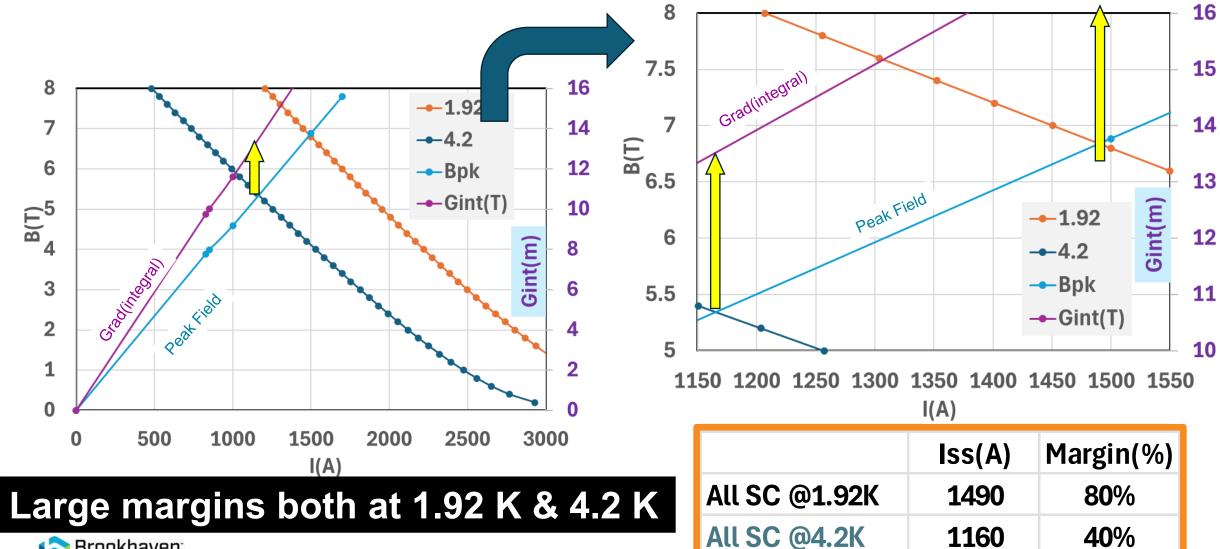
Optimum Integral Design for B0pF

Field superimposed on coil and iron at 850 Amps



Magnet Division

6-layer Optimum Integral Design for B0PF (6-around-1 sc cable - 1.92 K for operation, 4.2 K for testing)



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

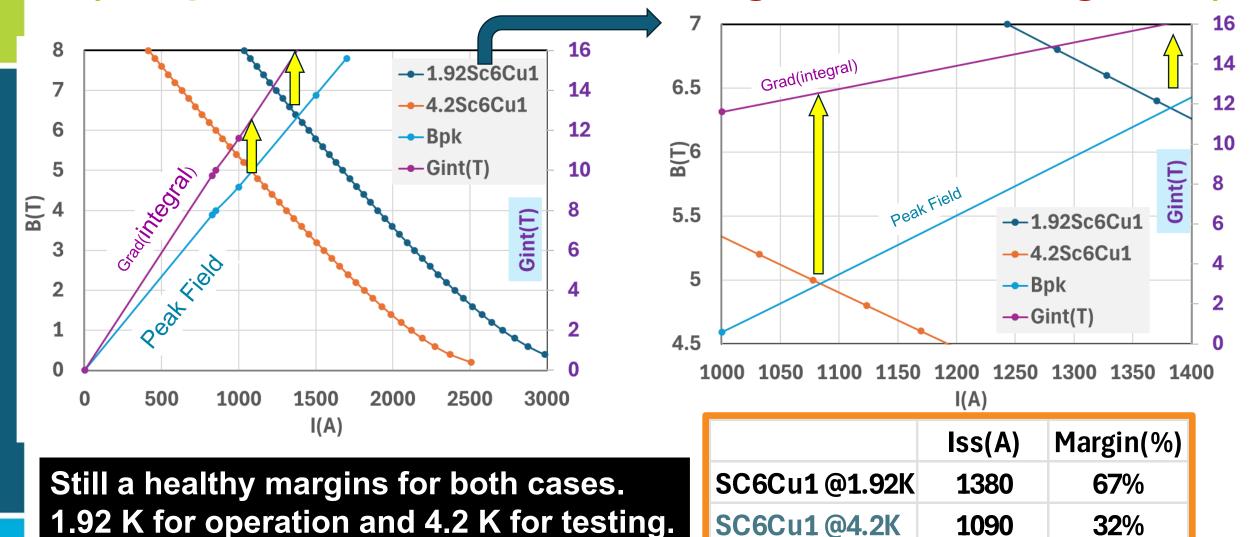
- Margin in the previous design is too excessive (80%), even after dropping a bit when the dipole field is superimposed.
 We can let it drop if that helps in quench protection.
- Making the center wire copper would help. It effectively increases the copper to super ratio (1.7 to 2.2). This should reduce the hot spot temperature and may prevent a quench.
- The penalty will be a 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 Br	ucker	
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
<u>Jcu@Qnch</u>	1276	A/mm^2
Idesign	827	Amp
<u>Jcu@design</u>	977	A/mm^2

6-layer Optimum Integral Quad Coils with 1 Cu Wire (6 super around 1 Cu wire – design 1.92 K; testing 4.2 K)





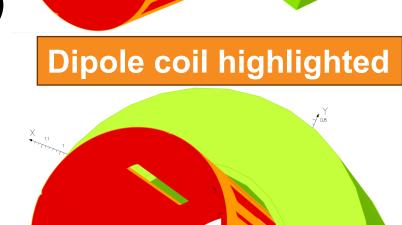
Next Step: Add Dipole Coils

- 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.



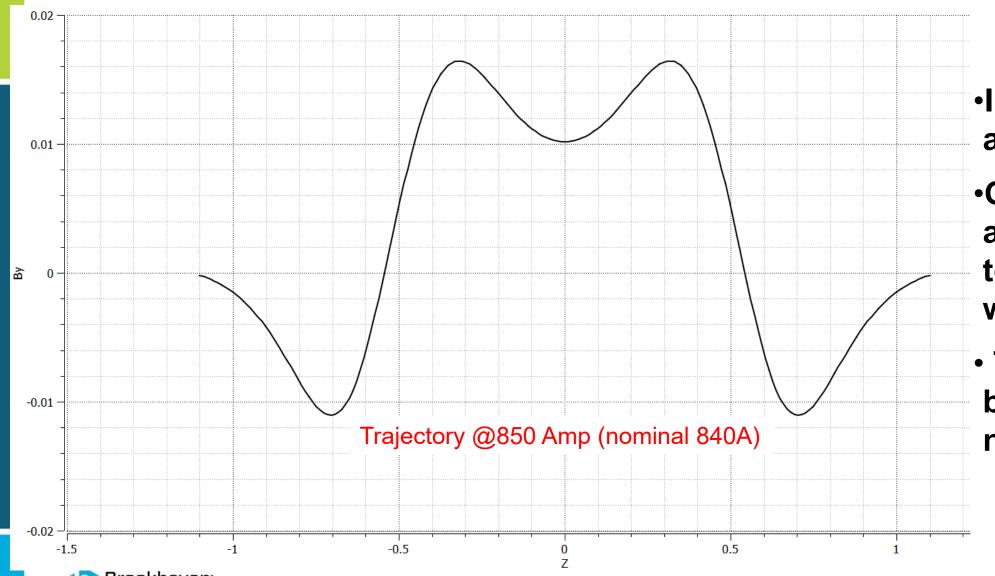
Dipole Coil(s) Added to the Quad in B0PF

- 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.



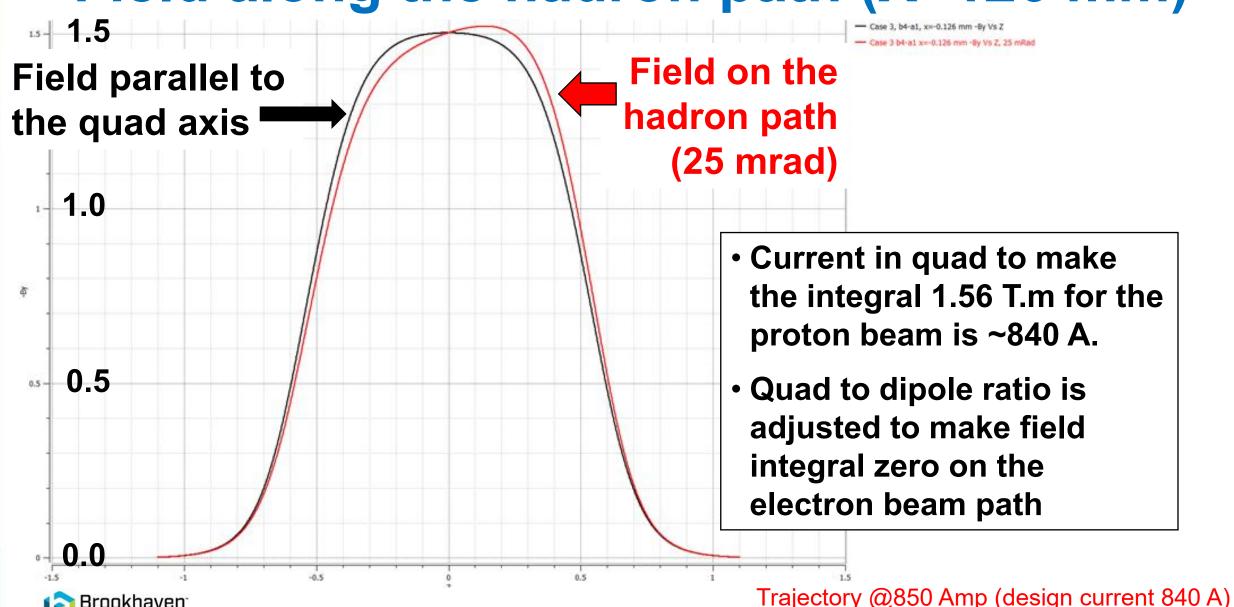


Field along the electron path (X=-34 mm)



- Integral field is almost zero.
- •Oscillations in B_v, 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)



Magnet Division

OID and Serpentine Designs for the Same Field Integral

1.6

1.5

1.4

1.3

1.2

1.1

1.2

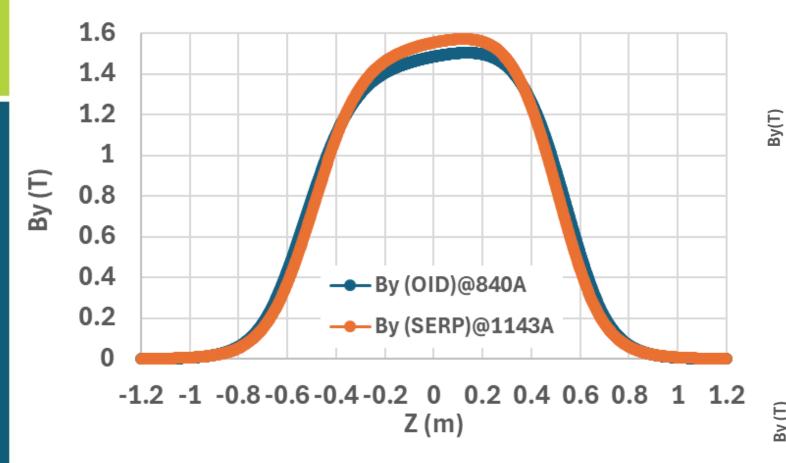
0.8

0.6

0.4

0.2

By (T)



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

- By (OID)@840A

By (SERP)@1143A

0.55

0.6

Z (m)

0.65

-0.2

--- By (OID)@840A

By (SERP)@1143A

Z(m)

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

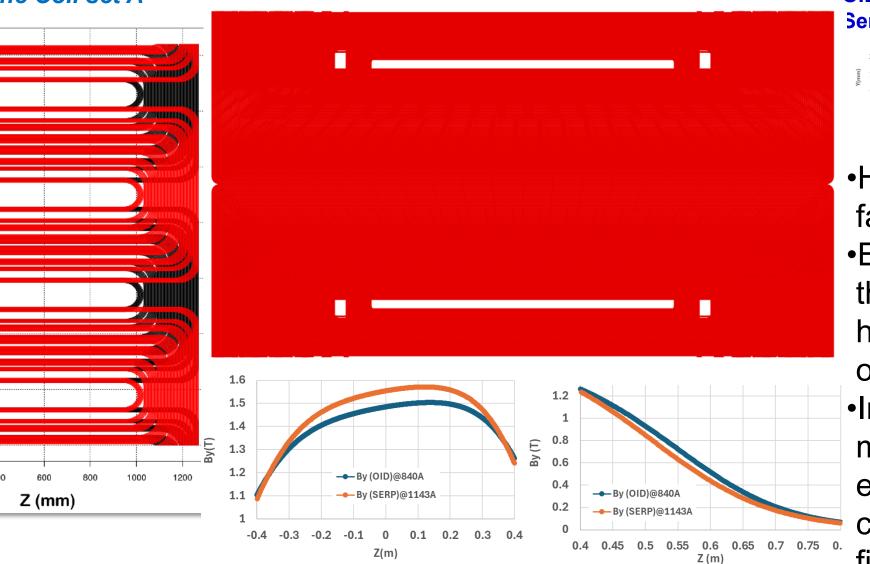
Serpentine Coil set A

300

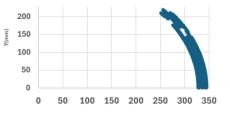
Theta (degrees)

8

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

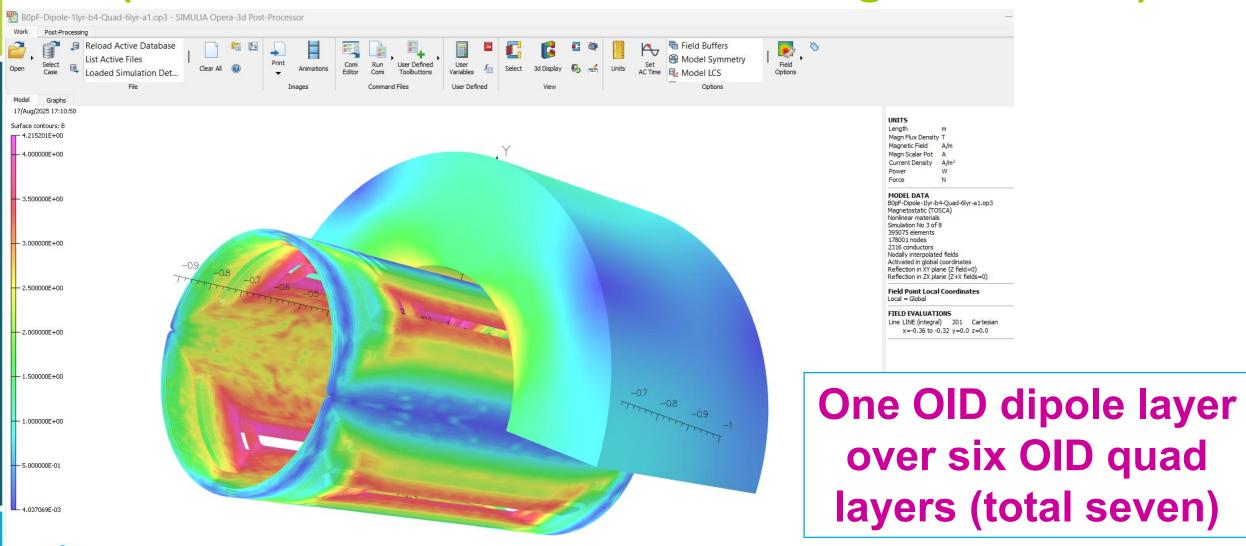


Less layers, less current. OID: 7 layers @840 A Vs. Serpentine: ten @1143A



- 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

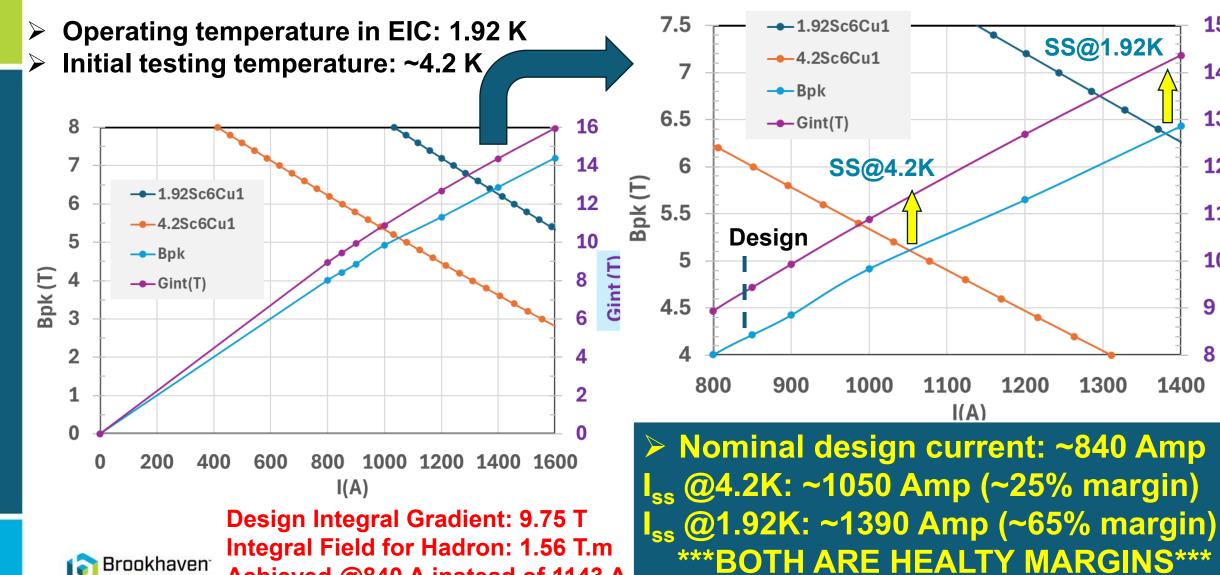
Model with field Superimposed at 850 A (nominal current for desired integral is 840 A)





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



12 SS@4.2K 10 1100 1200 1300 1400 **▶** Nominal design current: ~840 Amp I_{ss} @4.2K: ~1050 Amp (~25% margin)

SS@1.92K

14

Magnet Division

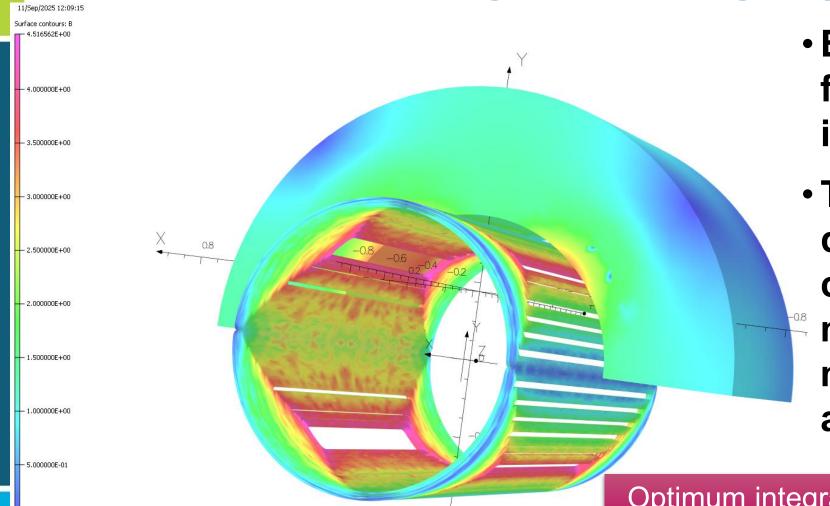
Achieved @840 A instead of 1143 A Optimum Integral Design for B0pF

OPTION B – COMBINED FUNCTION (QUAD+DIPOLE) MAGNET DESIGN

(each layer made combined function)



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

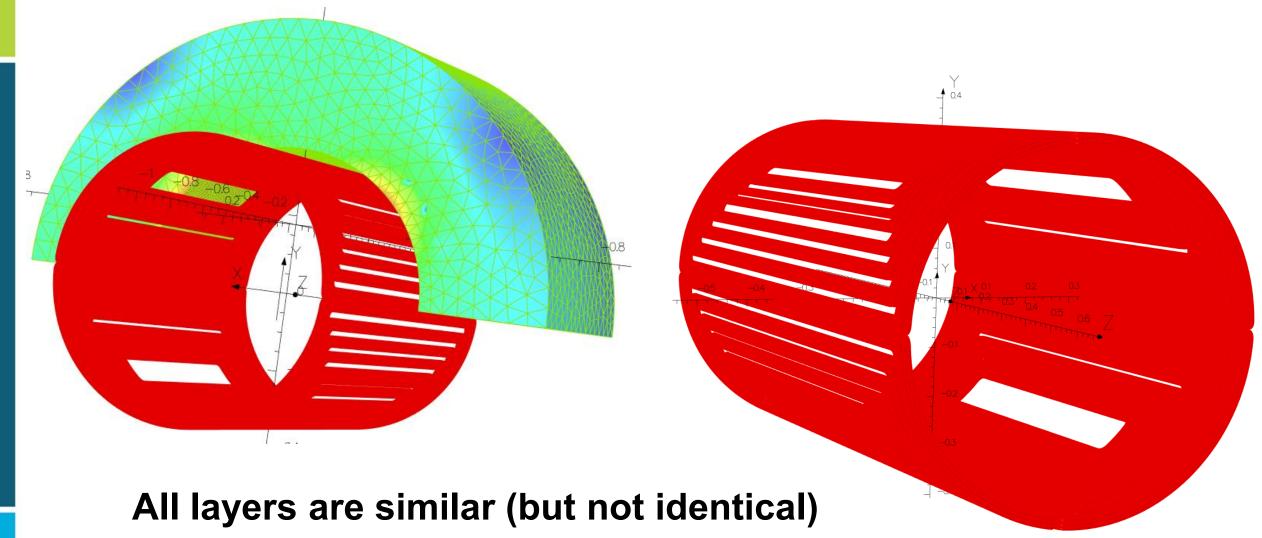


- Each layer is a combined function layer, and each is optimized Individually.
- The main component is quadrupole with a small component of dipole (in most combined function magnets, dipole is main and quadrupole is small)

Optimum integral design software was upgraded.

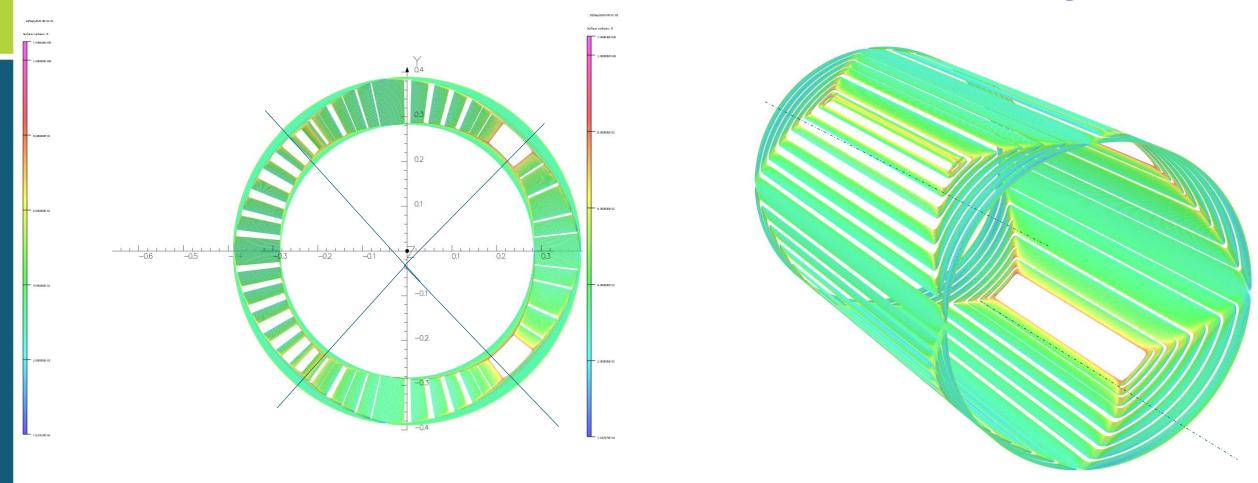
> A better solution possible with more upgrades.

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





Poles are shifted away from 45/90 degrees for an efficient optimization of the combined function design



(note a primary quad coil configuration with dipole superimposed)

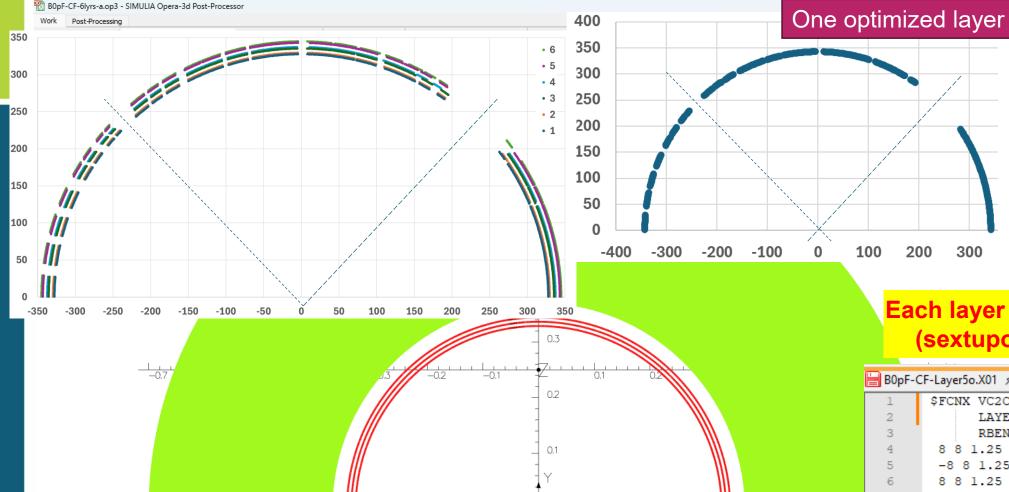


Six Layer Combined Function Design

(still six sc wires over the central cu wire in a 6-around-1 cable)



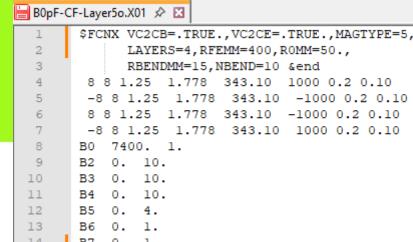
6-layer Combined Function Coil



Bn (T.m) bn*10^4(units 7421.3184 0.30777E-01 0.41471E-01 10000.0000 -0.68203E-07 -0.0164-0.1923 -0.79736E-06 0.67121E-05 1.6185 -0.2781-0.11534E-05 0.35714E-07 0.0086 0.0011 0.44686E-08 -0.0007 -0.29622E-08 0.20048E-09 0.0000 -0.0000 -0.52364E-10 0.40406E-11 0.0000 0.0000 0.11720E-11 -0.90136E-14 -0.0000 0.17211E-13 0.0000 0.0000 0.11462E-14 -0.50257E-15 -0.0000 -0.31427E-16 -0.0000 -0.93262E-17 -0.0000

INTEGRATED FIELD HARMONICS @50 mm

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





Coils imported from Optimum

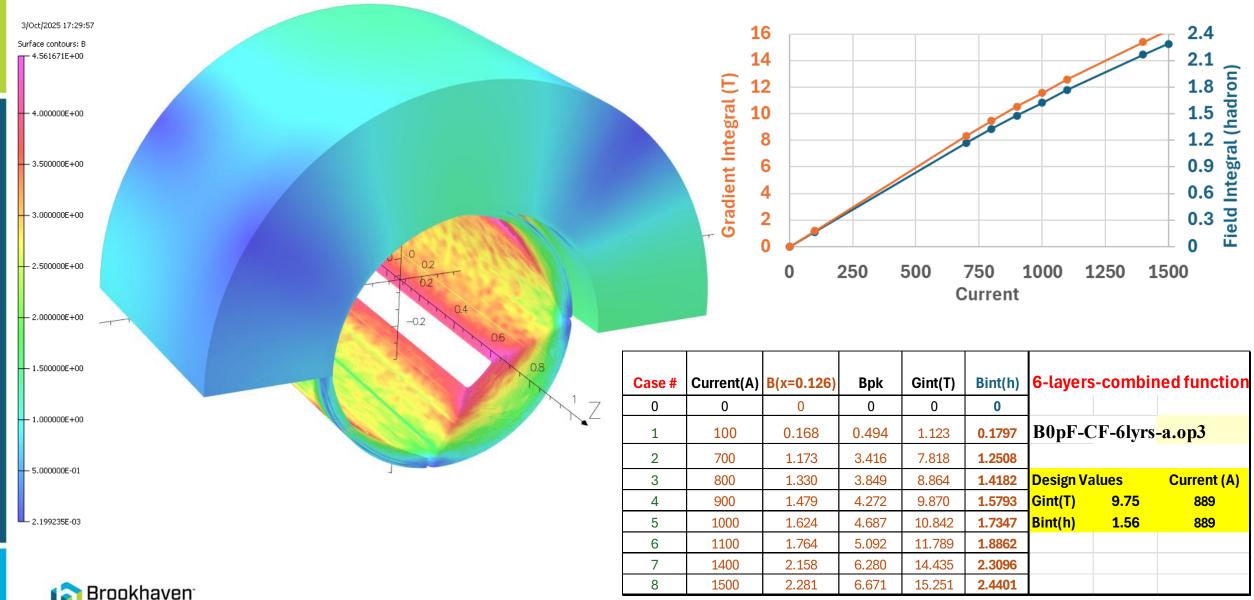
Integral code to OPERA3d

-0.1

200

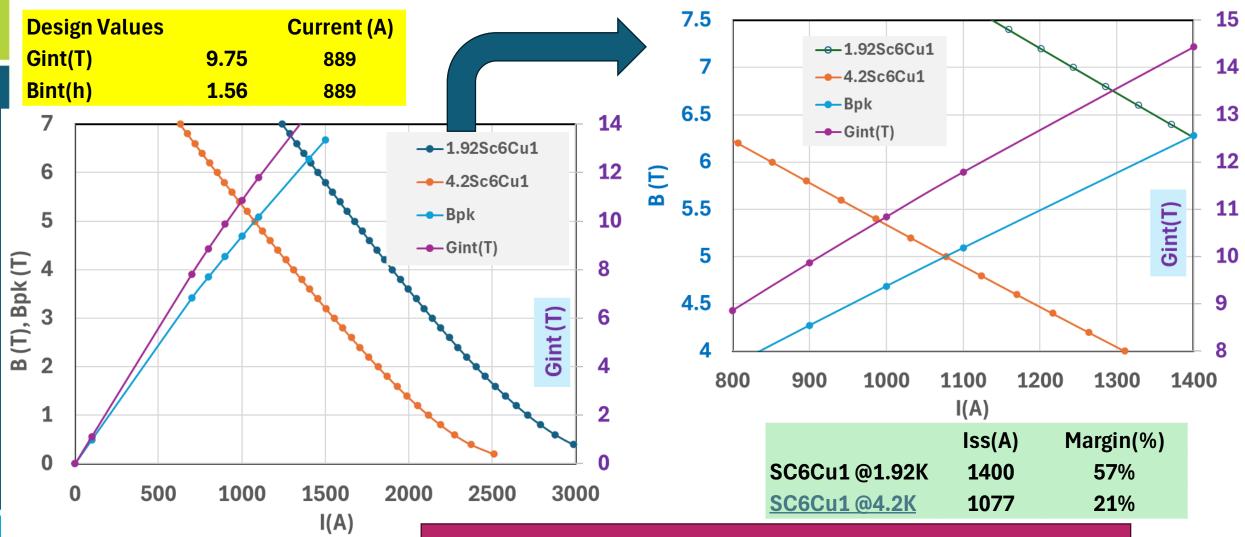
300

6-Layer Combined Function Magnet Design



Optimum Integral Design for B0pF

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

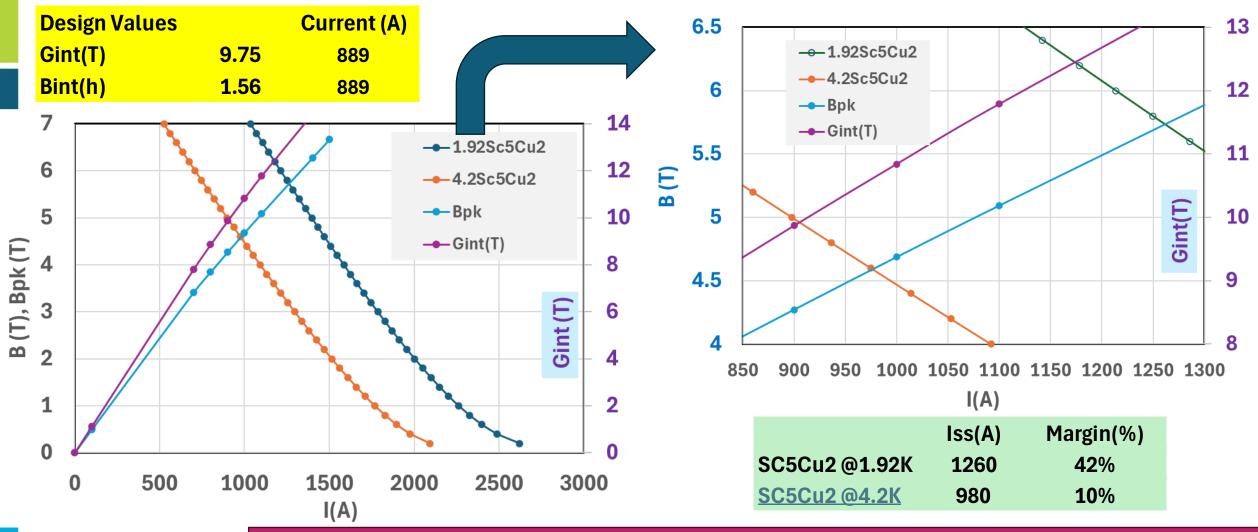




Optimum Integral Design for B0pF

Healthy margins both at 1.92 K & 4.2 K

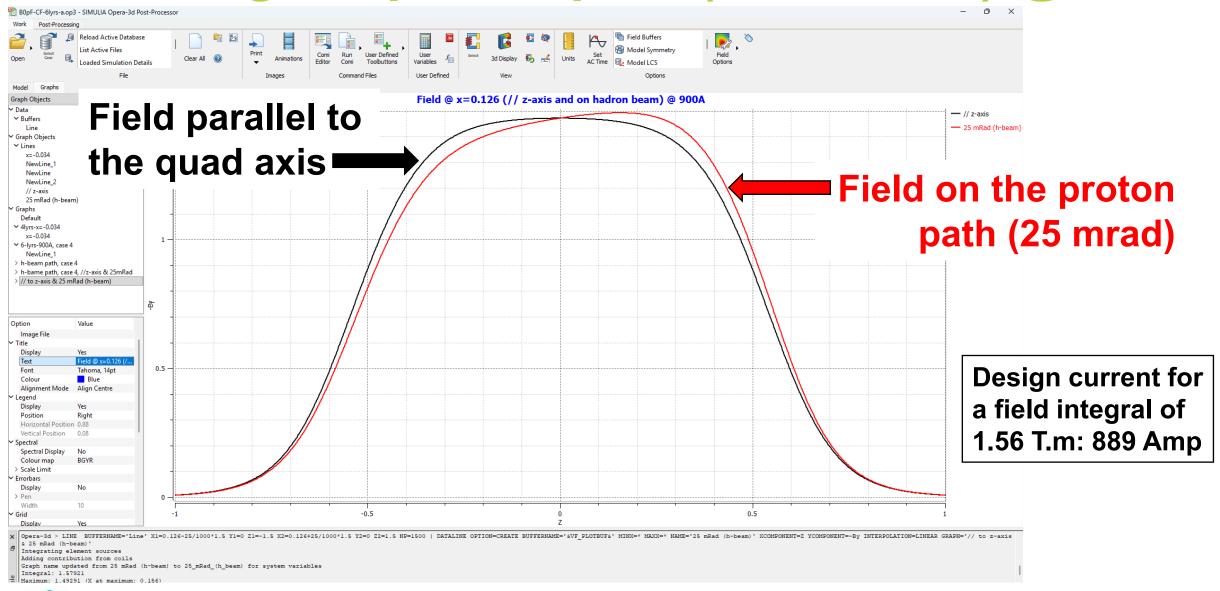
6-layer Optimum Integral Combined Function Design (pushing to 2 Cu wires for even better protection seems ok)



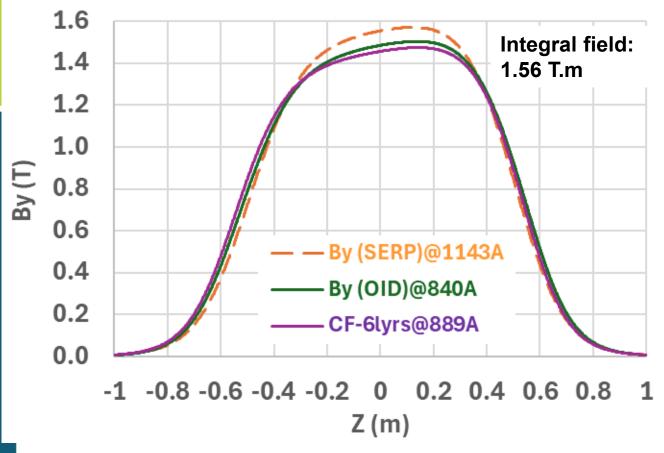


Healthy margins at 1.92 K (operation); workable at 4.2 K (testing)

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



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

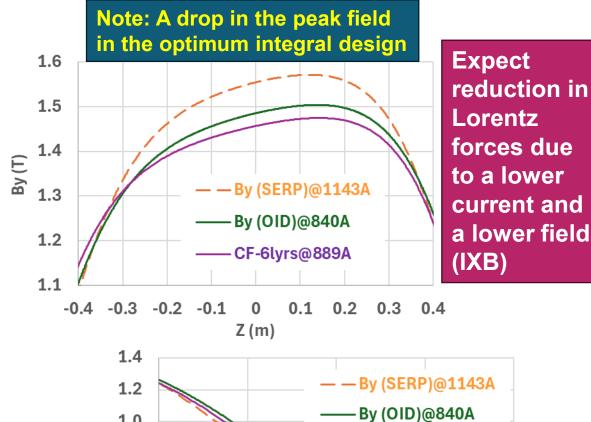


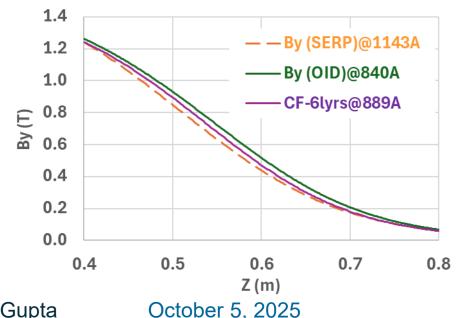


- > Serpentine design (8Q+2D): 10 layers @1143A
- > OID separate coils (6Q+1D): 7 layers @840 A
- > OID combined function (6CF): 6 layers @889 A

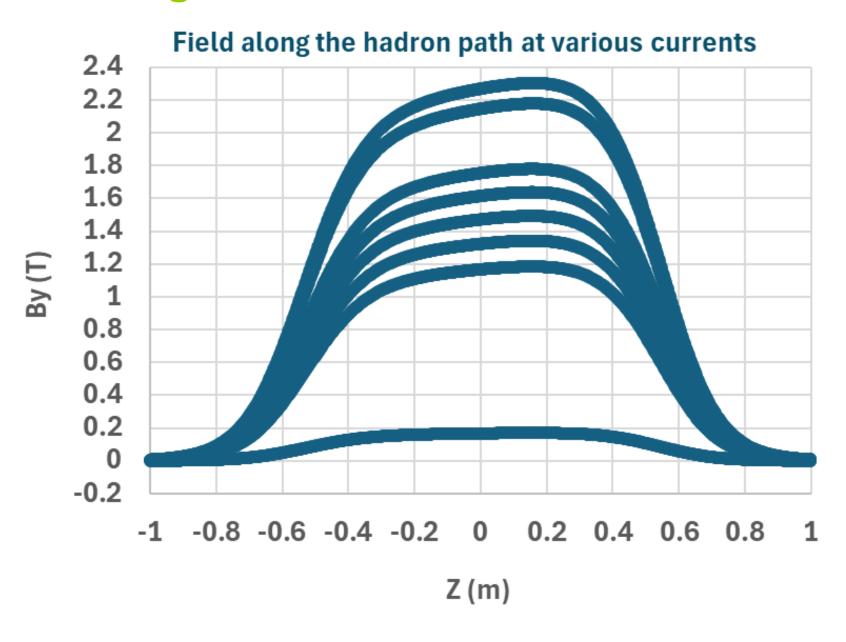
Optimum Integral Design for B0pF







Field Profile along the Hadron Path at Different Excitation

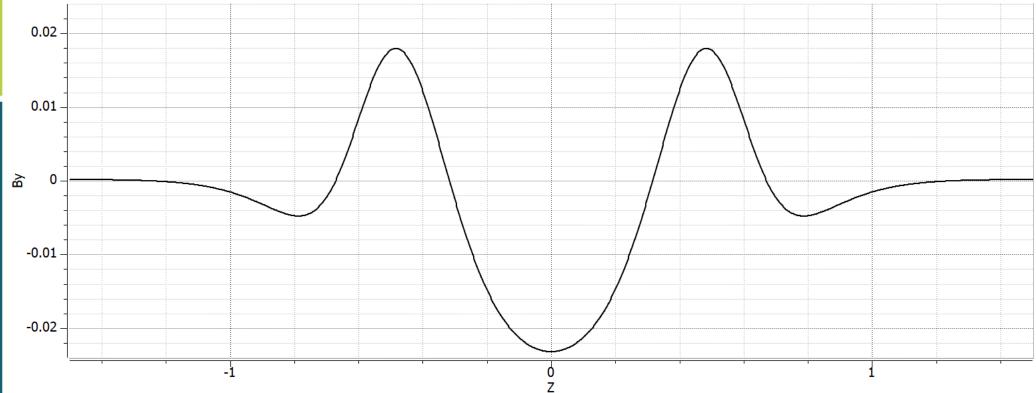




36

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





- Swing in B_v is ~0.02 T. It is a factor of two more than the initial goal of 0.01 T.
- The swing may be reduced by altering the body-end compensation for low integral harmonics. However, that may impact the efficiency (not desirable).
- How hard is this limit? This is not a beam dynamics question. Also, there is only one such magnet. Evaluate the requirement before compromising.



Other studies

- Several other cases were also examined in both options (separate function coils and combined function coils), including 4-layer (two coil sets) and 6-layer (three coil sets) optimization.
- Since 6-layer design, offered the best balance between the margin and the cost (may be subjective), only that solution was presented.
- Other cases can be discussed, if necessary, or if further investigation in quench analysis, etc. points to them possibly becoming a better overall solution.



Summary and the Next Step (1)

- Optimum integral design with six quad layers and one dipole layer satisfies all design requirements while operating at 840 A (current design 1143 A).
- 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, which should reduce hot spot temperature and provide better thermal stability against quench.
- The design can fit in our Dewar for 4.2 K testing with a comfortable margin to prove the design.
- Fewer layers also save on the cost and schedule.



Summary and the Next Step (2)

- Optimum integral design allows a combined function design (rather than quad and dipole in series).
- A 6-layer design operating at ~889 A meets the design requirements.
- This design still uses 6 super around 1 copper and maintains other positive aspects on the quench protection, testing and cost.
- Results look promising so far. It should reduce the stated risks in the present design (mainly quench protection). All other major aspects of the magnet B0pF (i.e., all other except the large quad and dipole coils), remain the same.
- Next step will be to perform independent magnetic analysis (already in works with RAT), and mechanical and quench analysis to evaluate the level of gains and evaluate risk reduction (retirement) matrix.



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
- \triangleright B1ApF (L = 1600 mm, id = 370 mm): ~4.3
- ➤ B1pF/B1ApF (L = 2500 mm, id = 363 mm): ~6.9
- \triangleright B0pF/Q0eF (L=1200 mm, id = 656 mm): ~1.8 (refer to quad)
- Magnet Division

 Optimum Integral Design for EIC -Ramesh Gupta Magnet Steering Group Meeting July 25, 2025

- ➤ 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.

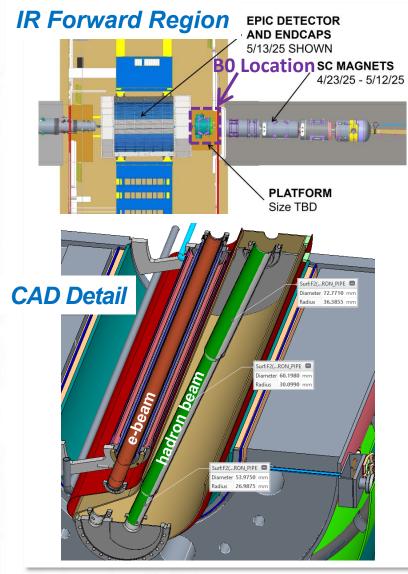
Following slides are from <2 days of work using the same cable as in serpentine. First look is promising!

Reference quide

~4 in guads



Scope



- 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.

October 5, 2025

Requirements

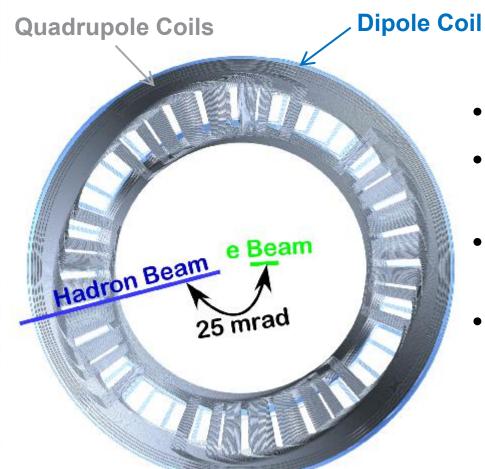


- Hadron and electron beams have 25 mrad relative angle and small separation at B0 spectrometer.
- Still, we need 1.56 T·m dipole strength for hadrons over a warm detector region for the experiment.
- The B0PF hadron dipole field is kept constant during collisions, independent of the hadron beam energy (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.

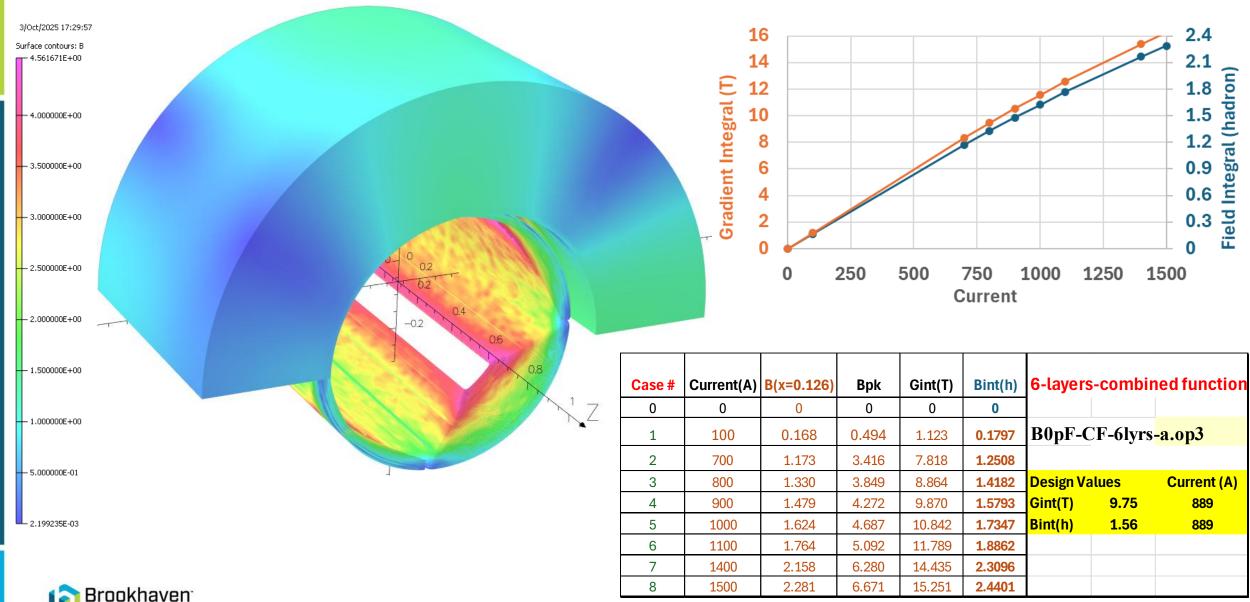
Magnet Division

Design



- 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.

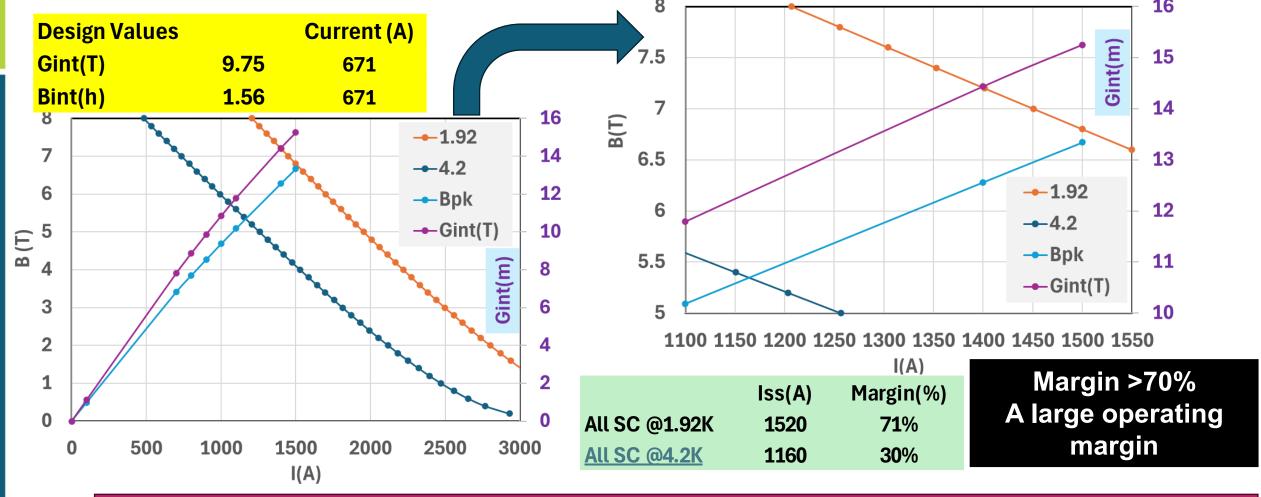
6-Layer Combined Function Optimum Integral Design



Optimum Integral Design for B0pF

6-layer Optimum Integral Combined Function Design

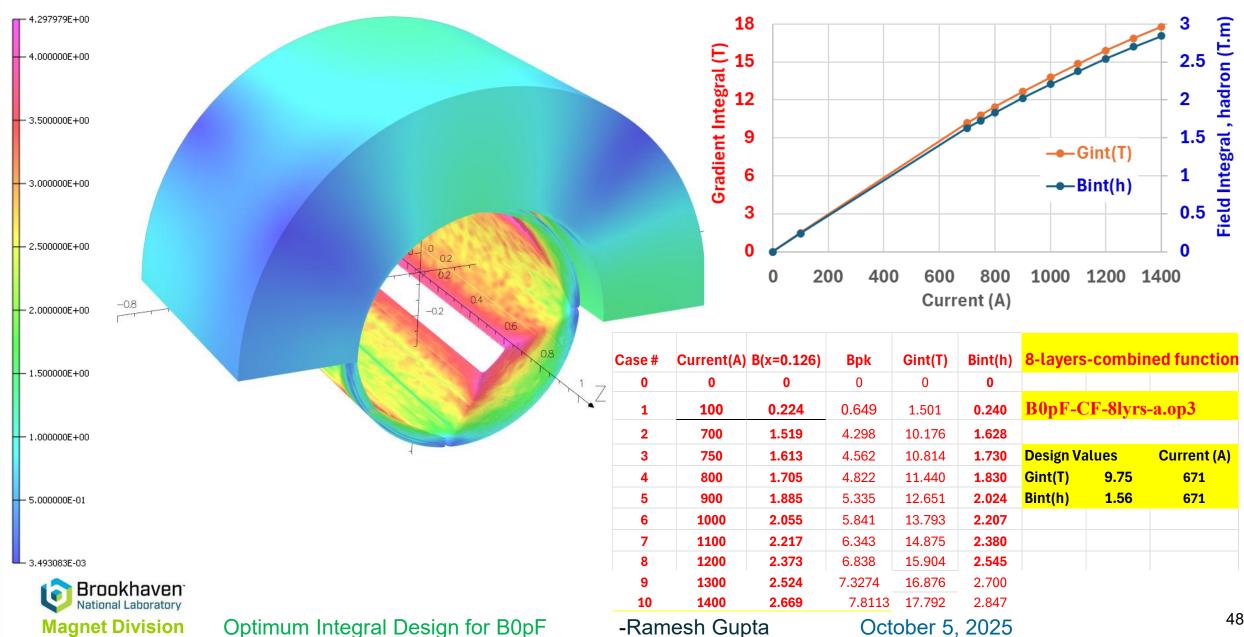
(present cable, all 7 SC wires- operation @1.92 K; testing @4.2 K)



Consider trading some operating margin to improve quench protection, such as, replacing central superconducting wire by copper wire ...

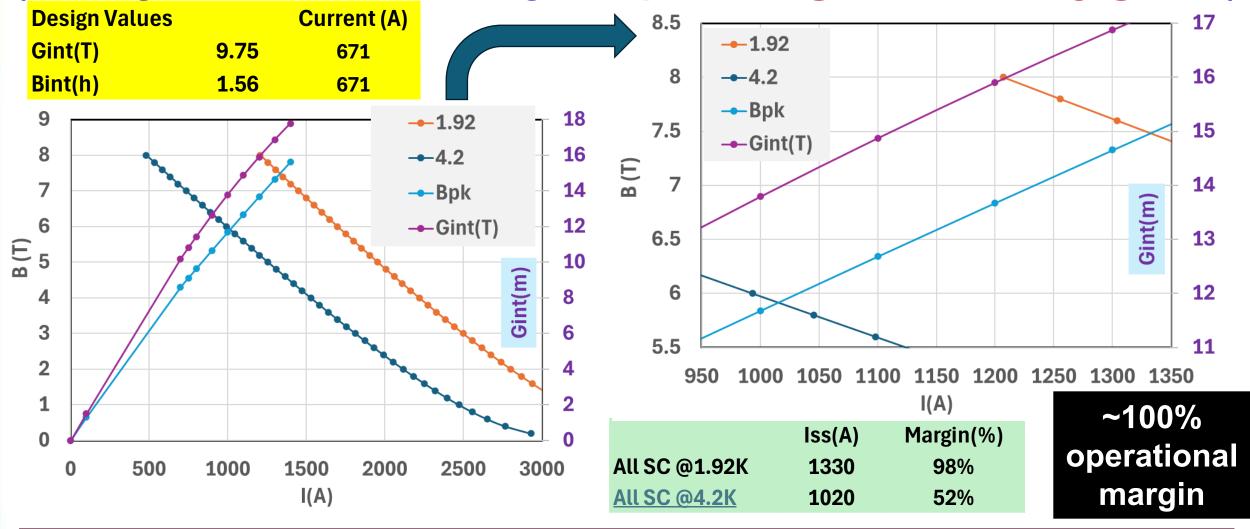
6

8-Layer Combined Function Optimum Integral Design



8-layer Optimum Integral Combined Function Design

(a design with too much margin – operation @1.92 K; testing @4.2 K)



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