5LOr1C-05

A Novel Optimum Integral Design for EIC Spectrometer Magnet B0pF

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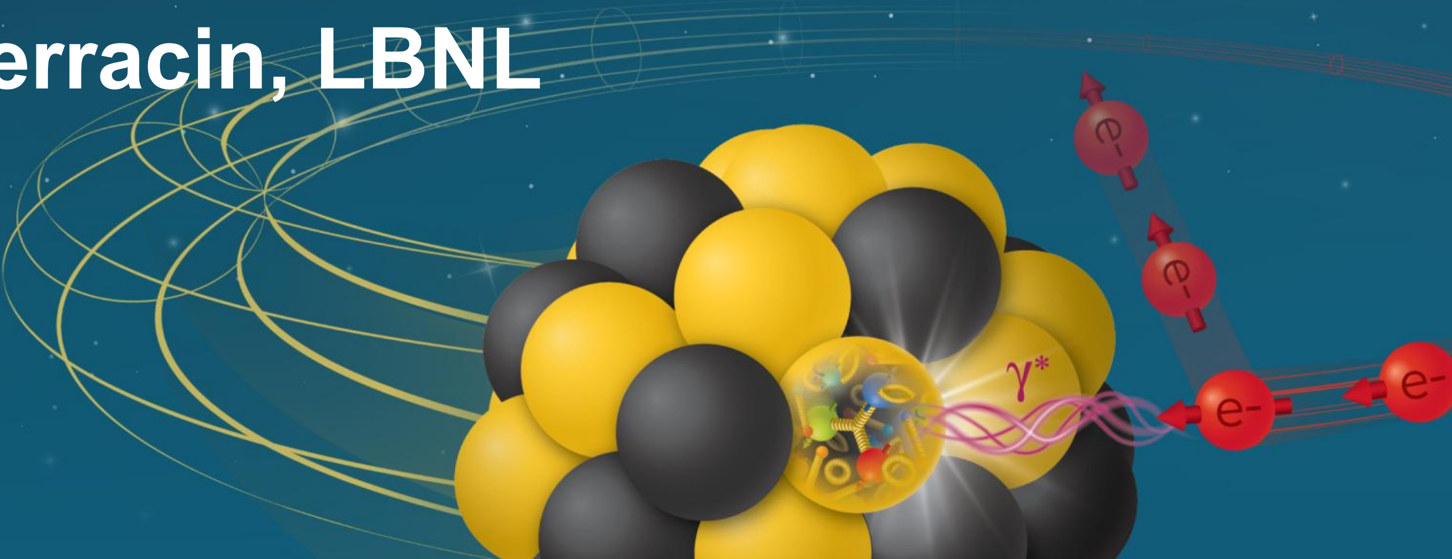


Electron-Ion Collider

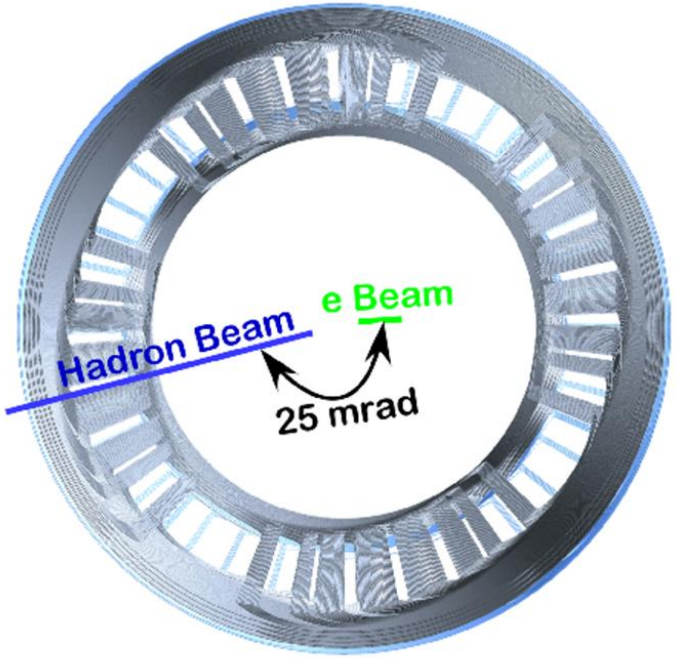
September 11, 2026

Introduction

- B0pF is one of the most challenging high field magnet in EIC IR due to its large aperture and short length (focus is on the main coils).
- Direct wind technology with small diameter cable, allows small bend radii in the ends for a relatively longer straight section.
- However, risk was still high in the original design.

Bpk~5.4 T, ID 656 mm

- Optimum Integral Design, instead of loosing integral field due to ends, takes advantage of the short length. Efficiency becomes higher.
- It also opens several design options.
- All design options reduce the risks significantly.
- One of them is chosen in the current design.



Length/ID= ~1.9

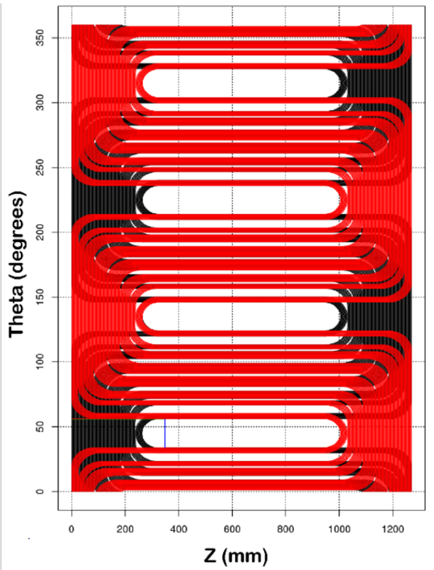
Original Design (Direct Wind Serpentine)

- **Coil ID: 656 mm; Coil length ~1240 mm**
- **Length/ID ratio: ~1.9 (small)**
- **Combined function field (dipole + quad)**
- **Peak Field on the conductor: ~5.4 T**

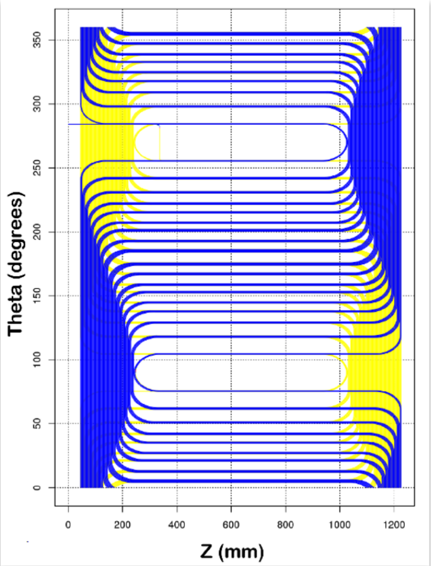
Original serpentine design with direct wind technology offered many advantages, including a longer straight section than it would be in a design with Rutherford cable, and an efficient continuous winding.

But there is a little flat-top (or 2-d section) due to a low length to diameter ratio. Thus a large fraction of field is lost due to ends.

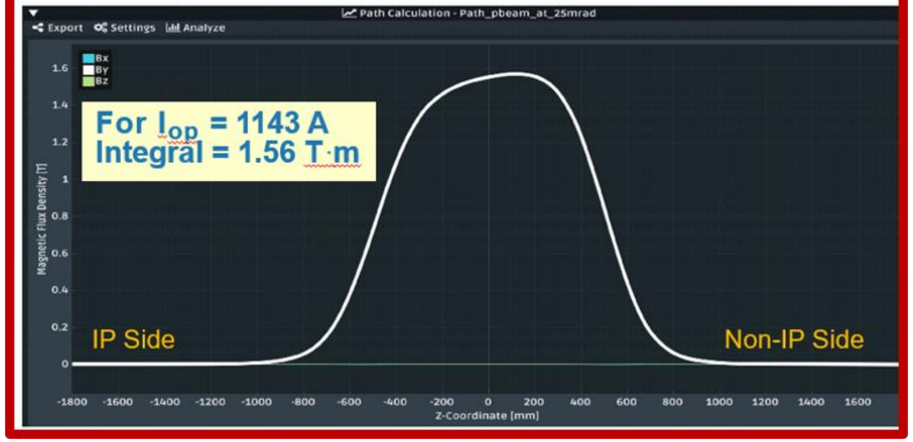
B0PF Quad Serpentine Coilset A



B0PF Dipole Serpentine Coilset



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



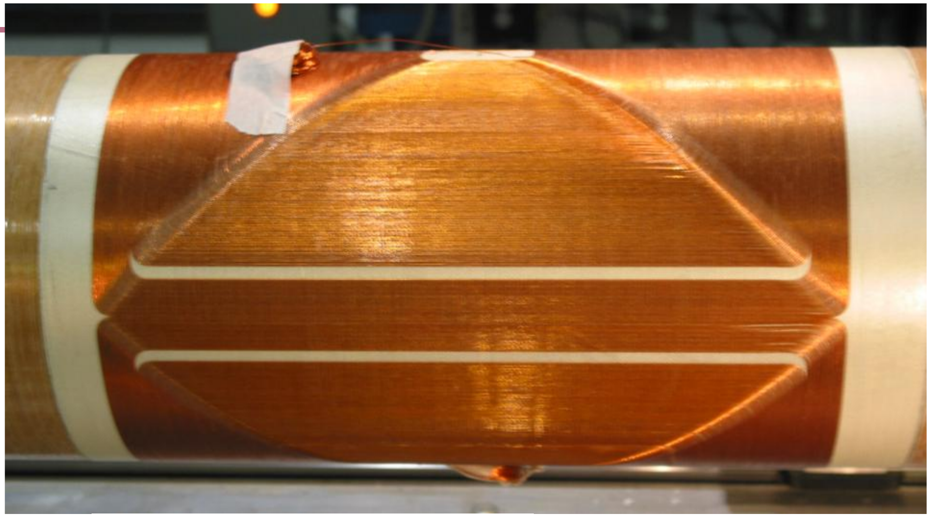
Optimum Integral Design (OID) Approach

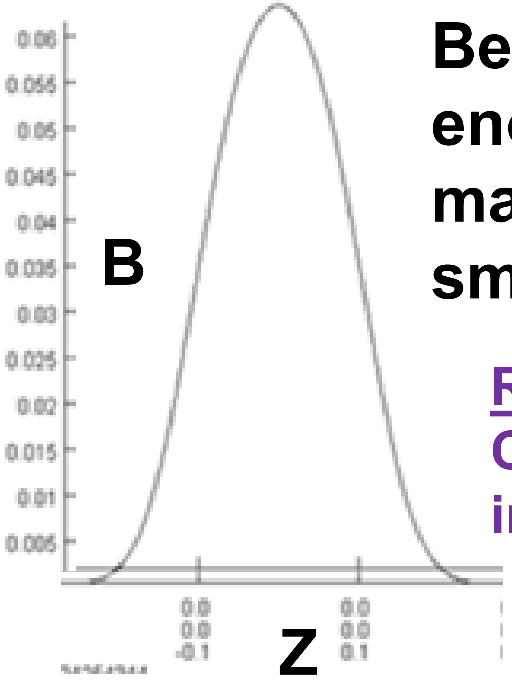
Optimize cross-section and ends together in a single step. And obtain a cosine theta current distribution in an integral sense:

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

(a) Turns at midplane extend full-length, (b) length of turns decreases linearly with the angle to help create a *cos(nθ) function*
(c) higher packing factor & longer lengths

✓ **Not only the loss in the integral field due to ends is essentially eliminated, ends help in the harmonic optimization!**





Benefits are enormous in a magnet with small flat-top

Reminder: Coil Length/ID in B0pF: ~1.9

Turning Optimum Integral Design Concept to Reality (1)

- Optimizing 3-d coil design from scratch takes one to two order of magnitude more time than the 2-d. This makes turning OID concept to reality nearly impossible.
- A code based on different methodology was developed that works fast. It directly computes and optimizes 3-d integral harmonics for each wire of length "*L*" at *(a,φ)*

<u>Integral harmonic</u>:

$$B_n = 10^4 \left(\frac{R_0}{a}\right)^n L.\ \cos\left[(n+1)\,\phi\right]$$

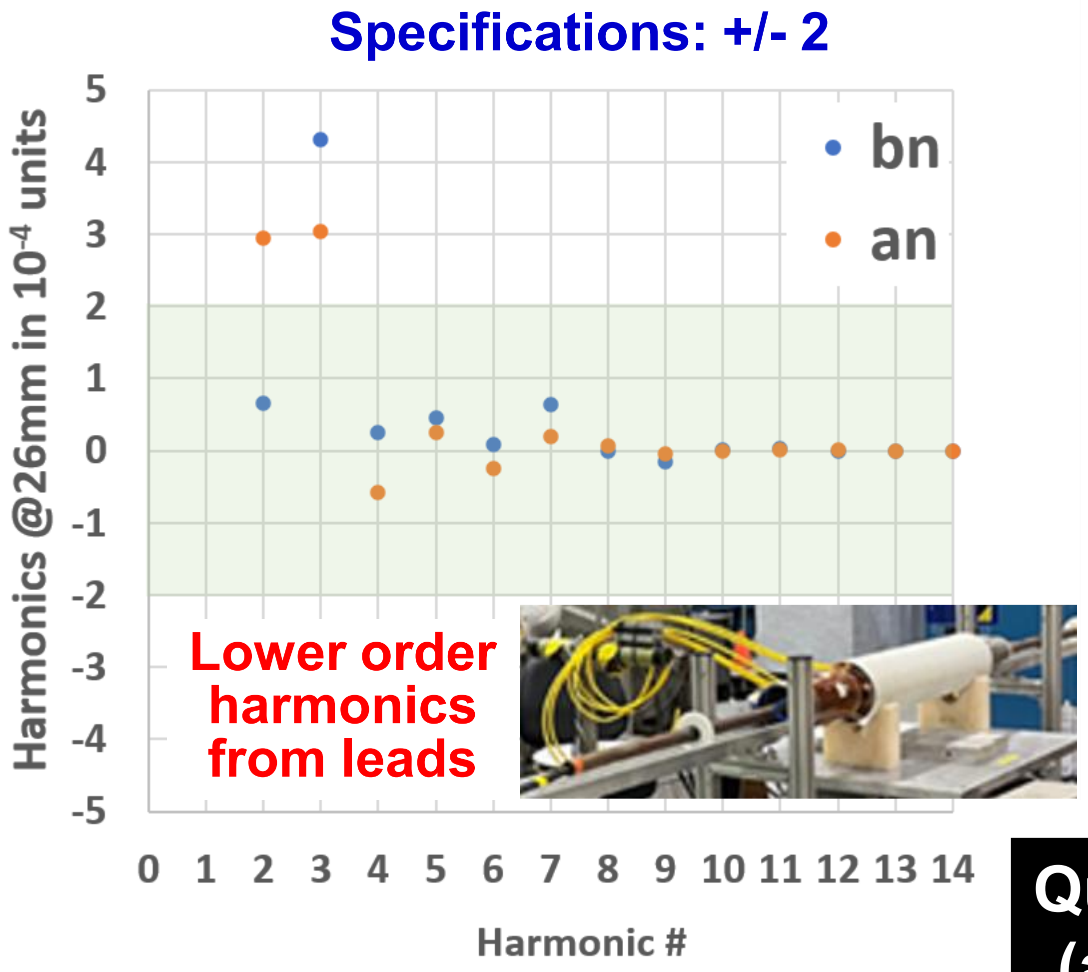
➢ It was further developed for optimizing combined function design and for optimizing harmonics at on axis and off-axes together (such as for e-beam and hadron beam).

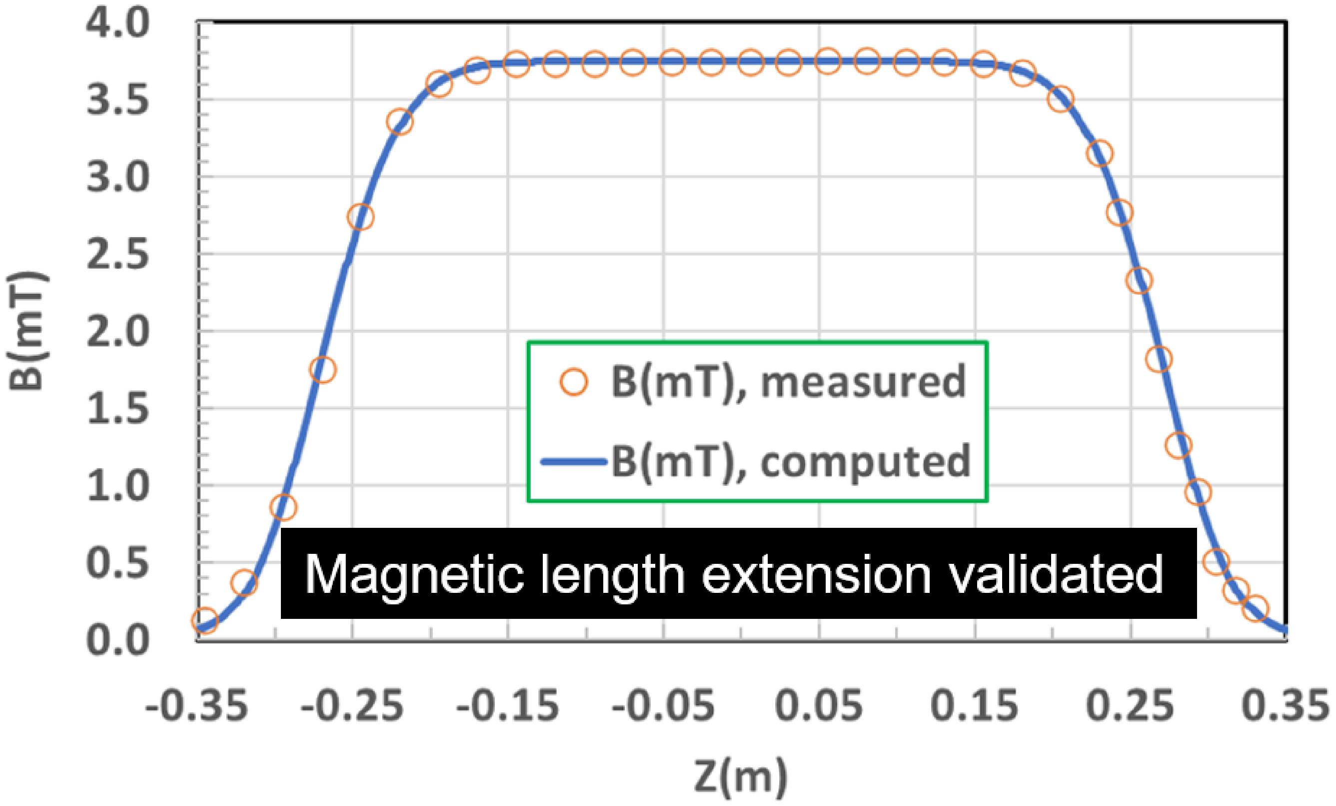
➢ **Software must facilitate optimization of designs as per the need of the machine and help develop new designs and concepts, rather than hold them back.**

➢ A new GUI based code (MADEO) is almost ready that has a better pre- and post-processors, and performs peak fields and many other useful calculations, as well.

Turning Optimum Integral Design Concept to Reality (2)

- **A new concept must be experimentally validated before it can be used in the machine. Same holds for the code.**



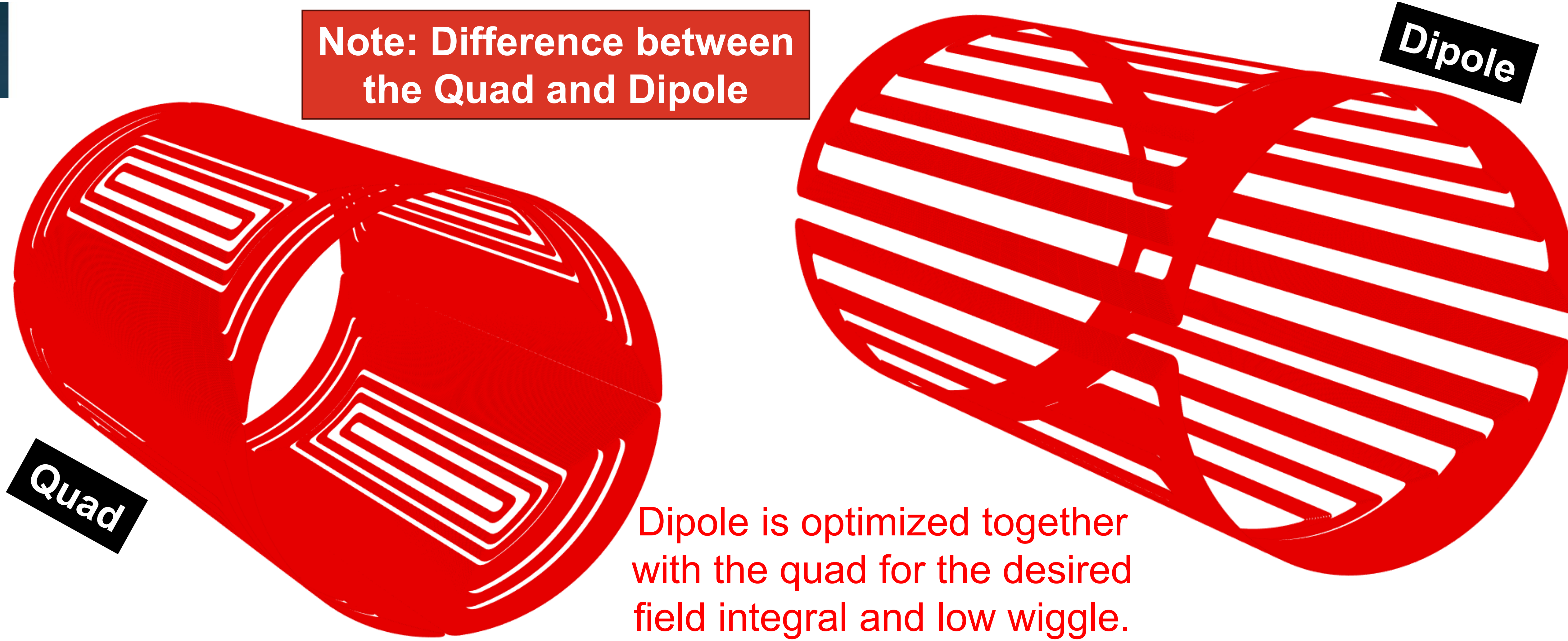


Quench performance meets EIC requirement (as good as in similar direct wind magnets)

Optimized 7-layer (6 quad + 1 dipole) OID Design

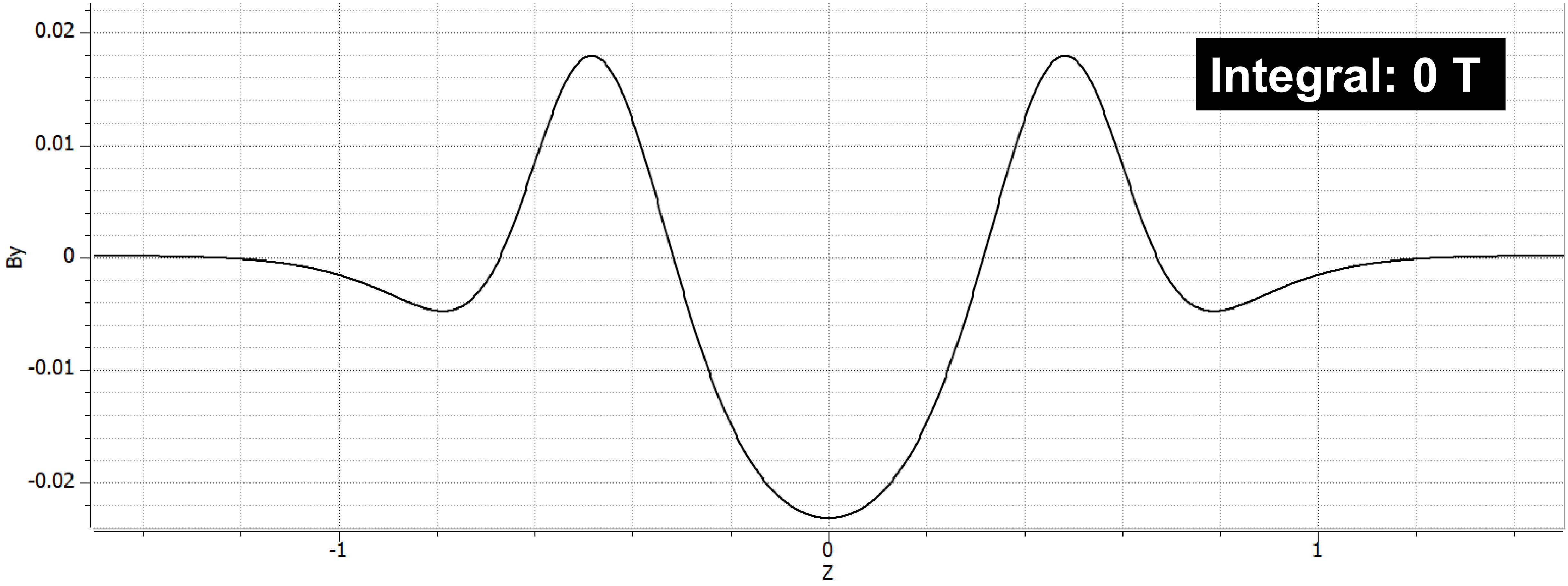
OID allows (a) longer turn at the midplane and, (b) packing more turns in the body. Also, ends help in harmonic optimization. Each layer is optimized individually.

Note: Difference between the Quad and Dipole



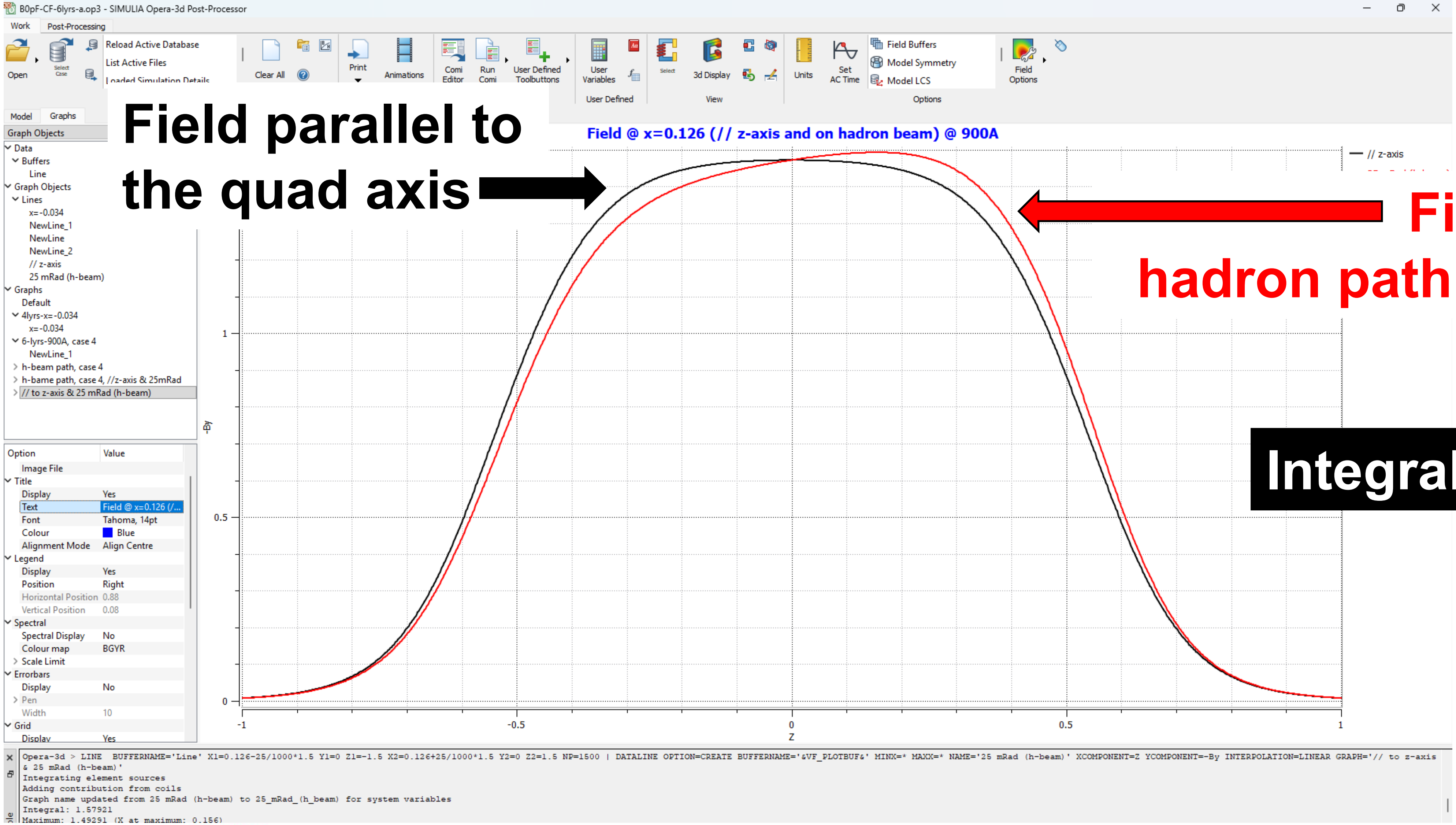
Dipole is optimized together with the quad for the desired field integral and low wiggle.

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



- Maximum variation in B_y along the electron path within +/- 0.02 T

Field along the hadron path (X=126 mm)



Field parallel to the quad axis

Field on the hadron path (25 mrad)

Integral: 1.56 T.m

Optimized Harmonics by the OID code at 220 mm Radius

Initial Guidance: $b_3(b_{2us})$ <3, $b_4(b_{3us})$ <5, $b_5(b_{4us})$ <10, higher <25

(achieved <<1 unit in each layer, well below the guidance)

Quad Layer 1

TOTAL NUMBER OF TURNS = 108
CHI SQUARE = 4.9496169826745984E-
INTEGRATED FIELD HARMONICS :

No.	Bn (T.m)	bn*10^4 (units)
1	0.42503E+00	10000.0000
5	0.50745E-08	0.0001
9	0.40715E-07	0.0010
13	-0.89046E-07	-0.0021
17	0.33983E-06	0.0080
21	0.14450E-05	0.0340
25	-0.69550E-06	-0.0164
29	-0.76843E-07	-0.0018

Quad Layer 3

TOTAL NUMBER OF TURNS = 110
CHI SQUARE = 0.14807616989128292
INTEGRATED FIELD HARMONICS :

No.	Bn (T.m)	bn*10^4 (units)
1	0.42775E+00	10000.0000
5	-0.15695E-05	-0.0367
9	-0.64879E-05	-0.1517
13	-0.14212E-04	-0.3322
17	0.11769E-04	0.2751
21	-0.11994E-05	-0.0280
25	-0.77247E-07	-0.0018
29	-0.36137E-07	-0.0008

Dipole Layer 5

TOTAL NUMBER OF TURNS = 118
CHI SQUARE = 0.49143448653194355
INTEGRATED FIELD HARMONICS :

No.	Bn (T.m)	bn*10^4 (units)
0	0.41104E+00	10000.0000
2	-0.24181E-06	-0.0059
4	0.16764E-05	0.0408
6	0.81339E-06	0.0198
8	-0.90486E-05	-0.2201
10	-0.11065E-05	-0.0269
12	0.32800E-04	0.7980
14	0.76289E-05	0.1856
16	-0.19487E-04	-0.4741
18	-0.87178E-05	-0.2121
20	-0.90354E-05	-0.2198
22	-0.23606E-05	-0.0574
24	-0.27120E-05	-0.0660
26	-0.84490E-06	-0.0206
28	0.34291E-06	0.0083
30	0.49103E-07	0.0012

Quad Layer 6

TOTAL NUMBER OF TURNS = 108
CHI SQUARE = 1.0923326022350466E-
INTEGRATED FIELD HARMONICS :

No.	Bn (T.m)	bn*10^4 (units)
1	0.41343E+00	10000.0000
5	0.23922E-07	0.0006
9	-0.15362E-06	-0.0037
13	-0.10027E-05	-0.0243
17	-0.50164E-05	-0.1213
21	-0.82271E-06	-0.0199
25	-0.41240E-07	-0.0010
29	-0.65076E-07	-0.0016

Quad Layer 2

TOTAL NUMBER OF TURNS = 107
CHI SQUARE = 0.20215782364584811
INTEGRATED FIELD HARMONICS :

No.	Bn (T.m)	bn*10^4 (units)
1	0.42560E+00	10000.0000
5	0.10593E-06	0.0025
9	0.11908E-05	0.0280
13	0.40257E-05	0.0946
17	0.22374E-04	0.5257
21	-0.63780E-06	-0.0150
25	-0.95453E-08	-0.0002
29	-0.55015E-07	-0.0013

Quad Layer 4

TOTAL NUMBER OF TURNS = 109
CHI SQUARE = 4.5360278986208868E-
INTEGRATED FIELD HARMONICS :

No.	Bn (T.m)	bn*10^4 (units)
1	0.43550E+00	10000.0000
5	0.13028E-06	0.0030
9	0.70204E-06	0.0161
13	0.25090E-05	0.0576
17	0.10696E-04	0.2456
21	-0.57733E-06	-0.0133
25	0.16169E-07	0.0004
29	-0.62011E-08	-0.0001

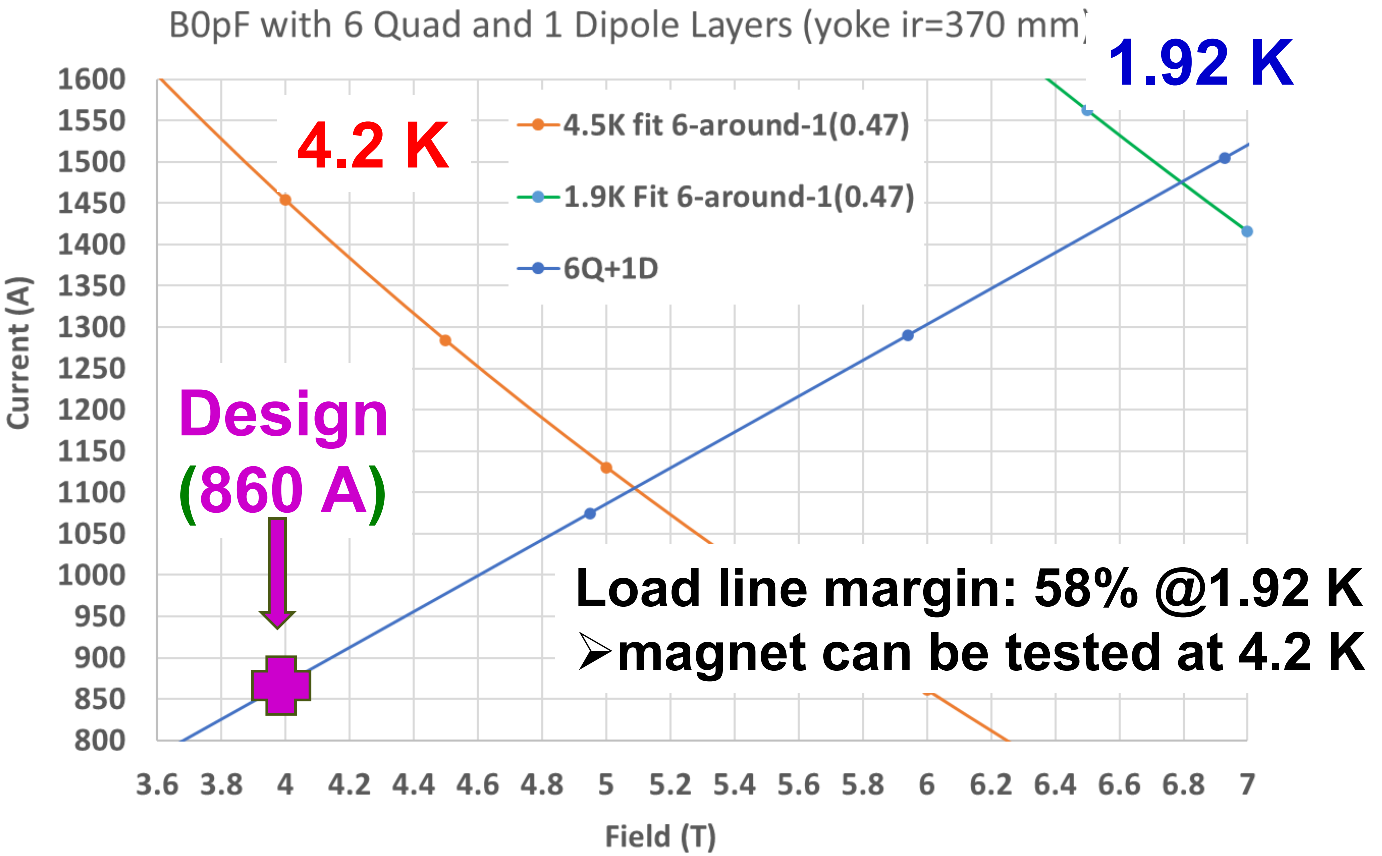
Quad Layer 7

TOTAL NUMBER OF TURNS = 109
CHI SQUARE = 1.3931129233185402E-
INTEGRATED FIELD HARMONICS :

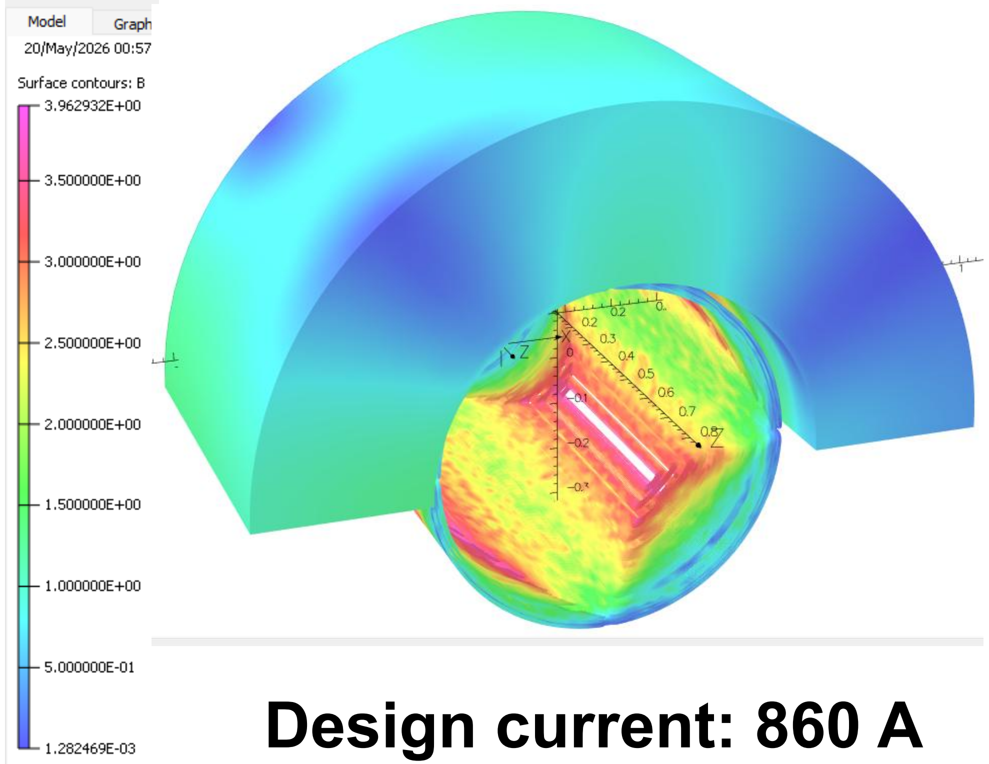
No.	Bn (T.m)	bn*10^4 (units)
1	0.42888E+00	10000.0000
5	0.46304E-07	0.0011
9	0.10484E-06	0.0024
13	0.53551E-06	0.0125
17	0.34295E-05	0.0800
21	-0.10977E-05	-0.0256
25	-0.27148E-07	-0.0006
29	-0.22039E-07	-0.0005

Correction for the rounded corner, rather than square end, is done in the next step.

Expected Performance of 6 Quad + 1 Dipole Layer OID



Load line margin: 58% @1.92 K
➢ **magnet can be tested at 4.2 K**



Design current: 860 A

(original 10-layer design: 1143 A)

- ➢ **Efficiency of OID produces the required integral field with a fewer layers, operating at a lower current. Also, even a few layer gave higher margin.**
- ➢ **A large margin gave us freedom to try many additional options (next slide).**

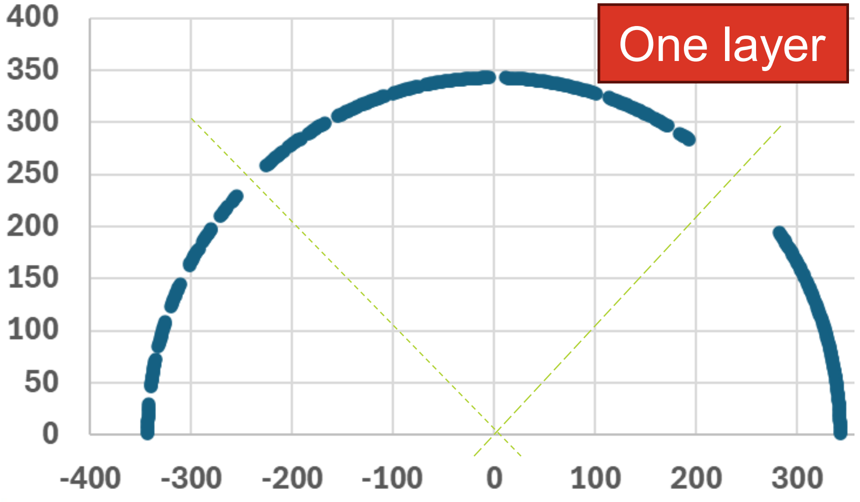
Combined Function Design

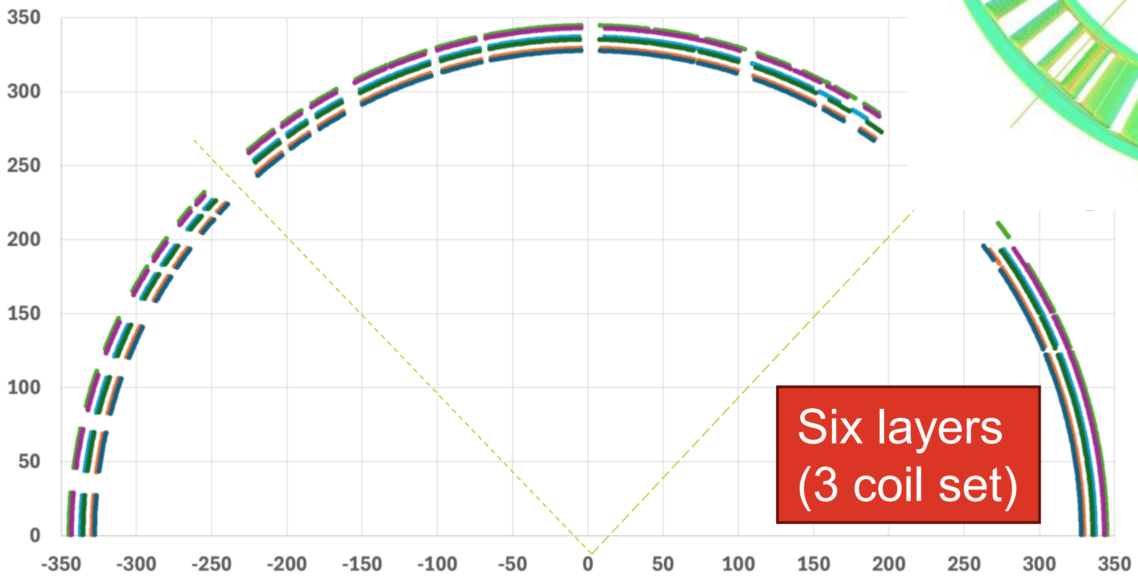
1. B0pF is basically a combined function magnet. Present 7-layer design has six quadrupole layers running in series with one dipole layer.

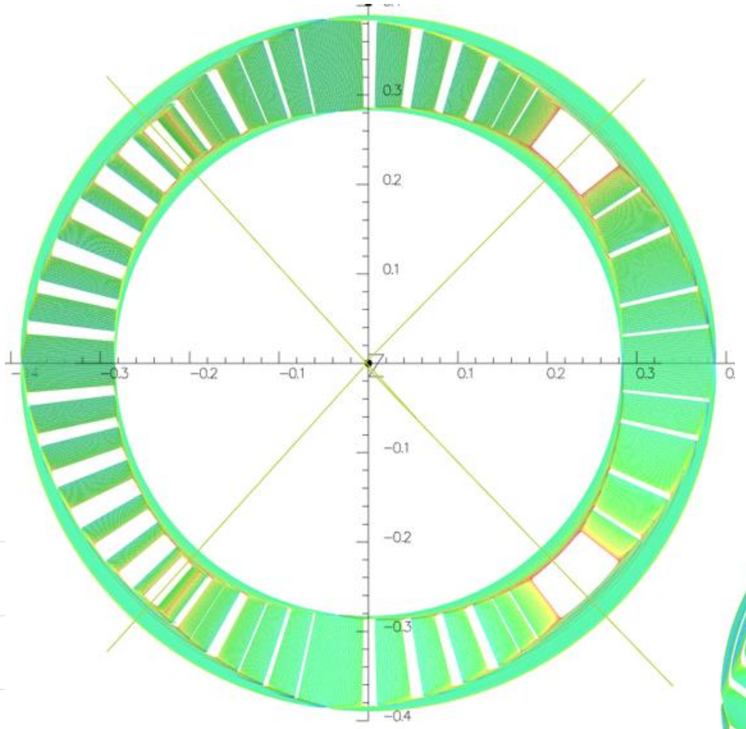
- An alternate set of designs have been developed in which each layer is made a combined function layer with a goal of each layer meeting the desired field gradient, field integral and field quality requirement.
- The design seems to offer several advantages, including further reduction in cost due to fewer layers.
  - ➢ A 6-layer design offered sufficient margin (original had 10 layers)

✓ **Software was updated to optimize combined function designs**

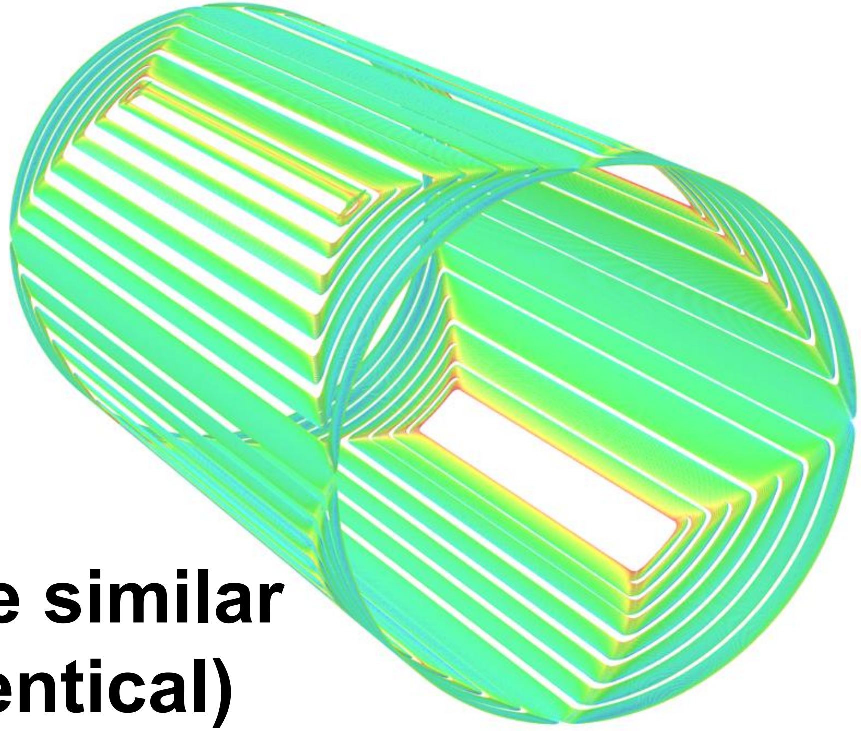
6-layer Combined Function Coil (each layer optimized individually)





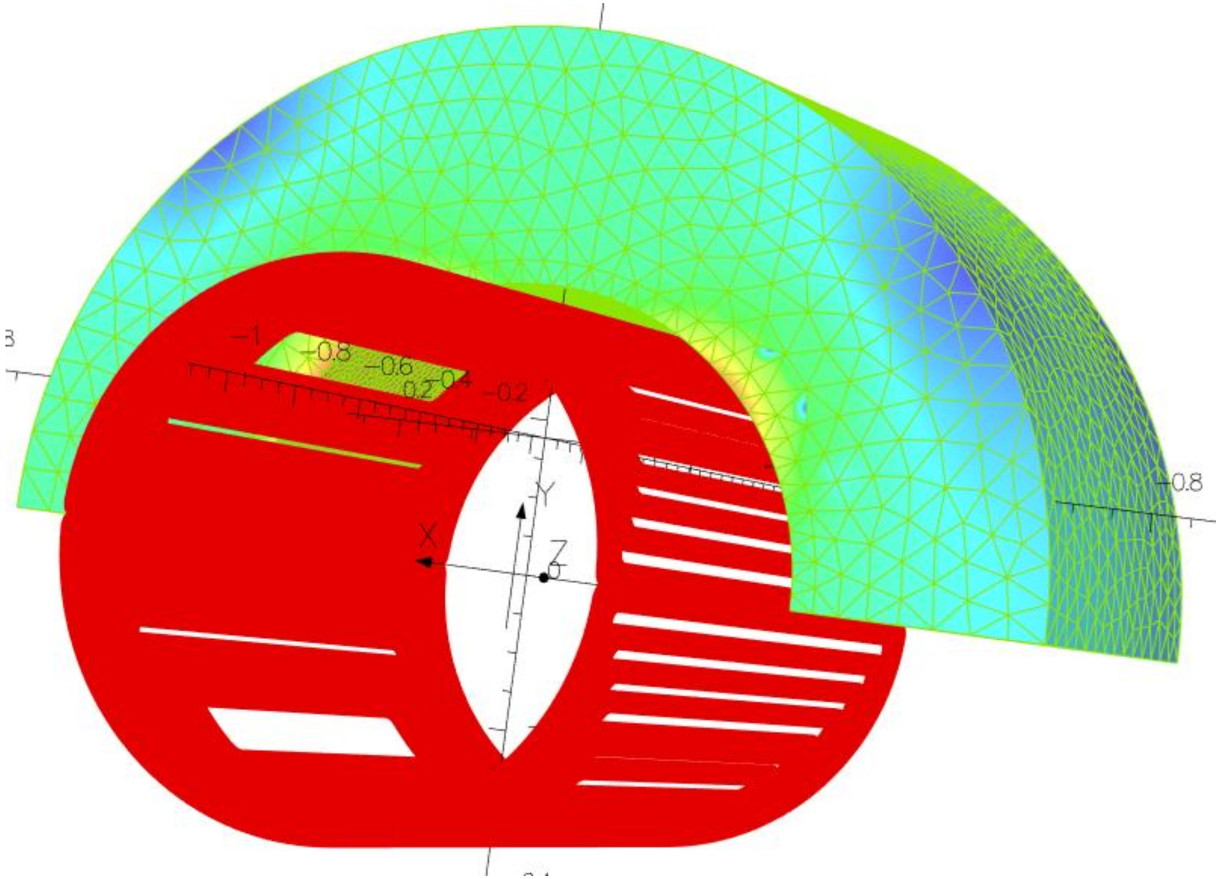


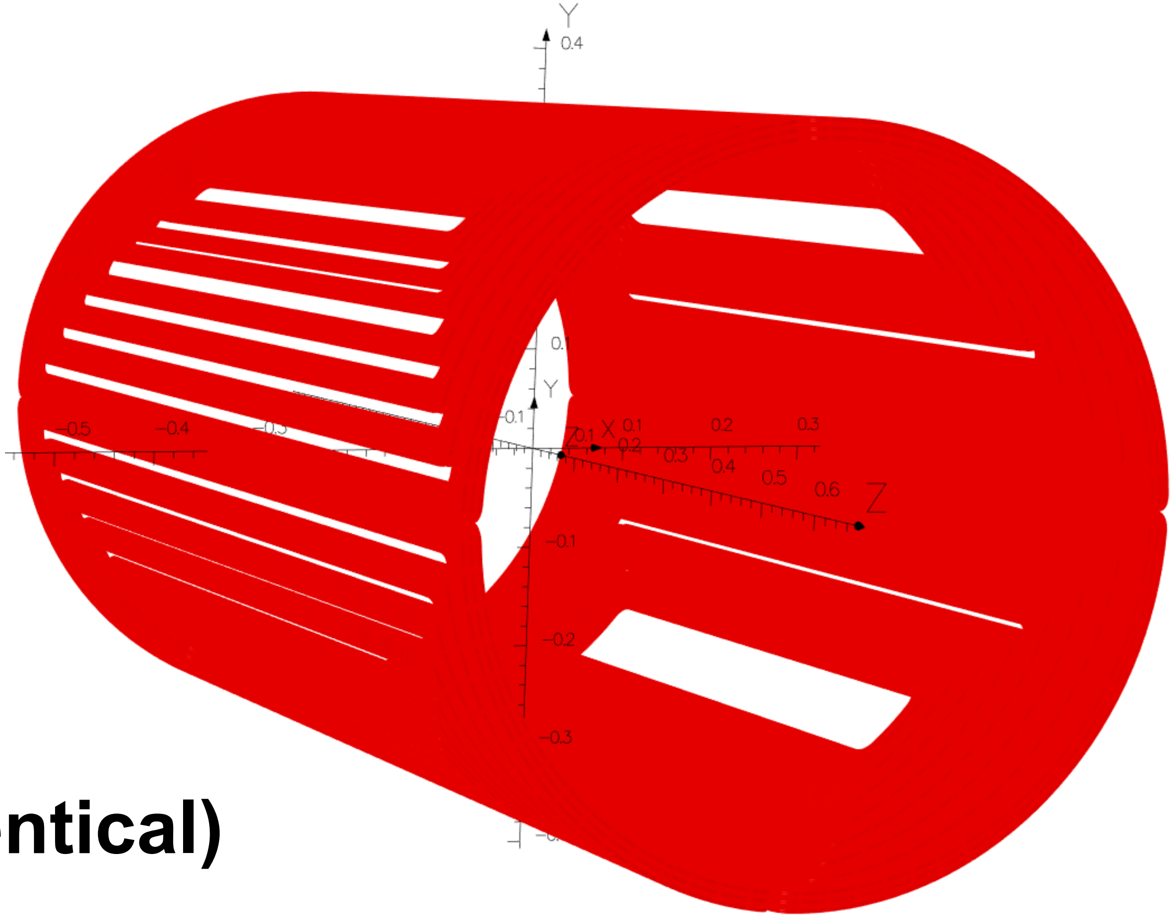
Note:
Broken left-right symmetry for combined function



All layers are similar (but not identical)

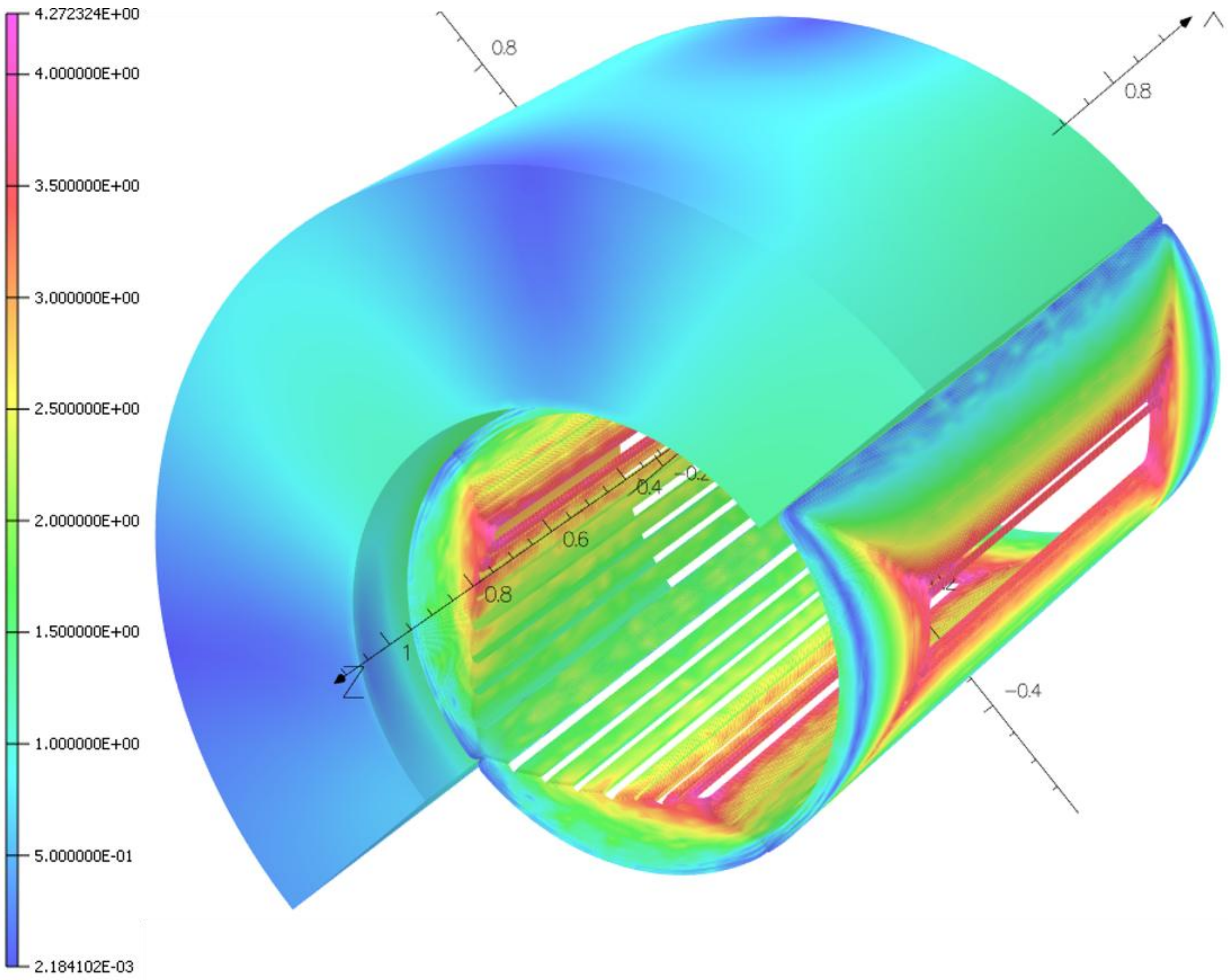
More views of a combined function design
(more turns on one side of quad adds dipole field)

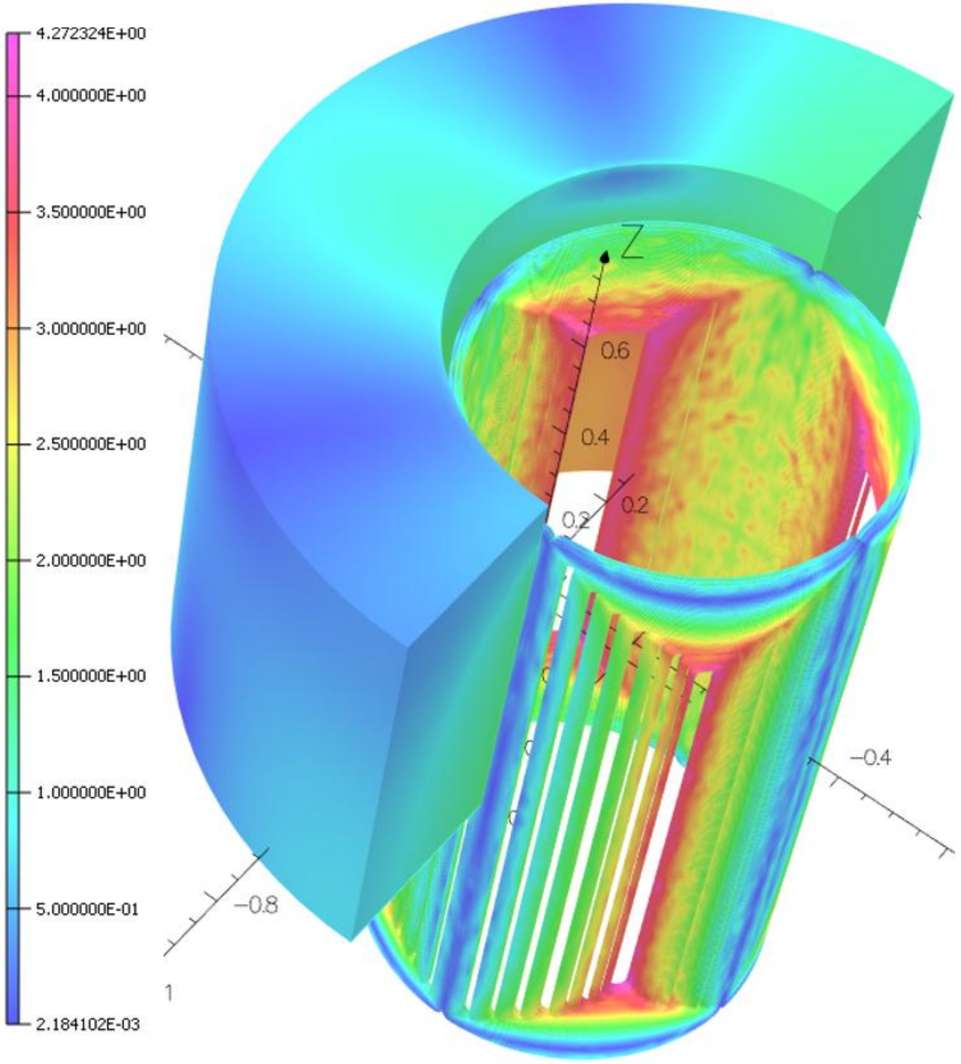




➢ **All layers are similar (but not identical)**

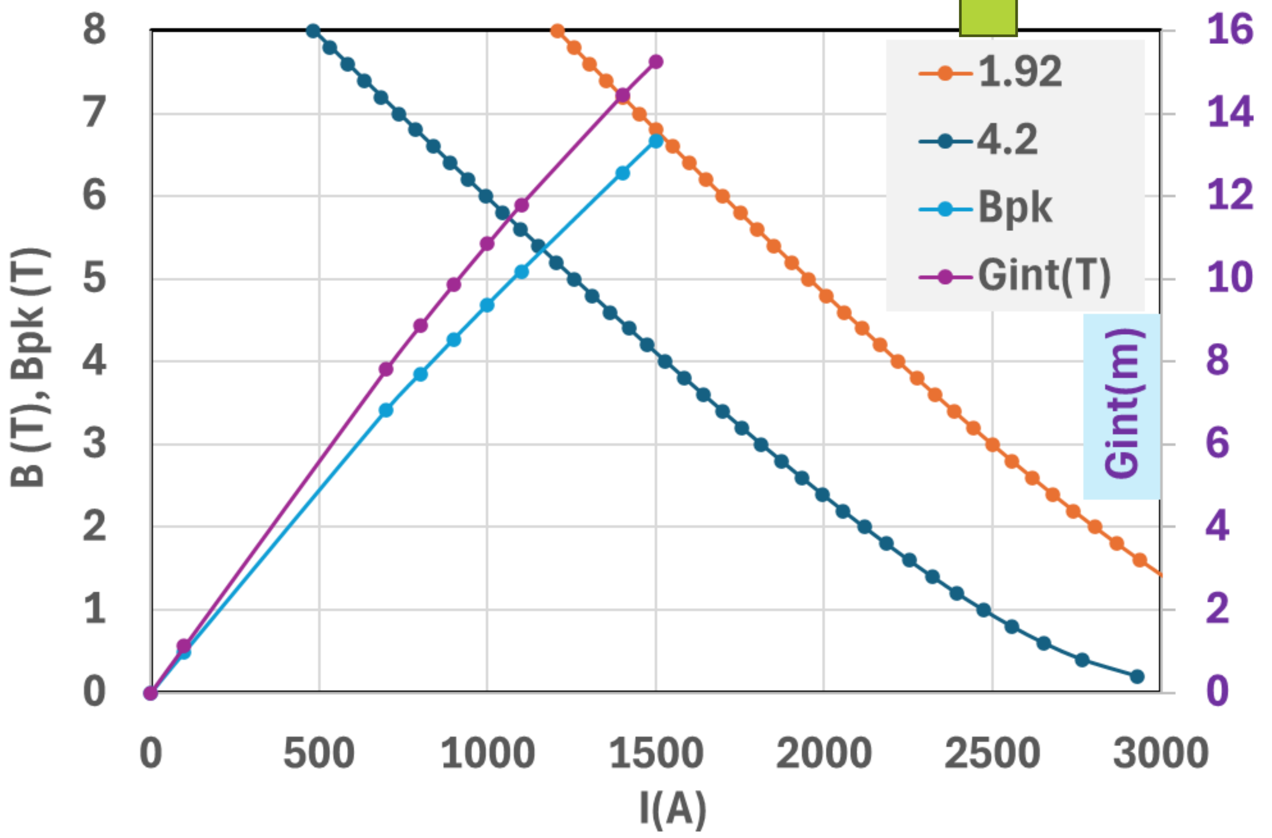
6-Layer Combined Function Coil in Yoke

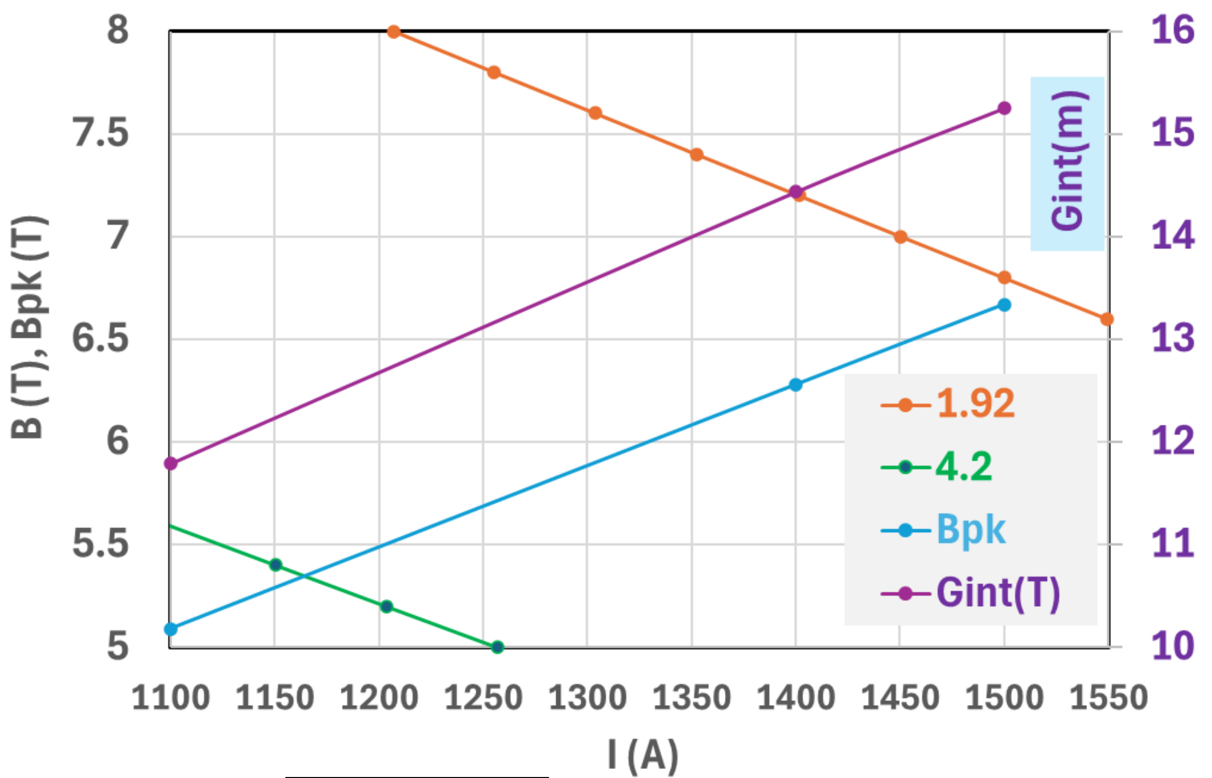




6-layer Optimum Integral Combined Function Design

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





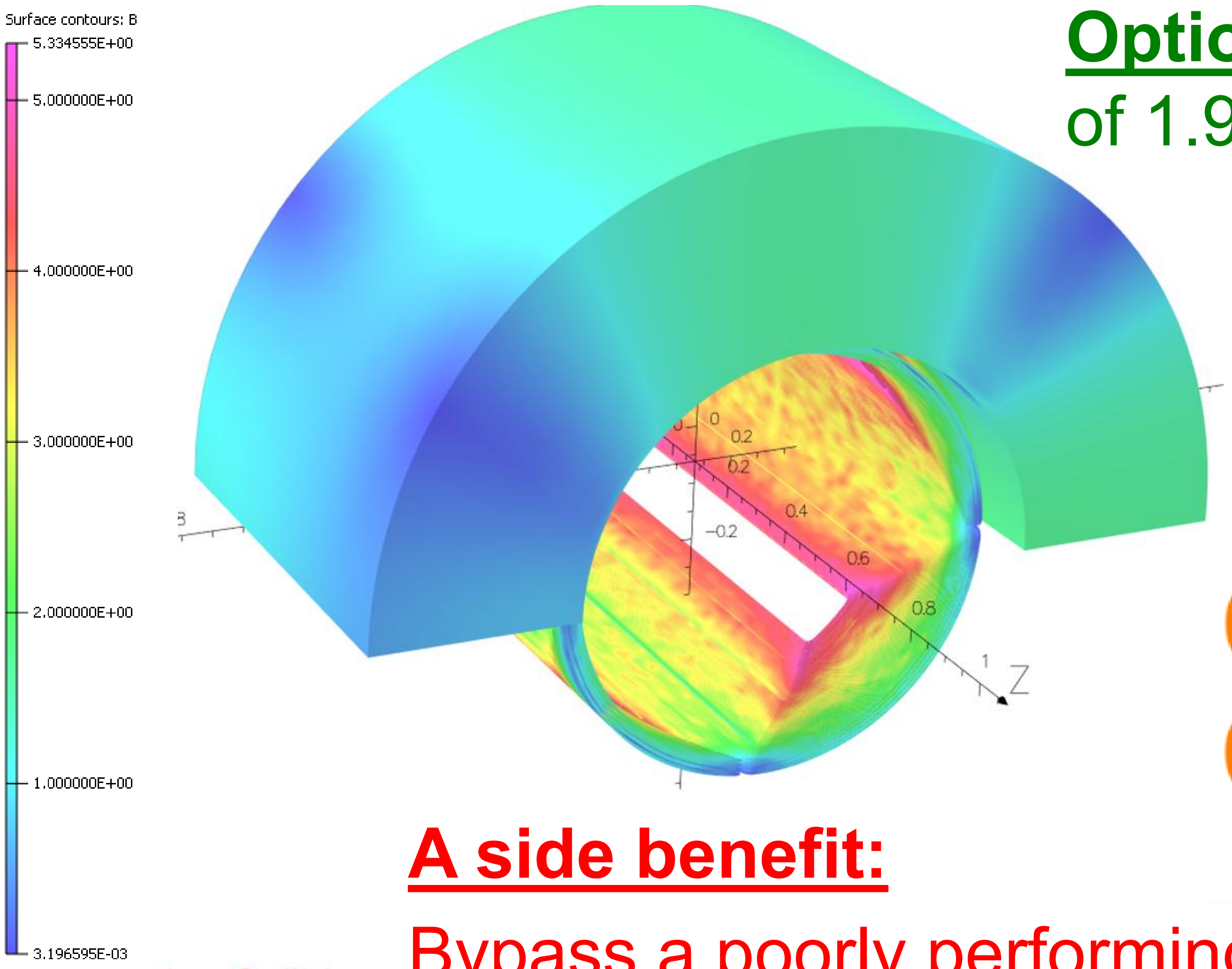
	Iss(A)
@1.92K	1520
@4.2K	1160

Load line margins
=> 58%
=> 77%

Large margin @1,92K; healthy margin @4.2K for testing

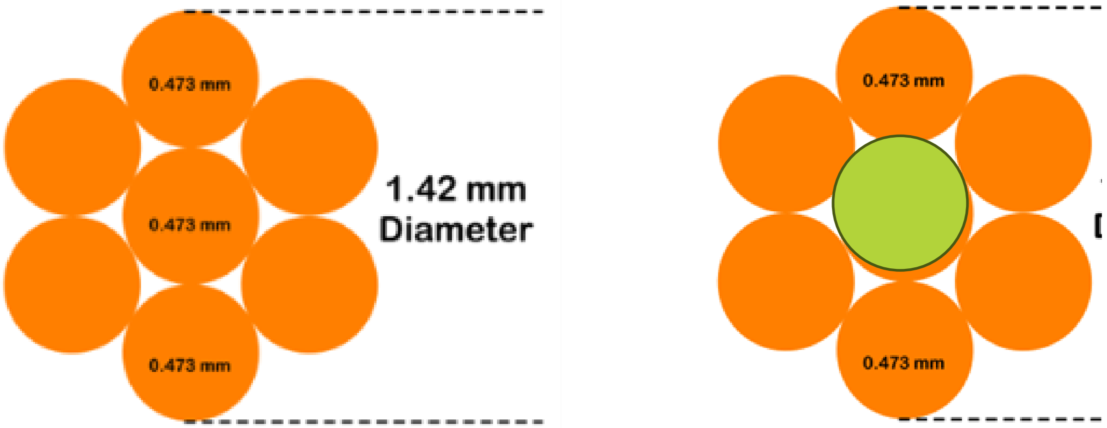
8-layer Combined Function Coil (each individually optimized)

8-layer design offers additional margin that can be used for:



Option 1: 4.2/4.6 K operation instead of 1.92 K with a sufficient margin

Option 2: Central wire made copper in the 6-around-1 cable for better quench protection



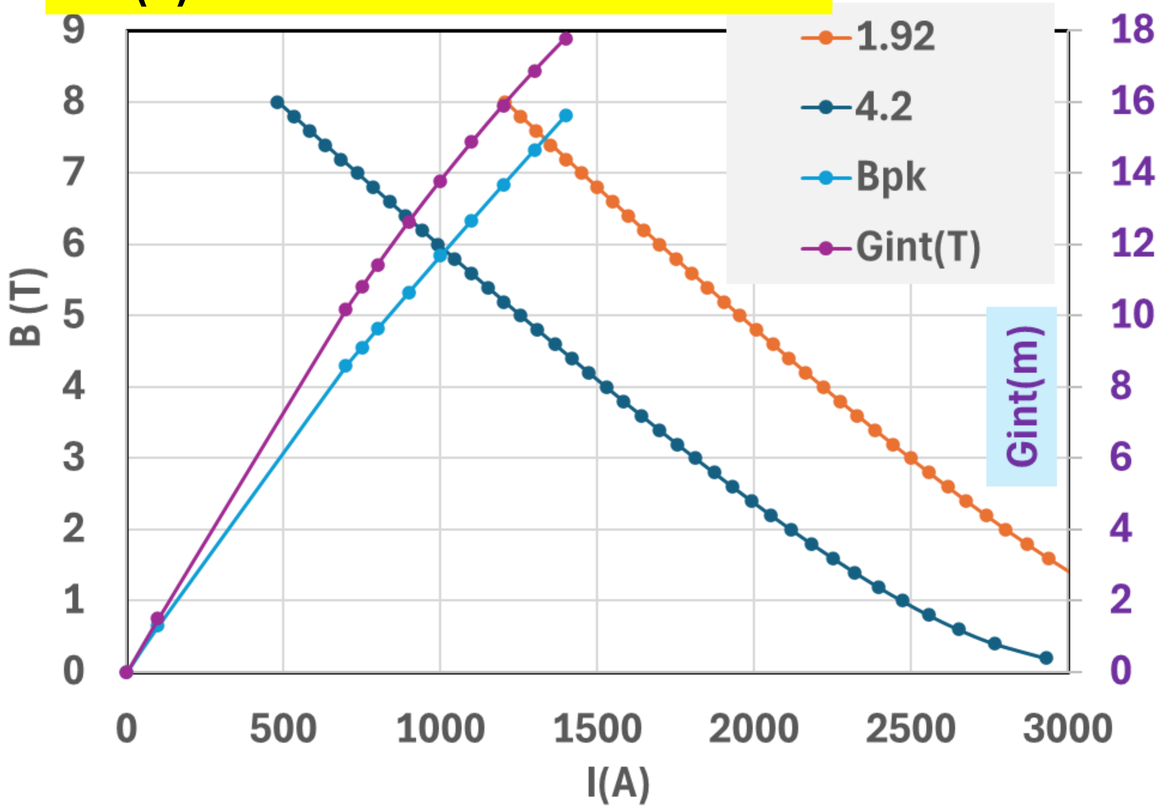
A side benefit:

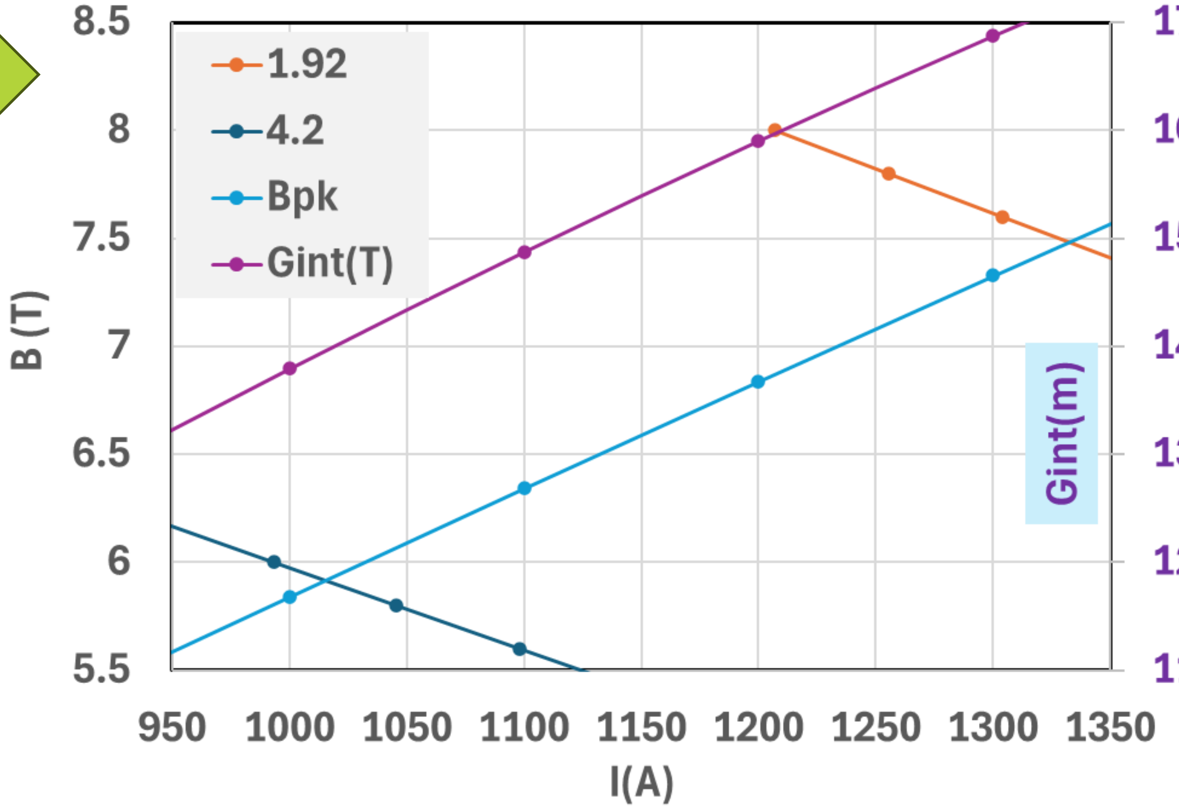
Bypass a poorly performing coil set and retain the magnet.

Possible 4K Combined Function Option 8-layer OID

- **Current reduced; margin increased!**

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



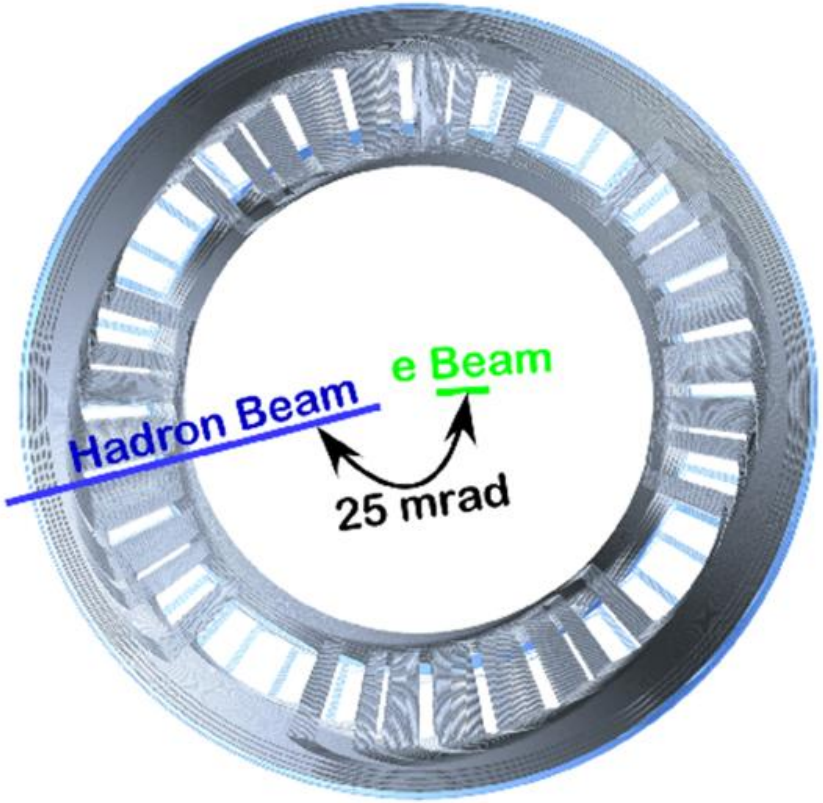


	Iss(A)	Load line(%)
1.92K	1330	51%
4.2K	1020	66%

Back to Separate Quad and Dipole Layer Design

A good field quality is needed not at the magnet axis but on the path of hadron and electron beams (both off-axes, with a small angle in between)

- It is easier to optimize harmonics in quad and dipole layers individually with symmetry helping to eliminate harmonics (particularly in quad layers – most of them are quad layers).
- Harmonic optimization was initially performed by minimizing them at center with a large reference radius that covers both beams.
- For better optimization, software is updated to optimize harmonics at multiple axes



Optimize for margin, etc. assuring a good field quality for beams

Quadrupole and Dipole Layers Optimized for off-Axis

Quadrupole Layer Harmonics

No.	hadron-beam -126mm@50mm bn*10^4 (units)	electron-beam 34mm@50mm bn*10^4 (units)	center 0mm@220mm bn*10^4 (units)
1	-3180.6604	1393.1587	-0.0004
2	10000.0000	10000.0000	10000.0000
3	0.0469	-0.0045	0.0008
4	-0.0265	-0.0001	0.0002
5	0.0211	0.0002	0.0002
6	-0.0080	0.0068	0.0083
7	0.0067	0.0001	0.0001
8	-0.0023	0.0000	0.0000
9	0.0005	0.0000	0.0000
10	-0.0194	-0.0229	-0.0281
11	-0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000
14	-1.3798	-1.6353	-2.0070

Dipole Layer Harmonics

hadron-beam -126mm@50mm bn*10^4 (units)	electron-beam 34mm@50mm bn*10^4 (units)	center 0mm@220mm bn*10^4 (units)
10000.0000	10000.0000	10000.0000
-0.0368	0.0010	0.0005
0.1300	0.0970	0.1855
-0.0546	-0.0001	0.0002
-0.0118	-0.0632	-0.1267
-0.0113	0.0003	0.0001
0.1365	0.2007	0.4012
-0.0001	0.0001	0.0000
0.3314	0.4975	0.9950
0.0002	0.0000	0.0000
0.9219	1.3829	2.7658
0.0000	0.0000	0.0000
-0.1275	-0.1912	-0.3824
0.0000	0.0000	0.0000

Optimize for margin, etc. assuring a good field quality for beams

SUMMARY: Benefits of the Optimum Integral Design in B0pF

- Reduced the number of layers from 10 to 6 (range: 5 to 8)
- Reduced the operating current from 1143 A to 889 A (up to 671 A)
- Reduced the peak field on conductor from 5.3 T to 4.2 T
- Reduced strain on conductor (IXB) and less accumulated Lorentz forces
- Improved load line fraction from 70% to 60% (up to 50%)
- Allowed a possible operation at 4.2 K instead of 1.92 K
- Allowed a possibility of central wire copper for better quench protection
- Benefit in quench protection (voltage to ground 950 V to 535 V)
- Reduced the number of external energy extraction circuits
- Eliminated the absolute need of the quench heaters

Extra slides

Initial Goals for the B0ApF Optimization

- New designs should significantly reduce the risks and, if possible, cost (raised by the review committees and the Magnet Steering Group also).
- Centers of hadron beam and of electron beam in B0pF are respectively at -126 mm +34 mm with a relative angle of 25 mR between them.
- Integral field should be 1.56 T.m on the hadron beam and zero on the electron beam (with maximum swing along the e-path < +/- 0.02 T).
- Above gives a nominal integral gradient of 1.56/(.034+.126) = 9.75 T.
- Harmonics specs are given along the electron and hadron beam paths.
- Harmonic optimization is initially performed by minimizing them at center with a large reference radius that covers both beams.
- Updated code allows a better optimization, since the harmonics at multiple axes can be directly optimized for electron and hadron beams.

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

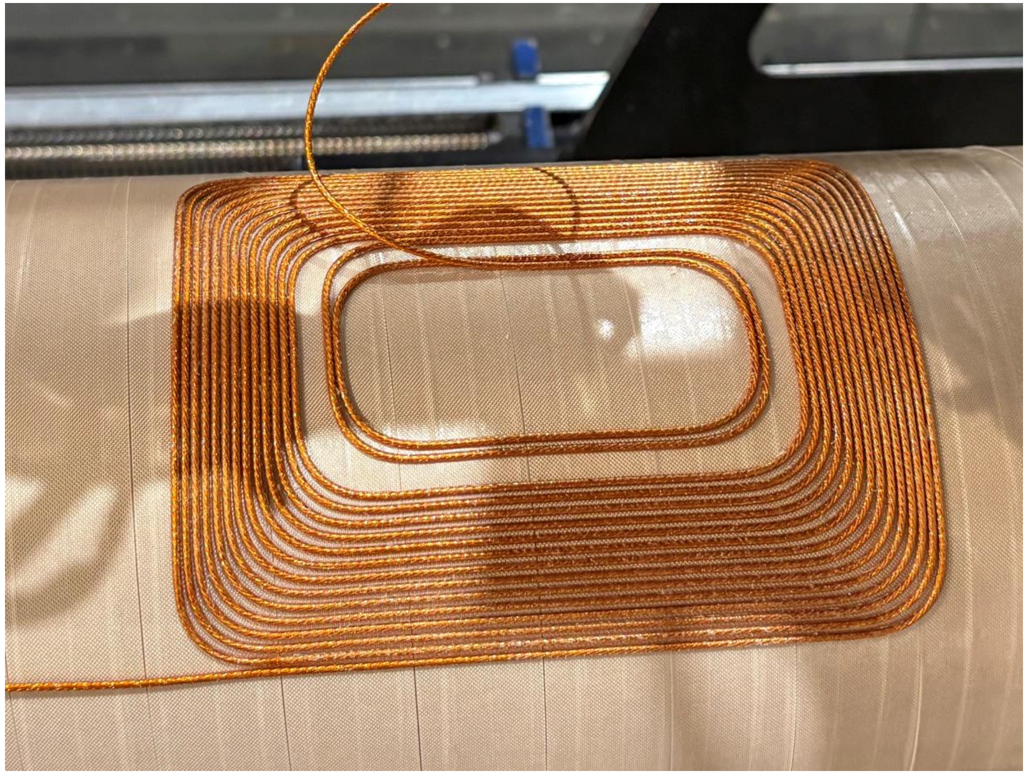
- Starting design with a big margin which allows a part to be traded for quench protection (e.g., higher cu/sc – too late).
- However, making the center wire copper (instead of super) is expected to help. This will improve the quench back.
- It should also increase effective cu/sc ratio (from 1.75 to 2.21), after the quench. This would reduce the hot spot temperature, beside the central wire effectively becoming a heater.
- The ramp rate reduction in I_c also will 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. The margin, however, is still very healthy.

➢ However, before making a choice, more analysis should be carried out, apart from any other consideration.

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

Continuous double-layer OID winding (no splices)



1st quadrant of the 1st layer wound midplane to pole
(instead of typical pole to pole in OID)

- Substrate placed along the length after filling gaps with fiberglass spacers and blue epoxy
- Substrate glues strongly for winding next layer
- 1st quadrant of 2nd layer wound
- Temporary spacer holder for winding removed