B1pF/B1ApF Direct Wind Optimum Integral Design Option

(a possible lower cost 4.5 K alternative)

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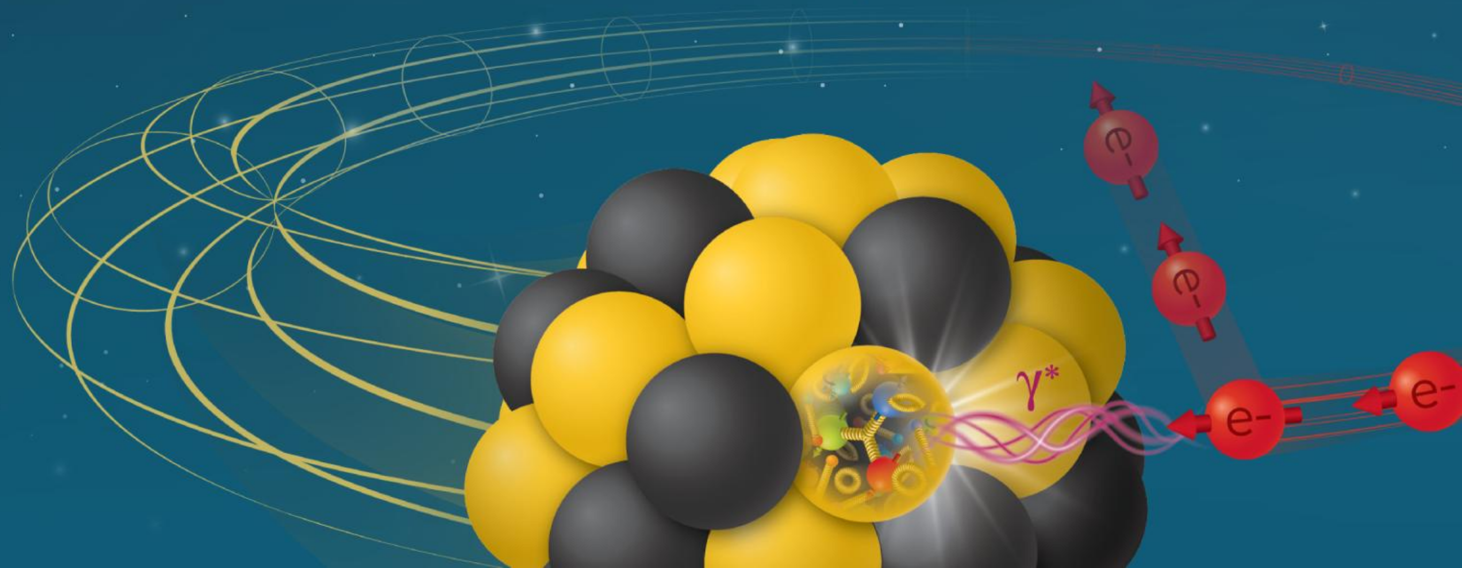
Electron-Ion Collider



Background and Introduction

- Current B1pF magnet under construction is based on Rutherford Cable. It has a coil inner radius of 150 mm, slot length of 3 meter, and a required integral of 10.34 T.m.
- A significant progress has been made in the EM design, mechanical design, test coil windings, etc.. This will be a key demonstration of a large aperture EIC IR magnet.
- With the magnet parameters of B1pF and B1ApF changing, it will be prudent to do a preliminary analysis (technical, schedule and budget) of the direct wind design option.
- A smaller coil length to diameter ratio makes Optimum Integral Dipole(OID) attractive.
- This study is for a bore i.r. of 161 mm (coil i.r. 185 mm for a 12.3 mm thick stainless-steel tube for direct wind coil, for an equivalent coil i.r. of 172.7 mm of cable magnet).
- In addition, interest in exploring 4.5 K operation for saving cost has been addressed.
- Initial results for 2.25 m long coil will be presented for both 1.92 K and 4.5 K operation (simply add a double layer for 4.5 K). Also examined cases for L=2.03 m and 1.91 m.

From Scott Berg (12/30/2025)

Reference designs (coil i.r.):
B1pF: 150 mm, 3 m, 10.34 T.m
B1ApF: 185 mm,1.91m, 4.08T.m

	Baseline Acceptance		Reduced Acceptance	
	Option 2	Option 4a	Option 2	Option 4a
Transverse Momentum Acceptance (GeV/c)	1.23	1.23	1.11	1.11
Neutral Cone Acceptance (mrad)	4.0	4.0	3.6	3.6
B0ApF Radius (mm)	40	39	36	35
B0ApF Integrated Field (T·m)	1.99	1.56	1.99	1.56
Q1ApF Entrance Radius (mm)	N/A	42	N/A	38
Q1ApF Exit Radius (mm)	53	52	48	47
Q1BpF Exit Radius (mm)	78	78	71	71
Q2pF Radius (mm)	131	131	118	118
B1pF/B1ApF Radius (mm)	156	⇨ 161	145	149
B1pF/B1ApF Integrated Field (T·m)	6.89	⇨ 6.37	6.91	6.49
Extra Space for B2pF (cm)	9	56	11	48

This study is for:
- **2.25 m**
- **161 mm**
- **6.37 T.m**
- **1.9 K and 4.5 K**

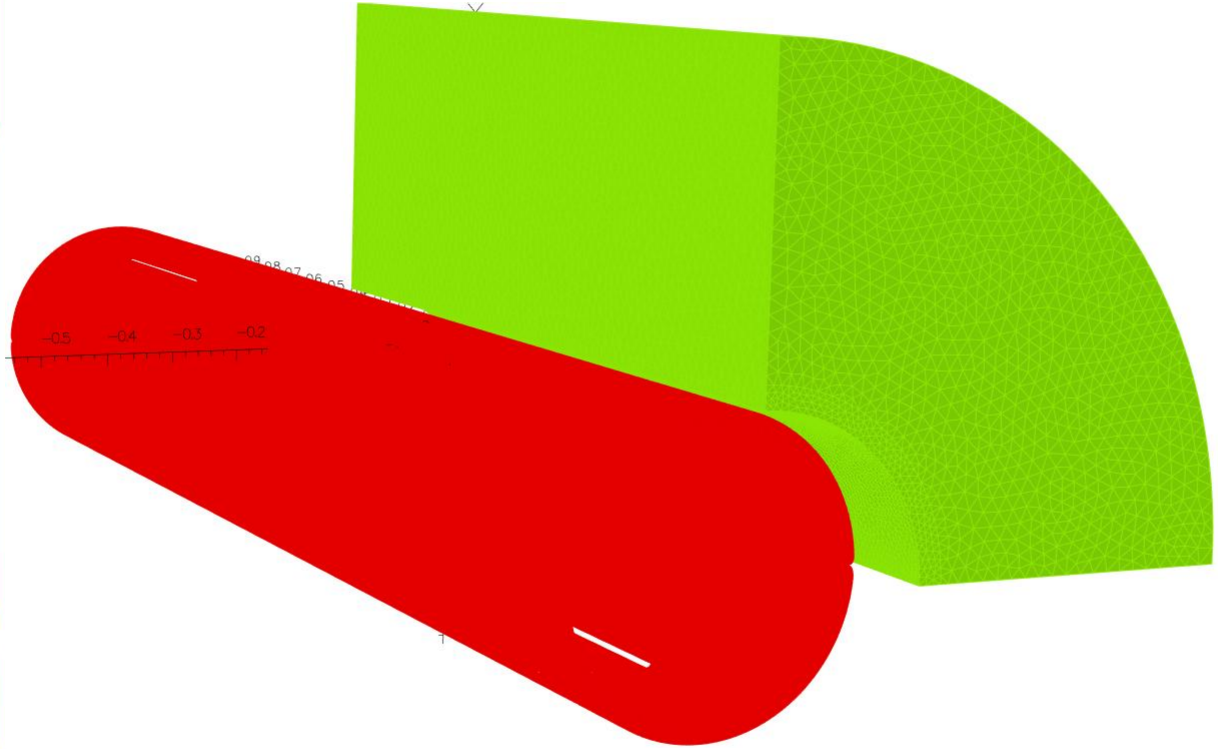
Quick turn around possible for other parameters

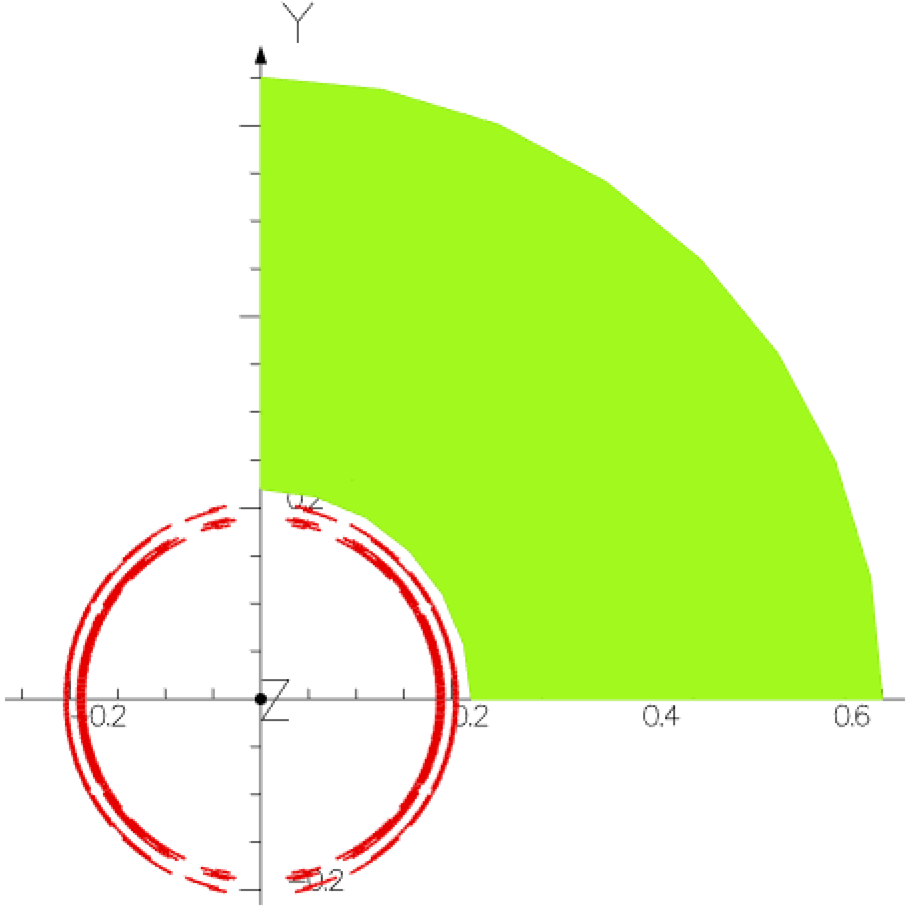
6-layer direct wind OID for B1pF/B1ApF

Initially designed for 1.92 K
(may be good for 4.5K, as well)

- **Coil length 2.25 m**
- **Coil inner radius 185 mm (161 mm bore, 172.7 mm SS tube)**

6-layer Optimum Integral Design for B1pF/B1ApF

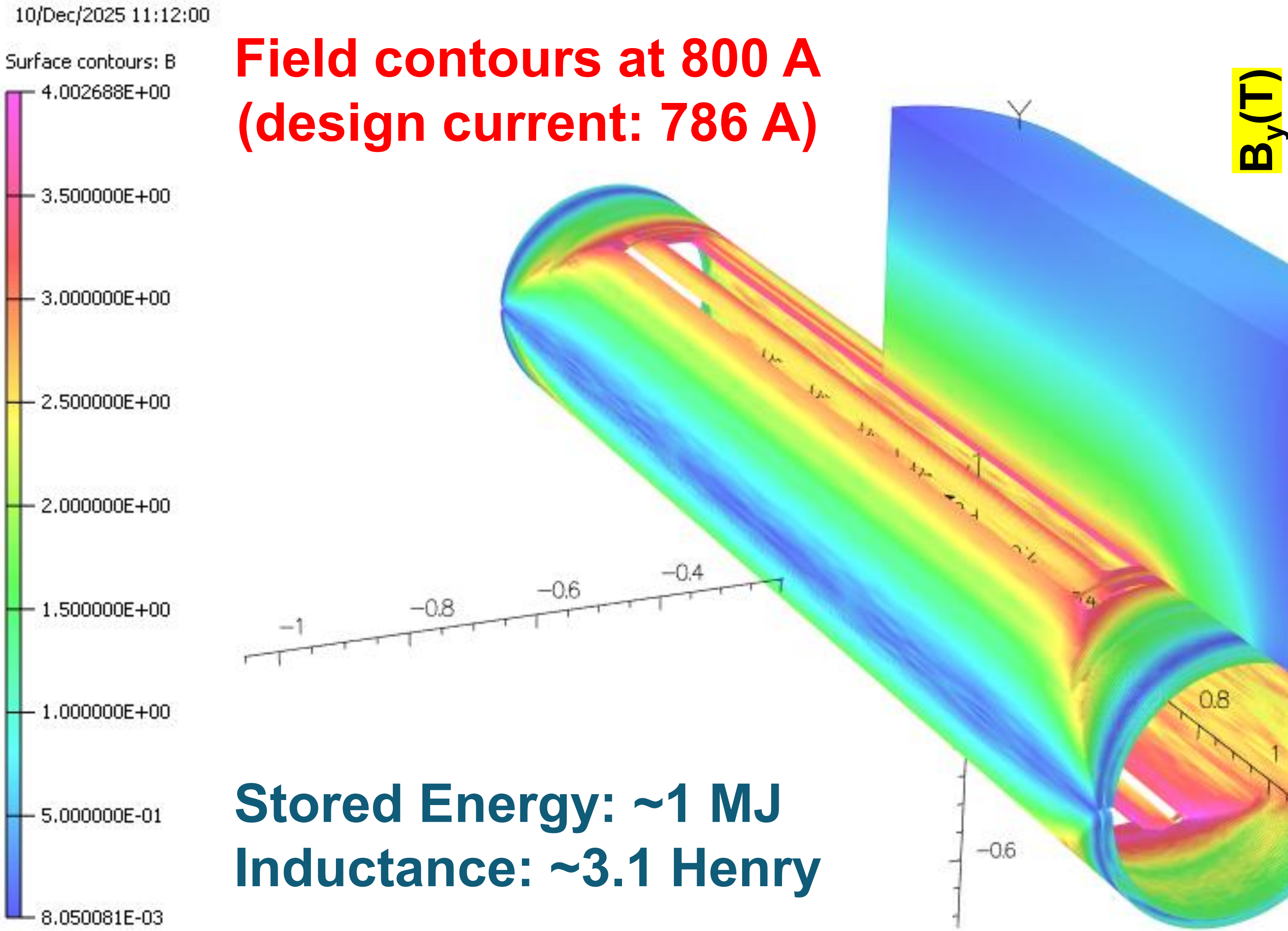


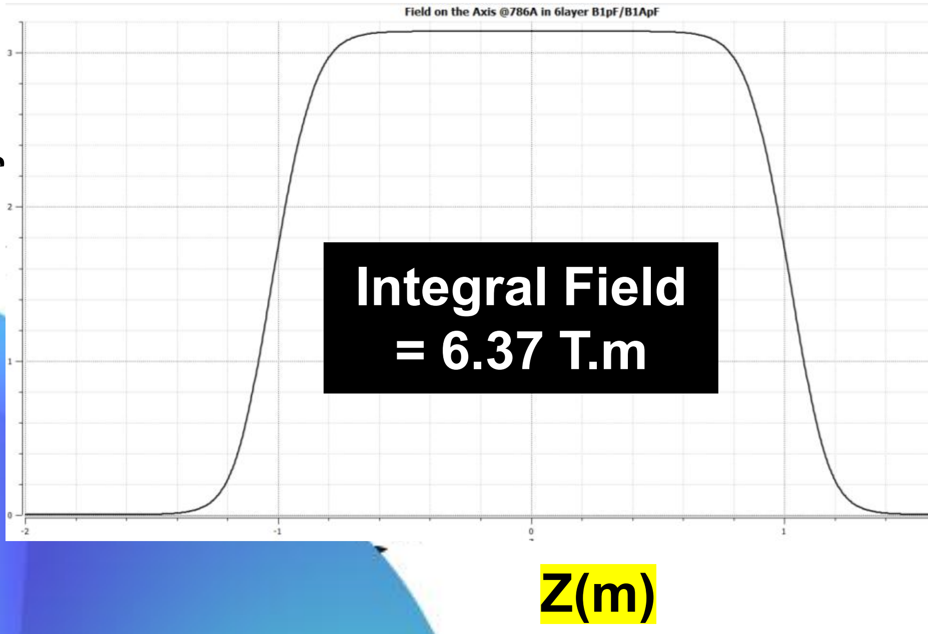


(6-around-1 cable with 0.47 mm wire)

6-layer Optimum Integral Design for B1pF/B1ApF

Field contours at 800 A
(design current: 786 A)





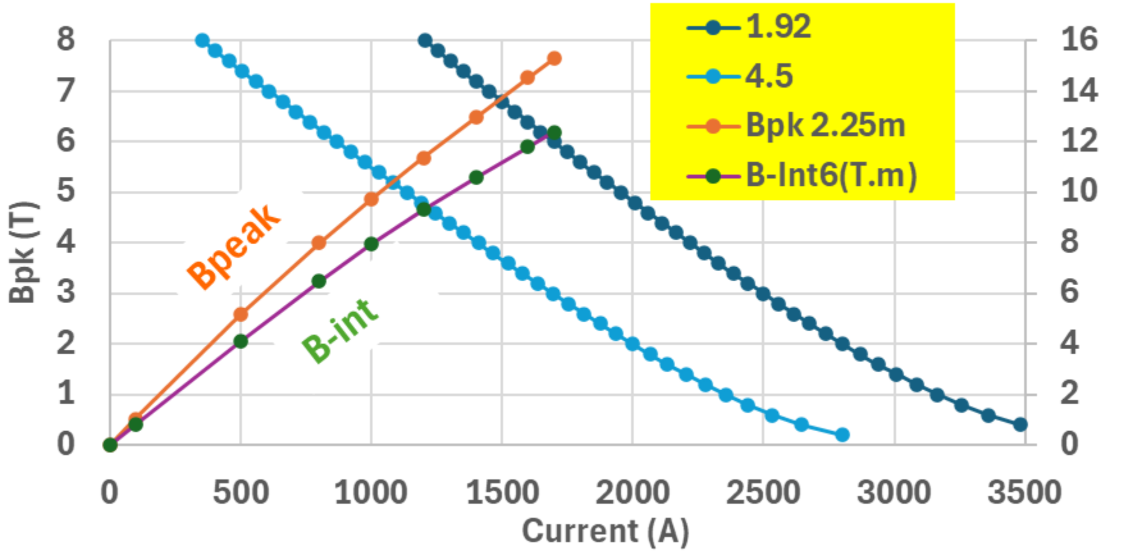
Stored Energy: ~1 MJ
Inductance: ~3.1 Henry

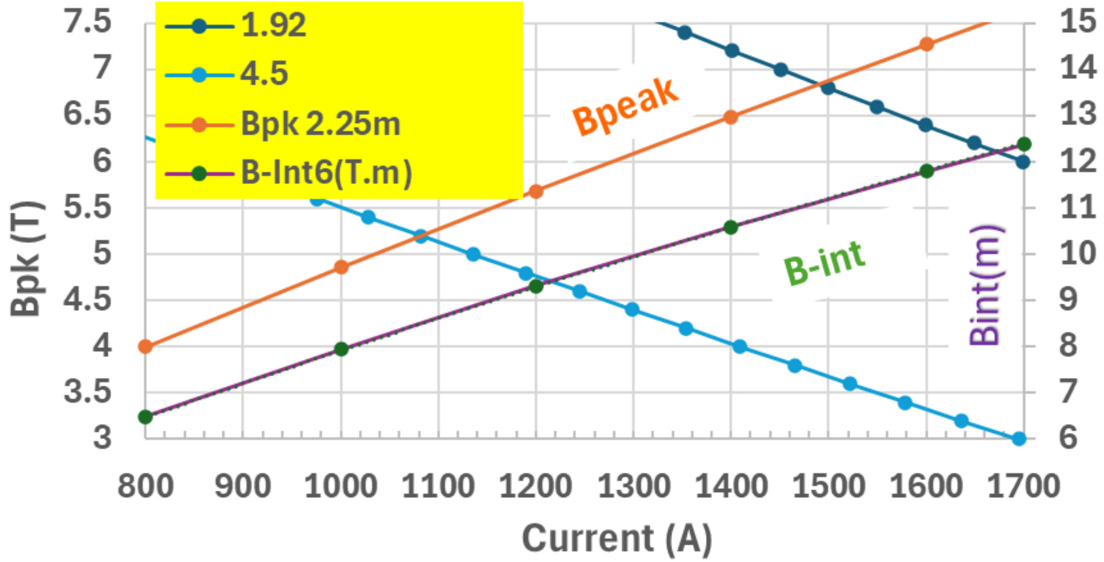
6-layer optimum integral design for B1pF/B1ApF

	B1pF/B1ApF 2.25 m, 6 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	786	3.14	3.93	6.37	
4.5 K	1082	4.23	5.26	8.60	73%
1.92 K	1490	5.68	7.06	11.56	53%

Bo(T)	Bpk (T)	B-Int6(T.m)	I (A)
0	0	0	0
0.404	0.518	0.820	100
2.021	2.589	4.101	500
3.194	4.003	6.485	800
3.908	4.861	7.946	1000
4.575	5.686	9.313	1200
5.201	6.486	10.594	1400
5.793	7.269	11.800	1600
6.078	7.654	12.376	1700

Peak field enhancement Bpk/Bo=1.25 (25%)





➢ **Promising results of a quick study, with a potential for even better outcome**

Computed field harmonics in the 6-layer design

B1ApF-6lyr-2_25m-b4.X01 | B1ApF-6lyr-2_25m-b4.X11

```
$FCNX VC2CB=.TRUE.,VC2CE=.TRUE.,
 MAGTYPE=2,LAYERS=6,RFEMM=220,R0MM=80
      RBENDMM=12,NBEND=10 &end
 3 3 2.25  1.6 185.0 1000 0.4 0.20
 3 3 2.25  1.6 187.2 1000 0.4 0.20
 3 3 2.25  1.6 189.4 1000 0.4 0.20
 3 3 2.25  1.6 191.6 1000 0.4 0.20
 3 3 2.25  1.6 202.8 1000 0.4 0.20
 3 3 2.25  1.6 205.0 1000 0.4 0.20
B2 0.  1.
B4 0.  5.
b6 0.  1.
b8 0.  1.
```

All harmonics <1 unit at 80 mm radius

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.81939E+01	10000.0000
2	-0.42307E-03	-0.5163
4	-0.53684E-03	-0.6552
6	0.35729E-03	0.4360
8	0.20201E-03	0.2465
10	-0.74409E-04	-0.0908
12	0.72814E-05	0.0089
14	0.53689E-06	0.0007
16	-0.33655E-06	-0.0004
18	0.69724E-07	0.0001
20	-0.79926E-08	-0.0000

Old US definition of harmonics: b2 is sextupole

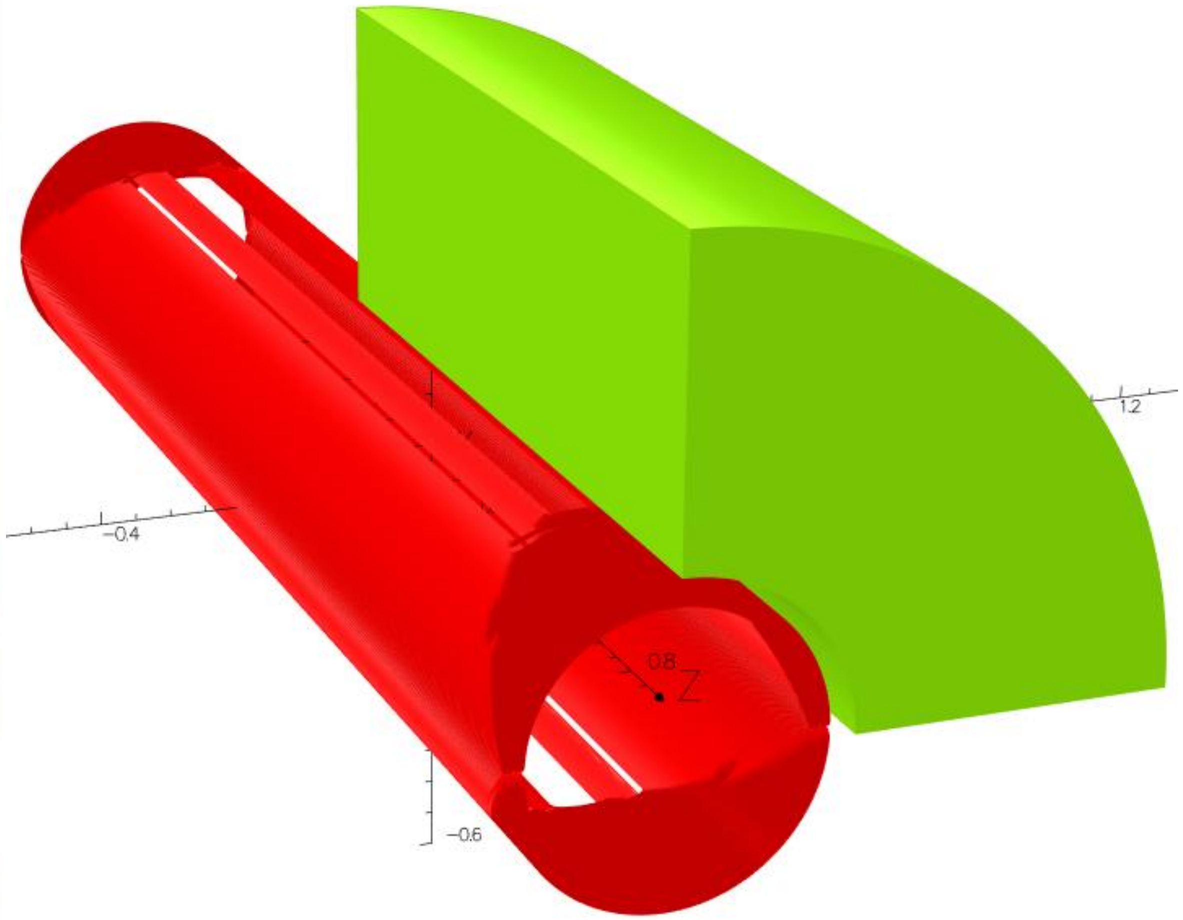
8-layer direct wind OID for B1pF/B1ApF

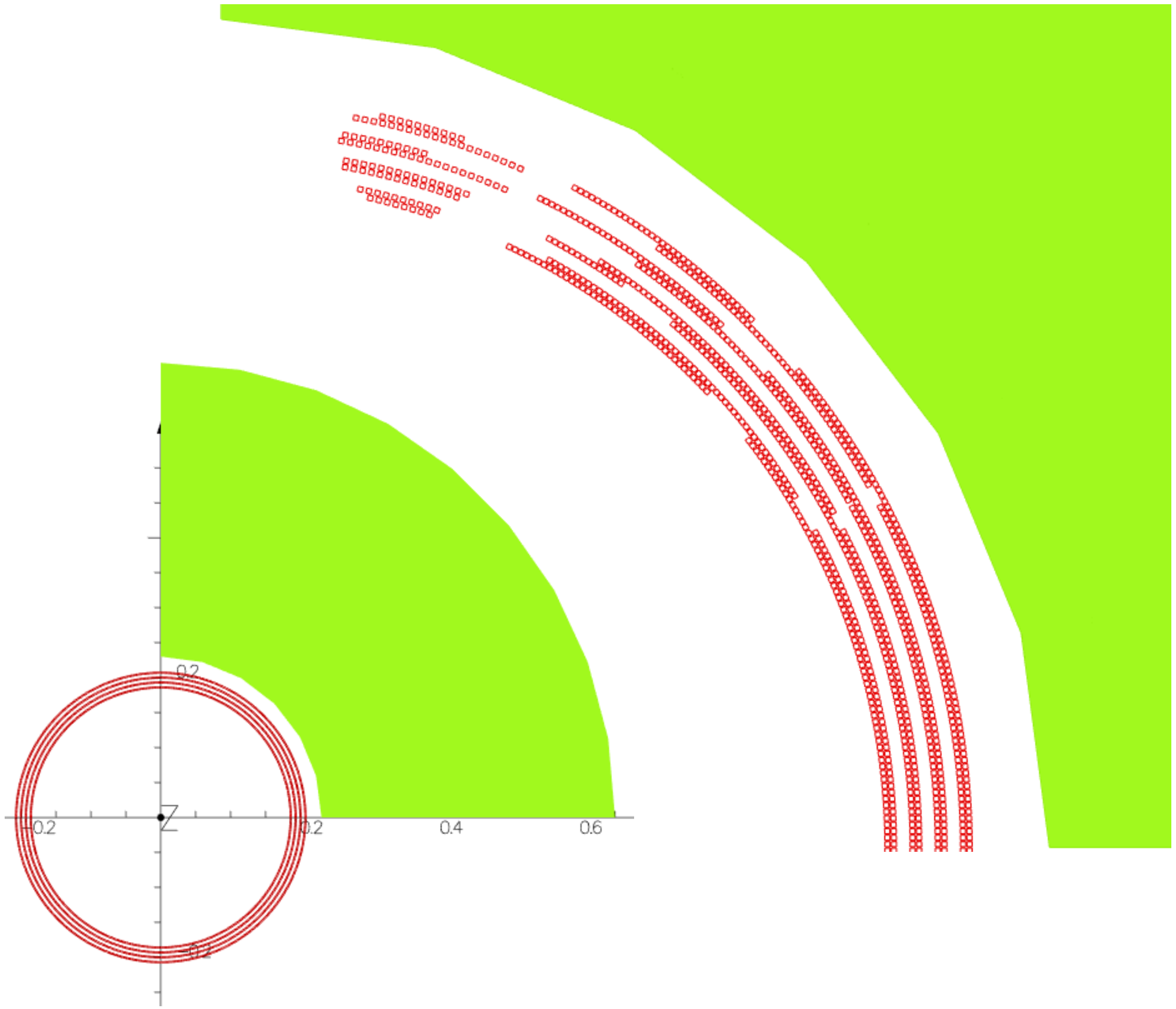
A design for a healthy margin at 4.5 K

(or add a double layer, If needed, after testing a 6-layer magnet)

- **Coil length 2.25 m**
- **Coil inner radius 185 mm (161 mm bore, 172.7 mm SS tube)**

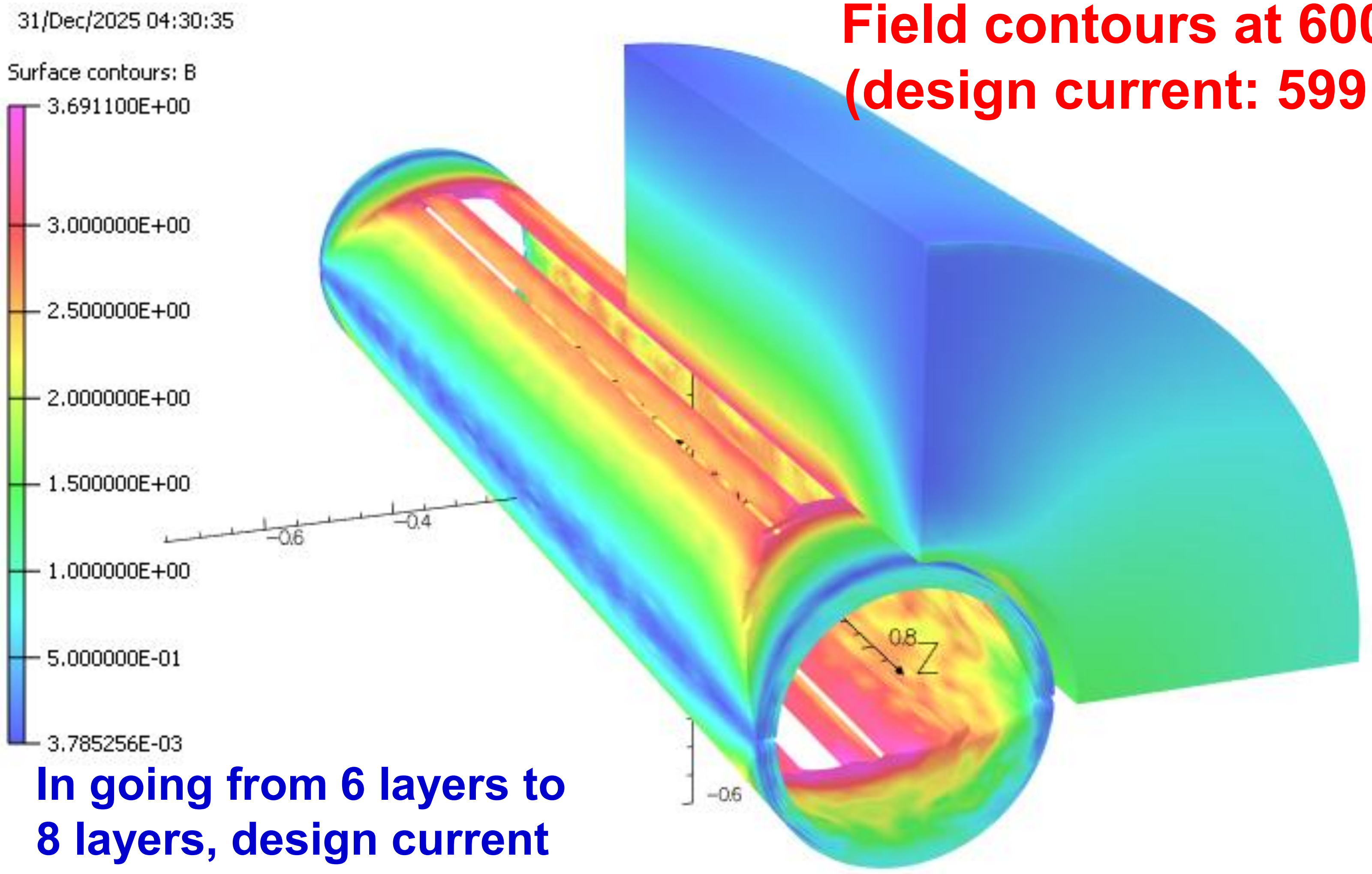
8-layer Optimum Integral Design for B1pF/B1ApF





(6-around-1 cable with 0.47 mm wire)

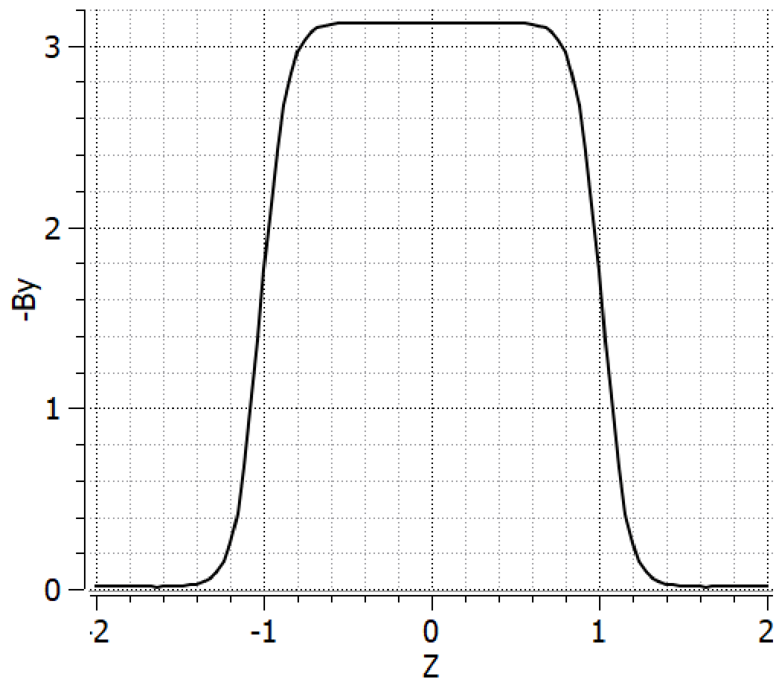
8-layer Optimum Integral Design for B1pF/B1ApF



Field contours at 600 A (design current: 599 A)

Integral Field= 6.37 T.m

Field along z-axis @600 A. 8 layers



In going from 6 layers to 8 layers, design current reduced from 786 A to 599 A

Stored Energy: ~1 MJ
Inductance: ~5.6 Henry

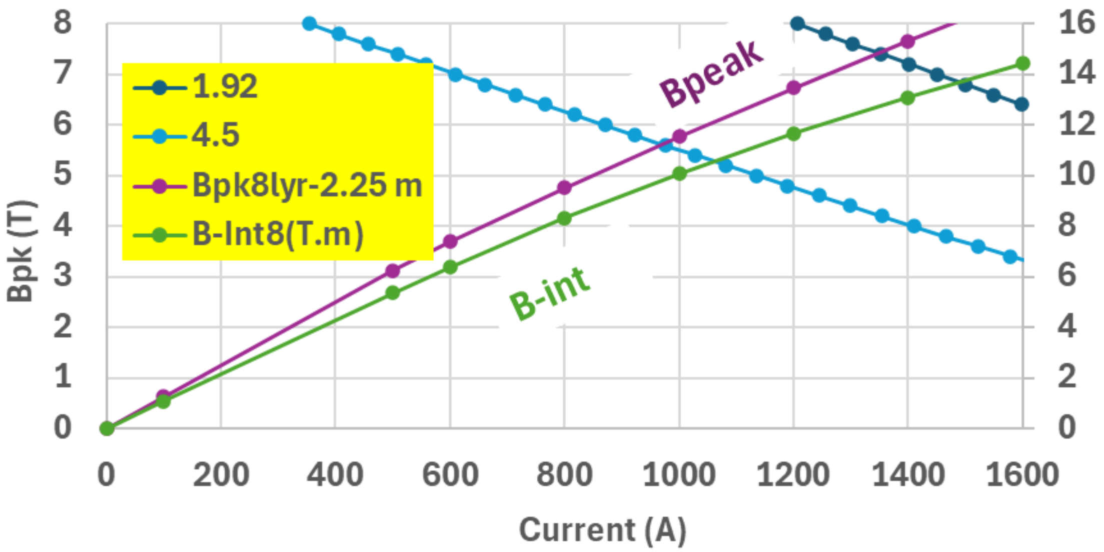
8-layer optimum integral design for B1pF/B1ApF

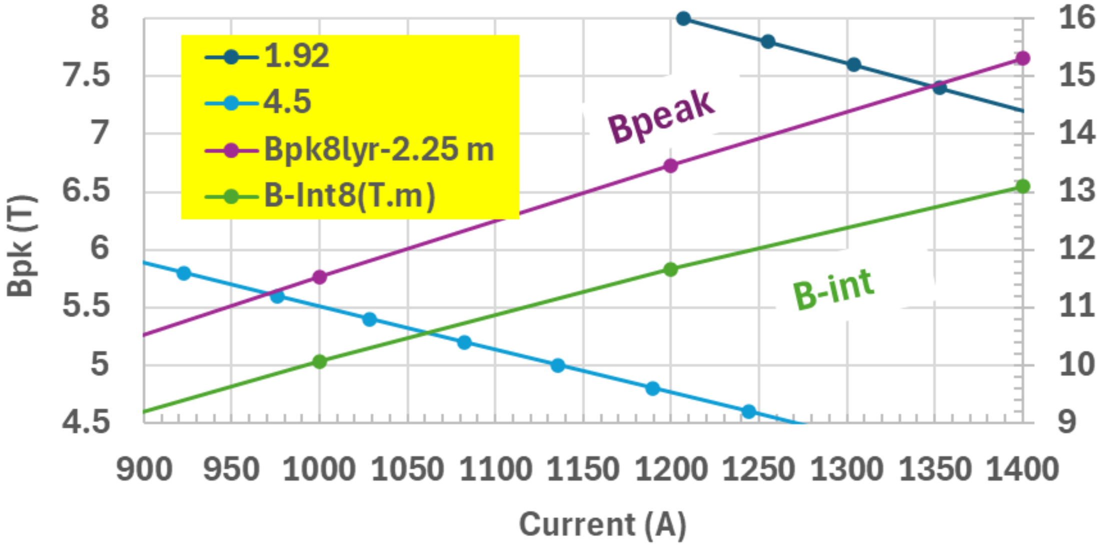
	B1pF/B1ApF 2.25 m, 8 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	599	3.12	3.68	6.37	
4.5 K	970	4.77	5.59	9.77	62%
1.92 K	1350	6.19	7.38	12.63	44%

I (A)	Bo(T)	Bpk (T)	B-Int8(T.m)
0	0	0	0
100	0.525	0.629	1.073
500	2.622	3.123	5.355
600	3.127	3.691	6.385
800	4.065	4.759	8.316
1000	4.919	5.766	10.069
1200	5.704	6.732	11.666
1400	6.424	7.656	13.098
1600	7.105	8.555	14.441

Peak field enhancement Bpk/Bo=1.17 (17%)

- **Outcome of optimization (reduced from 25%)**





Computed field harmonics in the 8-layer design

B1ApF-8lyr-2_25m-a2.X11 | B1ApF-8lyr-2_25m-a2.X01

```
$FCNX VC2CB=.TRUE.,VC2CE=.TRUE.,MAGTYPE=2
      LAYERS=8,RFEMM=220,R0MM=80.,
      RBENDMM=12,NBEND=10 &end
 3 3 2.25  1.6 185.0 1000 0.4 0.20
 3 3 2.25  1.6 186.8 1000 0.4 0.20
 3 3 2.25  1.6 192.0 1000 0.4 0.20
 3 3 2.25  1.6 193.8 1000 0.4 0.20
 3 3 2.25  1.6 199.0 1000 0.4 0.20
 3 3 2.25  1.6 200.8 1000 0.4 0.20
 3 3 2.25  1.6 206.0 1000 0.4 0.20
 3 3 2.25  1.6 207.8 1000 0.4 0.20
B2 0.  1.
B4 0.  5.
b6 0.  1.
b8 0.  1.
```

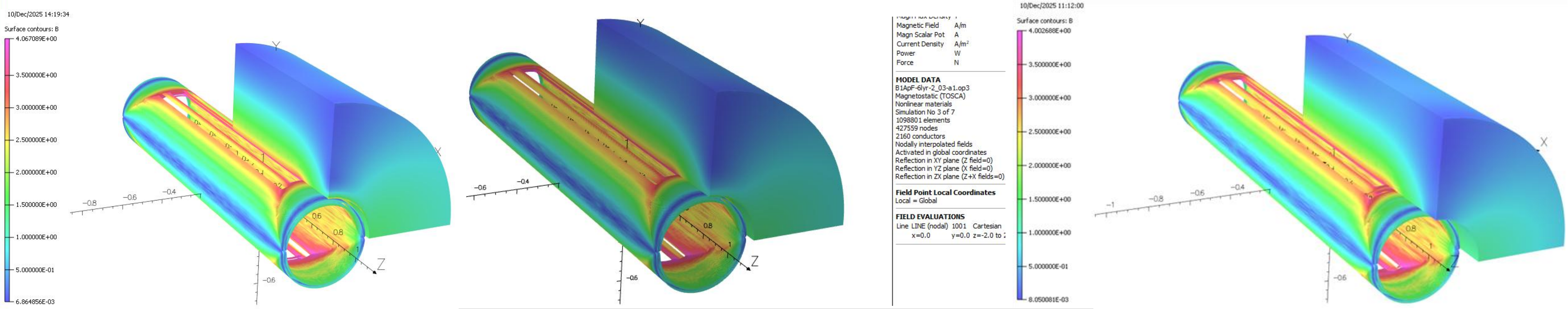
Old US definition of harmonics: b2 is sextupole

All harmonics <0.2 units at 80 mm radius

INTEGRATED FIELD HARMONICS :

No.	Bn(T.m)	bn*10^4(units)
0	0.11099E+02	10000.0000
2	0.18693E-05	0.0017
4	-0.29665E-05	-0.0027
6	0.91083E-04	0.0821
8	0.20223E-03	0.1822
10	-0.65127E-04	-0.0587
12	0.44188E-05	0.0040
14	0.12167E-05	0.0011
16	-0.43100E-06	-0.0004
18	0.73345E-07	0.0001
20	-0.52705E-08	-0.0000

Expected performance of the 6-layer OID for various length coils

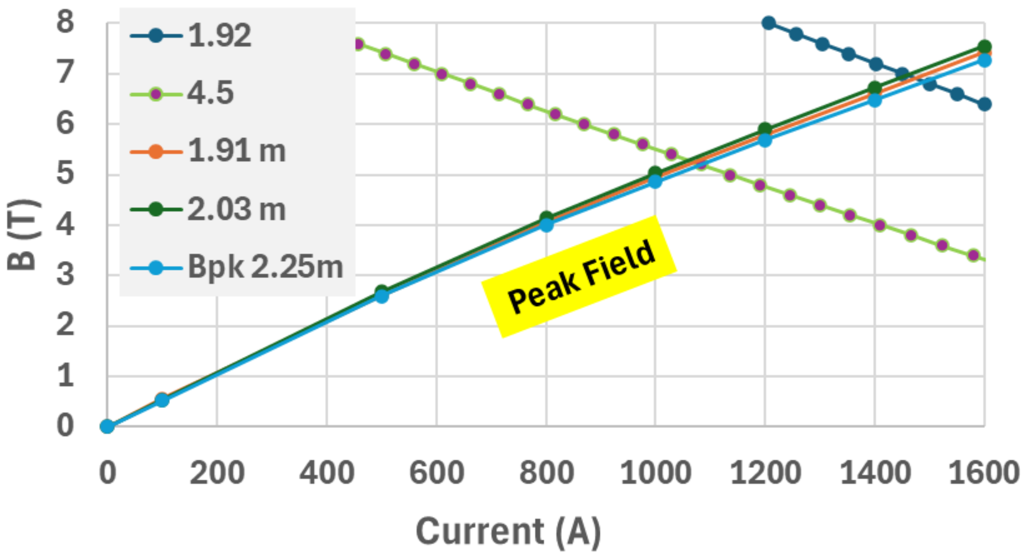


	1.91 m		
I (A)	Bo(T)	Bpk (T)	B-Intg(T.m)
0	0	0	0
100	0.405	0.561	0.683
500	2.023	2.608	3.415
800	3.195	4.067	5.397
1000	3.909	4.952	6.613
1200	4.572	5.801	7.745
1400	5.192	6.622	8.798
1600	5.775	7.419	9.779
1700	6.136	7.882	10.390

2.03 m		
Bo(T)	Bpk (T)	B-Intg(T.m)
0	0	0
0.406	0.537	0.737
2.027	2.683	3.682
3.203	4.141	5.819
3.918	5.034	7.128
4.583	5.894	8.347
5.205	6.727	9.484
5.791	7.540	10.548
6.153	8.011	11.207

Bpk 2.25m			
Bo(T)	**Bpk (T)**	**B-Int6(T.m)**	**I (A)**
0	**0**	**0**	**0**
0.404	**0.518**	**0.820**	**100**
2.021	**2.589**	**4.101**	**500**
3.194	**4.003**	**6.485**	**800**
3.908	**4.861**	**7.946**	**1000**
4.575	**5.686**	**9.313**	**1200**
5.201	**6.486**	**10.594**	**1400**
5.793	**7.269**	**11.800**	**1600**
6.078	**7.654**	**12.376**	**1700**

Computed Load Line Fraction for Various Length Coils

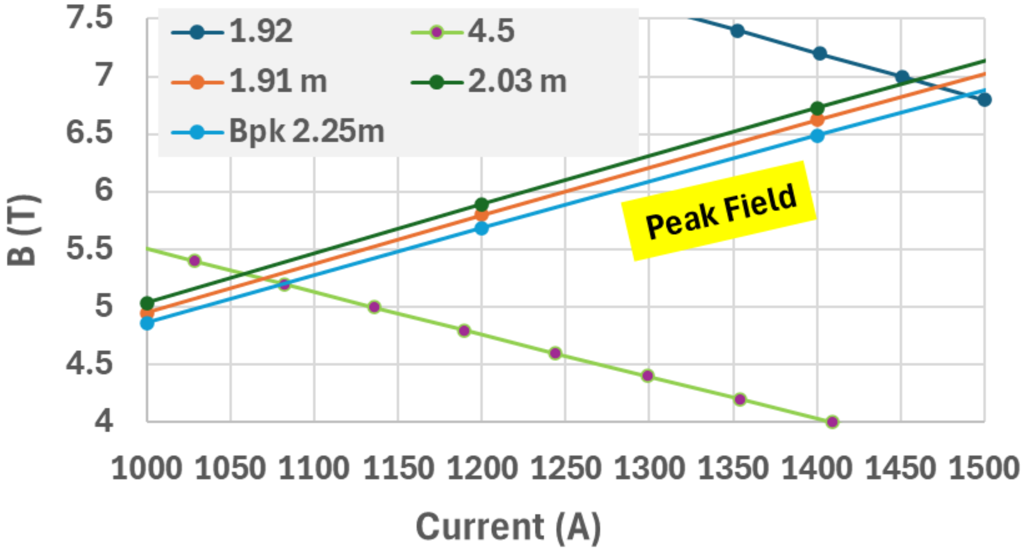


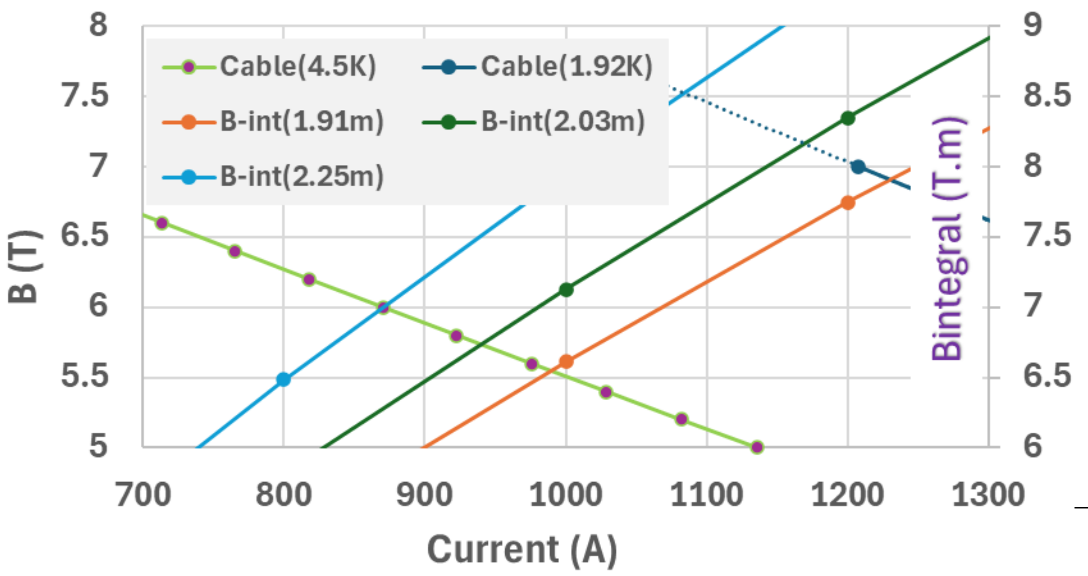
Computed margin (load line fraction) for 6-layer design over 6.37 T.m field integral:

- ➢ 1.92 K: 53% for 2.25 m; 60% for 2.03 m; 65% for 1.91m
- ➢ 4.5 K: 73% for 2.25 m; 83% for 2.03 m; 90%% for 1.91m

Computed/Estimated margin (load line fraction) for 8-layer design over 6.37 T.m field integral:

- ➢ 1.92 K: 44% for 2.25 m; 50% for 2.03 m; 50% for 1.91m
- ➢ **4.5 K: 62% for 2.25 m**; 70% for 2.03 m; 76% for 1.91m



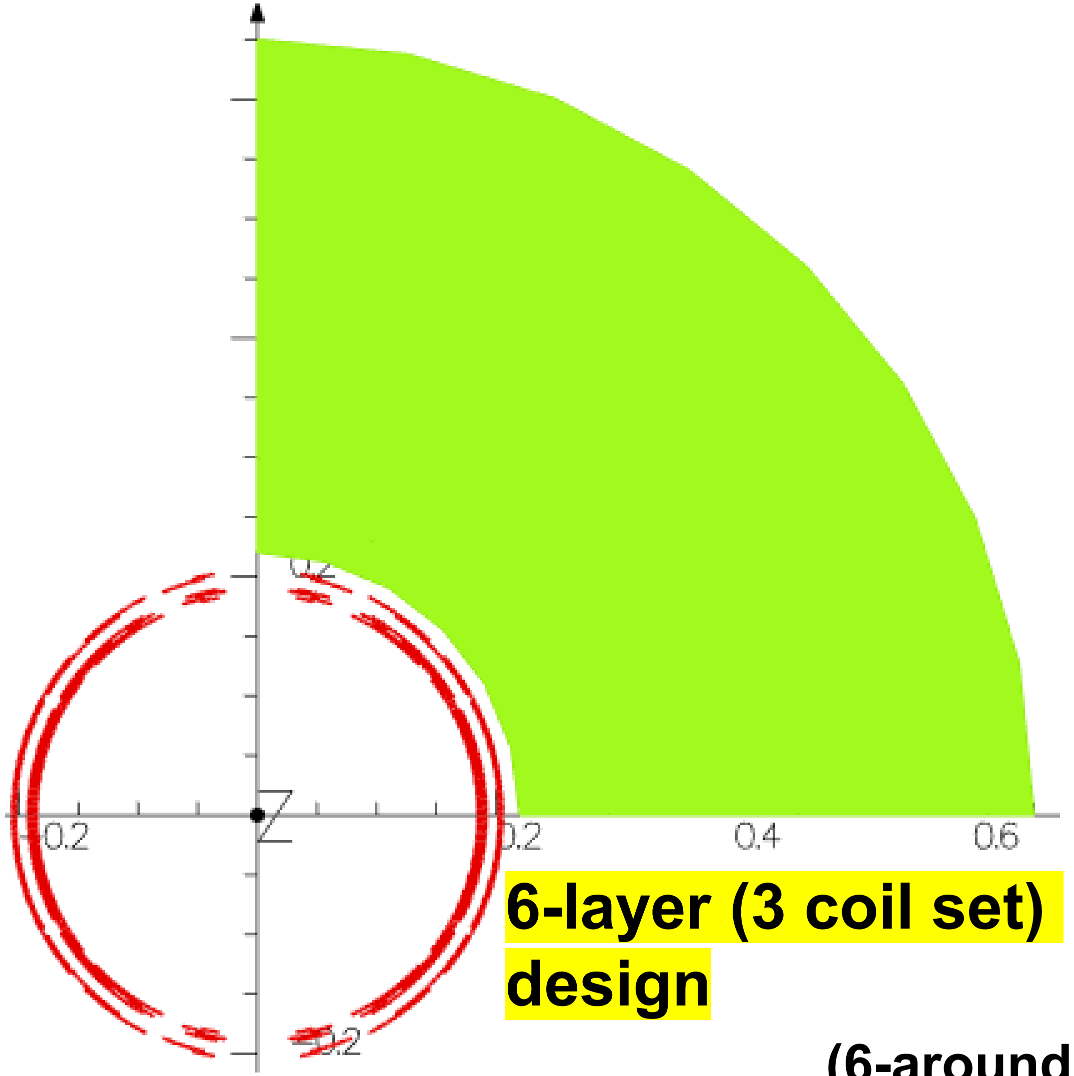


SUMMARY

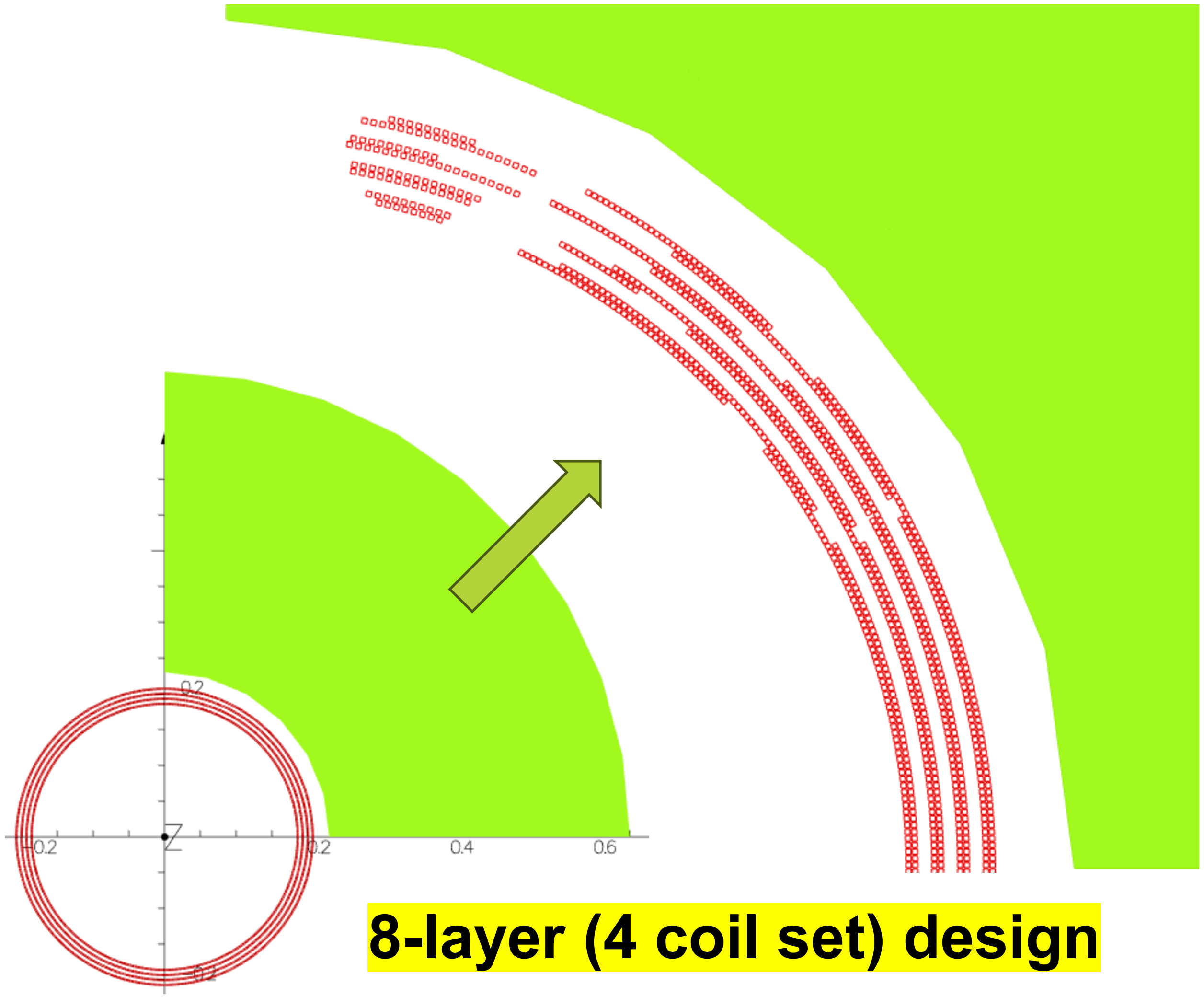
- While we continue with the construction of the baseline B1pF cable magnet design of a large aperture, respectable field NbTi magnet, (a very important and representative demonstration for all EIC IR magnets), changes in aperture, length and integral field opened the case for examining other options which could be more attractive now.
- For a clear bore of **161 mm** and coil inner radius of **185 mm** for a direct wind **2.25 m** long coil, optimum integral design requires only **3.1 T** for an integral field of **6.37 T.m**.
- **Initial work shows that only 8 layers are required for a margin of 62% on load line fraction 4.5 K and 6 layers for 53% at 1.92 K with optimum integral designs. A more optimized 6-layer design may work at 4.5 K for a modest field of 3.1 T.**
- **We should evaluate the relative technical, schedule and budget benefits of this DW OID as a value engineering (cost saving) 4.5 K option for B1pF/B1ApF.**
- Results seems to be promising enough to start quench and mechanical analysis now.

Extra Slides

6-layer and 8-layer Optimum Integral Design for B1pF/B1ApF



6-layer (3 coil set) design



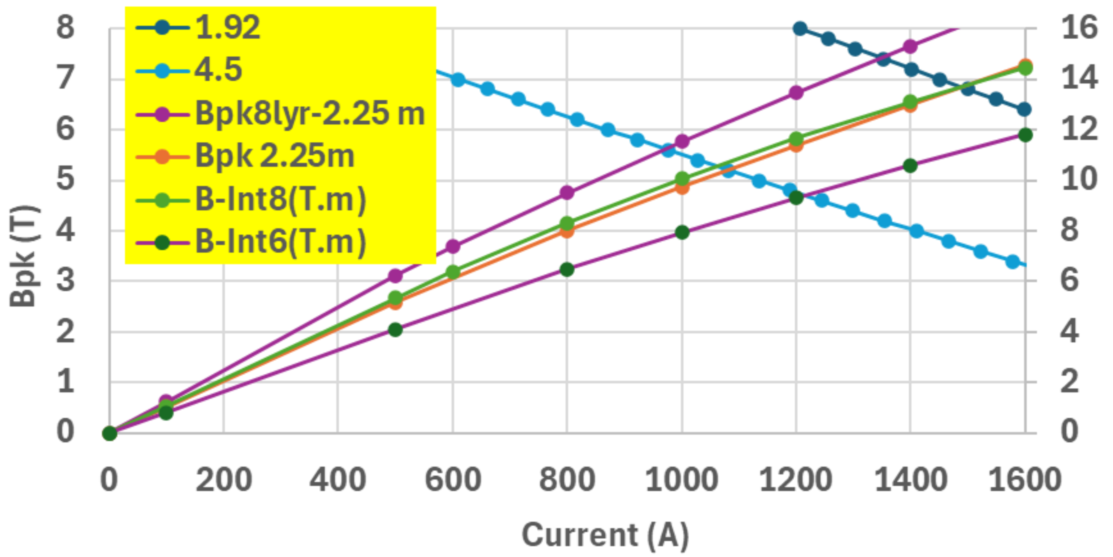
8-layer (4 coil set) design

(6-around-1 cable with 0.47 mm wire)

Comparison between 6-layer and 8-layer designs

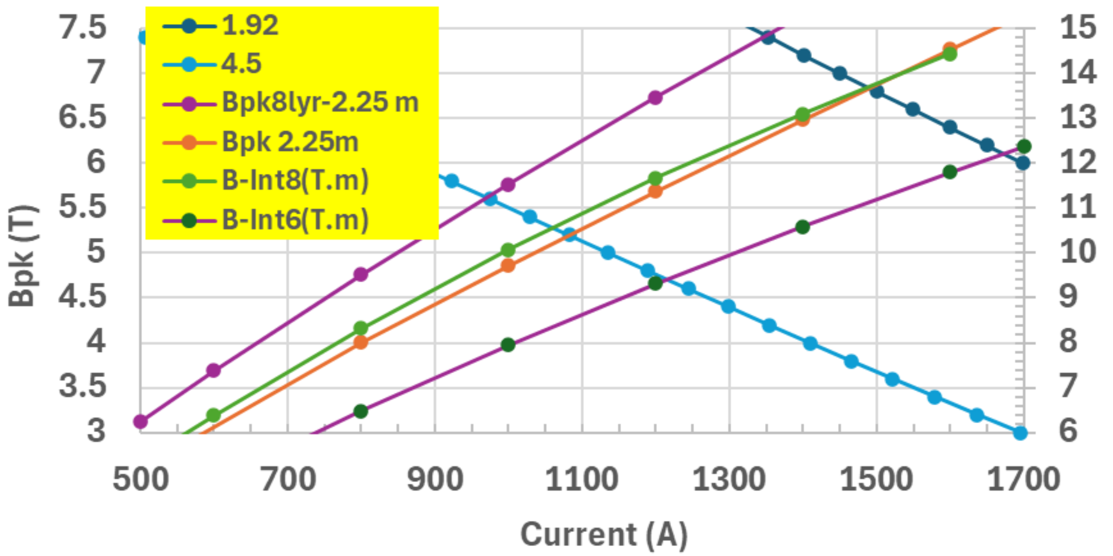
	B1pF/B1ApF 2.25 m, 6 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	786	3.14	3.93	6.37	
4.5 K	1082	4.23	5.26	8.60	73%
1.92 K	1490	5.68	7.06	11.56	53%

Stored Energy: ~1 MJ
Inductance: ~3.1 Henry



	B1pF/B1ApF 2.25 m, 8 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	599	3.12	3.68	6.37	
4.5 K	970	4.77	5.59	9.77	62%
1.92 K	1350	6.19	7.38	12.63	44%

Stored Energy: ~1 MJ
Inductance: ~5.6 Henry



Cumulative summary of different length 6-layer and 8-layer designs

	1.91 m		
I (A)	Bo(T)	Bpk (T)	B-Intg(T.m)
0	0	0	0
100	0.405	0.561	0.683
500	2.023	2.608	3.415
800	3.195	4.067	5.397
1000	3.909	4.952	6.613
1200	4.572	5.801	7.745
1400	5.192	6.622	8.798
1600	5.775	7.419	9.779
1700	6.136	7.882	10.390

2.03 m		
Bo(T)	Bpk (T)	B-Intg(T.m)
0	0	0
0.406	0.537	0.737
2.027	2.683	3.682
3.203	4.141	5.819
3.918	5.034	7.128
4.583	5.894	8.347
5.205	6.727	9.484
5.791	7.540	10.548
6.153	8.011	11.207

Bpk 2.25m			
Bo(T)	**Bpk (T)**	**B-Int6(T.m)**	**I (A)**
0	**0**	**0**	**0**
0.404	**0.518**	**0.820**	**100**
2.021	**2.589**	**4.101**	**500**
3.194	**4.003**	**6.485**	**800**
3.908	**4.861**	**7.946**	**1000**
4.575	**5.686**	**9.313**	**1200**
5.201	**6.486**	**10.594**	**1400**
5.793	**7.269**	**11.800**	**1600**
6.078	**7.654**	**12.376**	**1700**

	B1pF/B1ApF 2.25 m, 6 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	786	3.14	3.93	6.37	
4.5 K	1082	4.23	5.26	8.60	73%
1.92 K	1490	5.68	7.06	11.56	53%

	B1pF/B1ApF 2.03 m, 6 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	876	3.43	4.53	6.37	
4.5 K	1058	4.15	5.33	7.54	83%
1.92 K	1458	5.42	7.01	9.88	60%

	B1pF/B1ApF 1.91 m, 6 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	963	3.77	4.77	6.37	
4.5 K	1070	3.97	5.17	6.91	90%
1.92 K	1472	5.46	6.96	9.25	65%

	B1pF/B1ApF 2.25 m, 8 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	599	3.12	3.68	6.37	
4.5 K	970	4.77	5.59	9.77	62%
1.92 K	1350	6.19	7.38	12.63	44%

Estimated	B1pF/B1ApF 2.03 m, 8 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	667	3.41	4.25	6.37	
4.5 K	948	4.68	5.66	8.57	70%
1.92 K	1321	5.91	7.33	10.79	50%

Estimated	B1pF/B1ApF 2.25 m, 8 layers				Load Line Fraction
	I(A)	B0(T)	Bpk(T)	B-intg(T.m)	
At Design	734	3.74	4.47	6.37	
4.5 K	959	4.48	5.50	7.85	76%
1.92 K	1334	5.95	7.28	10.10	55%