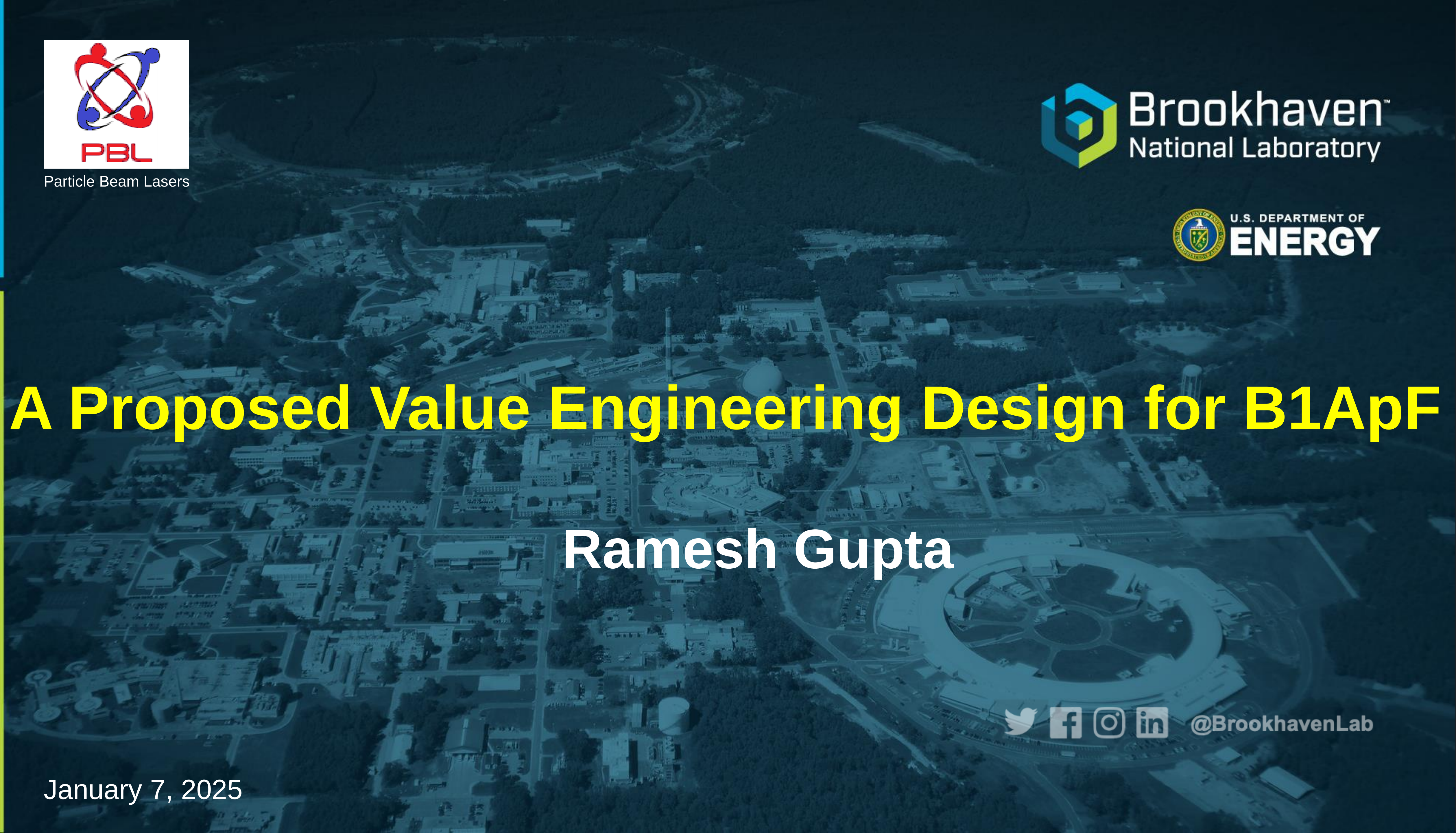


Particle Beam Lasers

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

A Proposed Value Engineering Design for B1ApF

Ramesh Gupta

@BrookhavenLab

January 7, 2025

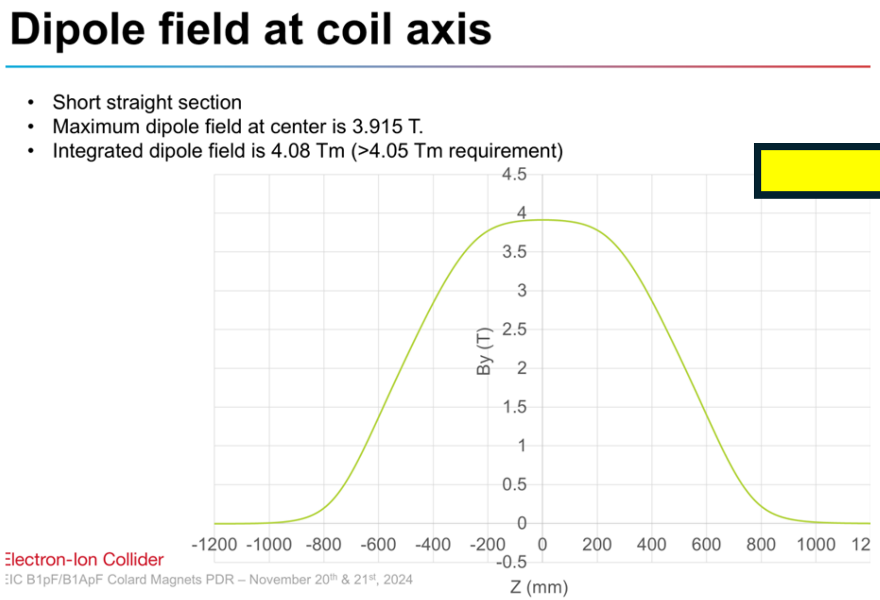
<<< SPOILER ALERT >>>

PBL/BNL team is carrying out a Phase II STTR, "*A new medium field superconducting magnet for the EIC*". One preliminary outcome:

- **Present design of EIC IR dipole B1ApF based on the Rutherford cable could be replaced by a 4-layer direct wind optimum integral dipole !**

Evaluate the overall impact on cost and schedule - value engineering

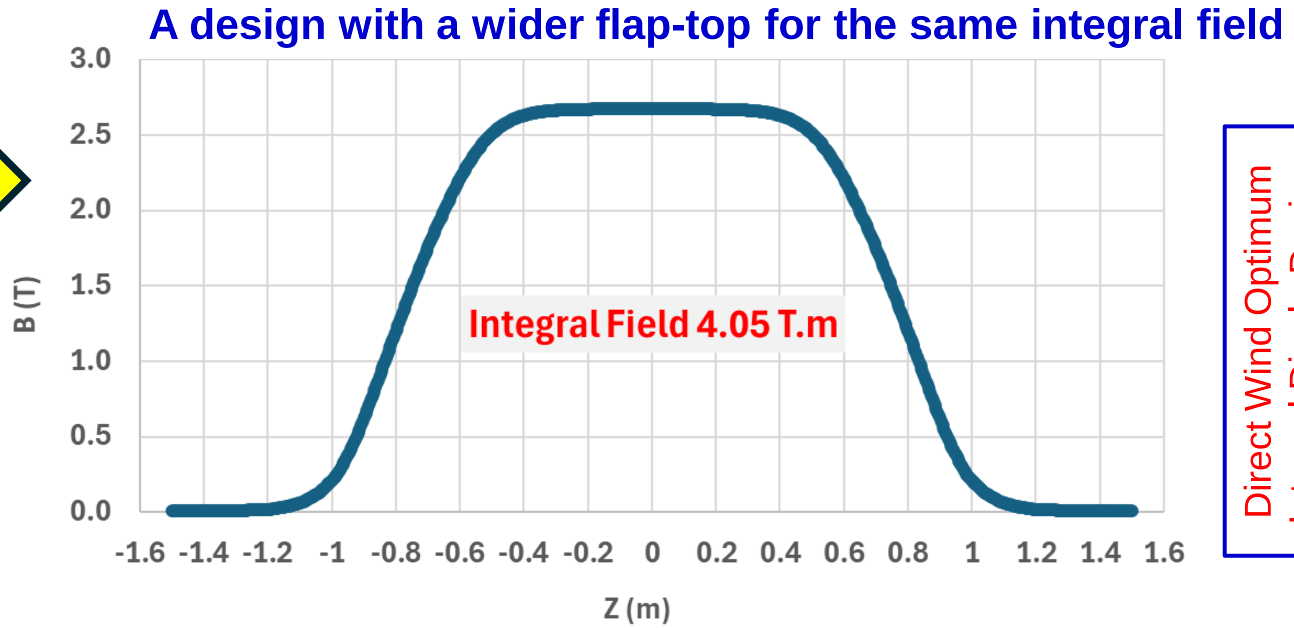
Cable magnet design
(courtesy Mithlesh Kumar)



Dipole field at coil axis

- Short straight section
- Maximum dipole field at center is 3.915 T.
- Integrated dipole field is 4.08 Tm (>4.05 Tm requirement)

lectron-Ion Collider
IC B1pF/B1ApF Colard Magnets PDR – November 20th & 21st, 2024

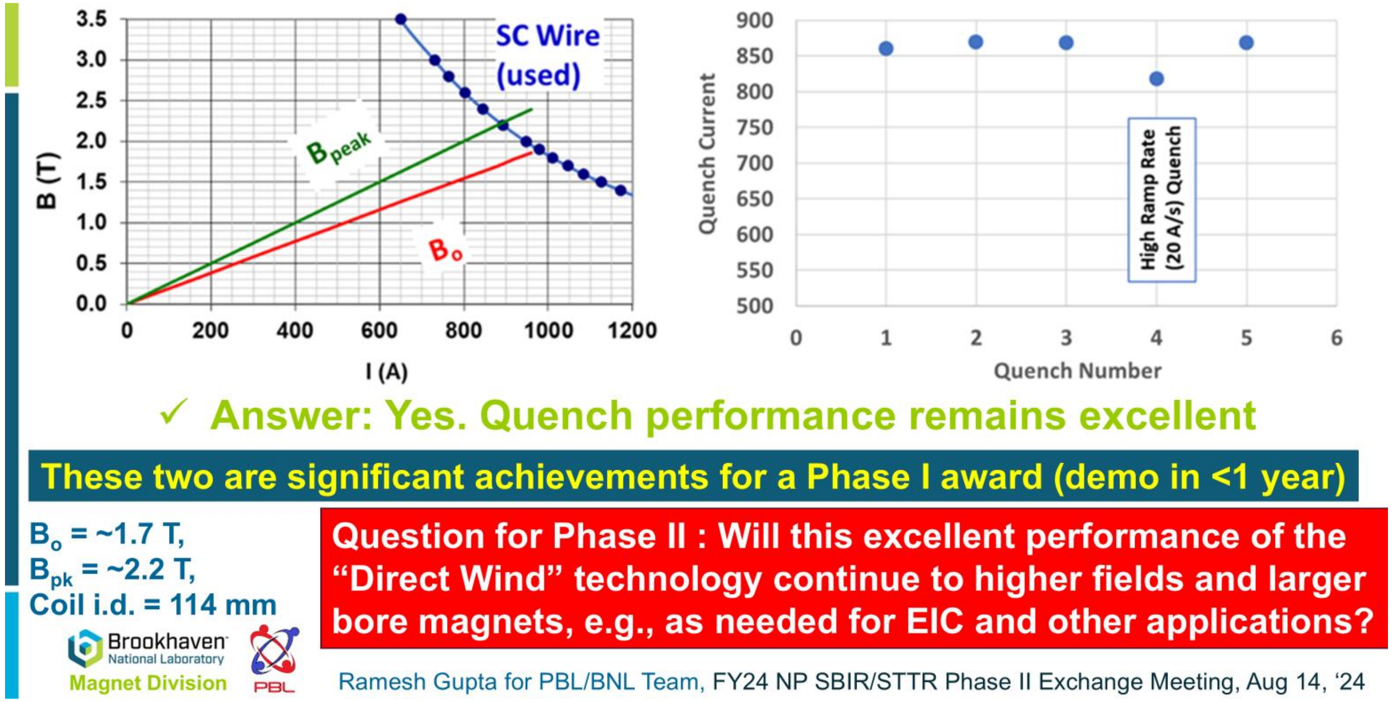


A design with a wider flap-top for the same integral field

Direct Wind Optimum
Integral Dipole Design

Technical impact: B_o goes down from ~4 T to ~2.6 T; forces/stresses go down as B^2

PBL/BNL Phase II STTR Proposal



✓ Answer: Yes. Quench performance remains excellent

These two are significant achievements for a Phase I award (demo in <1 year)

B_o = ~1.7 T,
B_{pk} = ~2.2 T,
Coil i.d. = 114 mm

Question for Phase II : Will this excellent performance of the “Direct Wind” technology continue to higher fields and larger bore magnets, e.g., as needed for EIC and other applications?

Ramesh Gupta for PBL/BNL Team, FY24 NP SBIR/STTR Phase II Exchange Meeting, Aug 14, ‘24

Company Name:	Particle Beam Lasers, Inc.
Address:	8800 Melissa Court Waxahachie, TX 75167-7279
Principal Investigator:	Ramesh Gupta, Ph.D.
Project Title:	A new medium field superconducting magnet for the EIC
Topic No. 37:	Nuclear Physics Accelerator Technology
Subtopic (g):	Magnet Development for Future Electron-Ion Colliders (EIC)
Grant Award Number:	DE-SC0021578

Task 8: Evaluation of the *Optimum Integral Design* for Other Applications: The *optimum integral design*, once demonstrated for EIC IR dipole B0Apf can be applied to other EIC magnets (dipoles and quadrupoles) to reduce the maximum field required for the same integral field in the allocated length of the magnet.

Overview

Optimum Integral Design:

- **Why, What, Where used?**

PBL/BNL STTR on the Direct Wind Optimum Integral Dipole B0ApF (NOT B1ApF):

- **What was demonstrated in Phase I**
- **What has been demonstrated so far in Phase II**
- **Status of the Phase II for B0ApF (all 12 layers wound, to be discussed briefly)**

Evaluation of the Optimum Integral Dipole for B1ApF under STTR

- **Initial results… Very Attractive! … Why so?**
- **Sanity check – are these results too good to be true? Are methods validated?**

Possible future work under EIC funding B1ApF+ (if go ahead is received)

Summary

Link to more information on the optimum integral dipole:
https://wpw.bnl.gov/rgupta/optimum-integral/

Conventional Design Approach

A two-step process of designing magnets:

Step 1: Optimize coil cross-section to obtain cosine theta like distribution (spread out turns):

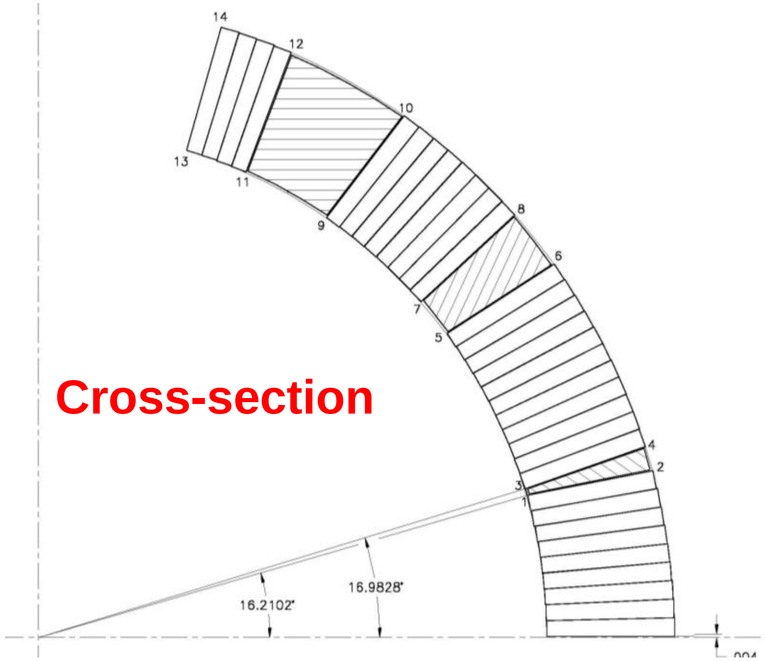
$$I(\theta) = I_o \cdot \cos(n\theta)$$

- ➢ This limits the number of turns in straight section

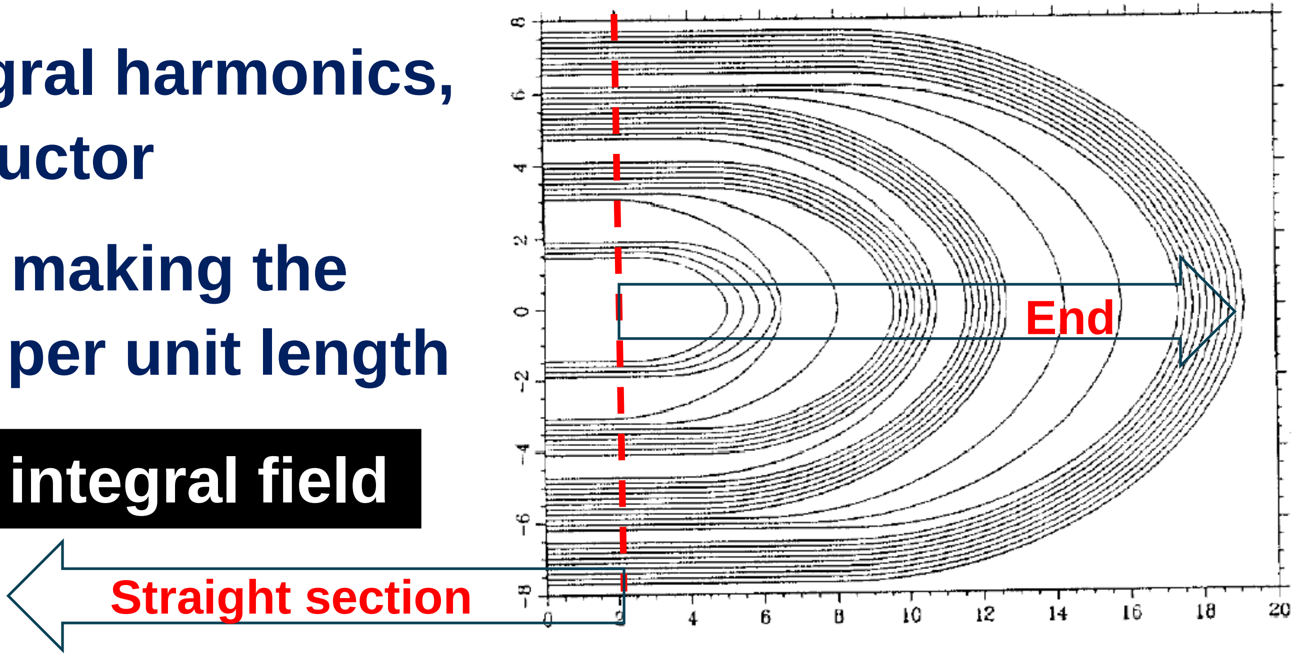
Step 2: Optimized ends to reduce integral harmonics, and to reduce peak field on the conductor

- ➢ This spreads out turns in the ends, making the ends longer, and reducing the field per unit length

Each step reduces the maximum integral field



Cross-section



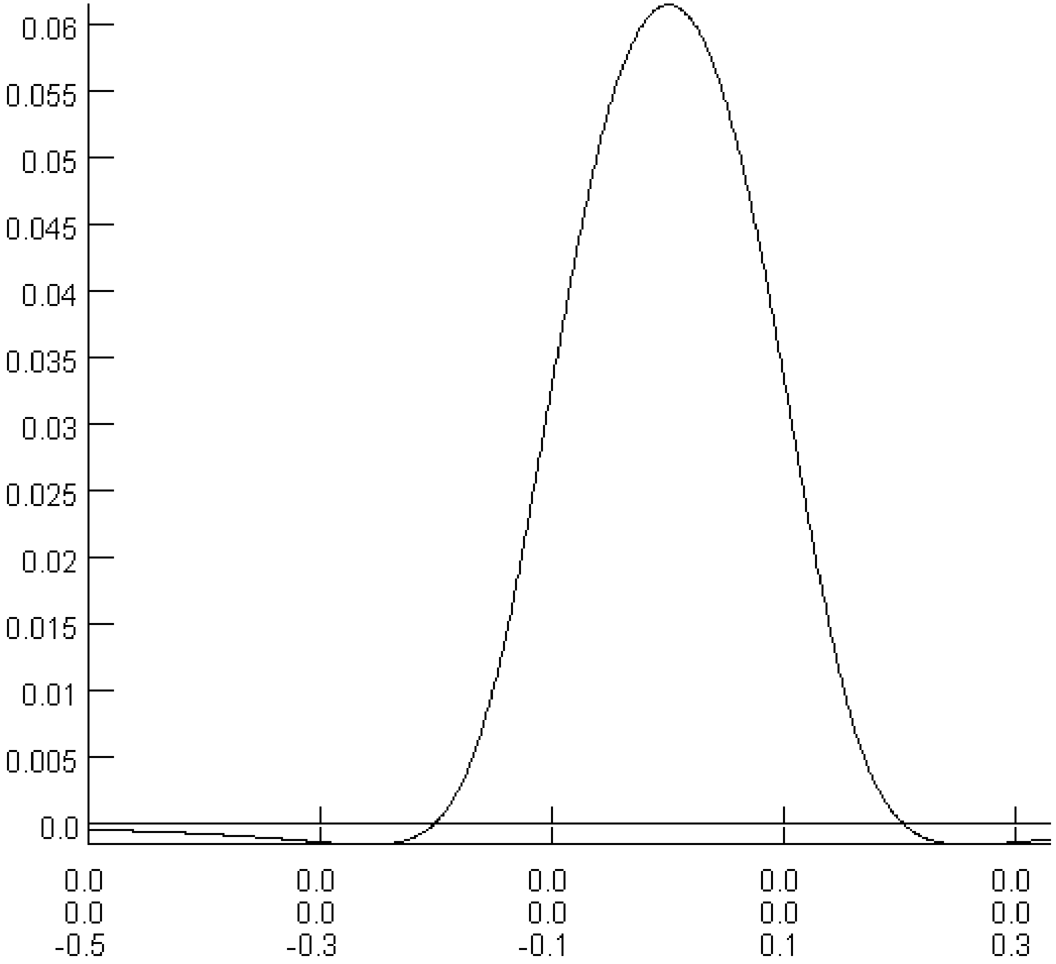
End

Straight section

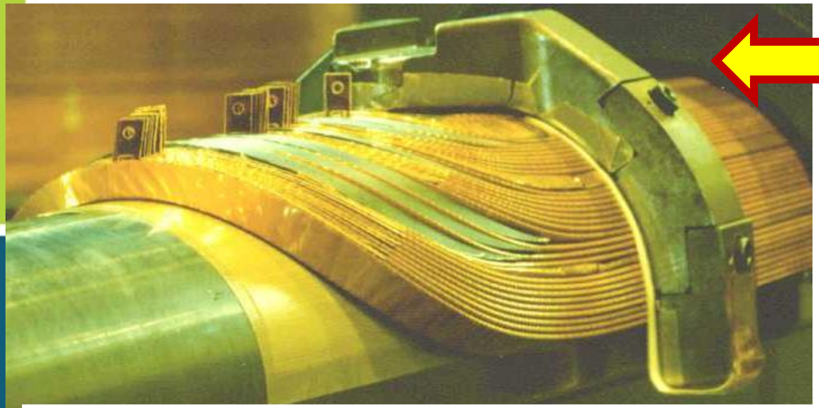
Motivation to the Integral Design Concept

(AGS corrector: Length = 300mm, diameter=182.8 mm)

- **In such a short dipole, there is little to no flat-top along the axis (so called body of the magnet).**
- **Since the axial field profile is not going to see "body" and "ends" <u>separately</u>, why not combine the two together for an <u>integral design optimization?</u>**
- **Can that be more efficient?**



Optimum Integral Design – What is new and why is it important?



RHIC Coil End (conventional)

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 => relative loss in field integral is significant in short magnets

EIC B0ApF Coil Ends (conventional, as in CDR)

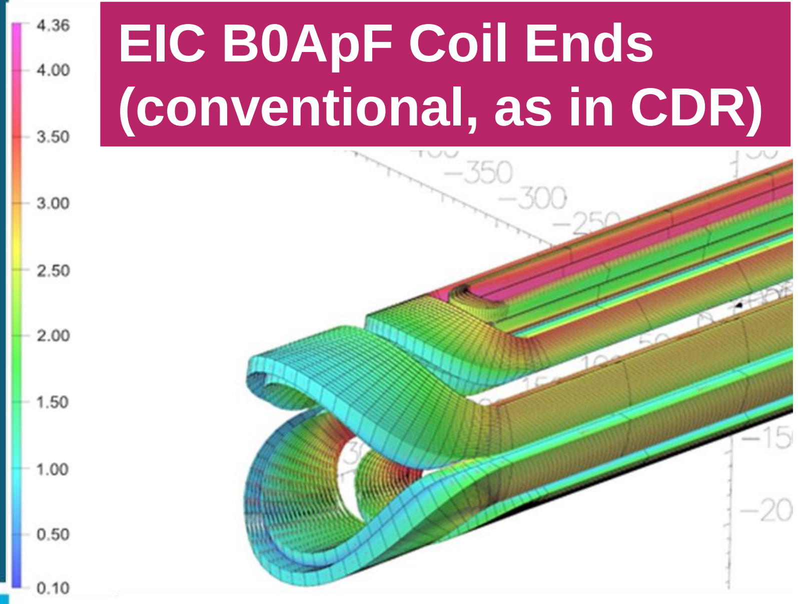


Figure 5: B0APF coil with field contour

Optimum Integral Design:

- End turns at midplane runs full length of the coil => almost no loss in space due to Ends
- Gain in magnetic length => about a coil diameter in dipole.
- This could be a significant fraction of total length in short magnets.

Basic Principle of the Optimum Integral Design

Modulation of the current in the straight section (SS) of the conventional designs:

$$I(\theta) = I_o \,.\, \cos(n\theta)$$

...and then ends are optimized separately.

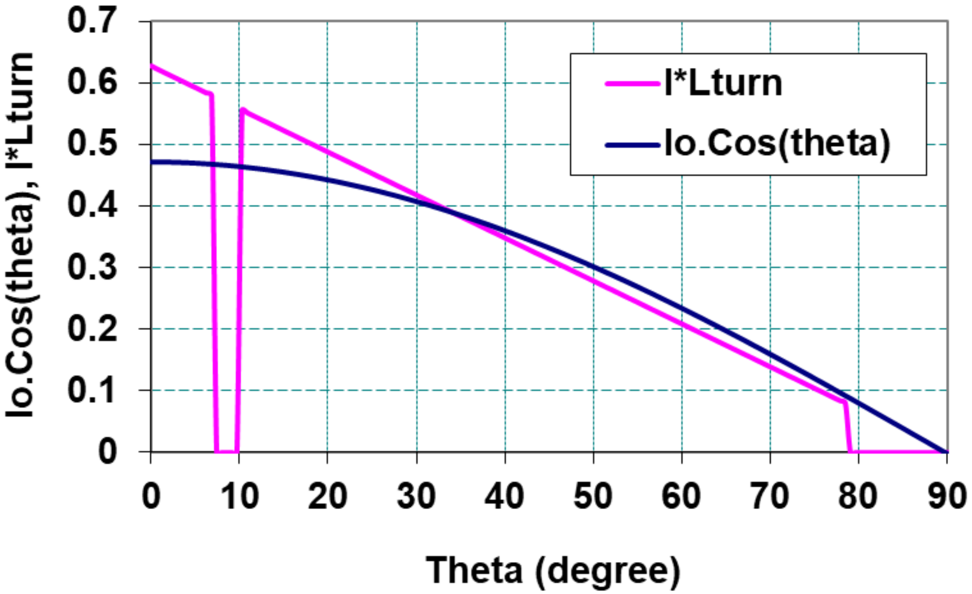
Contribution to field from the ends is small and field integral is primarily determined by the length of the SS.

In the optimum integral design, turns at midplane extend full length, while the length of other turns decreases with the angle.

Cos theta azimuthal distribution is obtained in an integral sense, i.e., not in "*I(θ)*", but in "*I(θ).L(θ)*":

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

Missing current from pole & one region



Magnet Division

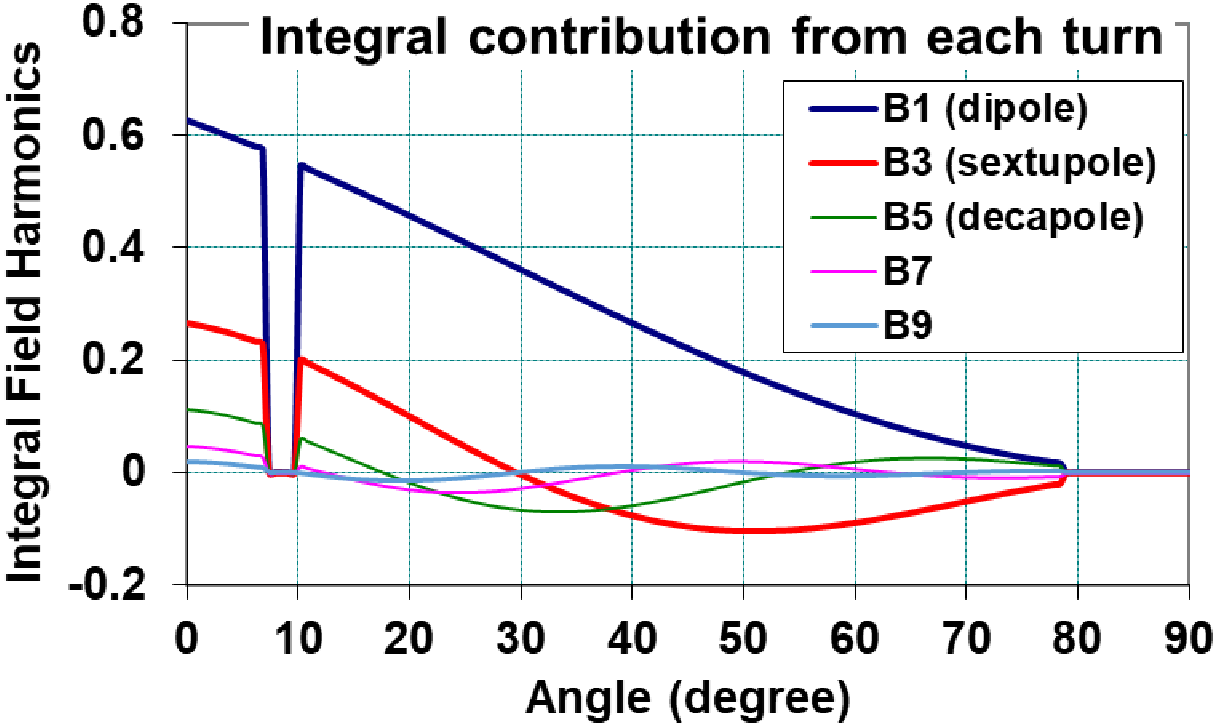
Computation and Optimization of Integral Field and Field harmonics

Missing current from pole and one region

for a line current located at (a, ϕ)

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

reference radius R_0



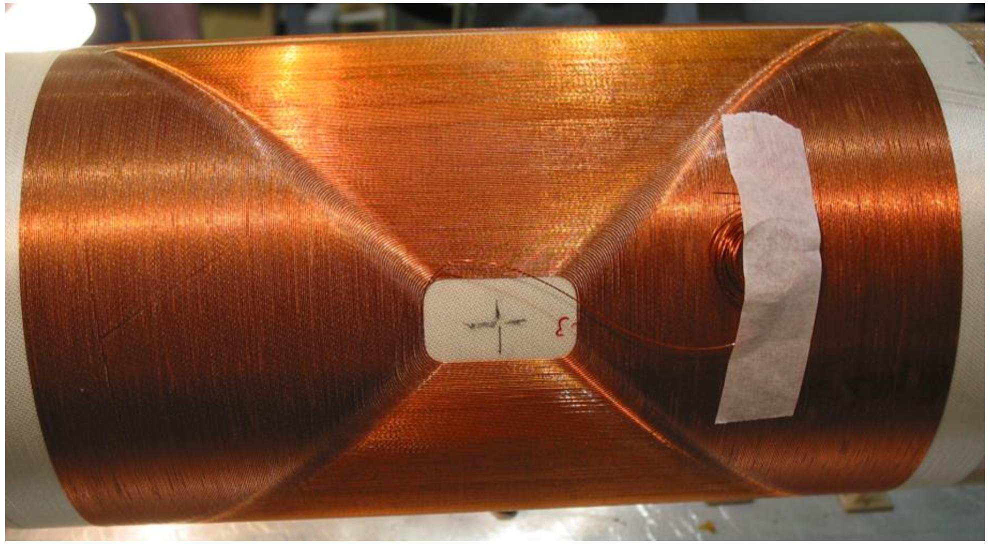
Integral Harmonics				
B1	B3	B5	B7	B9
37.29	0.94	-0.14	0.01	-0.02

For the optimum integral design, above formula is multiplied by the length of each turn to compute the integral field harmonics (B_n).

Turns at midplane contribute much more to field than turns at any other angle. In the “Optimum Integral Design” midplane turns extend full-length

First Optimum Integral Magnet: AGS Corrector Dipoles (2004)

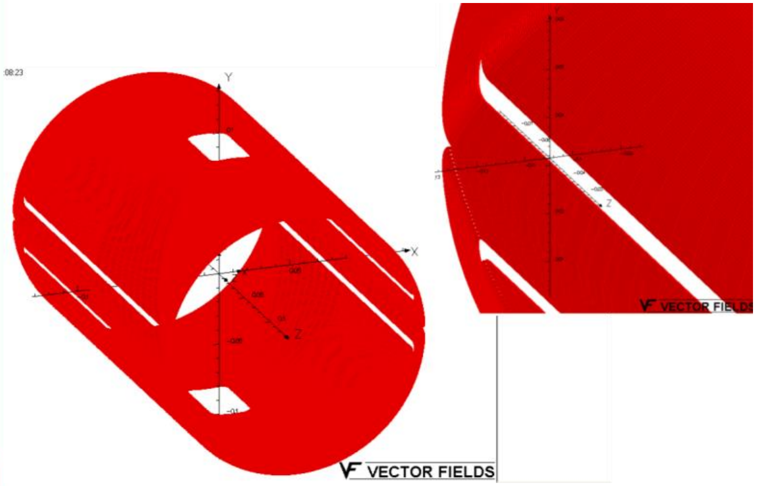
- **Note: Almost the full use of available azimuthal and axial space by the conductor (very high fill factor).**
- **Some space is needed for the leads at the pole.**
- **That, and a small azimuthal spacer was sufficient to modulate a natural variation in length for $I_o.L.\cos(\theta)$ to obtain field quality needed in corrector magnets**

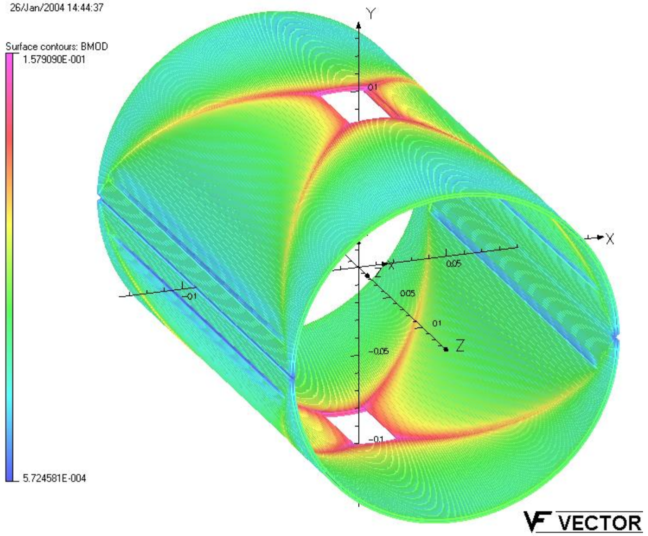


Only Direct Wind magnet installed in an accelerator at BNL (in AGS tunnel)

COMPUTED INTEGRAL FIELD HARMONICS IN THE AGS CORRECTOR DIPOLE DESIGN AT A REFERENCE RADIUS OF 60 MM. THE COIL RADIUS IS 90.8 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.0082 @ 25 A	0.4	0.8	-4.7	4.1	5.3	2.4

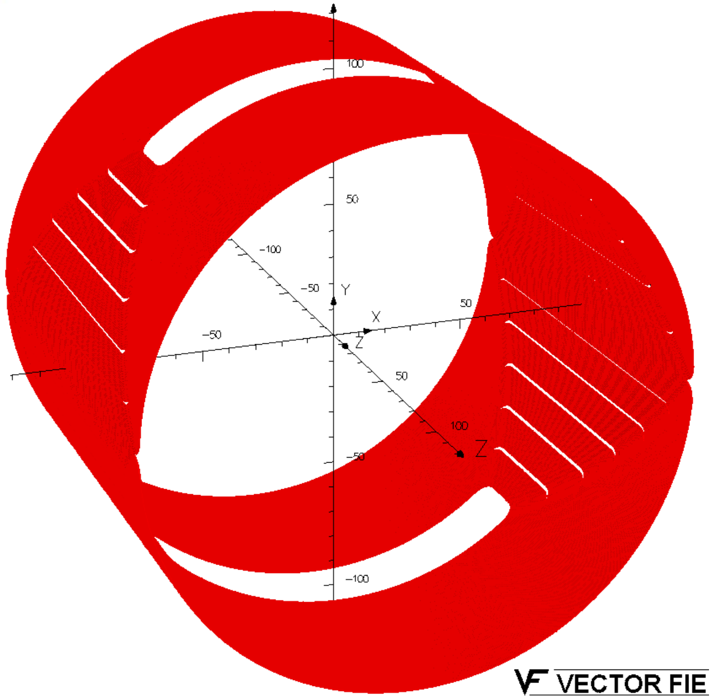




R. Gupta – "Optimum Integral Design for Optimizing Fields in Short Magnets (ASC2004)

Optimum Integral Design Opens a New Parameter Space

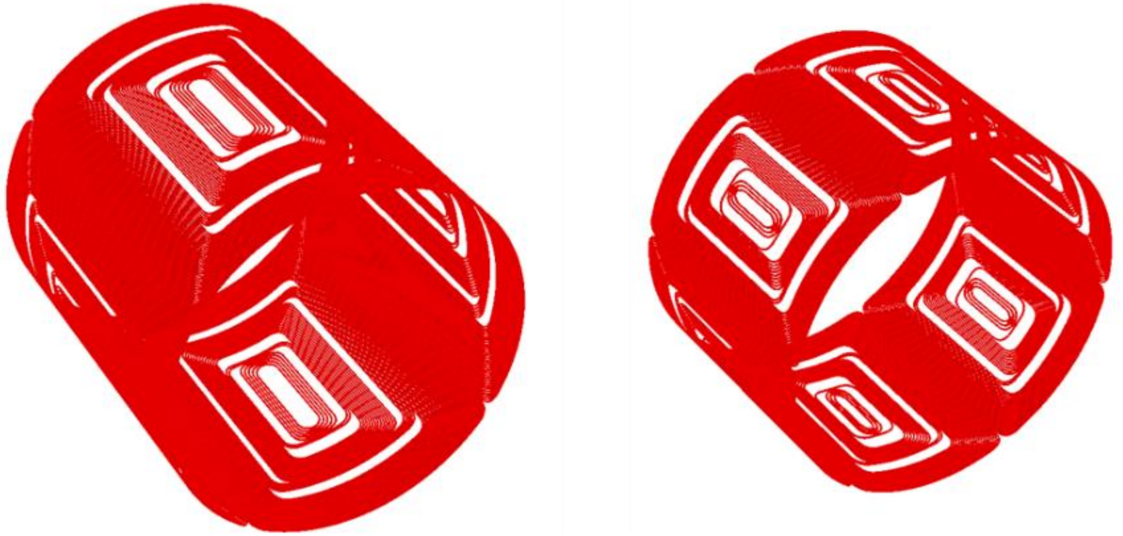
(a parameter space not considered practical for s.c. magnets before)



Model of a short length, high field quality dipole based on the Optimum Integral Design.

Coil length 175 mm; coil diameter 200 mm.

- **High field quality dipoles with coil length less than the coil diameter**
- **Quadrupole magnets with coil length less than the coil radius**
- **Sextupole magnets with coil length less than 2/3 of the coil radius**



(a design example with no spacers in the end)

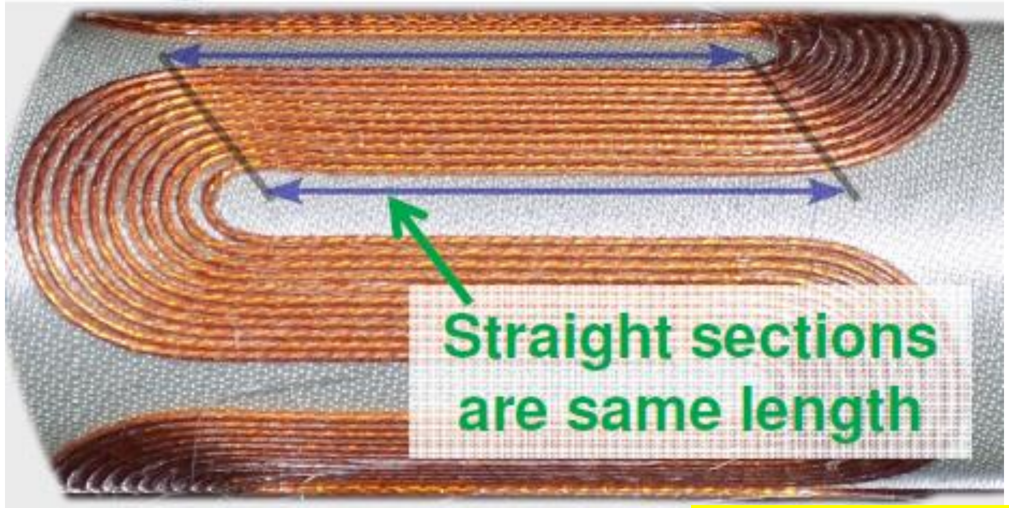
COMPUTED INTEGRAL FIELD HARMONICS FOR A SHORT DIPOLE (COIL LENGTH < DIAMETER) AT A RADIUS OF 66.6 MM. THE COIL RADIUS IS 100 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.00273 @ 25 A	0.0	0.0	0.0	0.0	0.0	0.0

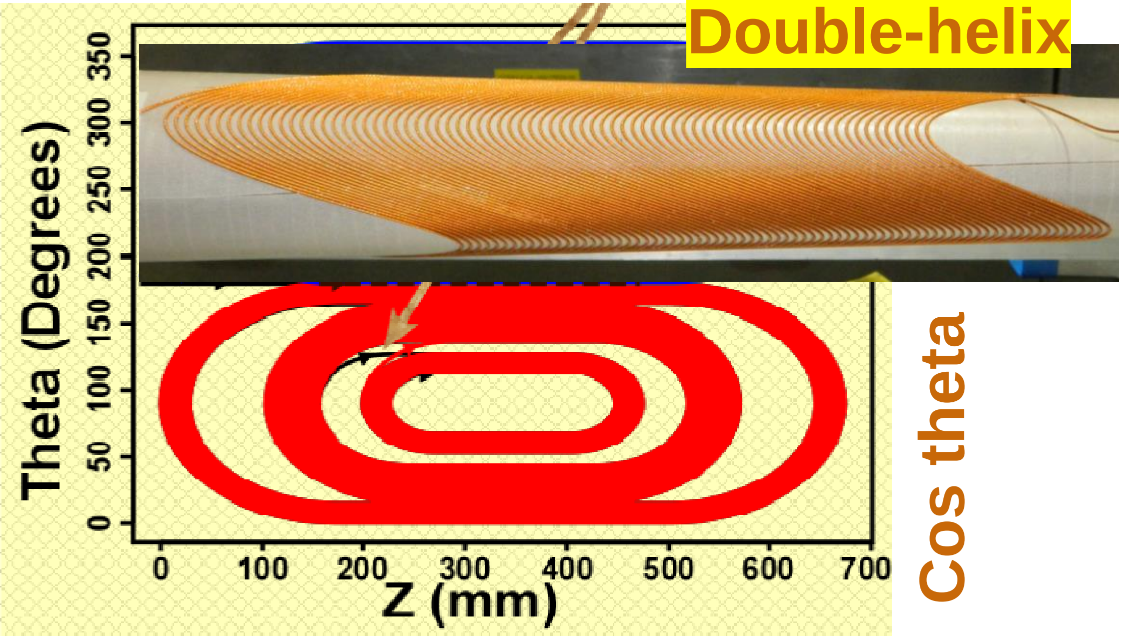
Can the benefits of the optimum integral design be used in EIC?

Length of the Straight Sections (SS) in Various Designs
(length of SS determines the integral field in short magnets)

- ***Space for turns in the Ends must be at least as much as that used in the arc of the straight section (usually more).***
- ***Thus, straight section will have ~1/3 of the length in a cos theta dipole or in a serpentine. It's worse in double-helix.***
- ***In the optimum integral design, straight section length is the full coil length.***

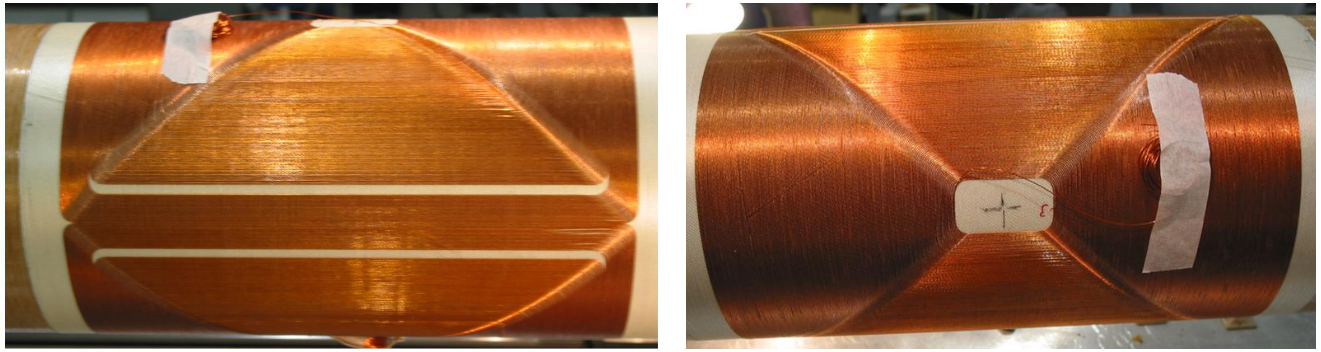


serpentine



Double-helix

Cos theta

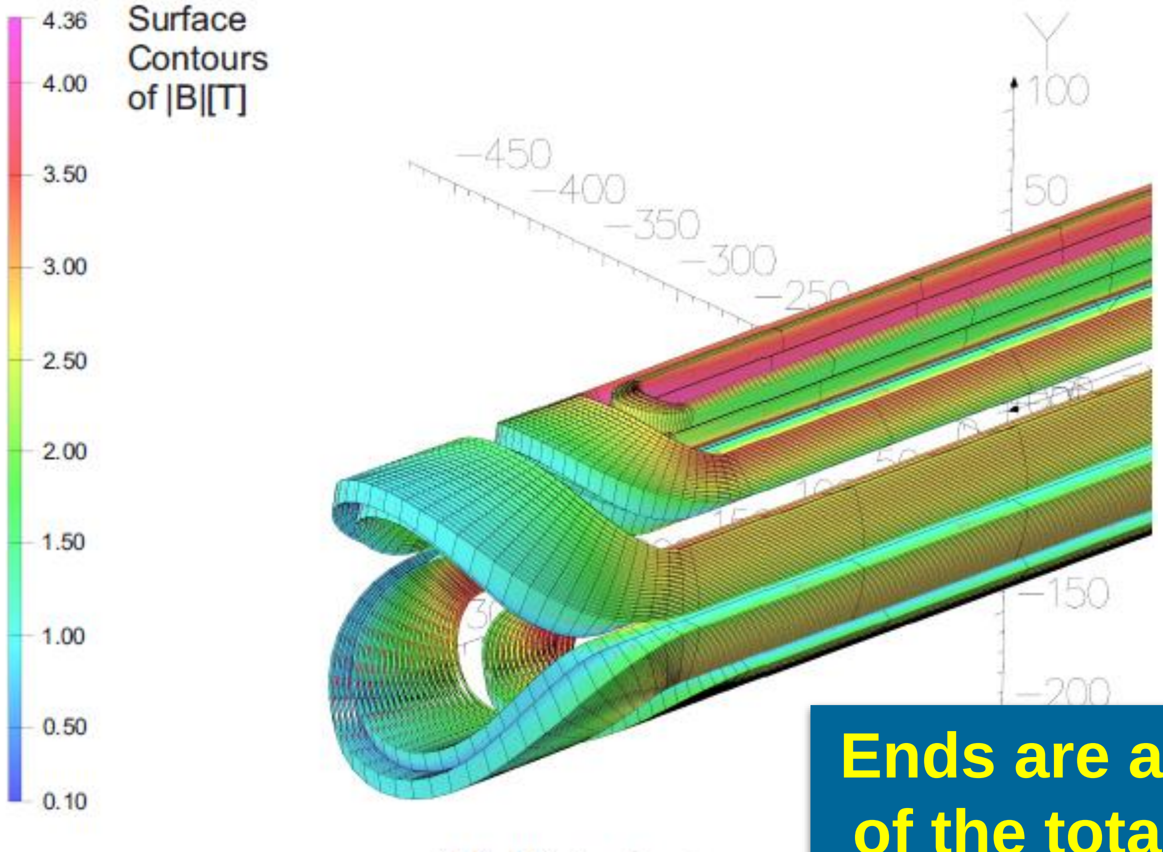


Optimum Integral

Motivation for SBIR/STTR – EIC IR has several short magnets

B0ApF is the smallest magnet. This may fit in the budget of an STTR

Conventional cosine (θ) design, as presented in pCDR:
(x-section and ends were optimized separately)



(a) Peak Field on the wire

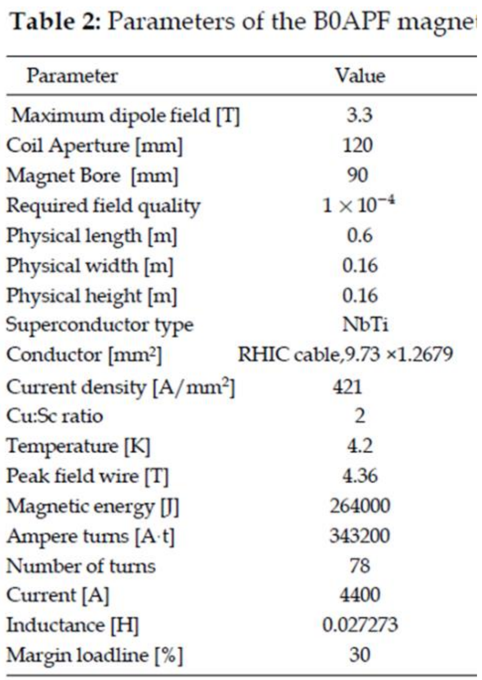
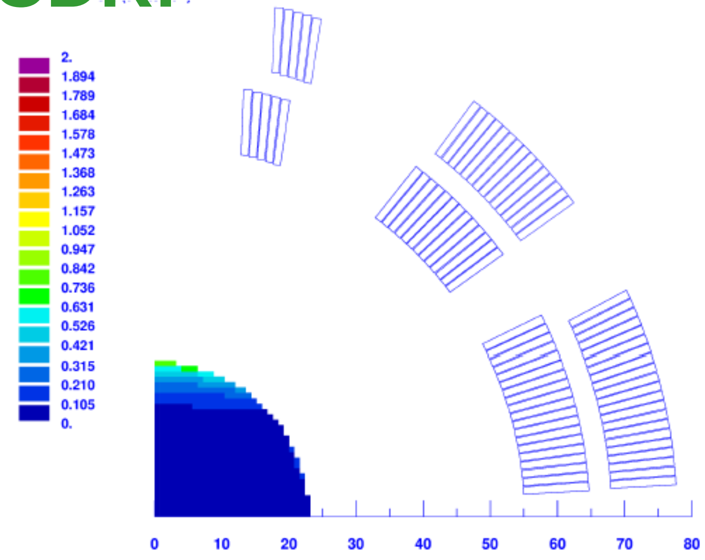
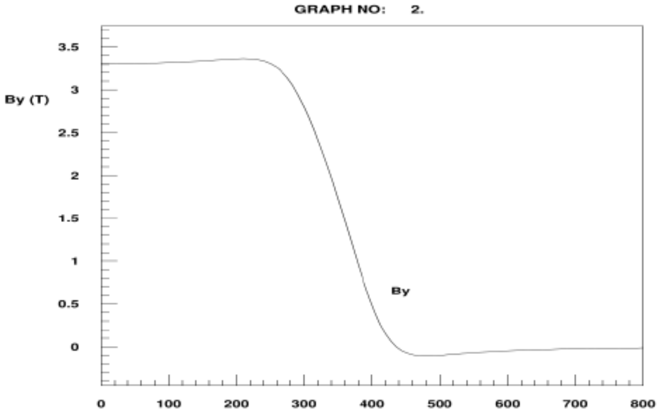


Table 2: Parameters of the B0APF magne

Parameter	Value
Maximum dipole field [T]	3.3
Coil Aperture [mm]	120
Magnet Bore [mm]	90
Required field quality	1×10^{-4}
Physical length [m]	0.6
Physical width [m]	0.16
Physical height [m]	0.16
Superconductor type	NbTi
Conductor [mm²]	RHIC cable,9.73 ×1.2679
Current density [A/mm²]	421
Cu:Sc ratio	2
Temperature [K]	4.2
Peak field wire [T]	4.36
Magnetic energy [J]	264000
Ampere turns [A·t]	343200
Number of turns	78
Current [A]	4400
Inductance [H]	0.027273
Margin loadline [%]	30



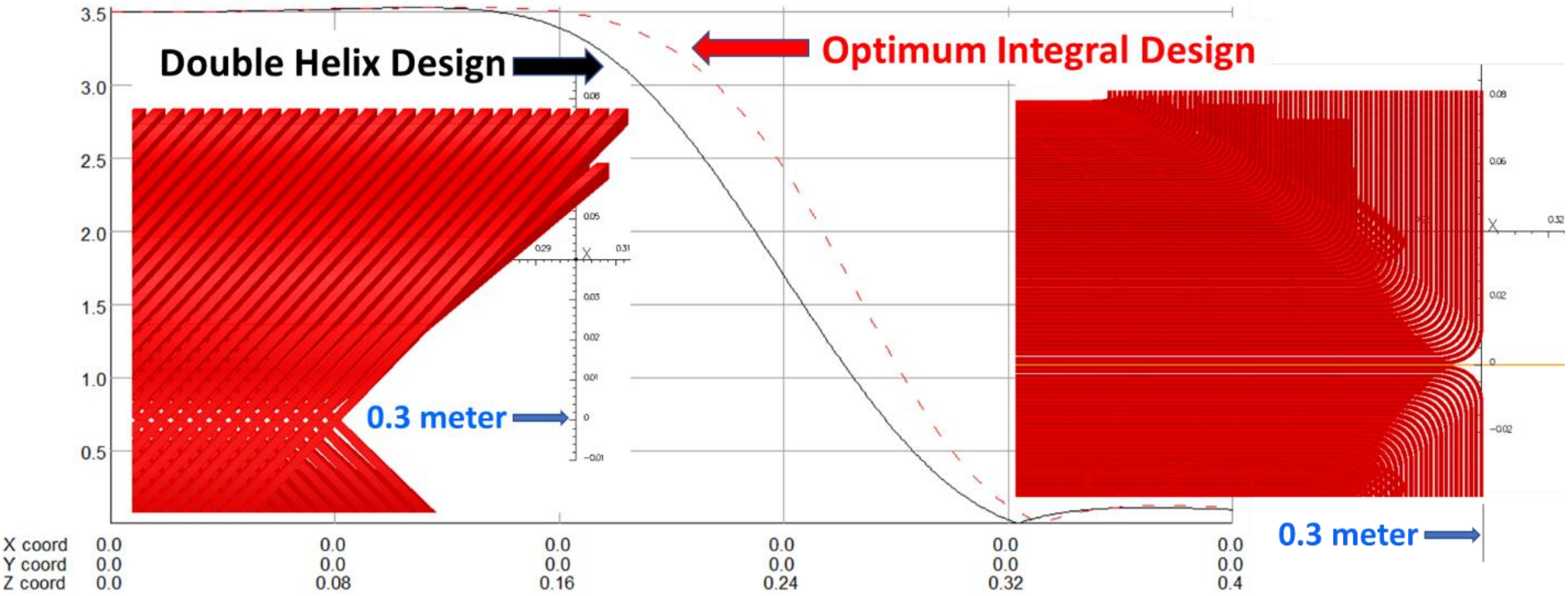
(a) Good field region



(b) Vertical magnetic field (Tesla) along the length of the magnet (mm)

Ends are a significant fraction of the total length and loss in integrated field is significant

Comparison of the other designs (double-helix) with the optimum integral was also made for the magnet B0ApF



Optimum integral design extends the magnetic length for the same coil length

Can the benefits of the optimum integral design be used in EIC?

A good topic for SBIR/STTR Program

PBL/BNL STTR on B0ApF

(Phase I: 200k$; Phase II: 1.15M$)

Goals: Phase I > a Proof-of-Principle dipole; Phase II > a Full-length R&D Magnet

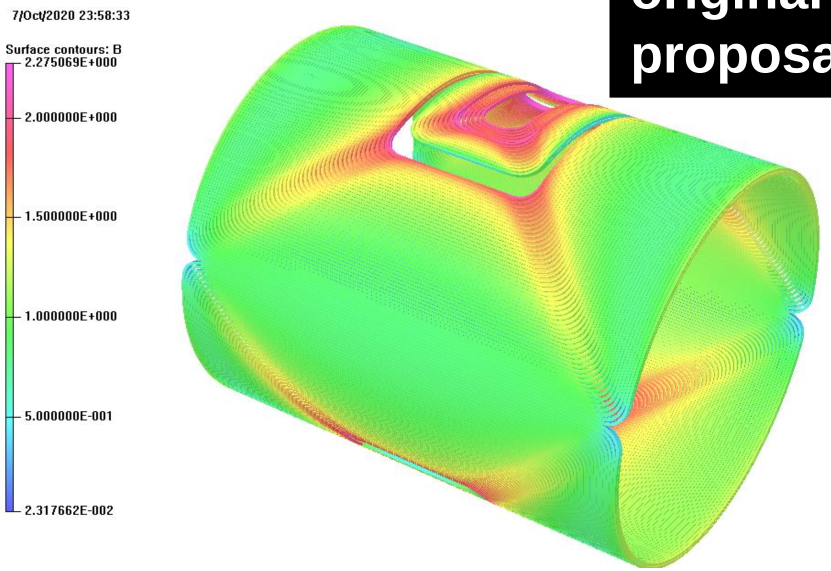
PBL SBIR/STTR Awards with BNL (EIC awards highlighted)

1.	A 6-D Muon Cooling System Using Achromat Bends and the Design, Fabrication and Test of a Prototype High Temperature (HTS) Solenoid for the System.	DE-FG02-07ER84855	August 2008	$850,000
2.	Study of a Final Cooling Scheme for a Muon Collider Utilizing High Field Solenoids.	DE-FG02-08ER85037	June 2008	$100,000
3.	Design of a Demonstration of Magnetic Insulation and Study of its Application to Ionization Cooling.	DE-SC000221	July 2009	$100,000
4.	Study of a Muon Collider Dipole System to Reduce Detector Background and Heating.	DE-SC0004494	June 2010	$100,000
5.	Study of a Final Cooling Scheme for a Muon Collider Utilizing High Field Solenoids: Cooling Simulations and Design, Fabrication and Testing of Coils.	DE-FG02-08ER85037	August 2010	$800,000
6.	Innovative Design of a High Current Density Nb_3Sn Outer Coil for a Muon Cooling Experiment.	DE-SC0006227	June 2011	$139,936
7.	Magnet Coil Designs Using YBCO High Temperature Superconductor (HTS).	DE-SC0007738	February 2012	$150,000
8.	Dipole Magnet with Elliptical and Rectangular Shielding for a Muon Collider.	DE-SC000	February 2013	$150,000
9.	A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets.	DE-SC0011348	February 2014	$150,000
10.	A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets.	DE-SC0011348	April 2016	$999,444
11.	Development of an Accelerator Quality High-Field Common Coil Dipole Magnet.	DE-SC0015896	June 2016	$150,000
12.	**Novel Design for High-Field, Large Aperture Quadrupoles for Electron-Ion Collider**	**DE-SC00186**	**April 2018**	**$150,000**
13.	**Field Compensation in Electron-Ion Collider Magnets with Passive Superconducting Shield**	**DE-SC0018614**	**April 2018**	**$150,000**
14.	HTS Solenoid for Neutron Scattering.	DE-SC0019722	February 2019	$150,000
15.	Quench Protection for a Neutron Scattering Magnet.	DE-SC0020466	February 2020	$200,000
16.	Overpass/Underpass Coil Design for High-Field Dipoles.	DE-SC002076	June 2020	$200,000
17.	**A New Medium Field Superconducting Magnet for the EIC (Phase I)**	**DE-SC0021578**	**February 2021**	**$200,000**
18.	**A New Medium Field Superconducting Magnet for the EIC (Phase II)**	**DE-SC0021578**	**April 2022**	**$1,1500,00**

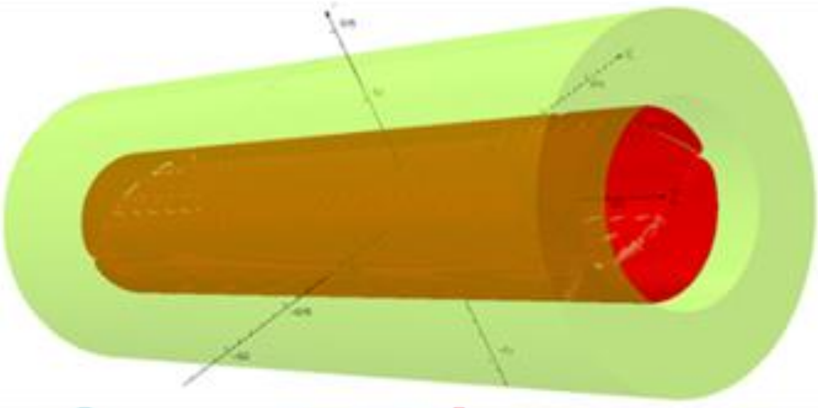
Phase I Optimum Integral Dipole

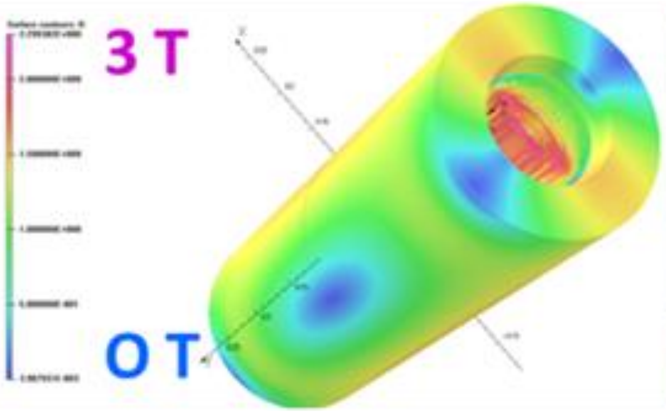
- Phase I original proposal had a scaled down version: short 150 mm long instead of the full-length 600 mm.
- However, detailed studies found that it wouldn't be a good technical representation of a full-length design.
- Moreover, 2 layers of 600 mm long Phase I coils can become part of the 10 layers of the Phase II.

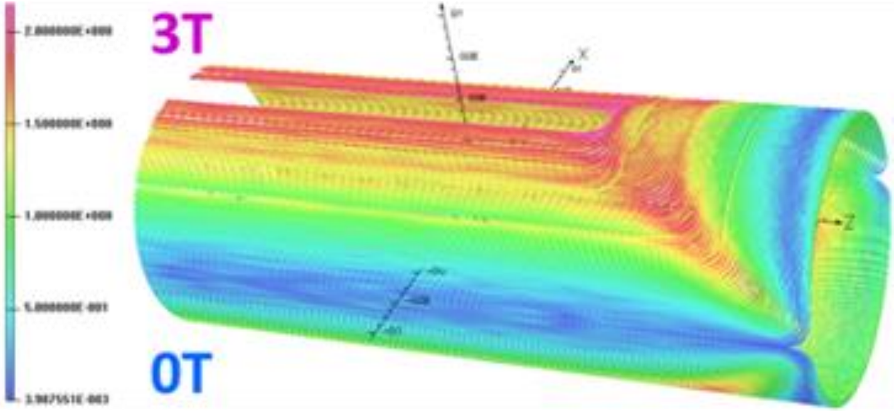
As in the original proposal



As built (two layers of full-length coil, designed, built & tested in the iron yoke)

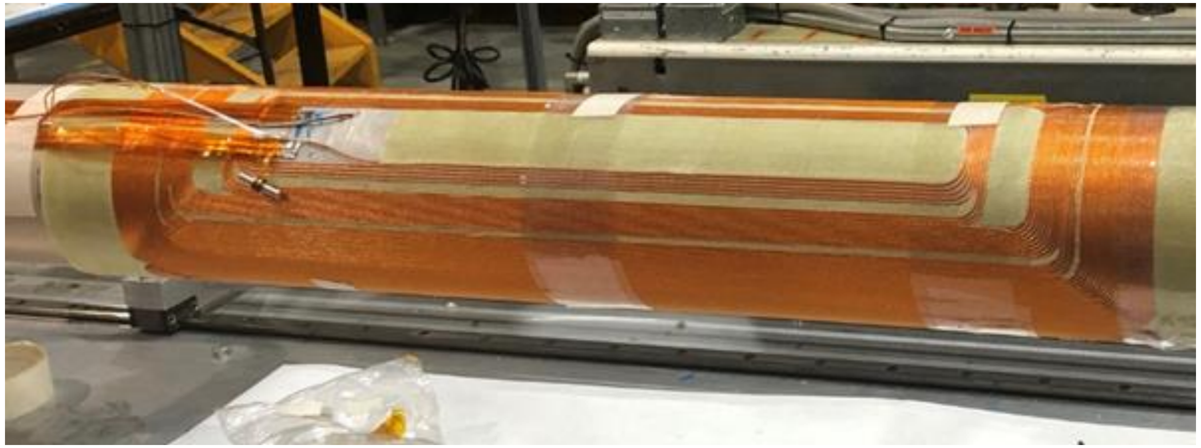


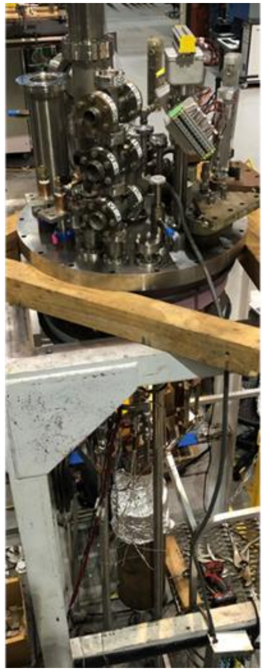


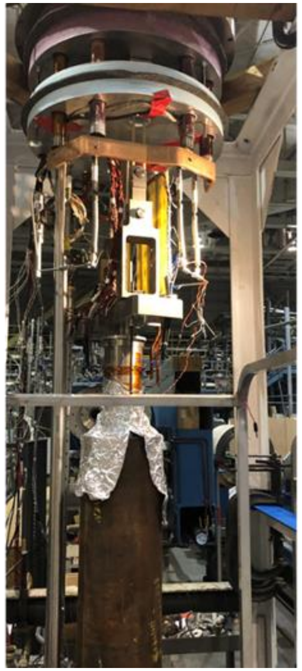


Optimum Integral Dipole PBL/BNL STTR for EIC B0ApF

(Phase I construction and testing)

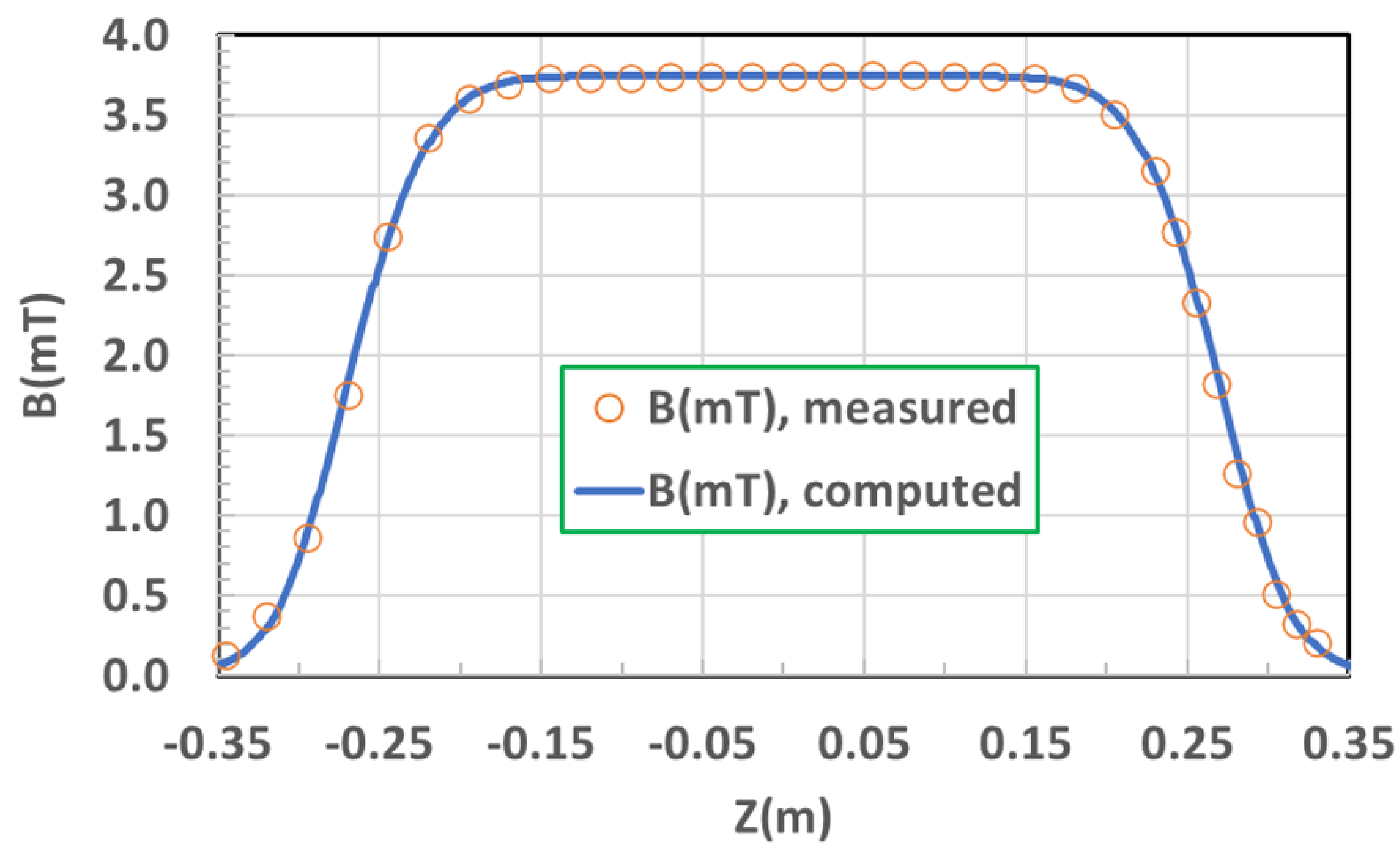






Question #1 for Phase 1:

Will optimum integral design extend the magnetic length as promised?



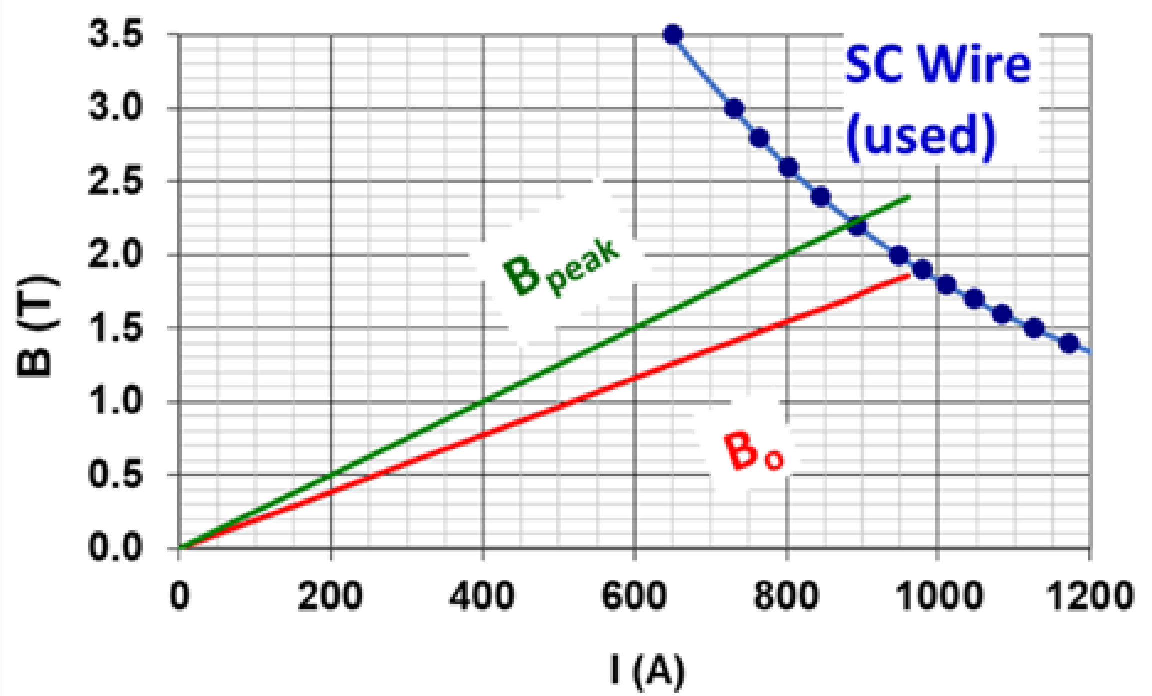
Major motivation of the optimum integral design

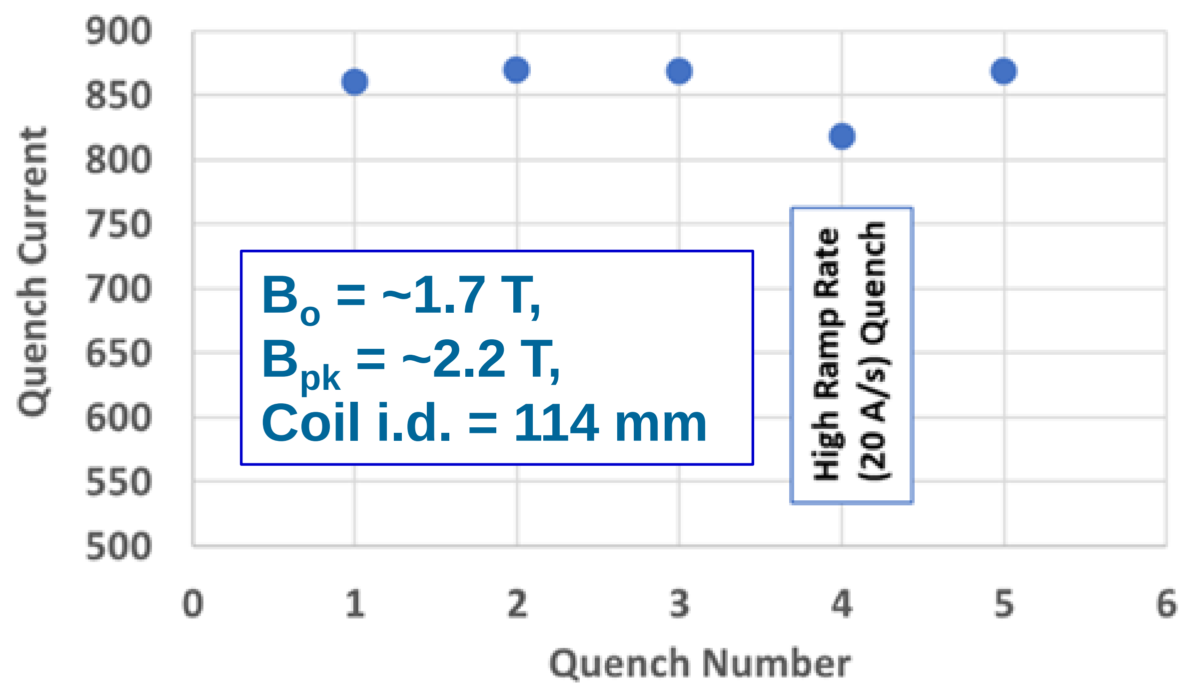
Answer:

✓ **Yes, it does!**

A good agreement between calculations and measurements

Question #2 for Phase 1: Will the direct wind coil based on the optimum integral have a good quench performance at this level?





B_o = ~1.7 T,
B_{pk} = ~2.2 T,
Coil i.d. = 114 mm

✓ **Answer: Yes... Predicted quench current reached without training !**

Two significant achievements for a Phase I award. A PoP SC magnet in <1 year.

Question for Phase II : Will this excellent performance of the "Direct Wind" technology continue to higher fields and larger bore magnets, e.g., as needed for EIC and other applications?

Status and Plans of Phase II

Overall Plan and Goals of Phase II

Final Goal (an ambitious goal for SBIR/STTR program):

10 layers, ~3.8 T bore field, ~4.2 T peak field, 114 mm coil i.d.

For comparison, RHIC dipole: 3.45 T bore field, 80 mm coil i.d.

Intermediate Goal for the Year 1:

1. Demonstration of a good field quality:

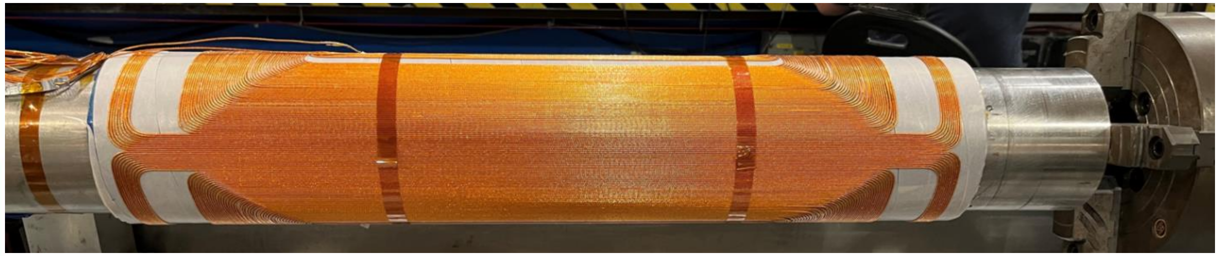
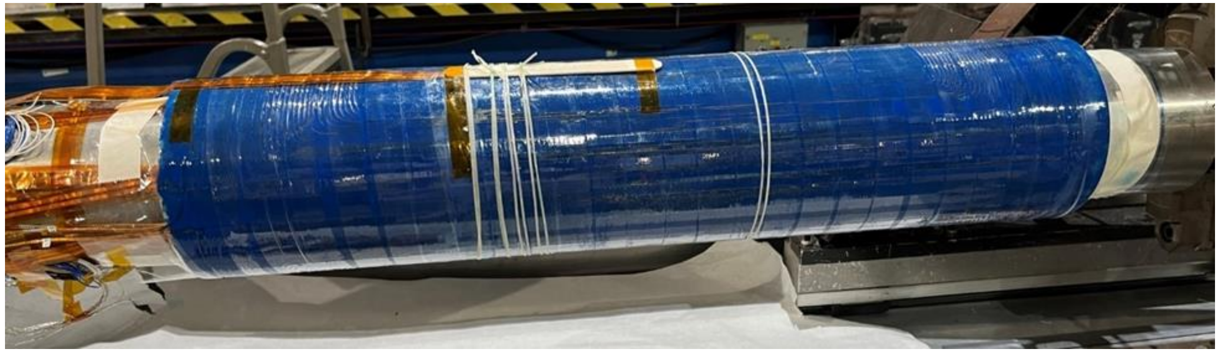
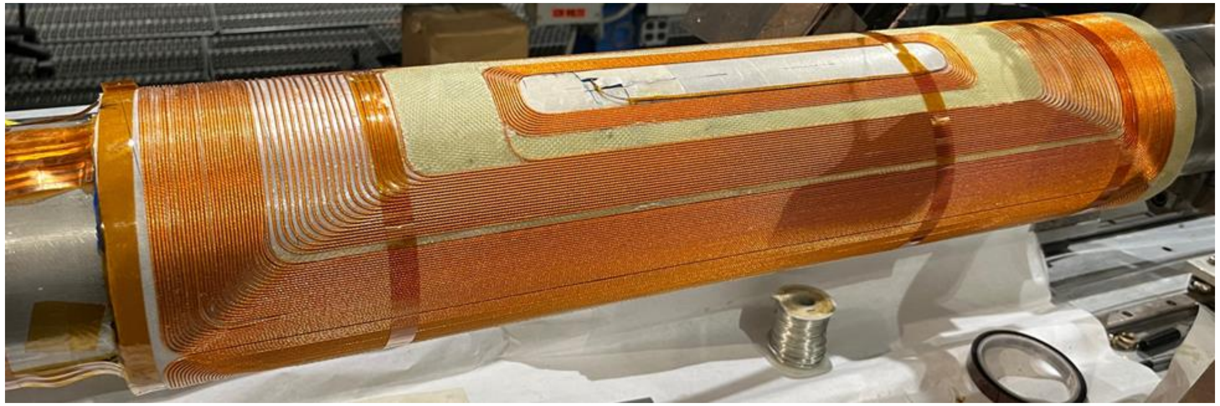
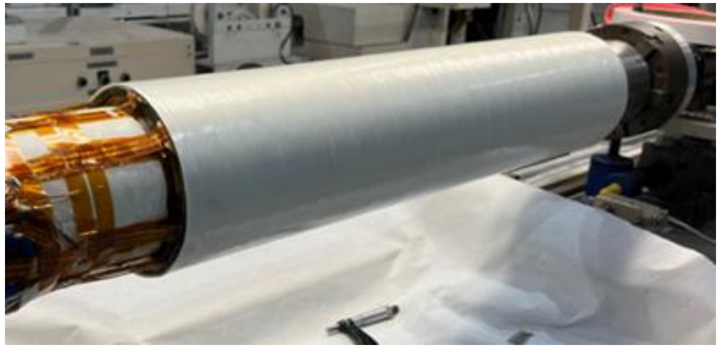
- **Validation of the optimum design and of the 3-D design software**

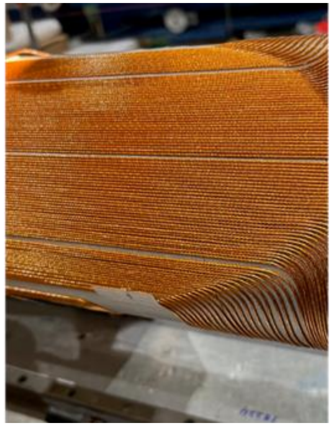
2. Construction and test of the direct wind coil with more layers

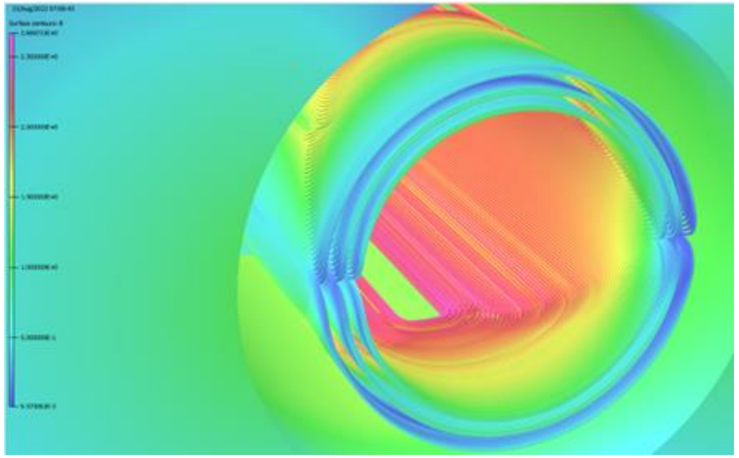
- **Goal: 6 layers, ~2.9 T bore field, ~3.5 T peak field, 114 mm coil i.d.**

Coil Winding, Magnet Design and Construction for Phase II (Year 1)

(a 6-layer optimum integral dipole designed, built and tested)



A Key Task: Develop *IntegralOpt* and Associated software

(to optimize coil designs, and to create files for coil winding and other software)

Optimum Integral Dipole for AGS was designed and built in 2004. Those direct-wind coils were optimized with a custom code and then wound with the "legacy software".

A key task of the PBL/BNL STTR:

- ☐ Task #1: The code *IntegralOpt* developed and ported in Phase I will go through a significant upgrade in Phase II and a user manual will be written…

- ✓ **This task is complete now. Twelve layers have been wound with the recent software on two different direct wind machines. No legacy software was used.**

- ✓ **The optimized design and the computed harmonics have been validated with the magnetic measurements.**

More on the *IntegralOpt* Code and Associated Software

- ✓ Optimum Integral code has been fully ported to work on the computers available currently. It is entirely based on the open-source, public domain software.

- ➢ The program optimizes 3-d coil design with a method different from ROXIE, etc. This alternate method is very fast as it optimizes both 2-d and 3-d coil designs together in a matter of minutes (not days) and that too with up to 200 variables.

- ➢ The software also creates a set of files for other codes, such as EM software OPERA3d, and input to modern direct wind machine software, etc.

- ❖ Moreover, thanks to the internal ATRO funds, it was updated a few months ago (with only a modest investment in time), so that it can be used for the serpentine pattern as well (a switch was there since 2004, but only implemented recently).

Field Quality Demonstration of the Design and of the Code

Warm testing of 6-layer design

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

*Leads may be contributing to lower order harmonics

- Good field quality despite several changes on the fly (as in most R&D projects)

- Next layers can compensate these small non-zero harmonics

A Design Change (not part of the original proposal)

An attempt to remove extra radial space taken by the leads in the design.

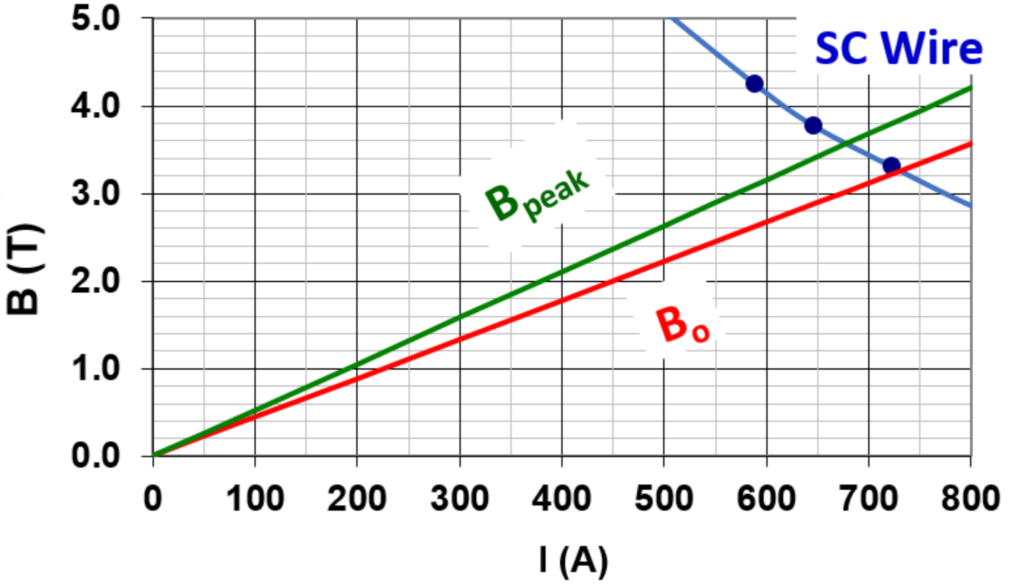
SBIR/STTR programs offer unique opportunities to innovate

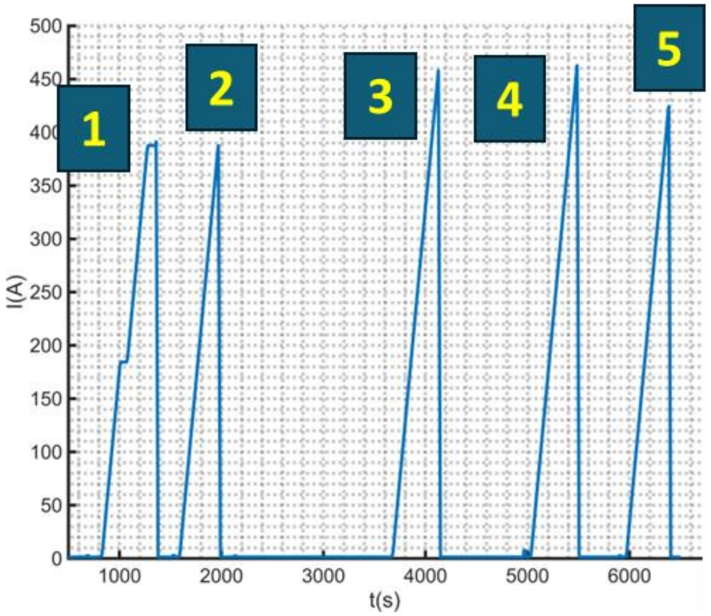
- However, one must be prepared that not all ideas will work
- Here is a case where one innovation for added improvements did not work 100%.
- The optimum integral design, and this STTR, as such, didn’t depend on this.
- Another change in the design has eliminated the above issue.

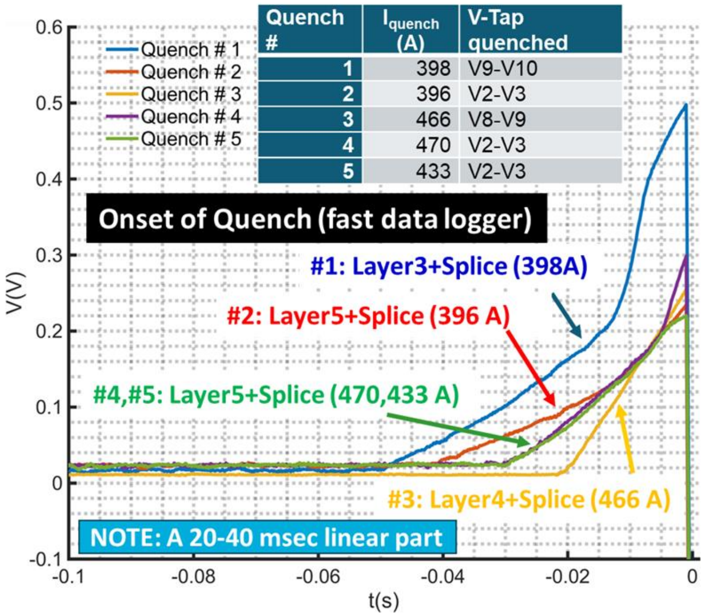
The STTR is back on track now to demonstrate feasibility of the optimum integral dipole for EIC – design, build and test a full-length prototype of EIC dipole B0ApF.

(more information in the backup slides)

Testing of the Intermediate 6-layer Optimum Integral Dipole







Quench #	I_{quench} (A)	V-Tap quenched
1	398	V9-V10
2	396	V2-V3
3	466	V8-V9
4	470	V2-V3
5	433	V2-V3

Onset of Quench (fast data logger)

#1: Layer3+Splice (398A)

#2: Layer5+Splice (396 A)

#4,#5: Layer5+Splice (470,433 A)

#3: Layer4+Splice (466 A)

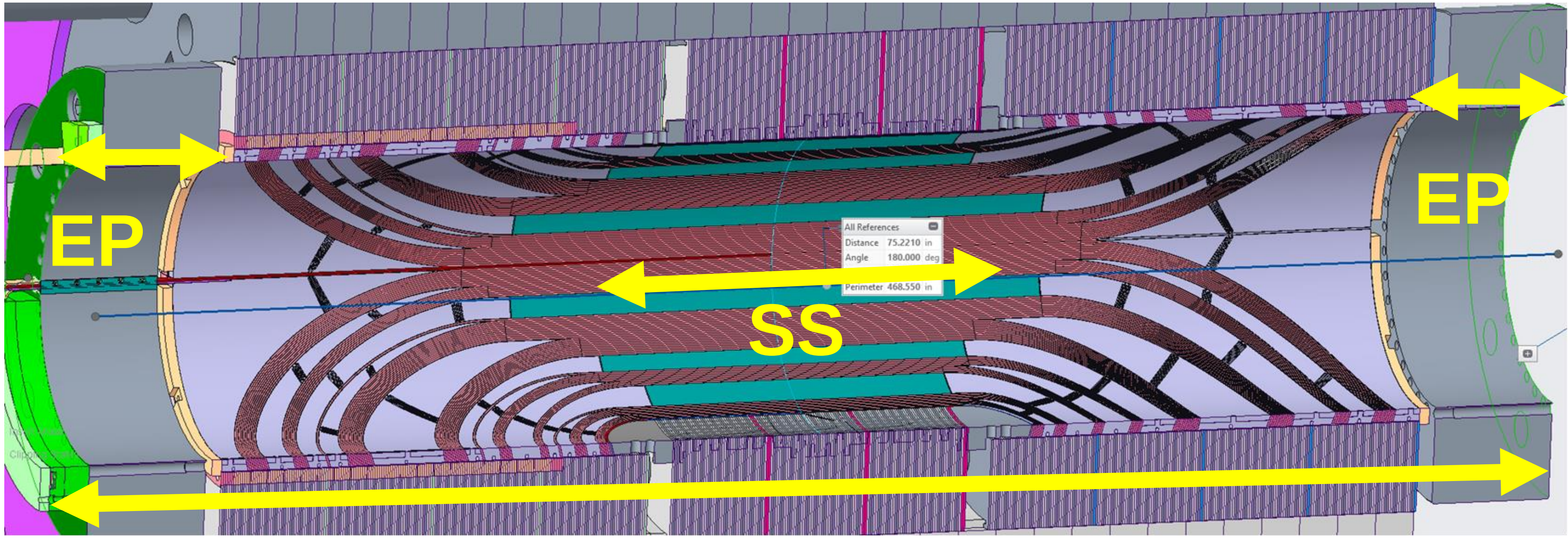
NOTE: A 20-40 msec linear part

- Magnet reached only ~70% of the short sample in 5 quenches.
- All quenches were in the layers where the new splice was used.
- Limited and/or insufficient cooling didn’t help- 1st energization was in <2 hours and subsequent ones with ~20 minutes or less wait.
- Limited budget of STTR allowed only ½ day of cryo-testing.
- Possibly a higher field could have been reached with more training.

Optimum Integral Dipole for B1ApF

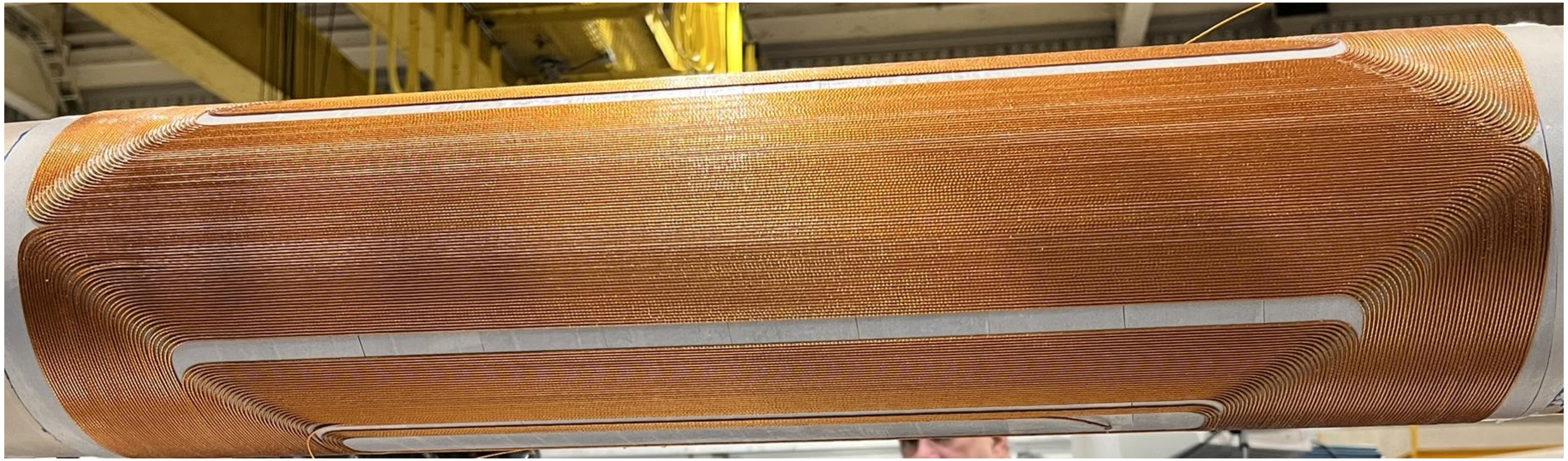
Possibility of an Optimum Integral Design for B1ApF

The present design of B1ApF is based on the cable magnet. It has a small Straight Section (SS). Moreover, End Plates (EP) take a significant space of the available slot-length.

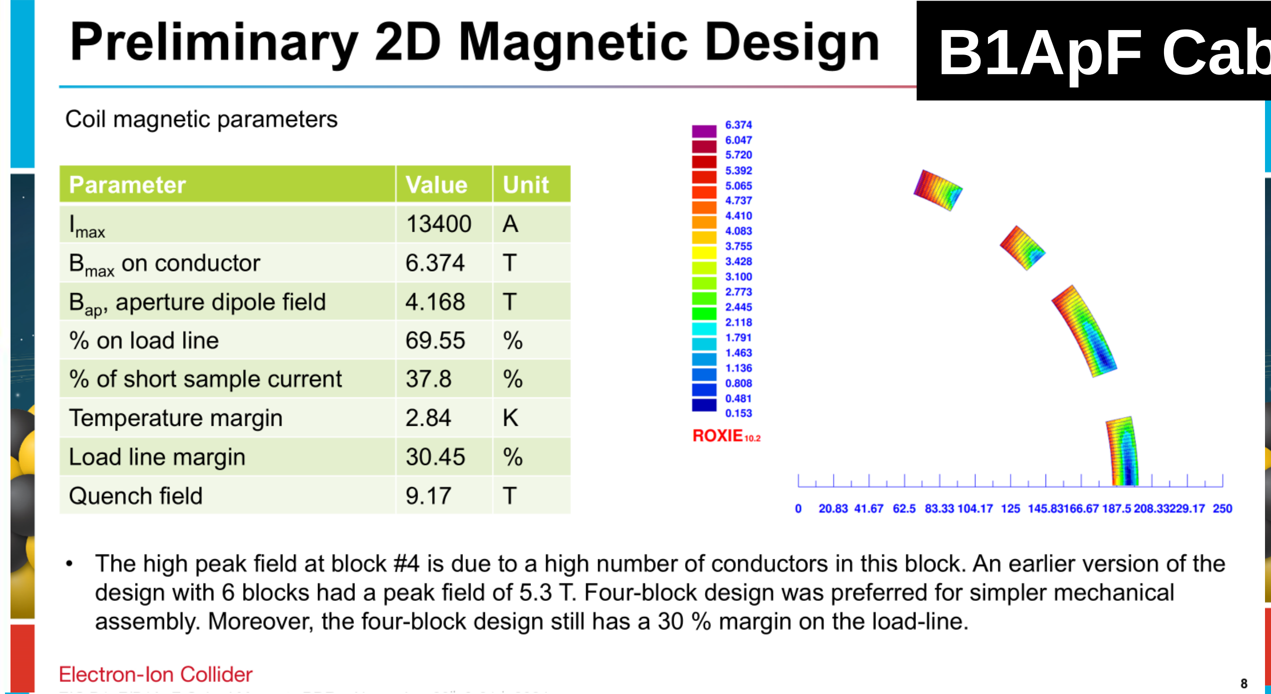


Total Length=1.91 m

In a direct-wind optimum integral dipole, the end plates will not be needed and the midplane turns (which create the maximum field) can extend to almost the full slot-length



B1ApF Cable Magnet Design (last review)



Preliminary 2D Magnetic Design

Coil magnetic parameters

Parameter	Value	Unit
I_{max}	13400	A
B_{max} on conductor	6.374	T
B_{ap}, aperture dipole field	4.168	T
% on load line	69.55	%
% of short sample current	37.8	%
Temperature margin	2.84	K
Load line margin	30.45	%
Quench field	9.17	T

- The high peak field at block #4 is due to a high number of conductors in this block. An earlier version of the design with 6 blocks had a peak field of 5.3 T. Four-block design was preferred for simpler mechanical assembly. Moreover, the four-block design still has a 30 % margin on the load-line.

Electron-Ion Collider

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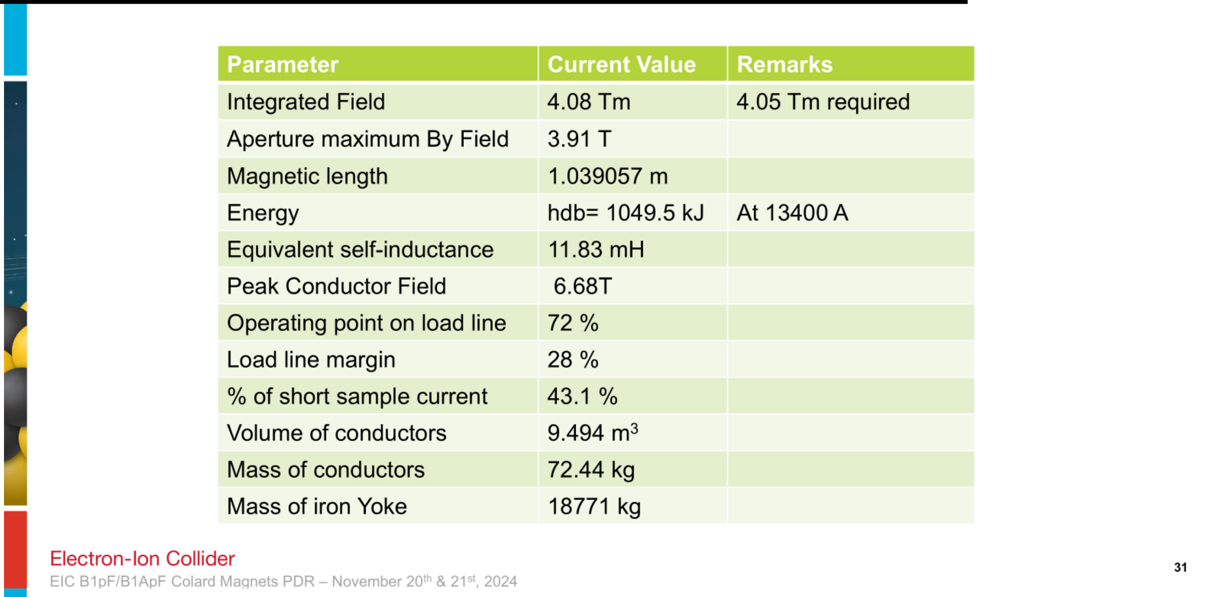

Charge #2-5

Parameter	Current Value	Remarks
Integrated Field	4.08 Tm	4.05 Tm required
Aperture maximum By Field	3.91 T	
Magnetic length	1.039057 m	
Energy	hdb= 1049.5 kJ	At 13400 A
Equivalent self-inductance	11.83 mH	
Peak Conductor Field	6.68T	
Operating point on load line	72 %	
Load line margin	28 %	
% of short sample current	43.1 %	
Volume of conductors	9.494 m^3	
Mass of conductors	72.44 kg	
Mass of iron Yoke	18771 kg	

Electron-Ion Collider

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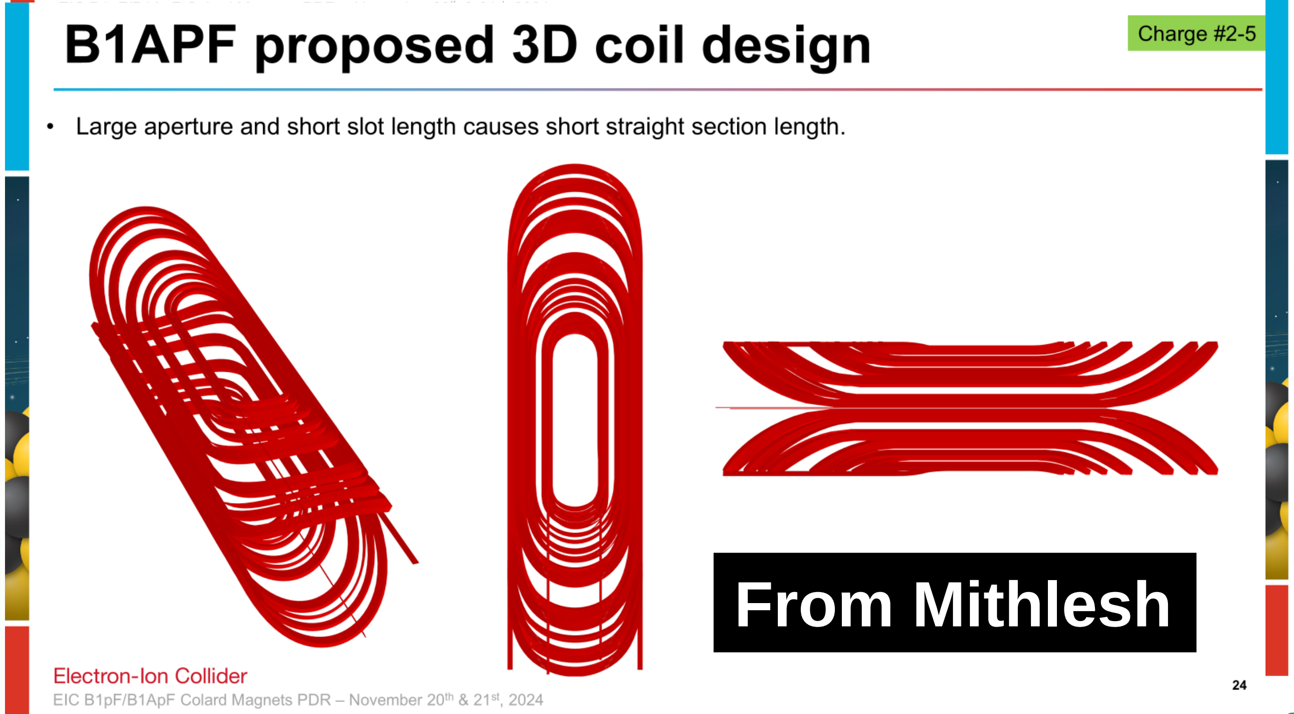

B1APF proposed 3D coil design

Charge #2-5

- Large aperture and short slot length causes short straight section length.

From Mithlesh

Electron-Ion Collider

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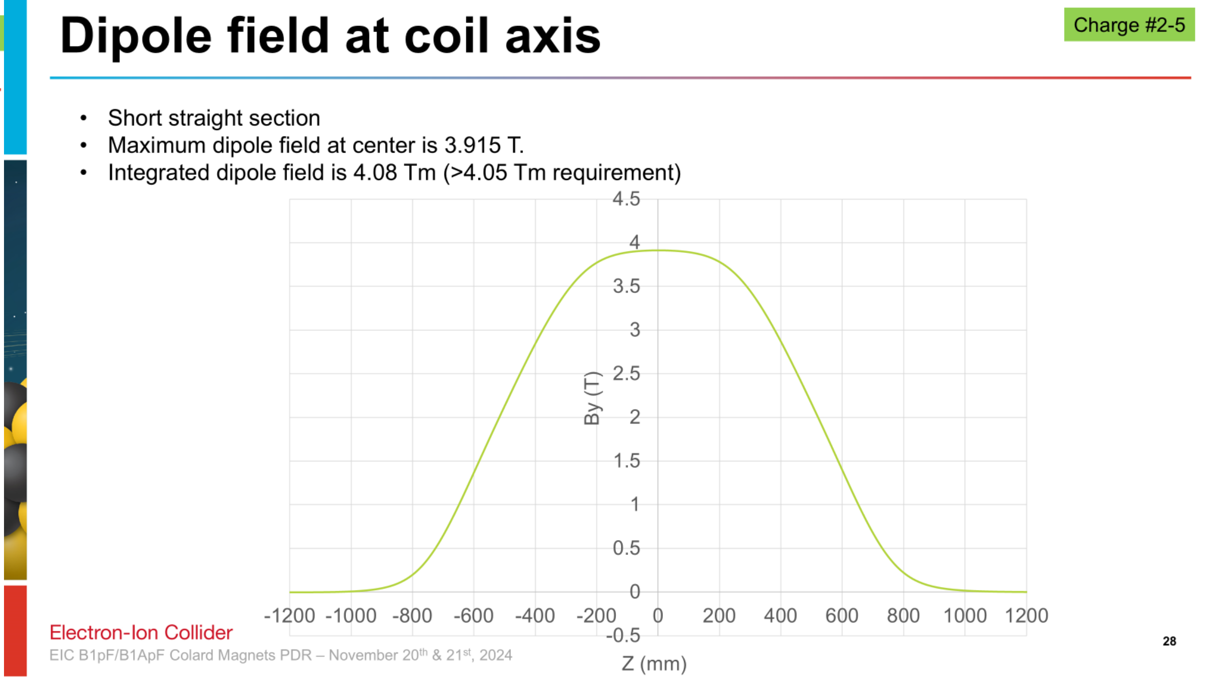

Dipole field at coil axis

Charge #2-5

- Short straight section
- Maximum dipole field at center is 3.915 T.
- Integrated dipole field is 4.08 Tm (>4.05 Tm requirement)

Electron-Ion Collider

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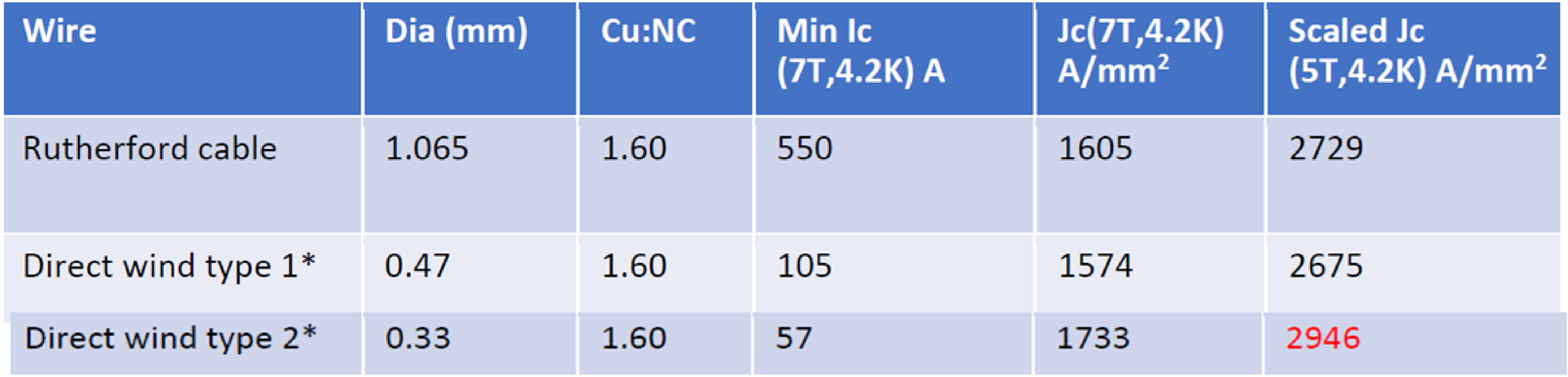
Basic Assumptions in Evaluating designs (1)

Rutherford Cable Magnet:

- **Use the design as presented in the last review**

Direct Wind Optimum Integral Dipole:



Wire	Dia (mm)	Cu:NC	Min Ic (7T,4.2K) A	Jc(7T,4.2K) A/mm^2	Scaled Jc (5T,4.2K) A/mm^2
Rutherford cable	1.065	1.60	550	1605	2729
Direct wind type 1*	0.47	1.60	105	1574	2675
Direct wind type 2*	0.33	1.60	57	1733	2946

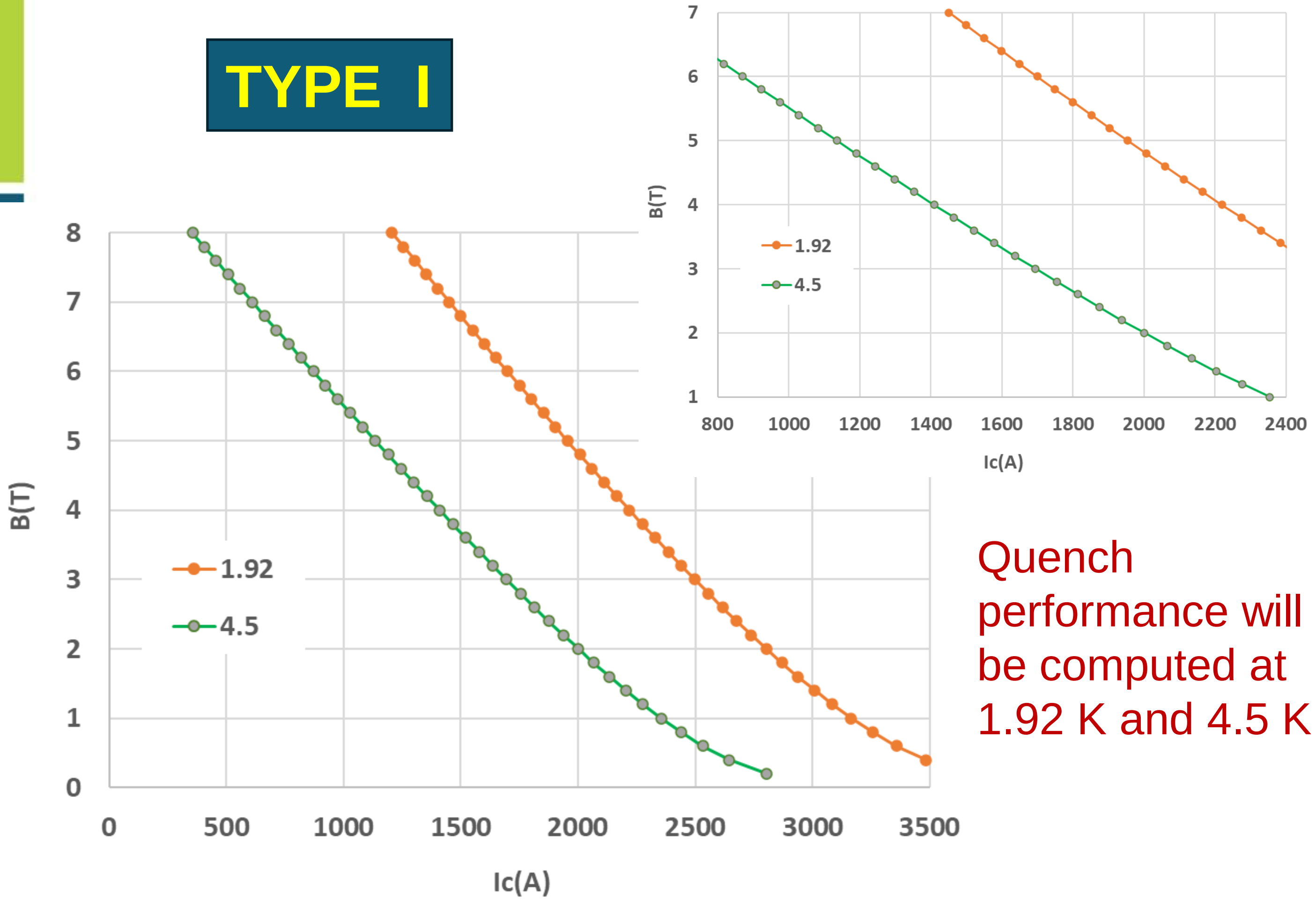
Minimum turn-to-turn spacing:

- **Type 1: 1.7 mm**
- **Type 2: 1,1 mm (as used in STTR)**

Larger spacing in the ends.

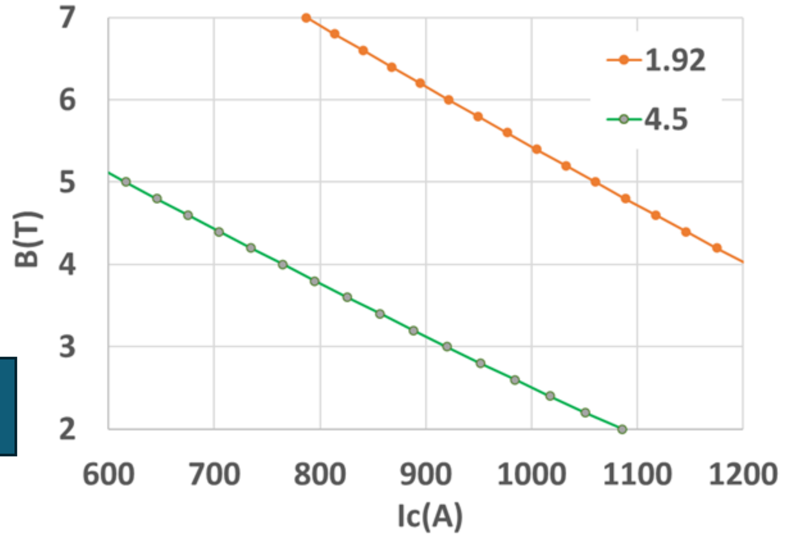
Cables (7 wires) Used in the Calculations (all except one with Type I)

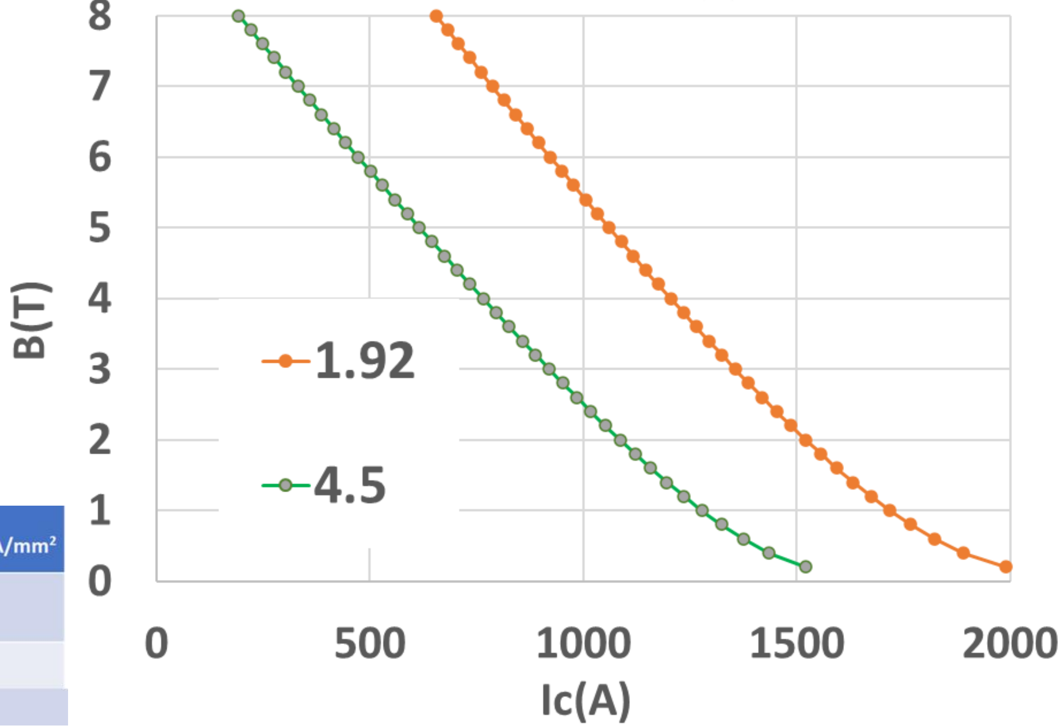
TYPE I



Quench performance will be computed at 1.92 K and 4.5 K

TYPE II





Numerical data included in the extra slides

Wire	Dia (mm)	Cu:NC	Min Ic (7T,4.2K) A	Jc(7T,4.2K) A/mm^2	Scaled Jc (5T,4.2K) A/mm^2
Rutherford cable	1.065	1.60	550	1605	2729
Direct wind type 1*	0.47	1.60	105	1574	2675
Direct wind type 2*	0.33	1.60	57	1733	2946

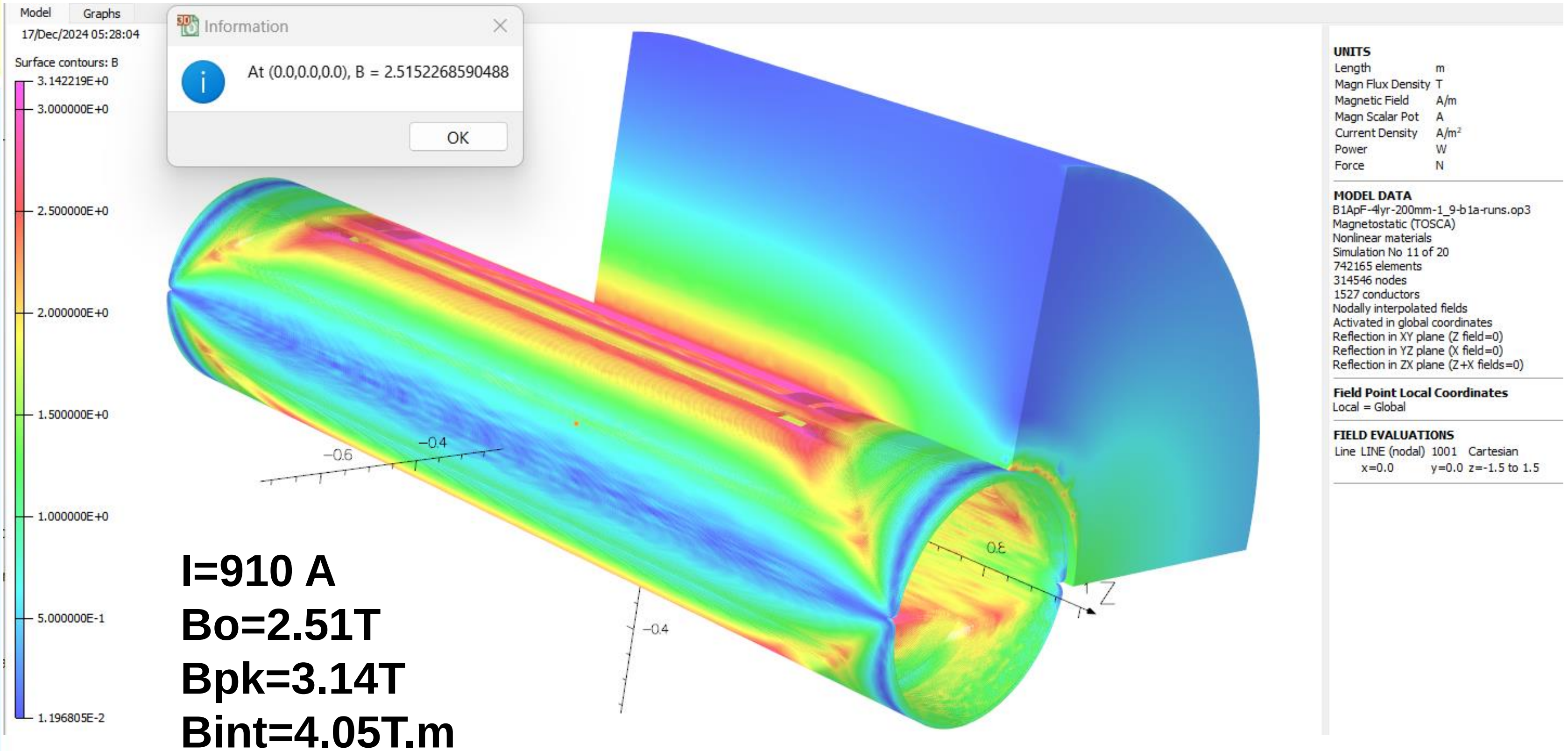
Self-imposed Guidelines in Developing Initial designs

- Inner radius of the additional tube in the Direct Wind B1ApF coil is made the same as the inner radius of the coil in the cable magnet (185 mm)
    - Note magnet before B1ApF is B1pF with coil inner radius of 150 mm
- Center of the cable in the first layer of the Direct Wind coil is placed at a radius of 200 mm to allow sufficient tube thickness (perhaps a smaller value will be sufficient)

- Design must meet the field quality (harmonics) and the integral field requirements.
- Note: All designs are the results of quick optimization for a evaluating the approach. They can be optimized more, but as such, are good enough for initial evaluation.

Initial Investigation of the Optimum Integral Dipole B1ApF

(4 layers or 2 double-layer design with Type I Wire)



At (0.0,0.0,0.0), B = 2.5152268590488

UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m²
Power	W
Force	N

MODEL DATA

B1ApF-4lyr-200mm-1_9-b1a-runs.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 11 of 20
742165 elements
314546 nodes
1527 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in YZ plane (X field=0)
Reflection in ZX plane (Z+X fields=0)

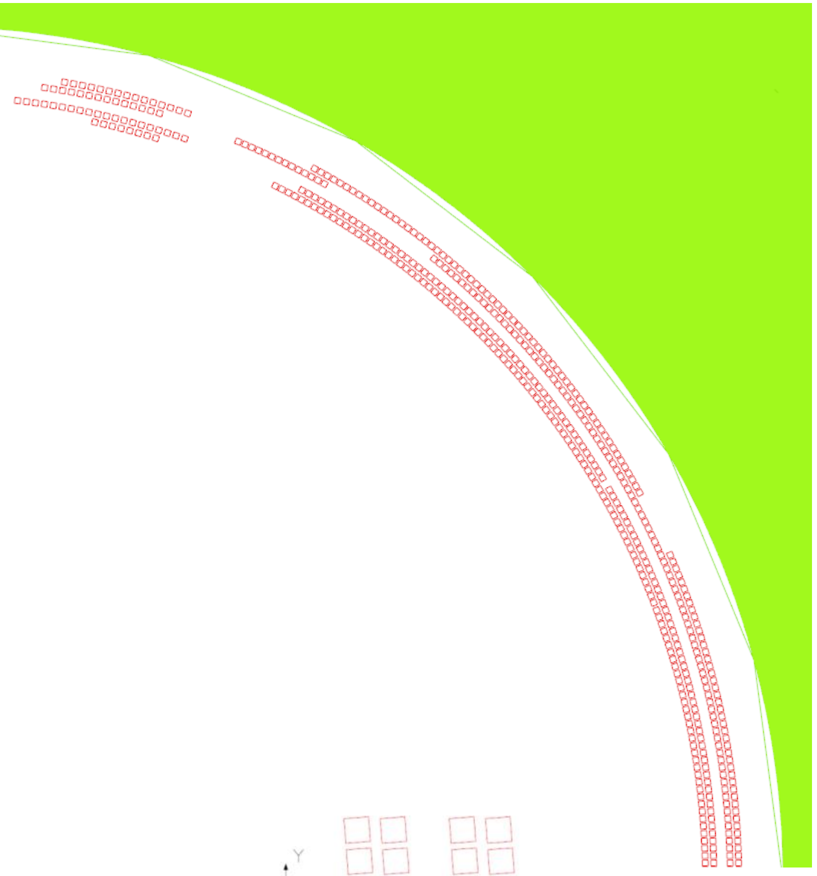
Field Point Local Coordinates

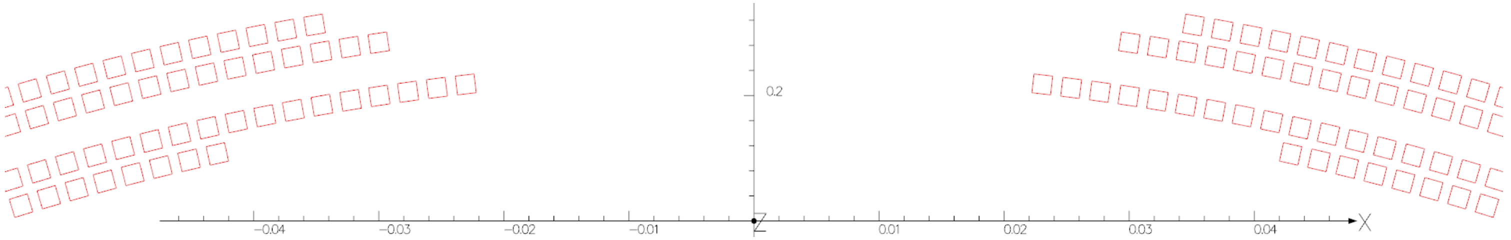
Local = Global

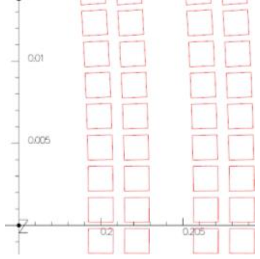
FIELD EVALUATIONS

Line LINE (nodal) 1001 Cartesian
x=0.0 y=0.0 z=-1.5 to 1.5

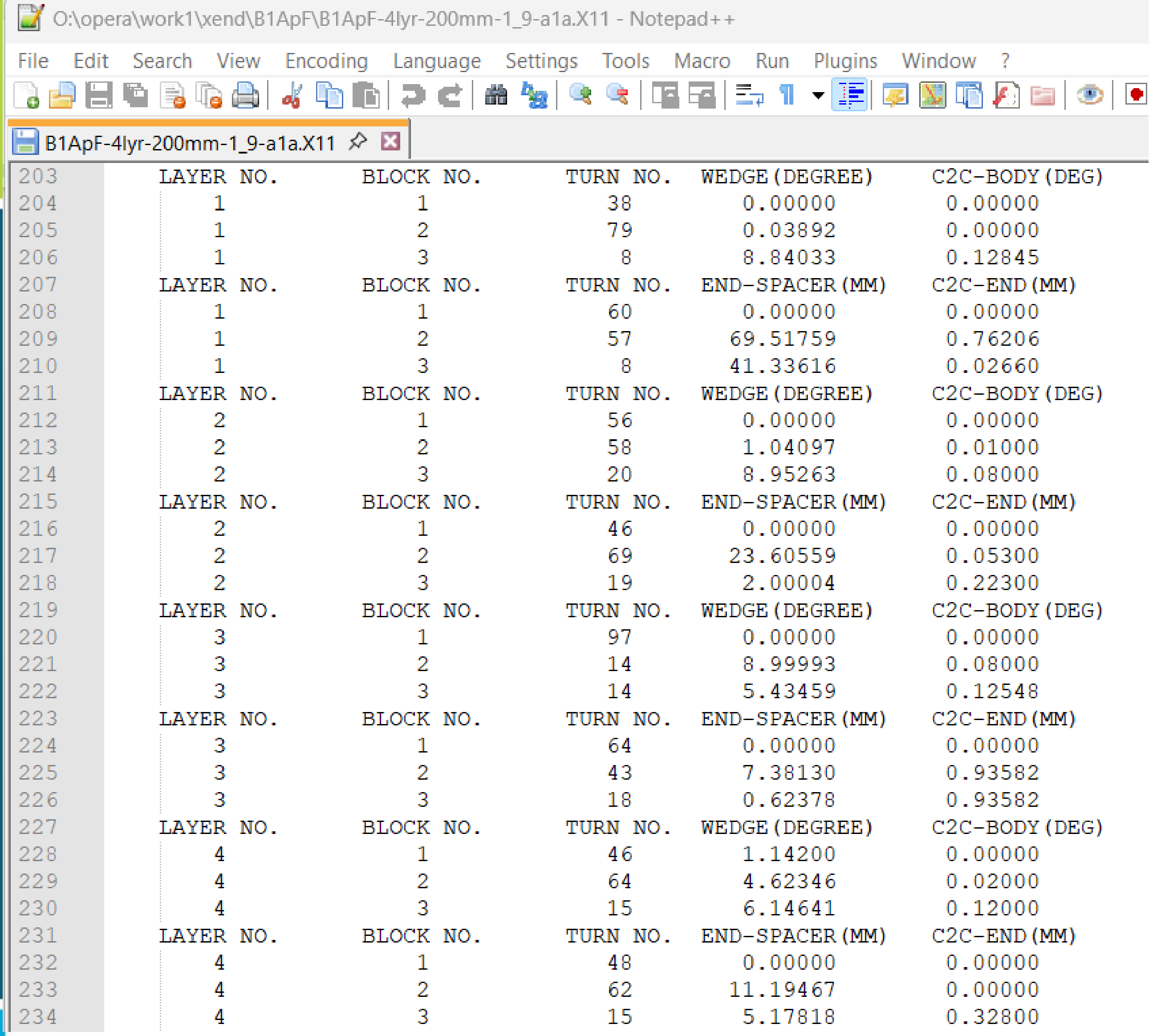
I=910 A
Bo=2.51T
Bpk=3.14T
Bint=4.05T.m





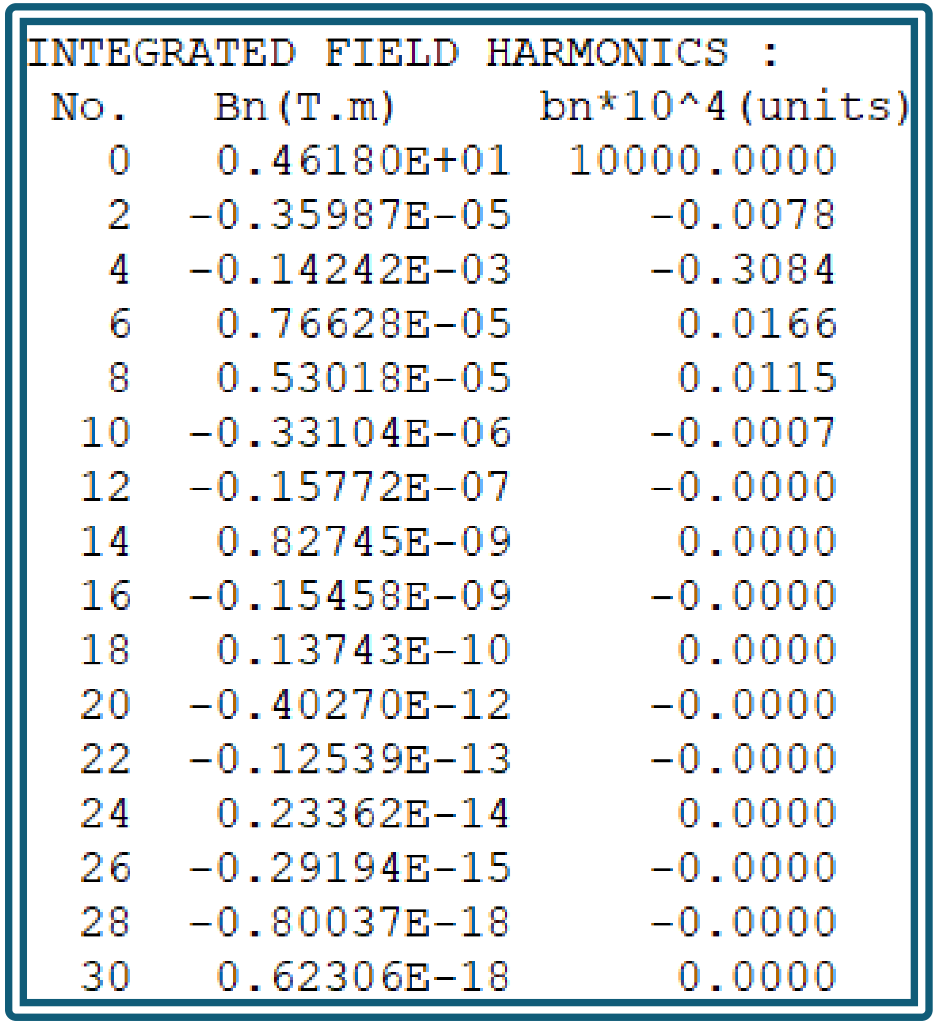


4-layer design Optimized with the Optimum Integral Code



```
        LAYER NO.      BLOCK NO.      TURN NO.  WEDGE(DEGREE)     C2C-BODY(DEG)
            1              1             38       0.00000           0.00000
            1              2             79       0.03892           0.00000
            1              3              8       8.84033           0.12845
        LAYER NO.      BLOCK NO.      TURN NO.  END-SPACER(MM)    C2C-END(MM)
            1              1             60       0.00000           0.00000
            1              2             57      69.51759           0.76206
            1              3              8      41.33616           0.02660
        LAYER NO.      BLOCK NO.      TURN NO.  WEDGE(DEGREE)     C2C-BODY(DEG)
            2              1             56       0.00000           0.00000
            2              2             58       1.04097           0.01000
            2              3             20       8.95263           0.08000
        LAYER NO.      BLOCK NO.      TURN NO.  END-SPACER(MM)    C2C-END(MM)
            2              1             46       0.00000           0.00000
            2              2             69      23.60559           0.05300
            2              3             19       2.00004           0.22300
        LAYER NO.      BLOCK NO.      TURN NO.  WEDGE(DEGREE)     C2C-BODY(DEG)
            3              1             97       0.00000           0.00000
            3              2             14       8.99993           0.08000
            3              3             14       5.43459           0.12548
        LAYER NO.      BLOCK NO.      TURN NO.  END-SPACER(MM)    C2C-END(MM)
            3              1             64       0.00000           0.00000
            3              2             43       7.38130           0.93582
            3              3             18       0.62378           0.93582
        LAYER NO.      BLOCK NO.      TURN NO.  WEDGE(DEGREE)     C2C-BODY(DEG)
            4              1             46       1.14200           0.00000
            4              2             64       4.62346           0.02000
            4              3             15       6.14641           0.12000
        LAYER NO.      BLOCK NO.      TURN NO.  END-SPACER(MM)    C2C-END(MM)
            4              1             48       0.00000           0.00000
            4              2             62      11.19467           0.00000
            4              3             15       5.17818           0.32800
```

Computed harmonics @55 mm (good field quality in coil geometry) low harmonic contents:

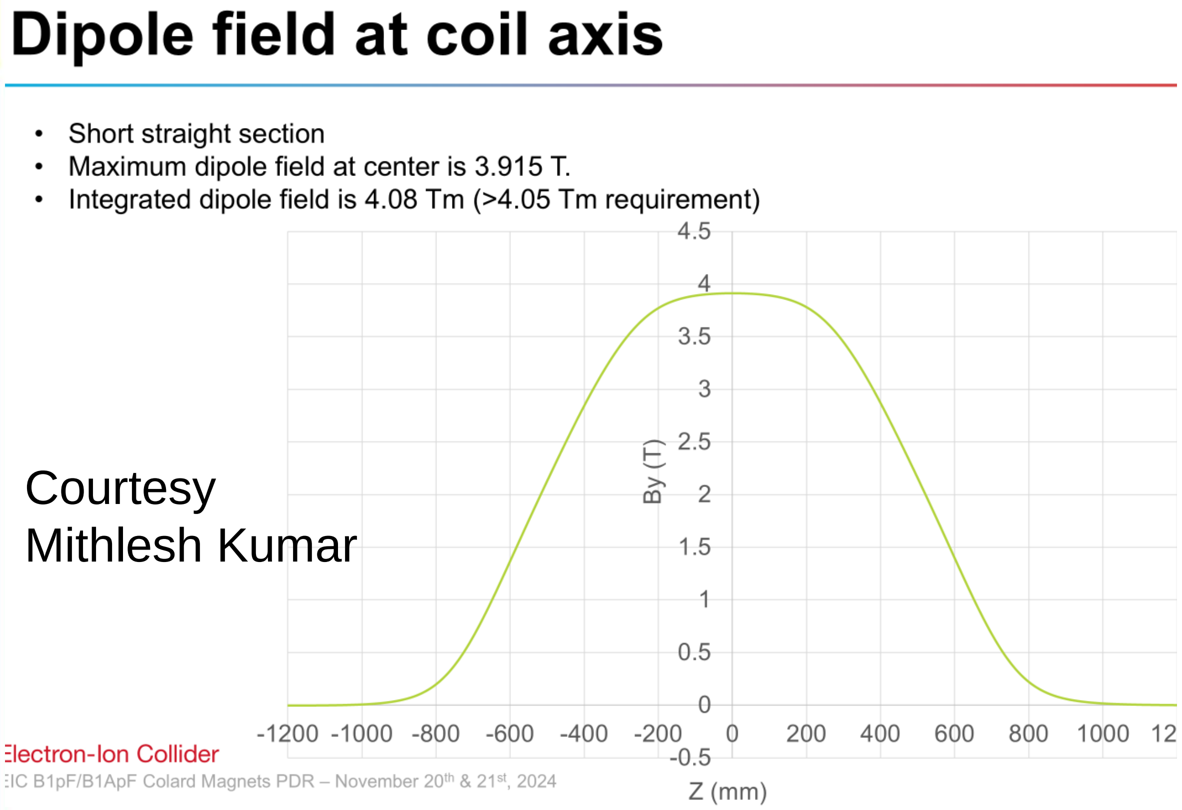


```
INTEGRATED FIELD HARMONICS :
 No.      Bn(T.m)        bn*10^4(units)
   0     0.46180E+01    10000.0000
   2    -0.35987E-05       -0.0078
   4    -0.14242E-03       -0.3084
   6     0.76628E-05        0.0166
   8     0.53018E-05        0.0115
  10    -0.33104E-06       -0.0007
  12    -0.15772E-07       -0.0000
  14     0.82745E-09        0.0000
  16    -0.15458E-09       -0.0000
  18     0.13743E-10        0.0000
  20    -0.40270E-12       -0.0000
  22    -0.12539E-13       -0.0000
  24     0.23362E-14        0.0000
  26    -0.29194E-15       -0.0000
  28    -0.80037E-18       -0.0000
  30     0.62306E-18        0.0000
```

Toal number of turns: 509

Comparison of Field Along the Axis for the Required Field Integral

Cable magnet design



Dipole field at coil axis

- Short straight section
- Maximum dipole field at center is 3.915 T.
- Integrated dipole field is 4.08 Tm (>4.05 Tm requirement)

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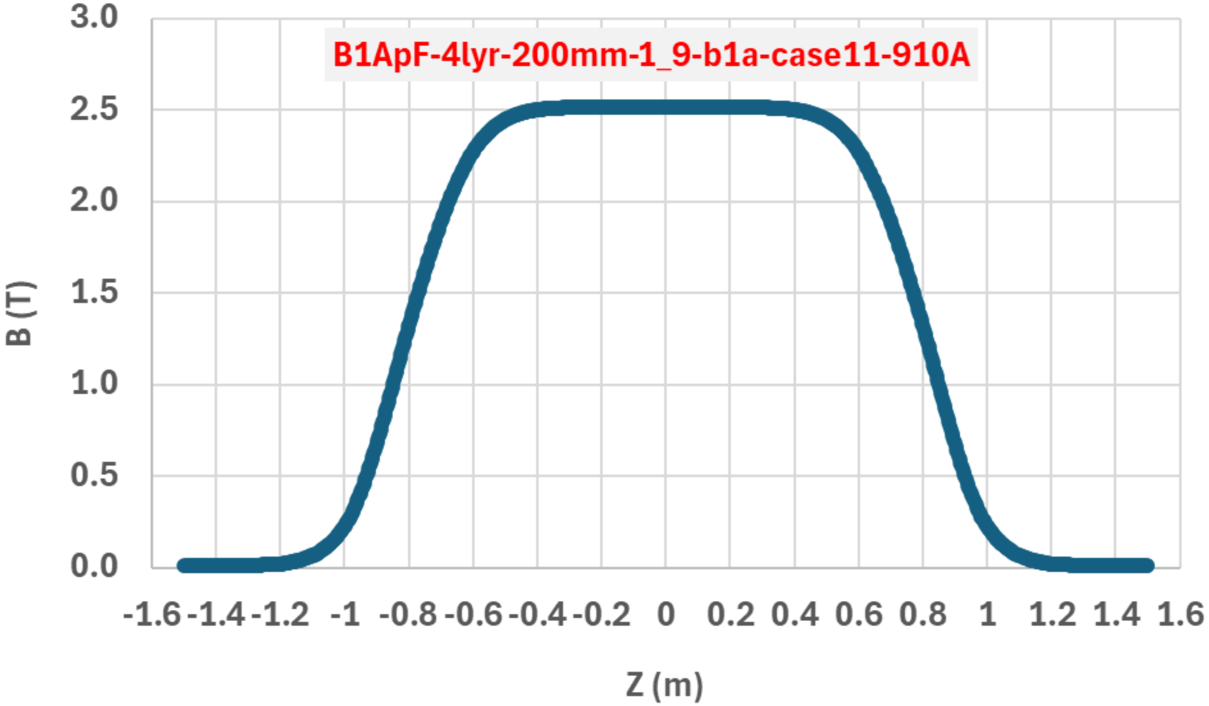
EIC B1pF/B1ApF Colard Magnets PDR – November 20th & 21st, 2024

Courtesy
Mithlesh Kumar

Optimum integral design

A wider flap-top and a lower maximum field

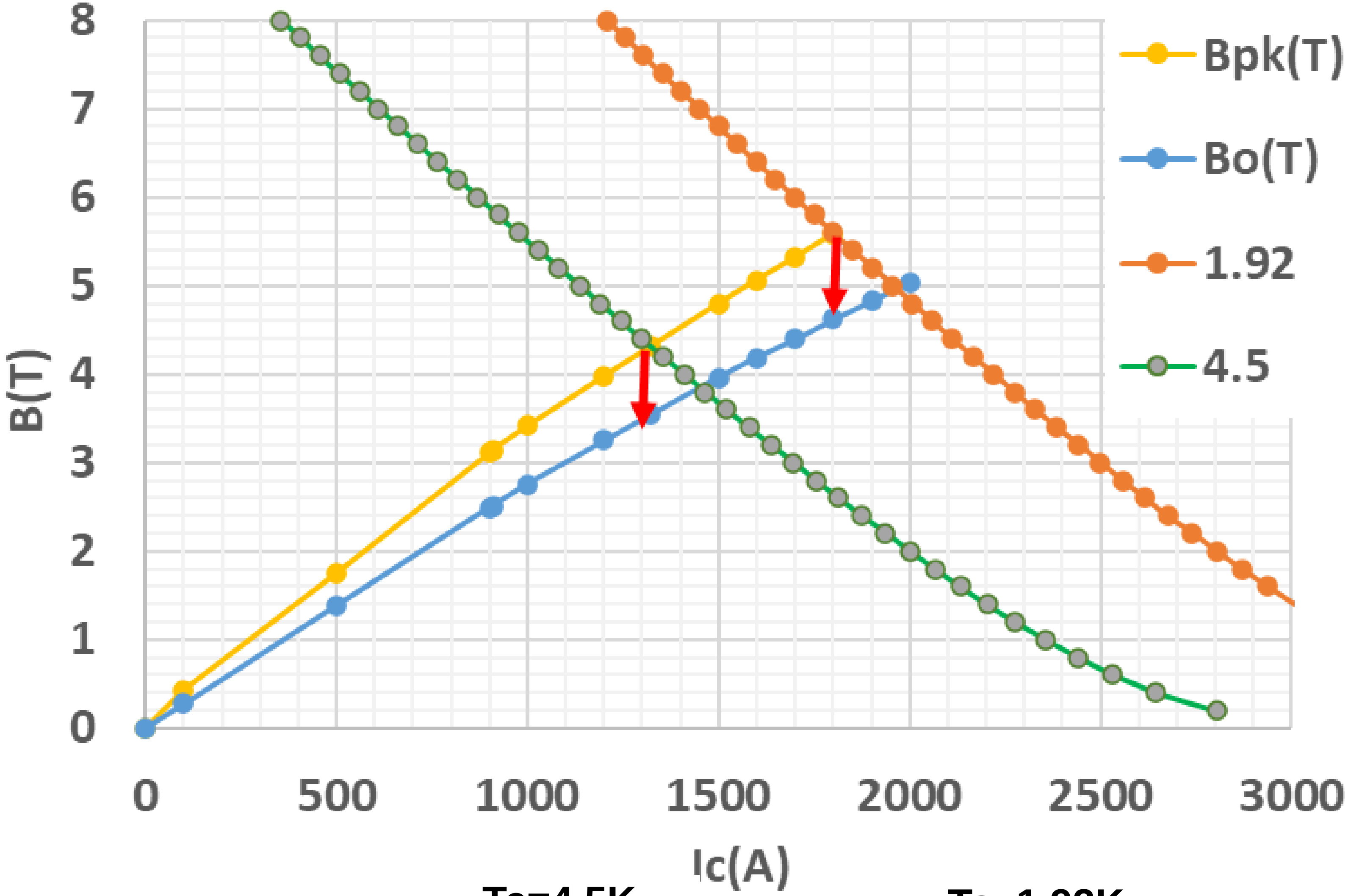


Design integral of 4.05 T.m @910 A
Maximum field at the center: 2.5 T

Stored Energy at design: 0.55 MJ
Inductance: 1.3 Henry

Compare the maximum field and the length of the flat-top

Computed Performance of 4-layer Direct Wind Optimum Integral Dipole



Design Current
910 A for 4.05 T.m

Load line Margin

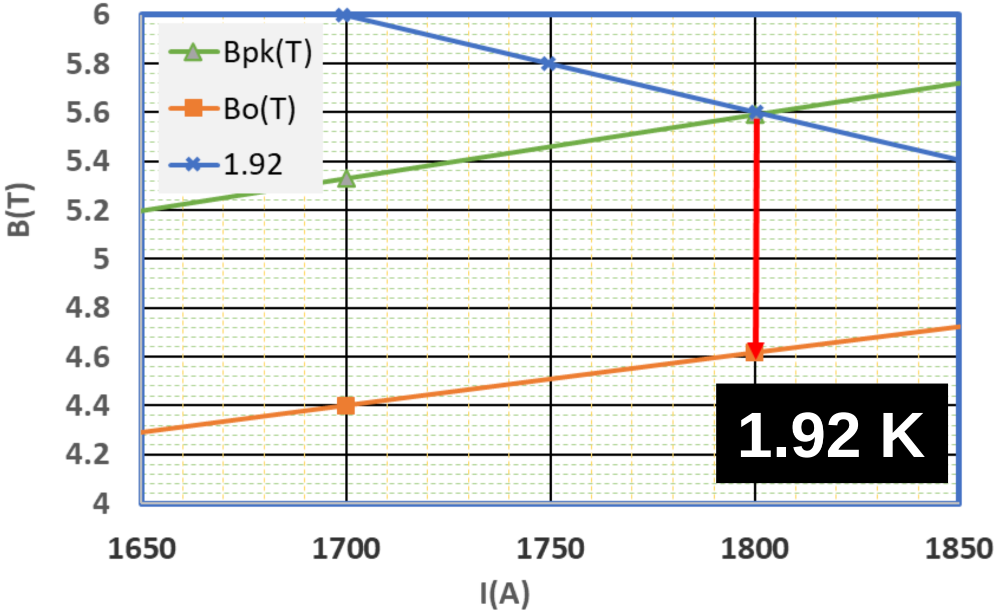
49%@1.92K

31%@4.5K

Tc=4.5K
Iss=1320 A
Bss=3.54 T
Bpk=4.31 T

Tc=1.92K
Iss=1800 A
Bss=4.62 T
Bpk=5.59T

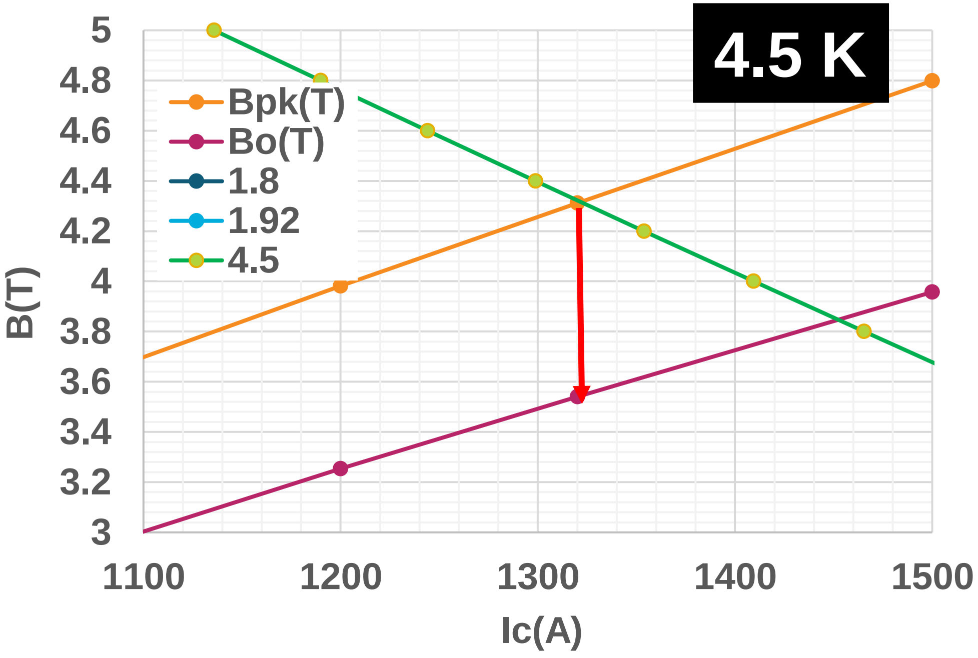
Computed Performance of 4-layer Direct Wind Optimum Integral Dipole



Since the margin is so large @1.92K, one can consider reducing the length, and operate at a higher current for the same field integral

Design Current
910 A for 4.05 T.m

Load line Margin
49%@1.92K
31%@4.5K



Because of the healthy margin @4.5K, one can validate the design or operate @4.5K

Computed Parameters of Optimum Integral B1ApF Dipole (4 layers)

Bint(T.m)	Iwire(A)	Bo(T)	Bpk(T)	B/I*1000	Bpk/Bo	Leff(m)
	0	0	0			
0.447	100	0.278	0.426	2.775	1.535	1.609
2.233	500	1.388	1.758	2.775	1.267	1.609
4.007	900	2.488	3.111	2.764	1.250	1.611
4.050	**910**	**2.515**	**3.142**	**2.764**	**1.249**	**1.610**
4.435	1000	2.753	3.414	2.753	1.240	1.611
5.254	1200	3.254	3.982	2.712	1.224	1.615
5.726	1320	3.540	4.312	2.682	1.218	1.618
6.412	1500	3.957	4.799	2.638	1.213	1.620
6.782	1600	4.181	5.065	2.613	1.211	1.622
7.145	1700	4.401	5.329	2.589	1.211	1.623
7.500	1800	4.617	5.590	2.565	1.211	1.624
7.848	1900	4.828	5.848	2.541	1.211	1.626
8.188	2000	5.035	6.104	2.518	1.212	1.626

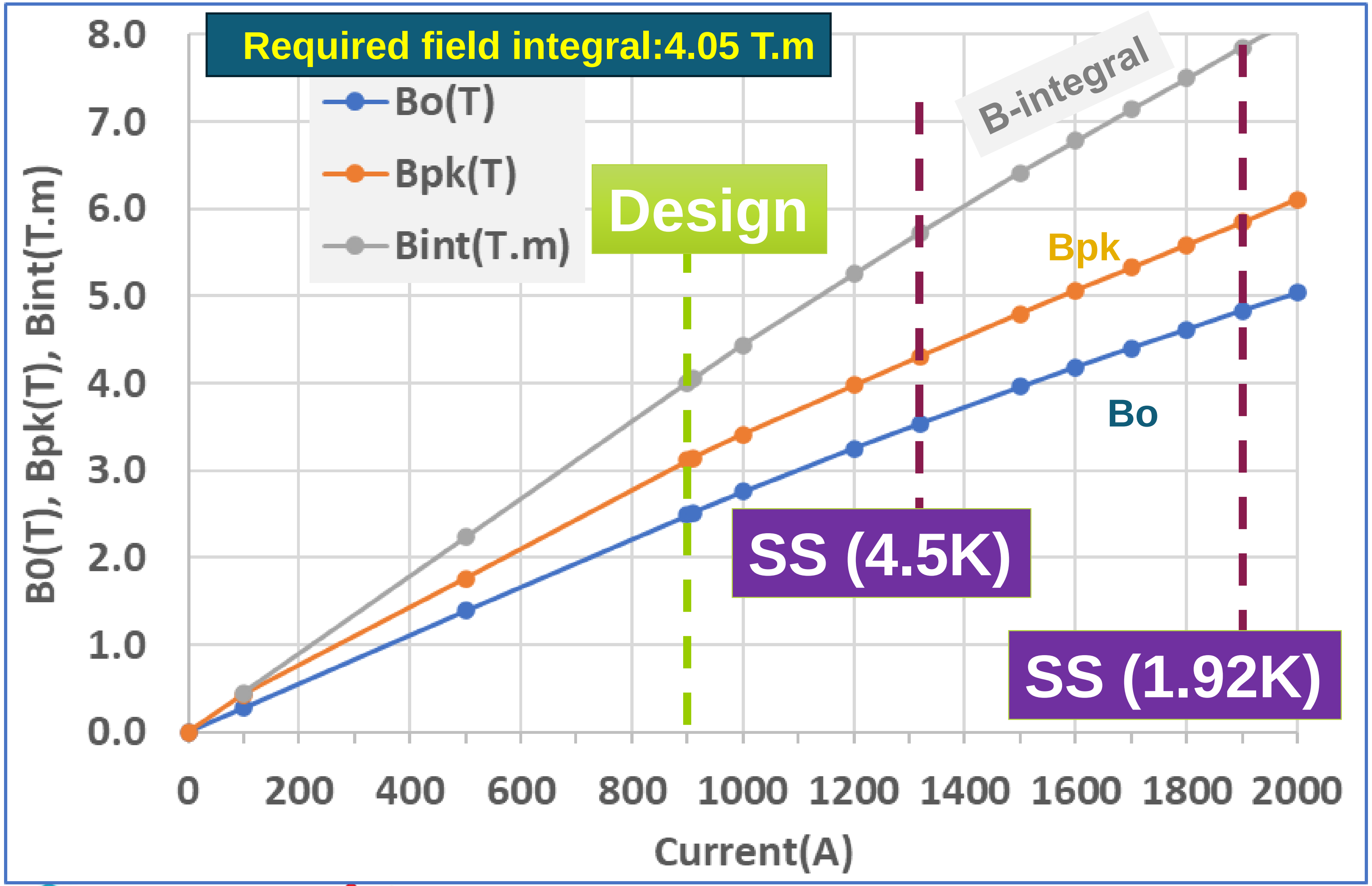
Design @910A

Short Sample@4.5K

Short Sample@1.92K

- Required integral gradient: 4.05 T.meter

Direct Wind Optimum Integral Dipole Option for B1ApF
(a healthy margin even at 4.5 K with just four layers of Type I)



Design Current
910 A for 4.05 T.m

Load line Margin

49%@1.92K

31%@4.5K

Sanity Check – Is It Too Good to be True?

As such the optimum integral design has been verified for B0ApF during the PBL/BNL STTR. However, let's do a sanity check of this design for B1ApF.

Compare the Amp-turns required for 1 Tesla central field

a)	cable magnet coil:	301,422 Amp.turns
b)	optimum integral coil:	331,813 Amp.turns

✓ It is reassuring that the two are within 10% of each-other

➢ A 10% difference is understandable since the two design are optimized with different criterion.

Intermediate Wrap-up of the Direct Wind Optimum Integral Option

- **A 4-layer direct wind optimum integral design for B1ApF will be much cheaper, and faster to design, built and test than the current B1ApF based on the Rutherford cable.**
- **Given that in the PBL/BNL STTR Phase I, a 2-layer direct-wind, optimum integral dipole was designed, built and tested in essentially six months, test results of a 4-layer B1ApF optimum integral dipole should be available in ~1 year and in ~1M$ (?).**
- **The central field in this design is significantly less than that in the cable magnet (~2.5 T as compared to ~4 T). This means lower Lorentz forces which implies that it's a technically less demanding design. Moreover, 2.5 T field seems to be in a comfortable zone for the direct wind technology, specially given a huge large margin in the design.**
- **A proof-of-principle dipole can be tested in the vertical dewar to full design field at 4 K with a yoke inner radius of ~220 mm and the outer radius to fit the Dewar.**
- **My recommendation will be that we further examine this option without any delay and start working to demonstrate, after appropriate necessary reviews.**
- **This is a prime example of "*value engineering*" that EIC should be proud to advertise!**

Motivation for looking at the other options:

This 4-layer design has too much margin (49% on load line, 92% over the operating), a better optimization is in order.

> Alternate #1: A 2-layer design (instead of 4) with Type I wire

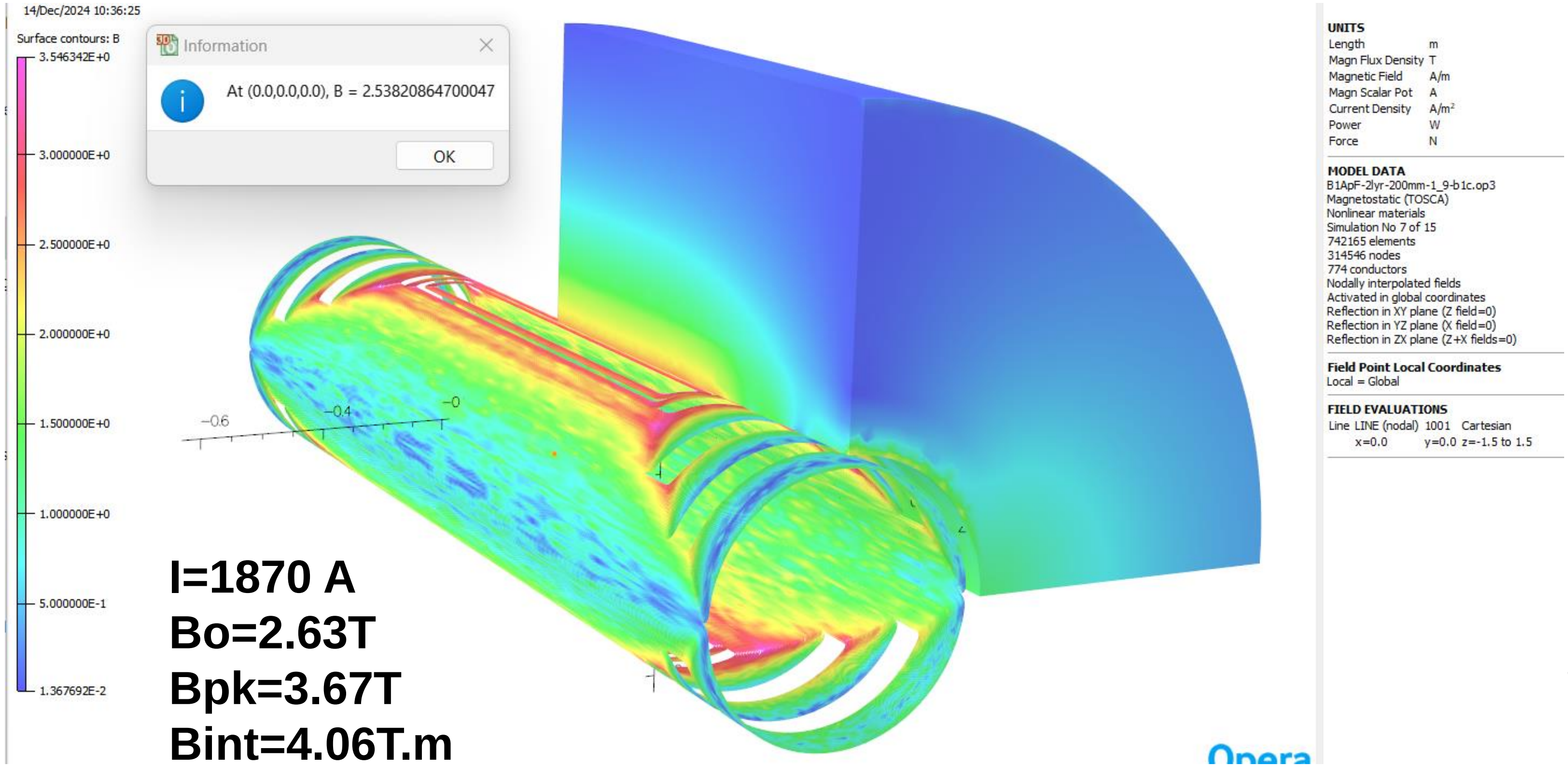
> Alternate #2: A 4-layer design with smaller wire (Type II)

Not examined: A 3-layer design with Type I wire

Alternate Option 1

A 2-layer design (only one double layer)

Initial Investigation of the Optimum Integral Dipole B1ApF (Direct wind, 2 layers or 1 double-layer, 1.92 K Operation)



At (0.0,0.0,0.0), B = 2.53820864700047

UNITS

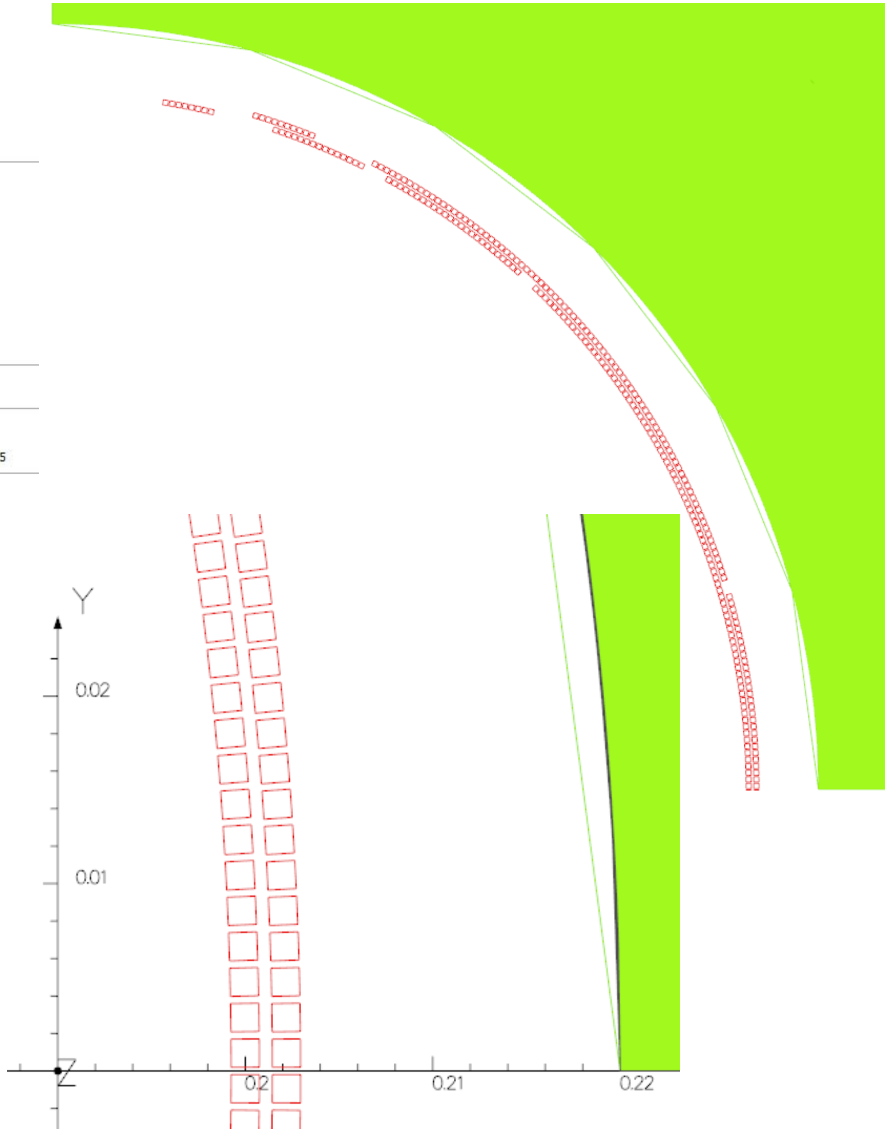
Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m^2
Power	W
Force	N

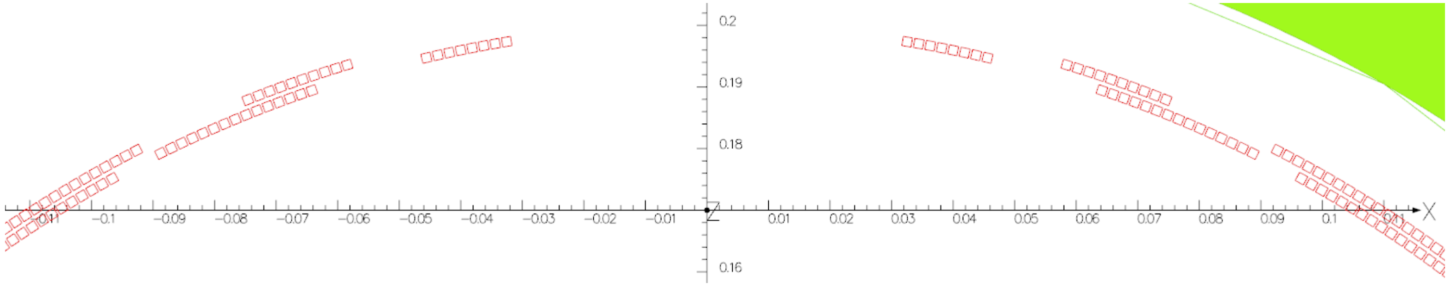
MODEL DATA
B1ApF-2lyr-200mm-1_9-b1c.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 7 of 15
742165 elements
314546 nodes
774 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in YZ plane (X field=0)
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates
Local = Global

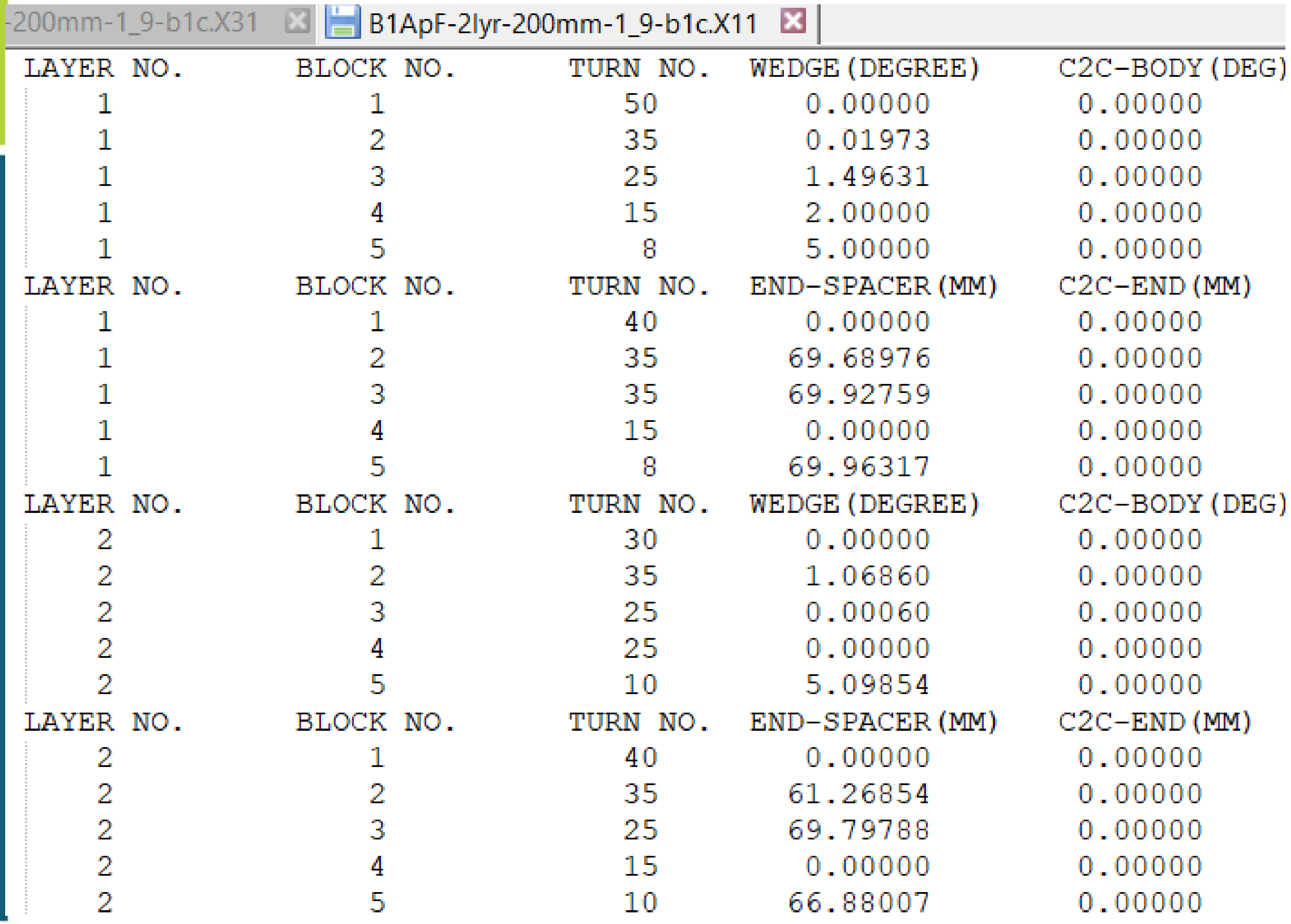
FIELD EVALUATIONS
Line LINE (nodal) 1001 Cartesian
x=0.0 y=0.0 z=-1.5 to 1.5

I=1870 A
Bo=2.63T
Bpk=3.67T
Bint=4.06T.m



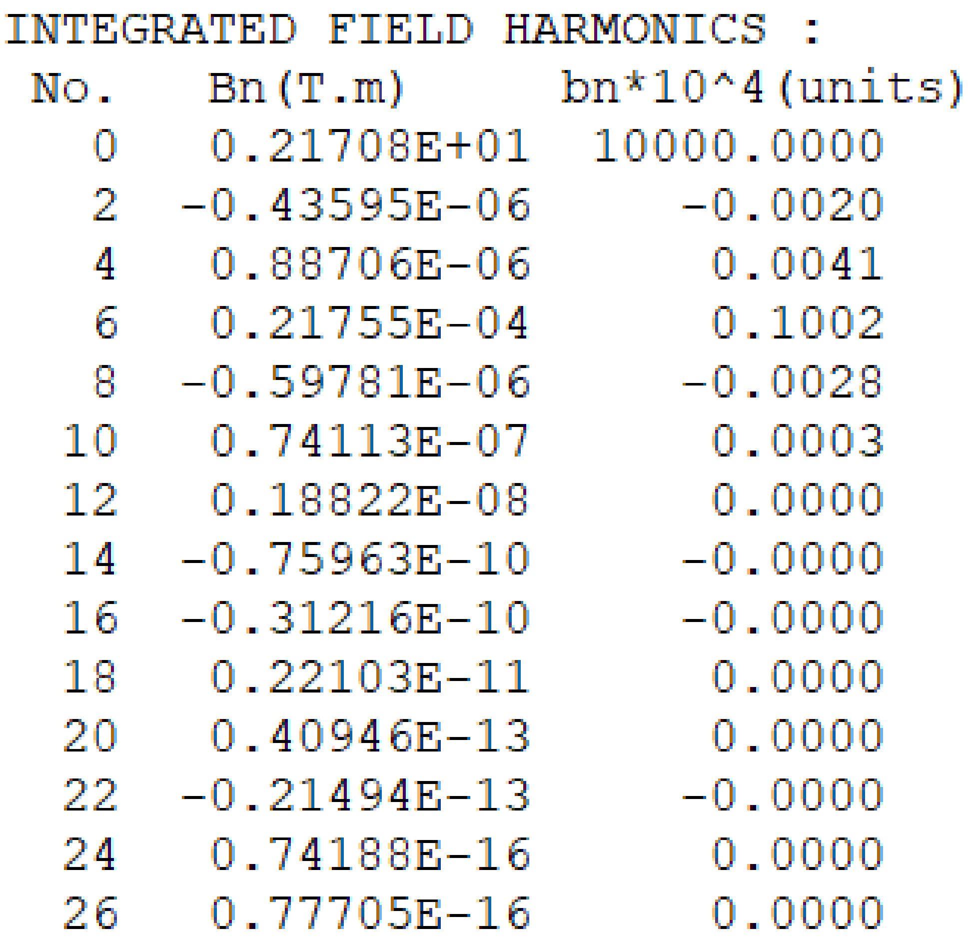


2-layer design Optimized with the Optimum Integral Code



```
LAYER NO.        BLOCK NO.        TURN NO.  WEDGE(DEGREE)      C2C-BODY(DEG)
    1                1               50       0.00000             0.00000
    1                2               35       0.01973             0.00000
    1                3               25       1.49631             0.00000
    1                4               15       2.00000             0.00000
    1                5                8       5.00000             0.00000
LAYER NO.        BLOCK NO.        TURN NO.  END-SPACER(MM)     C2C-END(MM)
    1                1               40       0.00000             0.00000
    1                2               35      69.68976             0.00000
    1                3               35      69.92759             0.00000
    1                4               15       0.00000             0.00000
    1                5                8      69.96317             0.00000
LAYER NO.        BLOCK NO.        TURN NO.  WEDGE(DEGREE)      C2C-BODY(DEG)
    2                1               30       0.00000             0.00000
    2                2               35       1.06860             0.00000
    2                3               25       0.00060             0.00000
    2                4               25       0.00000             0.00000
    2                5               10       5.09854             0.00000
LAYER NO.        BLOCK NO.        TURN NO.  END-SPACER(MM)     C2C-END(MM)
    2                1               40       0.00000             0.00000
    2                2               35      61.26854             0.00000
    2                3               25      69.79788             0.00000
    2                4               15       0.00000             0.00000
    2                5               10      66.88007             0.00000
```

Computed harmonics @55 mm (good field quality in coil geometry) low harmonic contents:

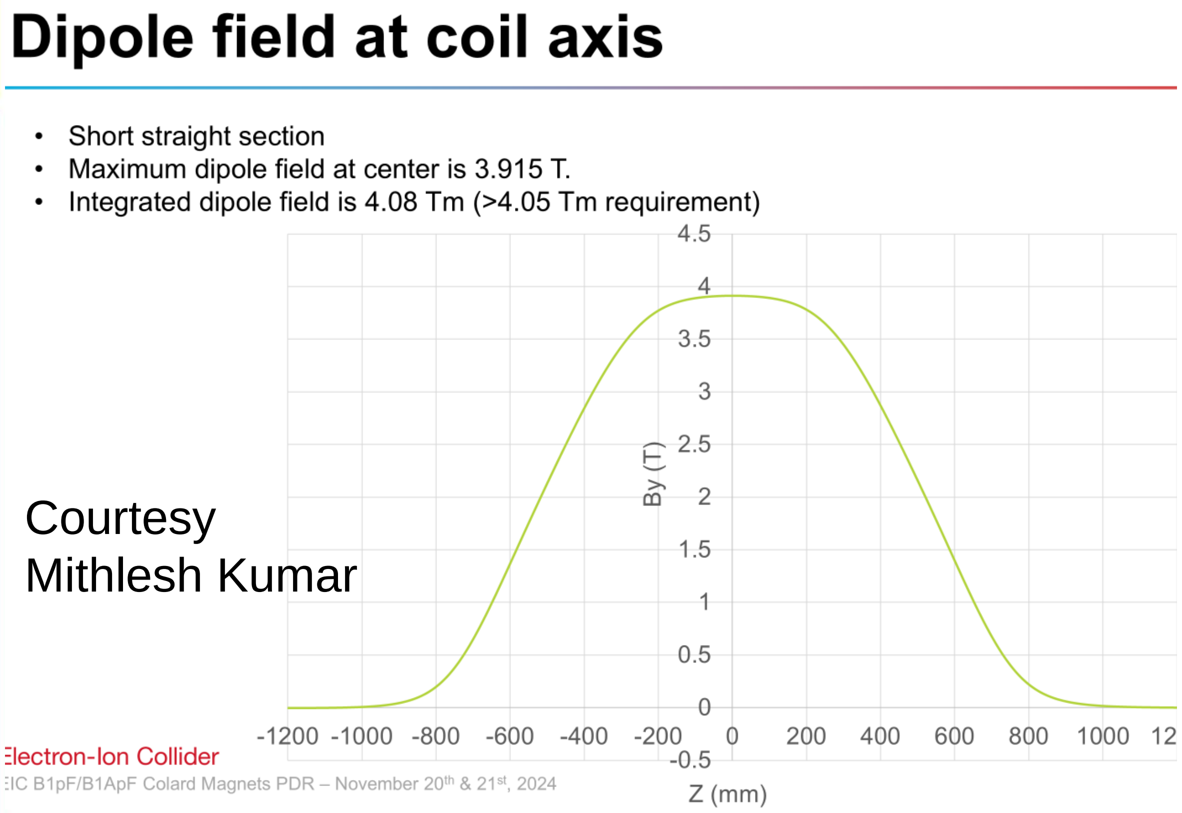


```
INTEGRATED FIELD HARMONICS :
 No.      Bn(T.m)        bn*10^4(units)
   0    0.21708E+01    10000.0000
   2   -0.43595E-06       -0.0020
   4    0.88706E-06        0.0041
   6    0.21755E-04        0.1002
   8   -0.59781E-06       -0.0028
  10    0.74113E-07        0.0003
  12    0.18822E-08        0.0000
  14   -0.75963E-10       -0.0000
  16   -0.31216E-10       -0.0000
  18    0.22103E-11        0.0000
  20    0.40946E-13        0.0000
  22   -0.21494E-13       -0.0000
  24    0.74188E-16        0.0000
  26    0.77705E-16        0.0000
```

Number of turns: 258

Comparison of the Field Along the Axis for the Required Field Integral

Cable magnet design



Dipole field at coil axis

- Short straight section
- Maximum dipole field at center is 3.915 T.
- Integrated dipole field is 4.08 Tm (>4.05 Tm requirement)

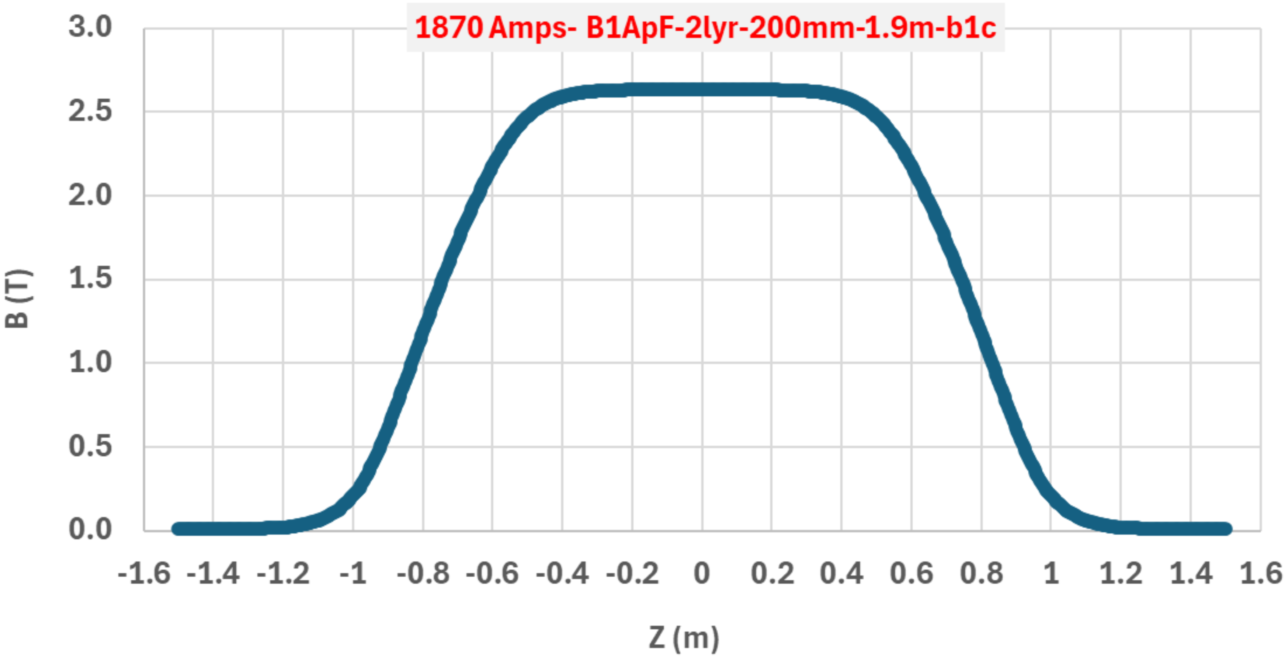
lectron-Ion Collider

IC B1pF/B1ApF Colard Magnets PDR – November 20th & 21st, 2024

Courtesy
Mithlesh Kumar

Two-layer Optimum integral design

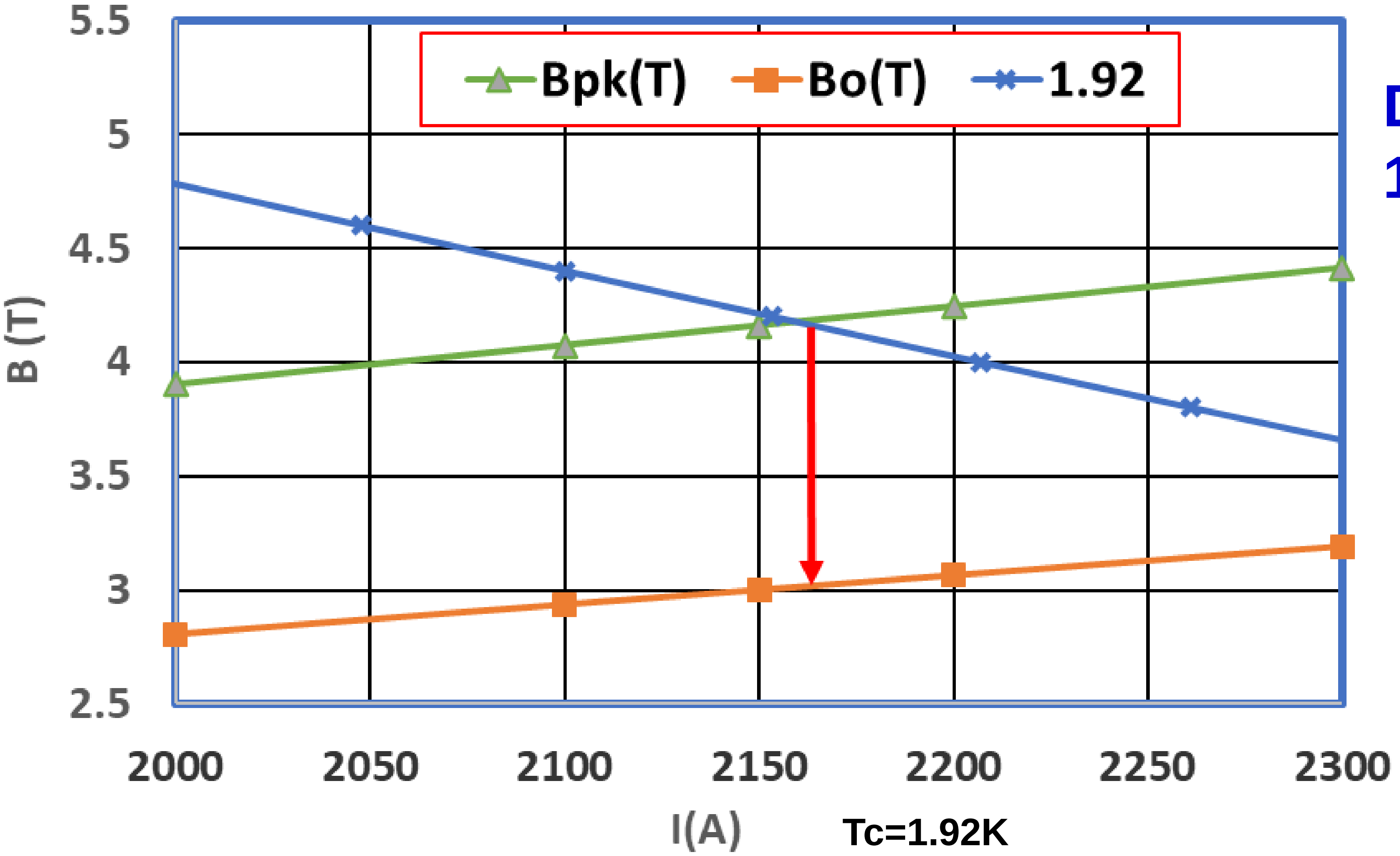
A wider flap-top and a lower maximum field



Design integral of 4.05 T.m @1870 A
Maximum field at the center: 2.5 T

Stored Energy at design: 0.56 MJ
Inductance: 0.32 Henry

Computed Quench Performance at 1.92 K of 2-layer Design



Tc=1.92K
Iss=2160 A
Bss=3.01 T
Bpk=4.17T

Design Current
1870 A for 4.06 T.m

Load line Margin
13%@1.92K

16% margin over the design field

The design could perhaps be optimized more to gain 5% or so. And that may be ok, if past good performance of direct wind technology is repeated. But this may be cutting a bit too close.

Computed Parameters of Optimum Integral B1ApF Dipole (2-layer design operating@1.92K)

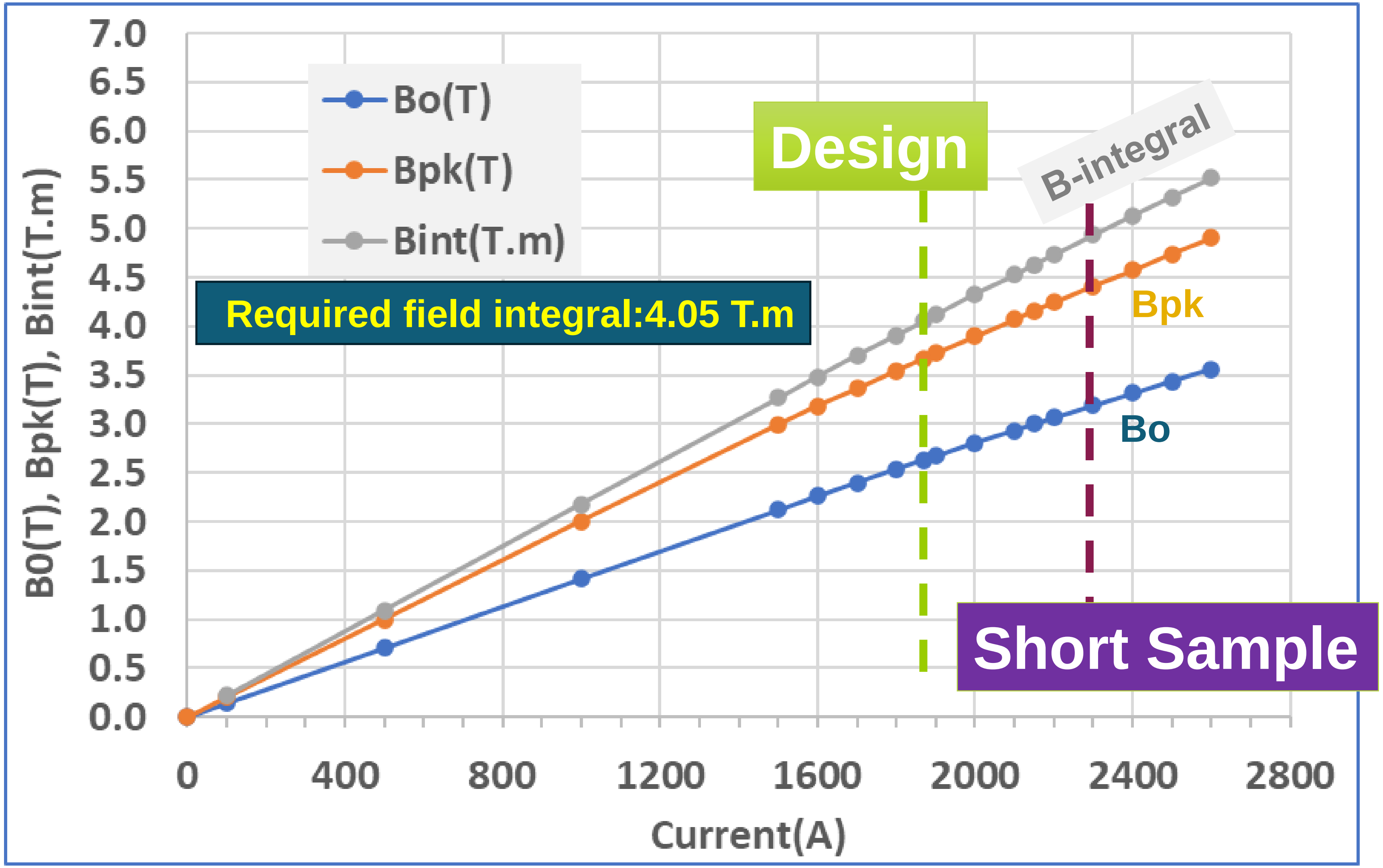
Bint(T.m)	Iwire(A)	Bo(T)	Bpk(T)	B/I*1000	Bpk/Bo	Leff(m)
	0	0	0			
0.218	100	0.142	0.200	1.416	1.414	1.540
1.091	500	0.708	1.001	1.416	1.413	1.540
2.181	1000	1.416	2.002	1.416	1.414	1.540
3.269	1500	2.123	2.993	1.415	1.410	1.540
3.485	1600	2.263	3.182	1.414	1.406	1.540
3.699	1700	2.401	3.365	1.412	1.402	1.541
3.911	1800	2.538	3.546	1.410	1.397	1.541
4.058	**1870**	**2.633**	**3.672**	**1.408**	**1.395**	**1.541**
4.121	1900	2.673	3.725	1.407	1.394	1.542
4.328	2000	2.806	3.901	1.403	1.390	1.542
4.532	2100	2.936	4.073	1.398	1.387	1.544
4.634	**2150**	**3.000**	**4.159**	**1.395**	**1.386**	**1.545**
4.734	2200	3.064	4.243	1.393	1.385	1.545
4.934	2300	3.191	4.412	1.387	1.383	1.546
5.131	2400	3.315	4.578	1.381	1.381	1.548
5.326	2500	3.438	4.743	5.326	1.380	1.549
5.519	2600	3.560	4.907	1.369	1.378	1.550

Design @1870A

Short Sample 2150

- Required integral gradient: 4.05 T.meter

A More Positive Look at the Optimum Integral Direct Wind Option
(just two layers of Type I wire sufficient for 1.92 K operation)



Design Current
1870 A for 4.06 T.m

Load line Margin
13%@1.92K

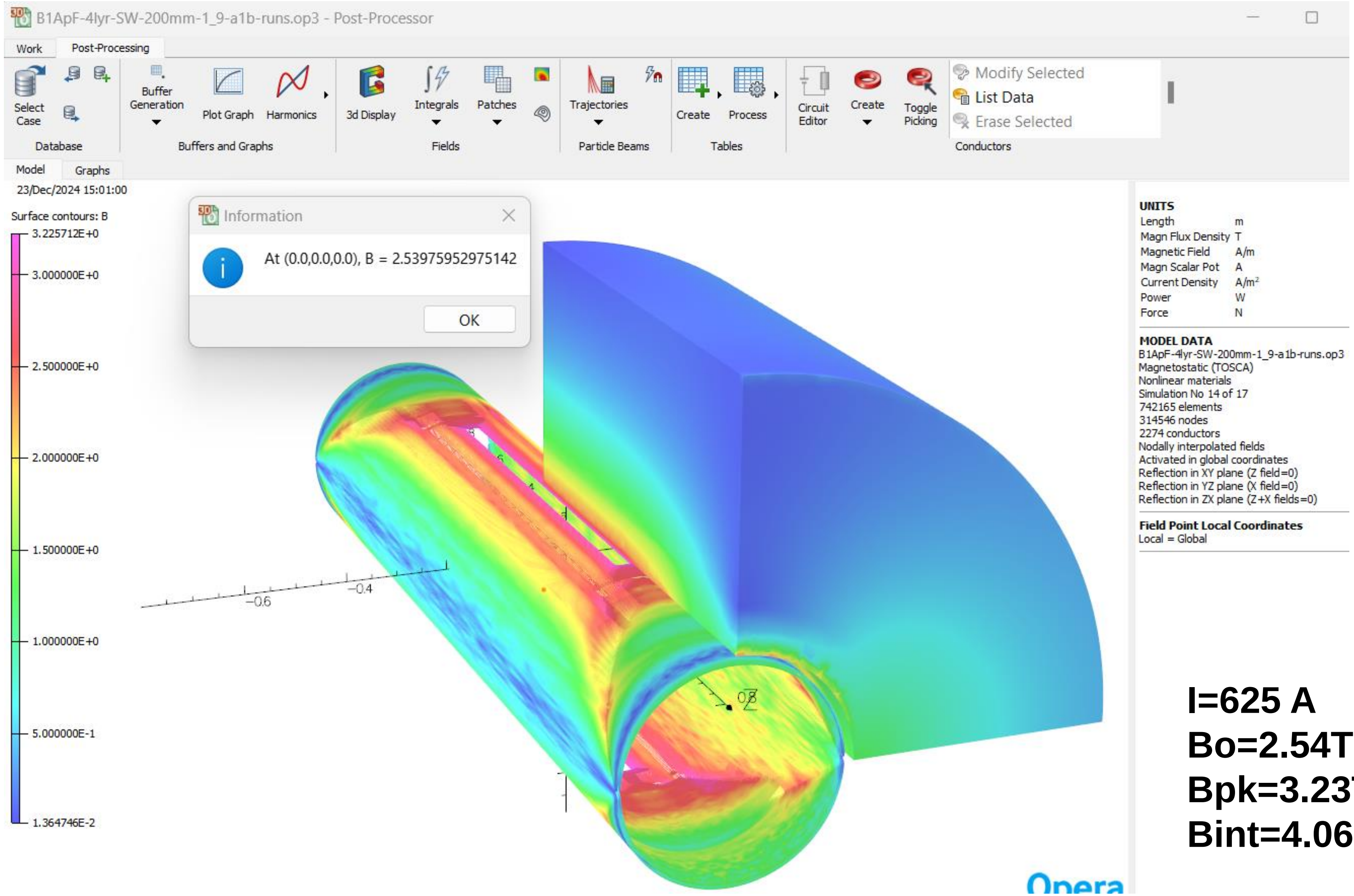
16% margin over the design field

This may be a bit too tight!

Alternate Option 2

A 4-layer design, but with (smaller) Type II wire

Initial Investigation of the Optimum Integral Dipole B1ApF (Direct wind, 4 layers or 2 double-layer, Type II Wire Option)



23/Dec/2024 15:01:00

Surface contours: B

At (0.0,0.0,0.0), B = 2.53975952975142

UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m^2
Power	W
Force	N

MODEL DATA

B1ApF-4lyr-SW-200mm-1_9-a1b-runs.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 14 of 17
742165 elements
314546 nodes
2274 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in YZ plane (X field=0)
Reflection in ZX plane (Z+X fields=0)

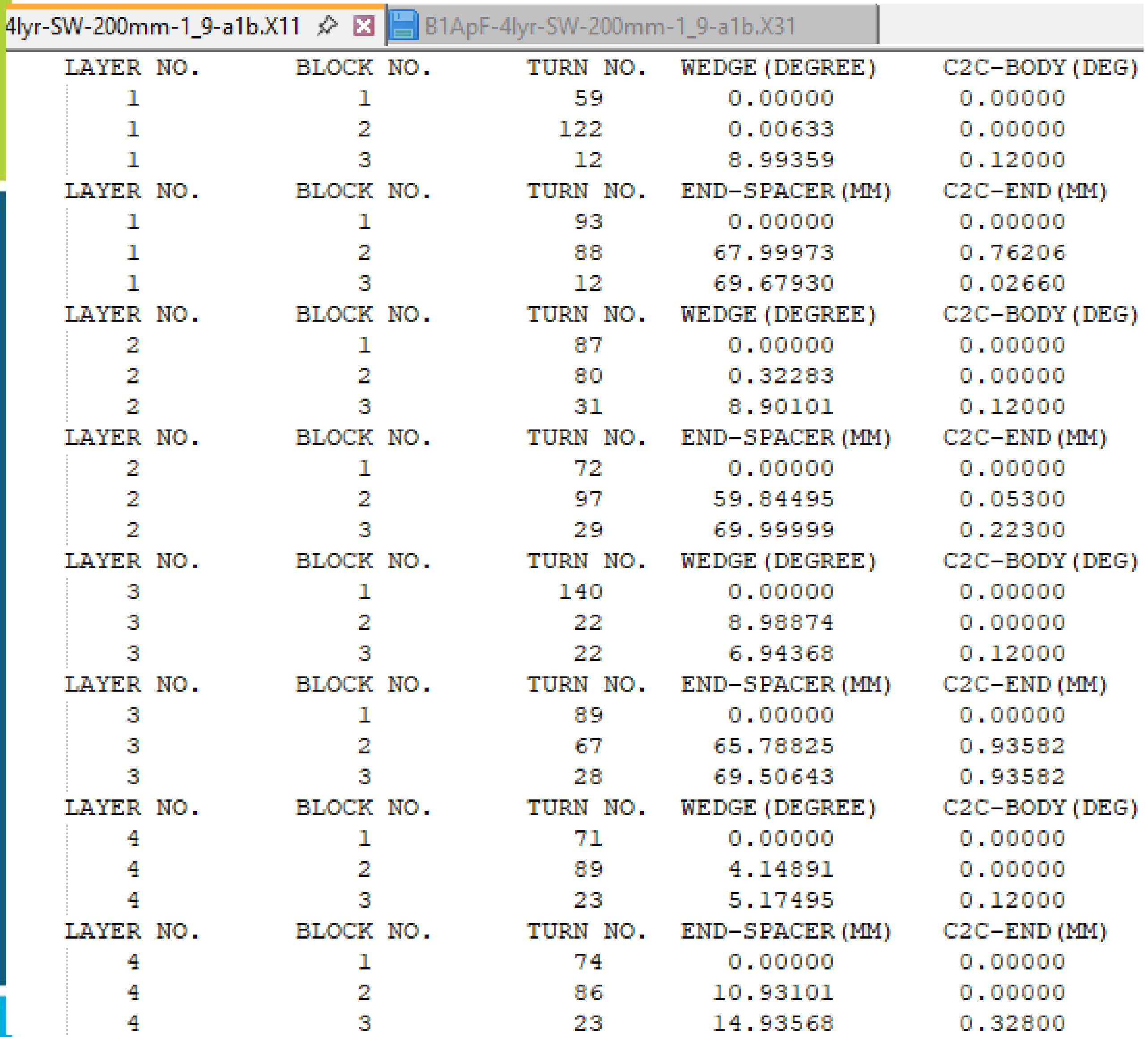
Field Point Local Coordinates

Local = Global

Type II wire is smaller

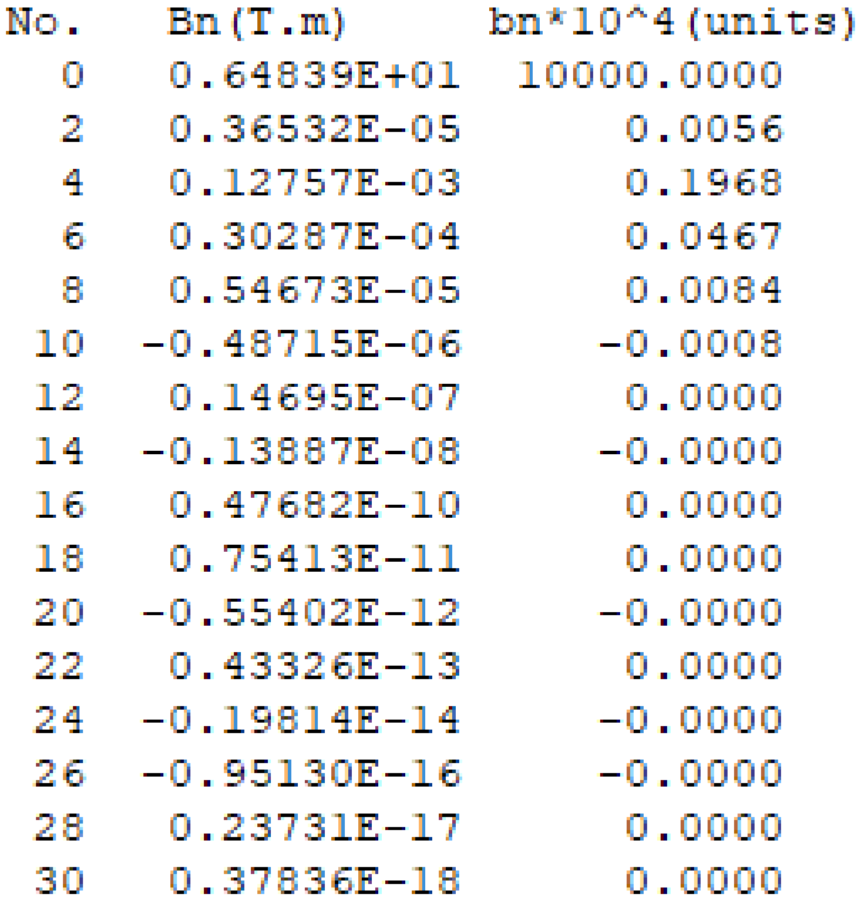
I=625 A
Bo=2.54T
Bpk=3.23T
Bint=4.06T.m

4-layer Type II Wire Design Optimized with the Optimum Integral Code



```
LAYER NO.    BLOCK NO.    TURN NO.  WEDGE(DEGREE)    C2C-BODY(DEG)
    1            1           59       0.00000          0.00000
    1            2          122       0.00633          0.00000
    1            3           12       8.99359          0.12000
LAYER NO.    BLOCK NO.    TURN NO.  END-SPACER(MM)   C2C-END(MM)
    1            1           93       0.00000          0.00000
    1            2           88      67.99973          0.76206
    1            3           12      69.67930          0.02660
LAYER NO.    BLOCK NO.    TURN NO.  WEDGE(DEGREE)    C2C-BODY(DEG)
    2            1           87       0.00000          0.00000
    2            2           80       0.32283          0.00000
    2            3           31       8.90101          0.12000
LAYER NO.    BLOCK NO.    TURN NO.  END-SPACER(MM)   C2C-END(MM)
    2            1           72       0.00000          0.00000
    2            2           97      59.84495          0.05300
    2            3           29      69.99999          0.22300
LAYER NO.    BLOCK NO.    TURN NO.  WEDGE(DEGREE)    C2C-BODY(DEG)
    3            1          140       0.00000          0.00000
    3            2           22       8.98874          0.00000
    3            3           22       6.94368          0.12000
LAYER NO.    BLOCK NO.    TURN NO.  END-SPACER(MM)   C2C-END(MM)
    3            1           89       0.00000          0.00000
    3            2           67      65.78825          0.93582
    3            3           28      69.50643          0.93582
LAYER NO.    BLOCK NO.    TURN NO.  WEDGE(DEGREE)    C2C-BODY(DEG)
    4            1           71       0.00000          0.00000
    4            2           89       4.14891          0.00000
    4            3           23       5.17495          0.12000
LAYER NO.    BLOCK NO.    TURN NO.  END-SPACER(MM)   C2C-END(MM)
    4            1           74       0.00000          0.00000
    4            2           86      10.93101          0.00000
    4            3           23      14.93568          0.32800
```

Computed harmonics @55 mm (good field quality in coil geometry) low harmonic contents:

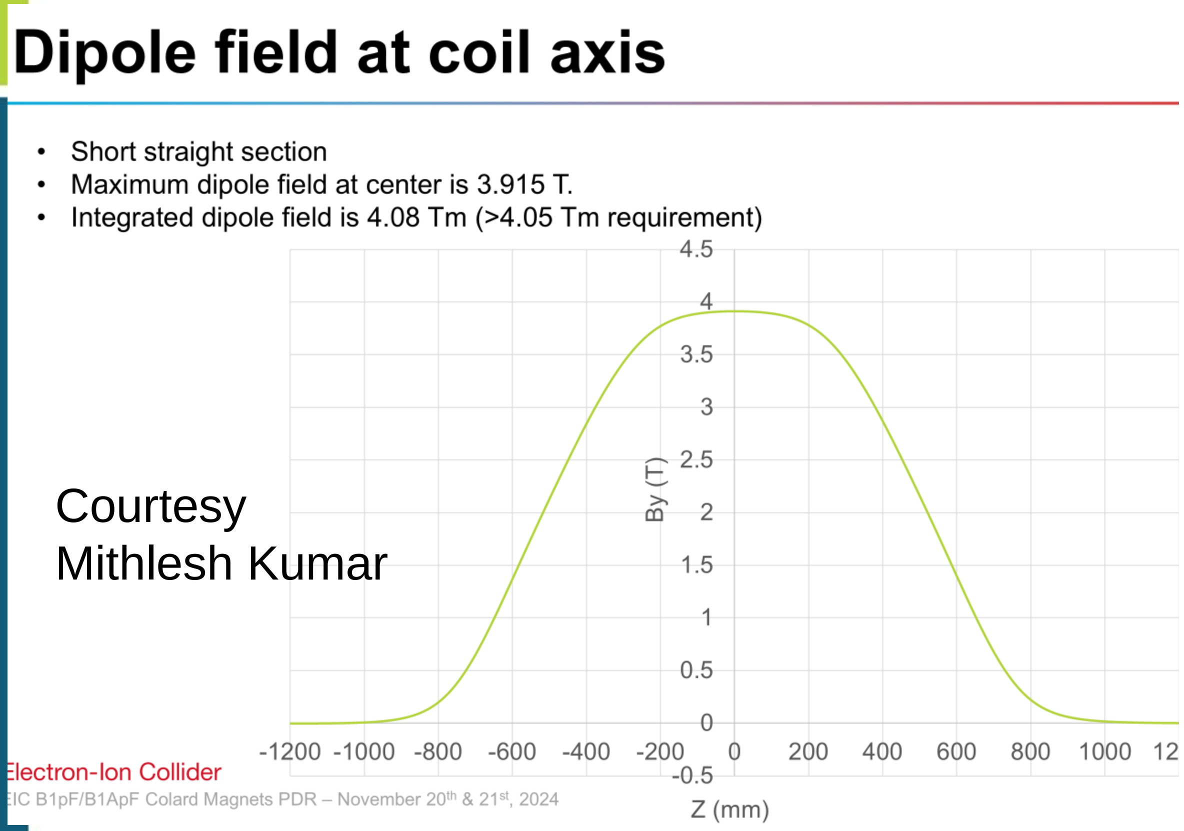


```
No.    Bn(T.m)        bn*10^4(units)
 0    0.64839E+01    10000.0000
 2    0.36532E-05       0.0056
 4    0.12757E-03       0.1968
 6    0.30287E-04       0.0467
 8    0.54673E-05       0.0084
10   -0.48715E-06      -0.0008
12    0.14695E-07       0.0000
14   -0.13887E-08      -0.0000
16    0.47682E-10       0.0000
18    0.75413E-11       0.0000
20   -0.55402E-12      -0.0000
22    0.43326E-13       0.0000
24   -0.19814E-14      -0.0000
26   -0.95130E-16      -0.0000
28    0.23731E-17       0.0000
30    0.37836E-18       0.0000
```

Toal number of turns: 758

Comparison of the Field Along the Axis for the Required Field Integral

Cable magnet design



Dipole field at coil axis

- Short straight section
- Maximum dipole field at center is 3.915 T.
- Integrated dipole field is 4.08 Tm (>4.05 Tm requirement)

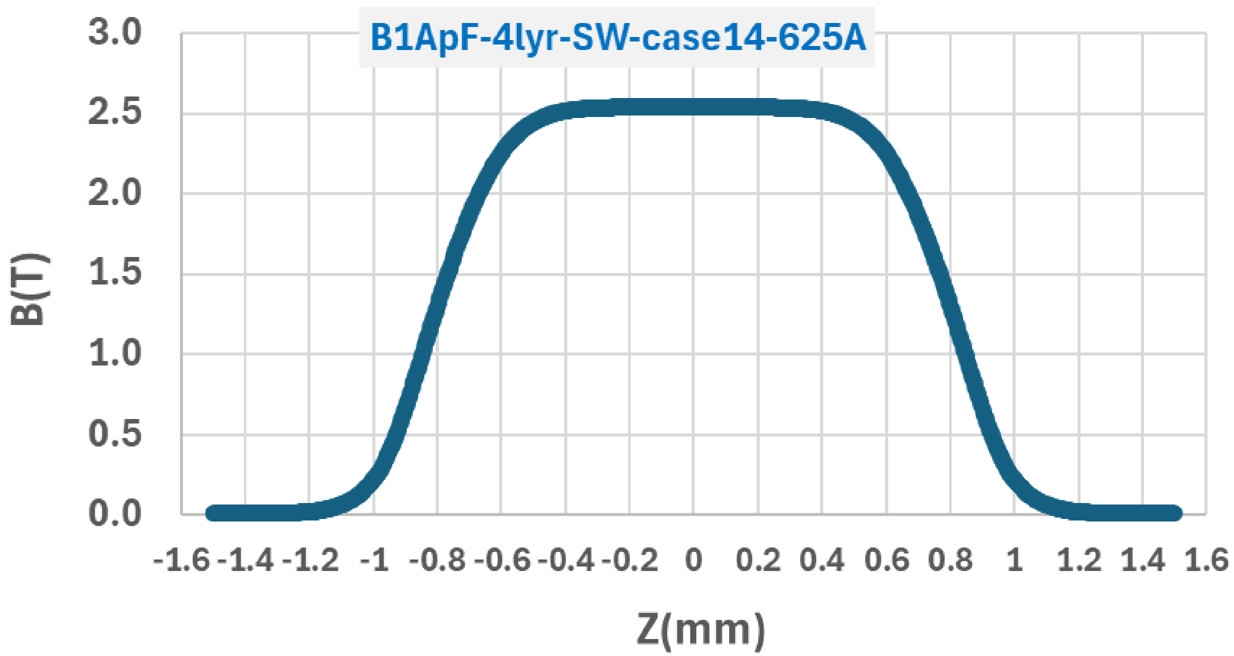
Electron-Ion Collider

EIC B1pF/B1ApF Colard Magnets PDR – November 20th & 21st, 2024

Courtesy
Mithlesh Kumar

Optimum integral design

Four layers with smaller wire at 625 A
A wider flap-top and a lower maximum field

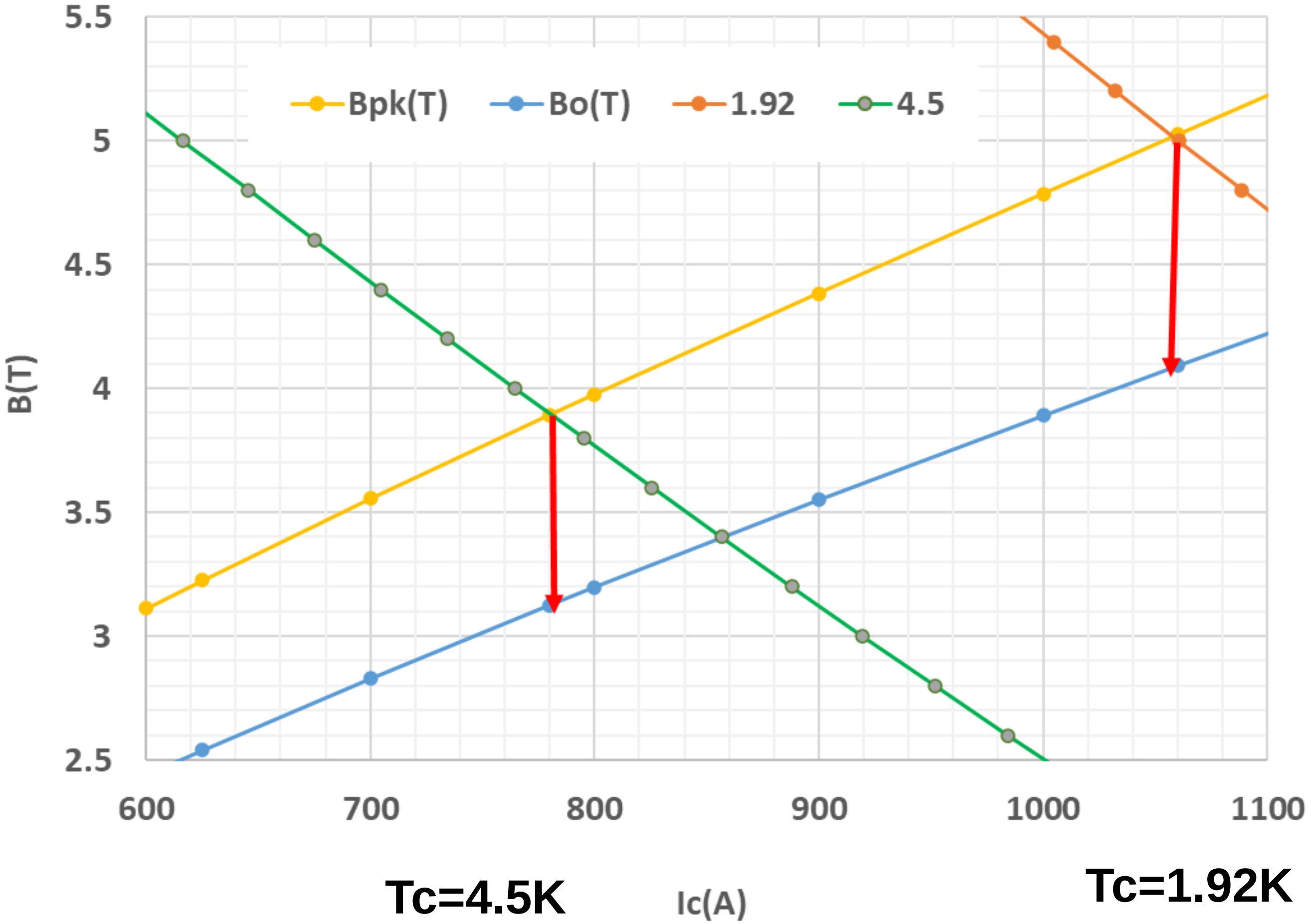


Design integral of 4.05 T.m @625 A
Maximum field at the center: 2.54 T

Stored Energy at design: 0.55 MJ
Inductance: 2.8 Henry

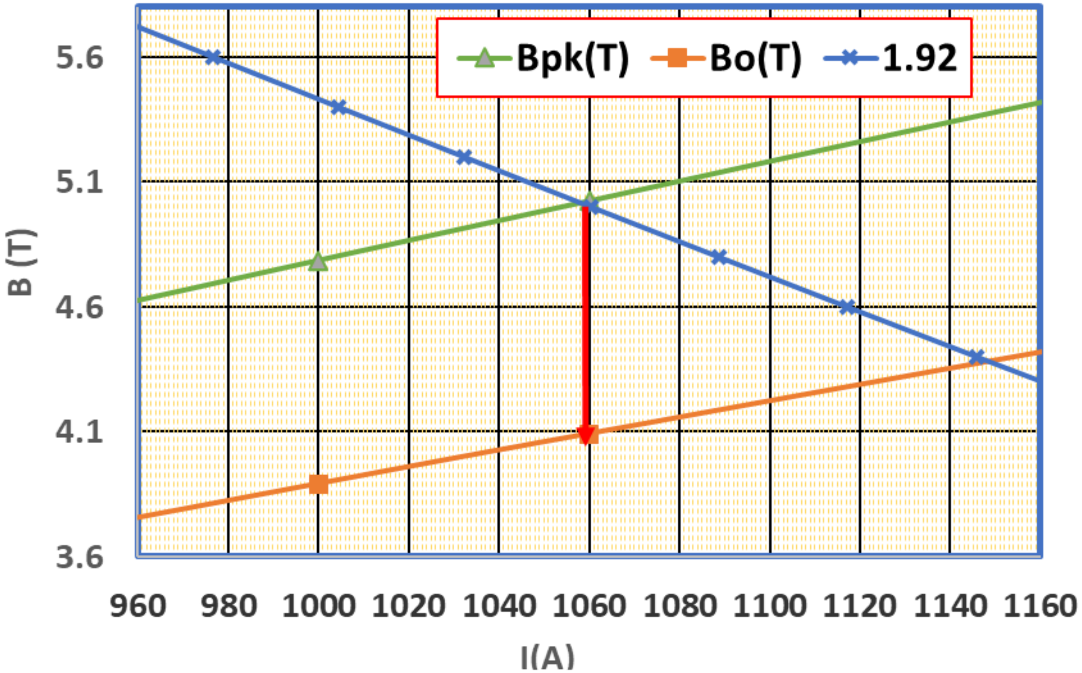
Not surprisingly, the inductance is larger than in other designs, but the current is lower.

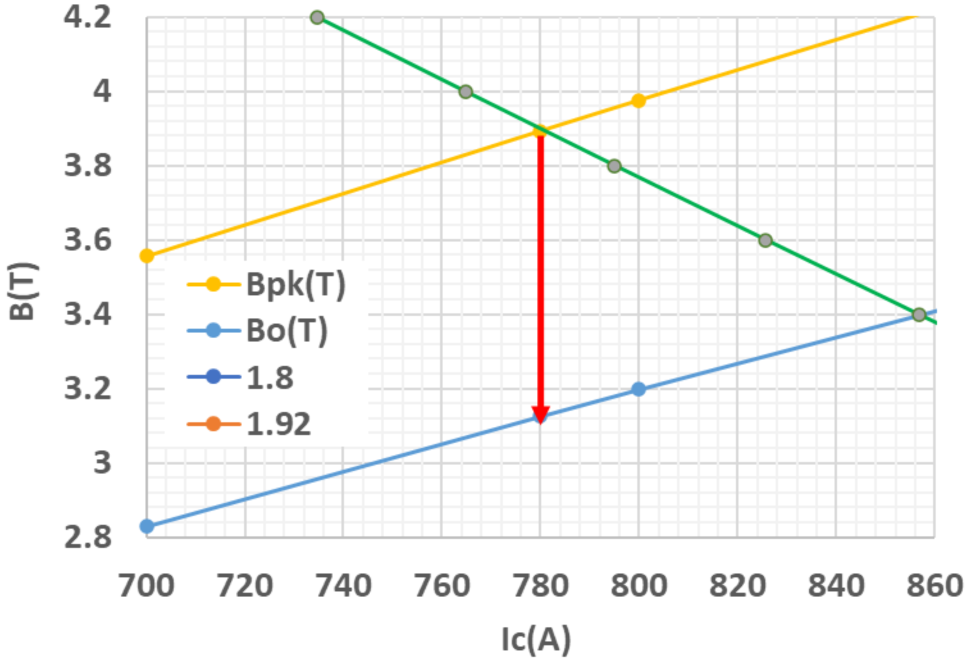
Computed Performance of a Direct-Wind Optimum Integral Dipole Design with four layers Type II Wire



Tc=4.5K
Iss=780 A
Bss=3.12T
Bpk=3.89T

Tc=1.92K
Iss=1060 A
Bss=4.09T
Bpk=5.02T





Computed Parameters of Optimum Integral B1ApF Dipole (4-layer Type II design @1.92K and @ 4.5K)

Bint(T.m)	Iwire(A)	Bo(T)	Bpk(T)	B/I*1000	Bpk/Bo	Leff(m)
	0	0	0			
0.651	100	0.408	0.588	4.082	1.439	1.595
3.255	500	2.040	2.642	4.080	1.295	1.596
3.898	600	2.441	3.112	4.068	1.275	1.597
4.056	**625**	**2.54**	**3.226**	**4.064**	**1.270**	**1.597**
4.522	700	2.829	3.556	4.041	1.257	1.598
5.003	**780**	**3.125**	**3.893**	**4.006**	**1.246**	**1.601**
5.120	800	3.197	3.976	3.996	1.244	1.602
5.697	900	3.550	4.384	3.944	1.235	1.605
6.257	1000	3.892	4.786	3.892	1.230	1.608
6.584	**1060**	**4.092**	**5.024**	**3.860**	**1.228**	**1.609**
7.326	1200	4.545	5.574	3.788	1.226	1.612

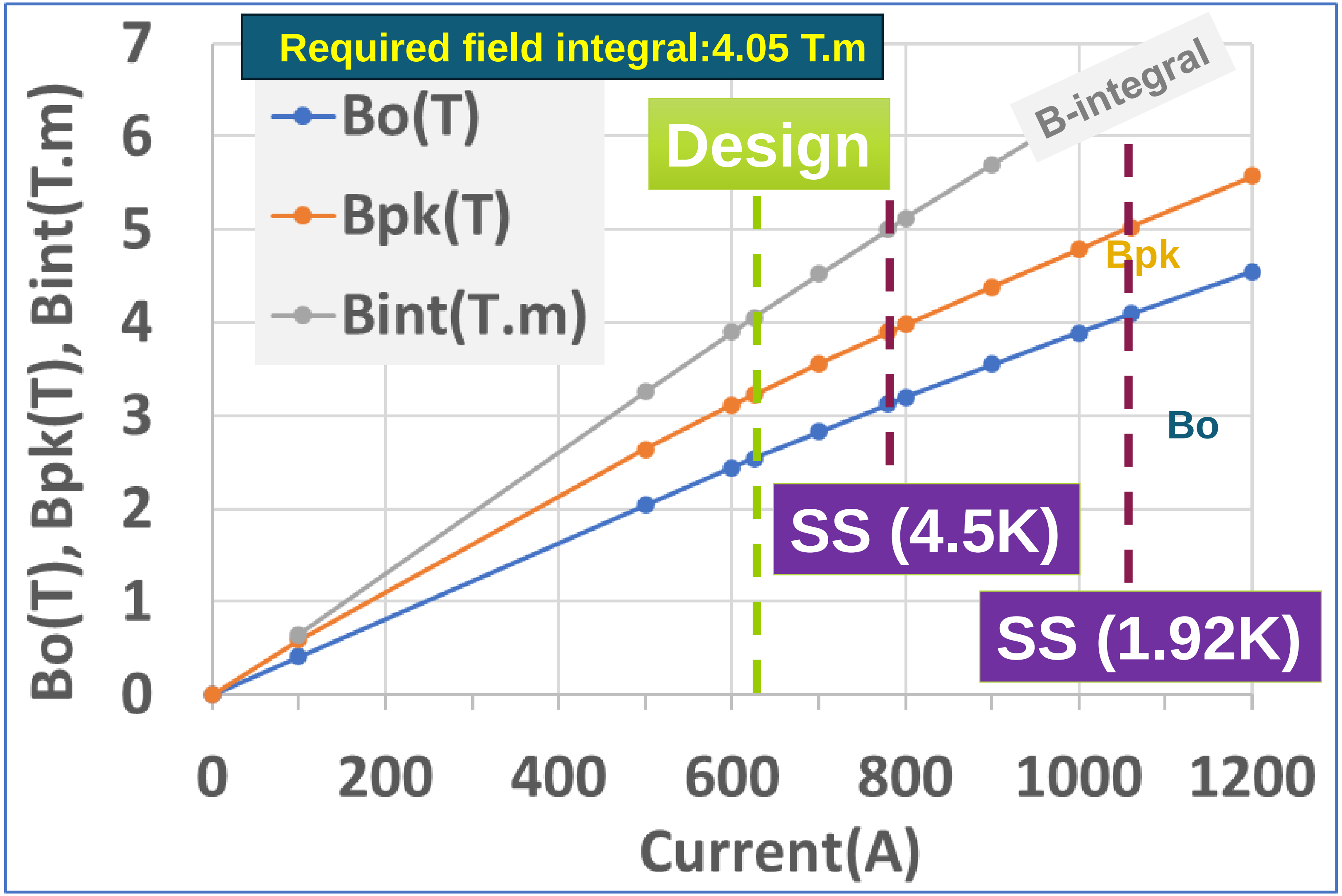
Design @625A

SS(4.5K) @780

SS(1.92K) @1060

- Required integral gradient: 4.05 T.meter

Yet another Option for the Optimum Integral Direct Wind
(a reasonable margin even at 4.5 K with four layers of Type II)



Design Current
625 A for 4.06 T.m

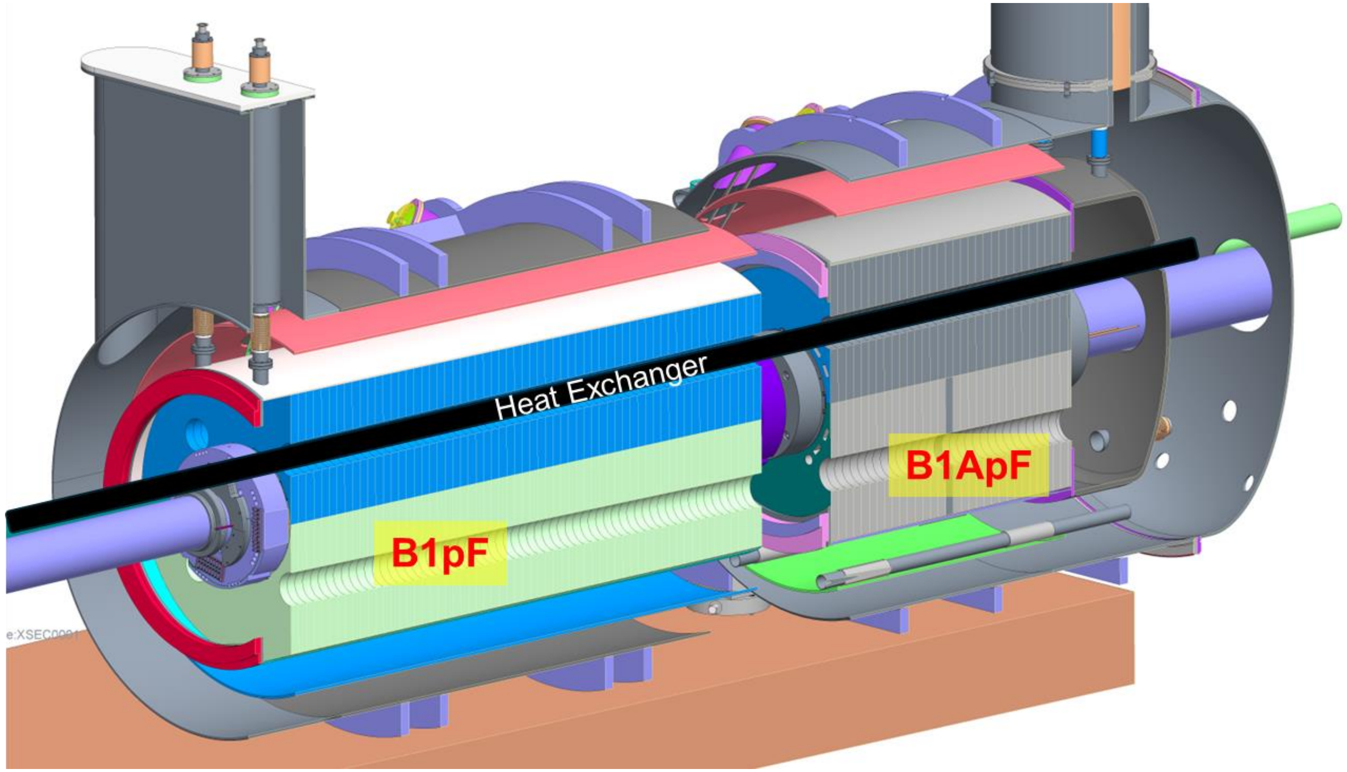
Load line Margin

41%@1.92K

20%@4.5K

A More Enterprising Option

> **Looking beyond just B1ApF**



A More Enterprising Option to Consider

In addition to possibly making B1ApF a direct wind magnet, imagine B1pF as two B1ApF. Then three identical B1ApF will generate the same total integral field (4.05+10.34 ~14.4 T.m); each 14.4/3=4.8 T.m

- Note: I am not suggesting to slow down the B1pF cable magnet program. I suggest consider a direct wind B1ApF option with above parameter (1.75 m long, 4.8 T.m).

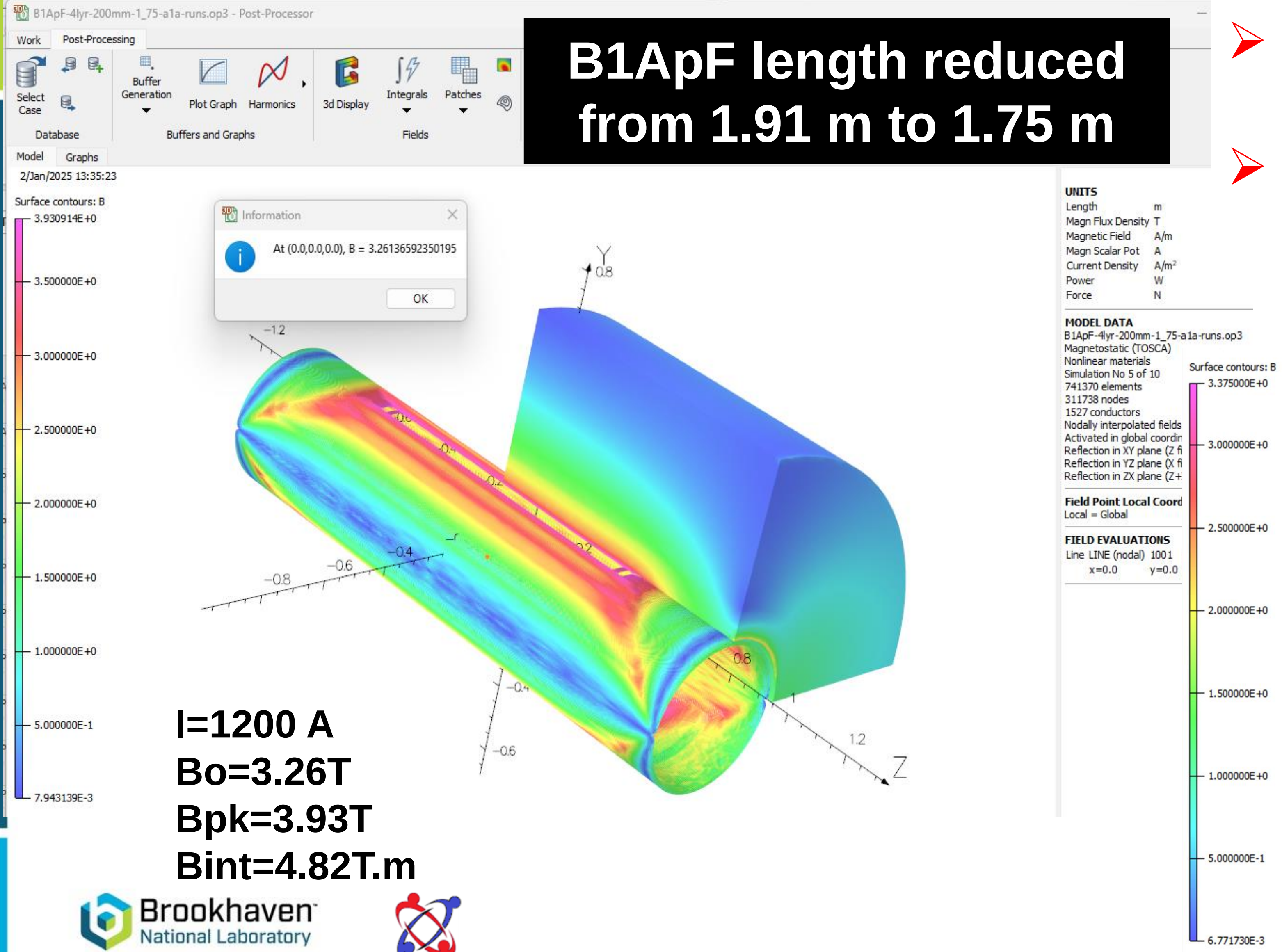
❑ Coils will be identical, even if some have larger aperture than the minimum required.

❑ This will reduce the variety of magnet coils and reduce the number of spares, etc.

❑ Yoke will be different, but yokes can be stored separately and assembled as needed.

- **Compare various interfaces between B1pF & B1ApF Vs 3 B1ApF coils.**

Optimum Integral Dipole B1ApF Optimized so that two of these could replace one of B1pF (**4 layers, Type I Wire**)



B1ApF length reduced from 1.91 m to 1.75 m

B1ApF-4lyr-200mm-1_75-a1a-runs.op3 - Post-Processor

2/Jan/2025 13:35:23

Surface contours: B

Information

At (0.0,0.0,0.0), B = 3.26136592350195

UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/m²
Power	W
Force	N

MODEL DATA

B1ApF-4lyr-200mm-1_75-a1a-runs.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 5 of 10
741370 elements
311738 nodes
1527 conductors
Nodally interpolated fields
Activated in global coordir
Reflection in XY plane (Z fi
Reflection in YZ plane (X fi
Reflection in ZX plane (Z+

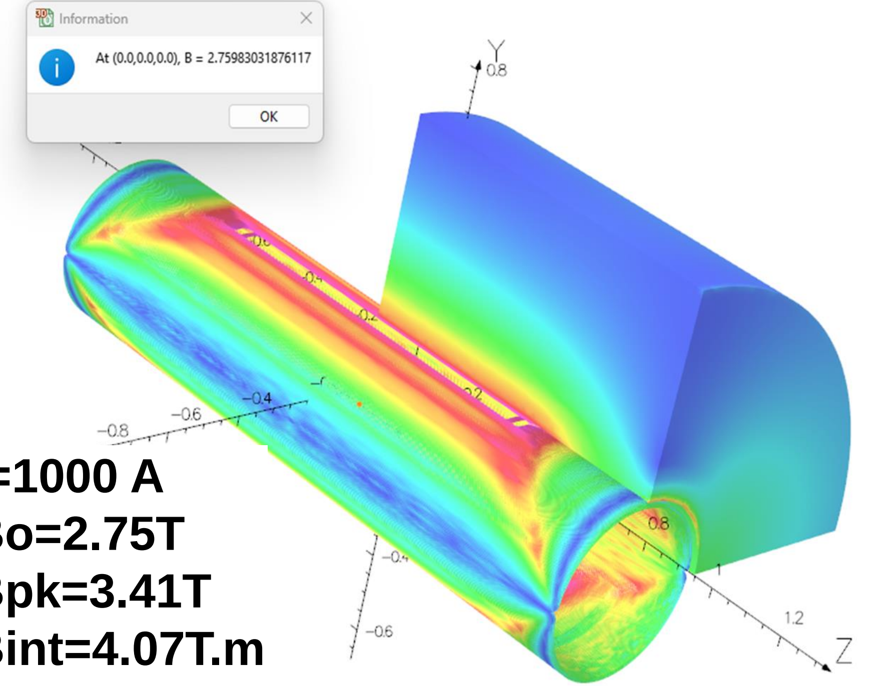
Field Point Local Coord
Local = Global

FIELD EVALUATIONS
Line LINE (nodal) 1001
x=0.0 y=0.0

Surface contours: B

I=1200 A
Bo=3.26T
Bpk=3.93T
Bint=4.82T.m

- Required field integral for B1ApF only option is 4.05 T.m.
- It increases to 4.8 T.m for three B1ApF replacing B1pF & B1ApF.



Information

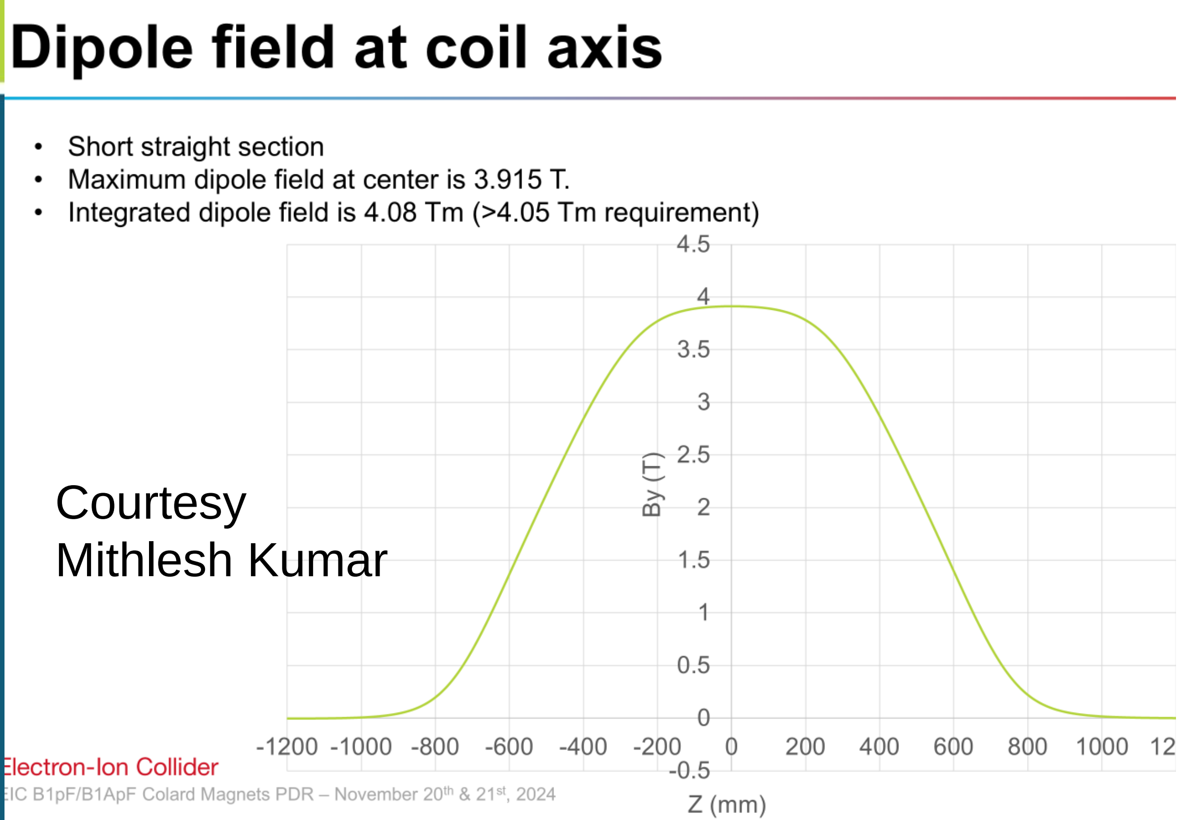
At (0.0,0.0,0.0), B = 2.75983031876117

I=1000 A
Bo=2.75T
Bpk=3.41T
Bint=4.07T.m

Comparison of the Field Along the Axis for the Required Field Integral

(two B1Apf >> One B1pF option)

Cable magnet design



Dipole field at coil axis

- Short straight section
- Maximum dipole field at center is 3.915 T.
- Integrated dipole field is 4.08 Tm (>4.05 Tm requirement)

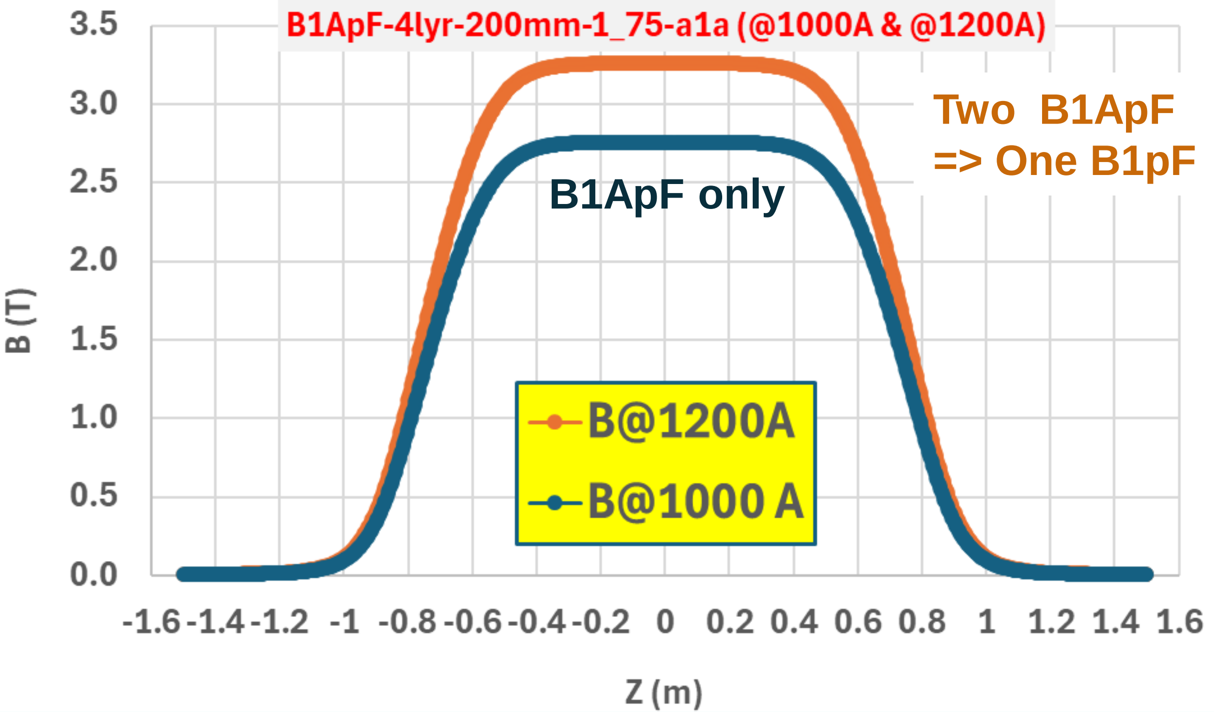
Electron-Ion Collider

EIC B1pF/B1ApF Colard Magnets PDR – November 20th & 21st, 2024

Courtesy
Mithlesh Kumar

Optimum integral design

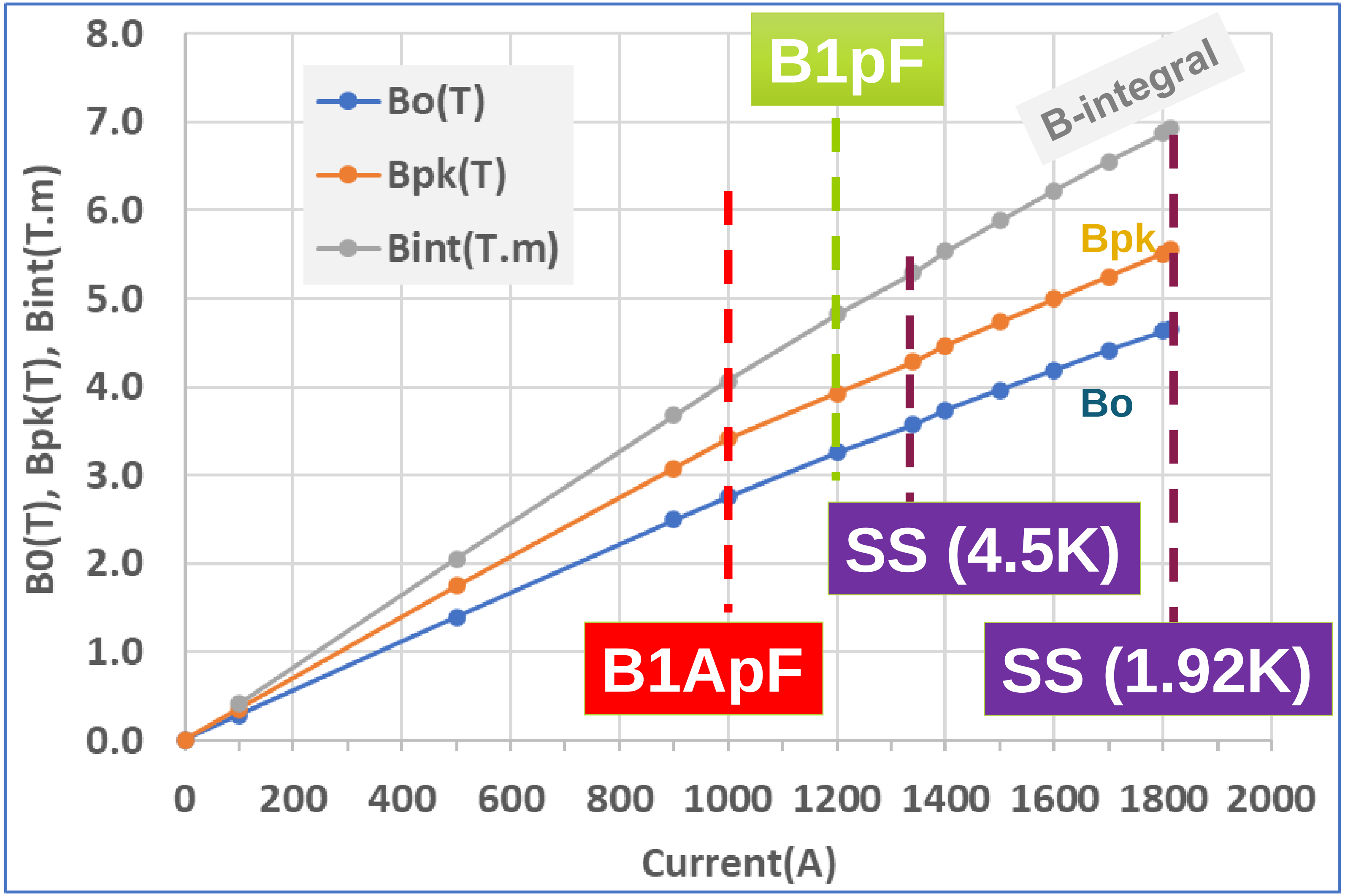
Four layers higher field integral option
A wider flap-top and a lower maximum field



Design integral of 4.05 T/m @1000 A for B1ApF option only.
Integral of 4.8 T.m @1200 A for 2 B1ApF making 1 B1pF.
Maximum field at the center: 2.8 T and 3.2 T

Inductance: 1.2 Henry
Stored Energy at design: 0.86 MJ @1200 A

Yet another Option for the Optimum Integral Direct Wind
(a reasonable margin even at 4.5 K with four layers of Type II)



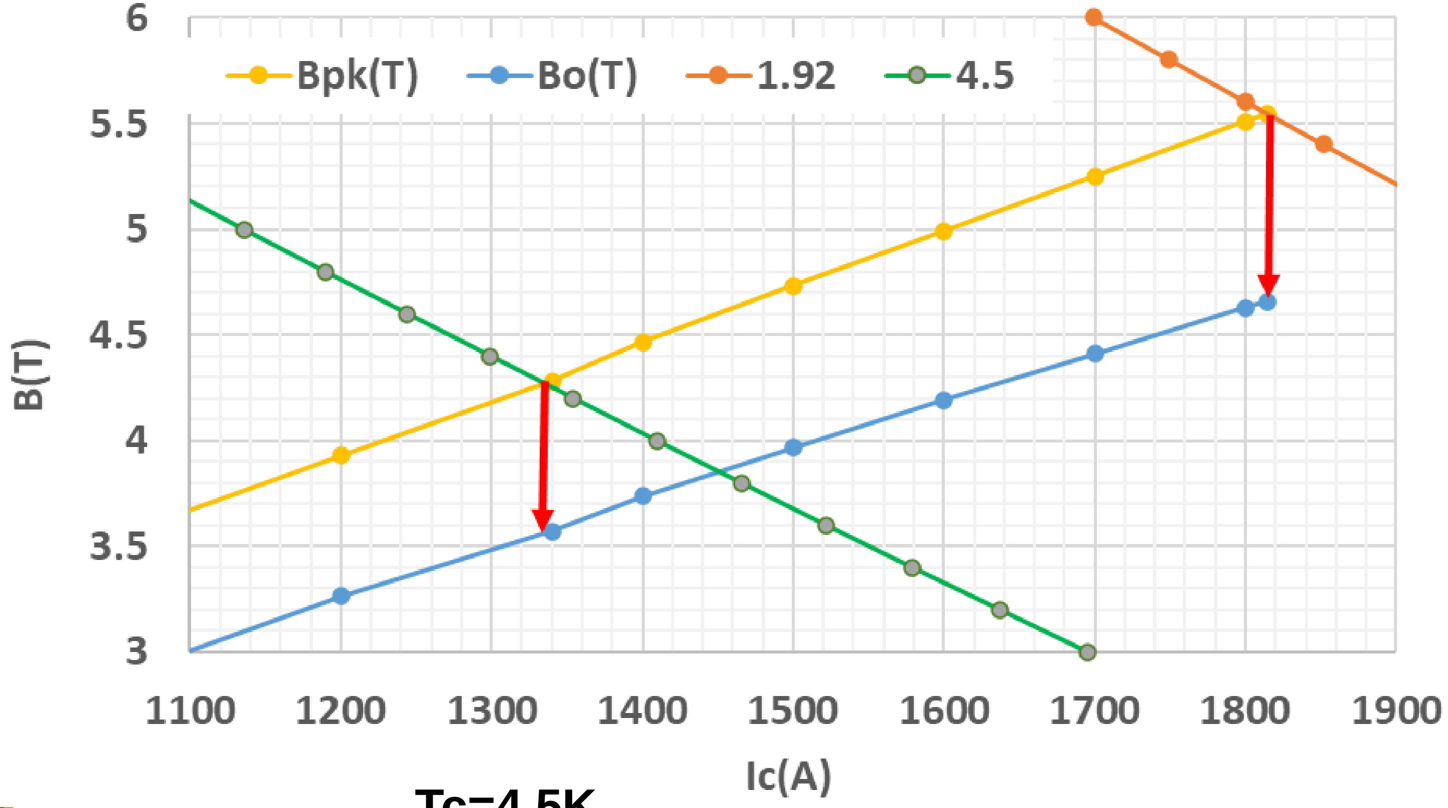
Design Current for B1ApF:
1000 A for 4.07 T.m

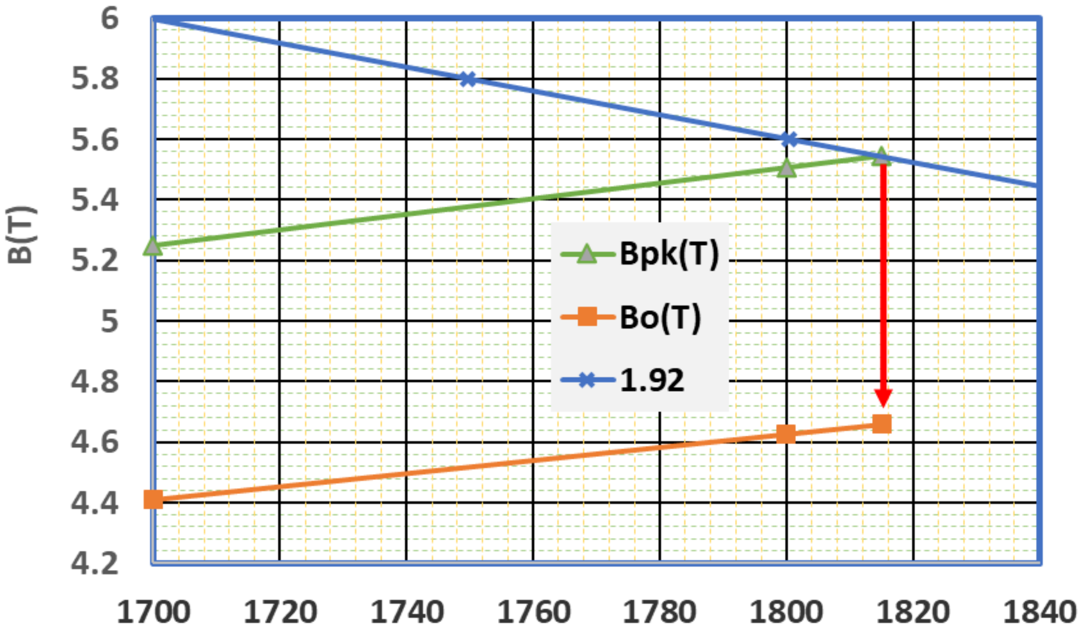
Load line Margin:
45%@1.92K
25%@4.5K

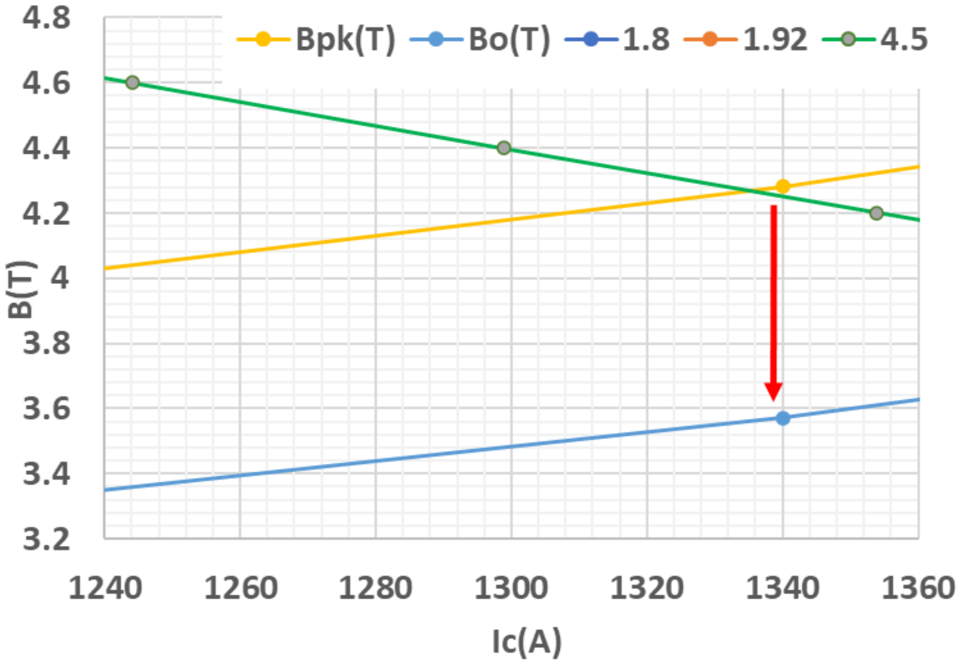
Design Current for B1pF:
1200 A for 4.82 T.m

Load line Margin:
34%@1.92K
10%@4.5K

Computed Performance of a Direct-Wind Optimum Integral 4-Layer Design Optimize for B1pF and B1ApF





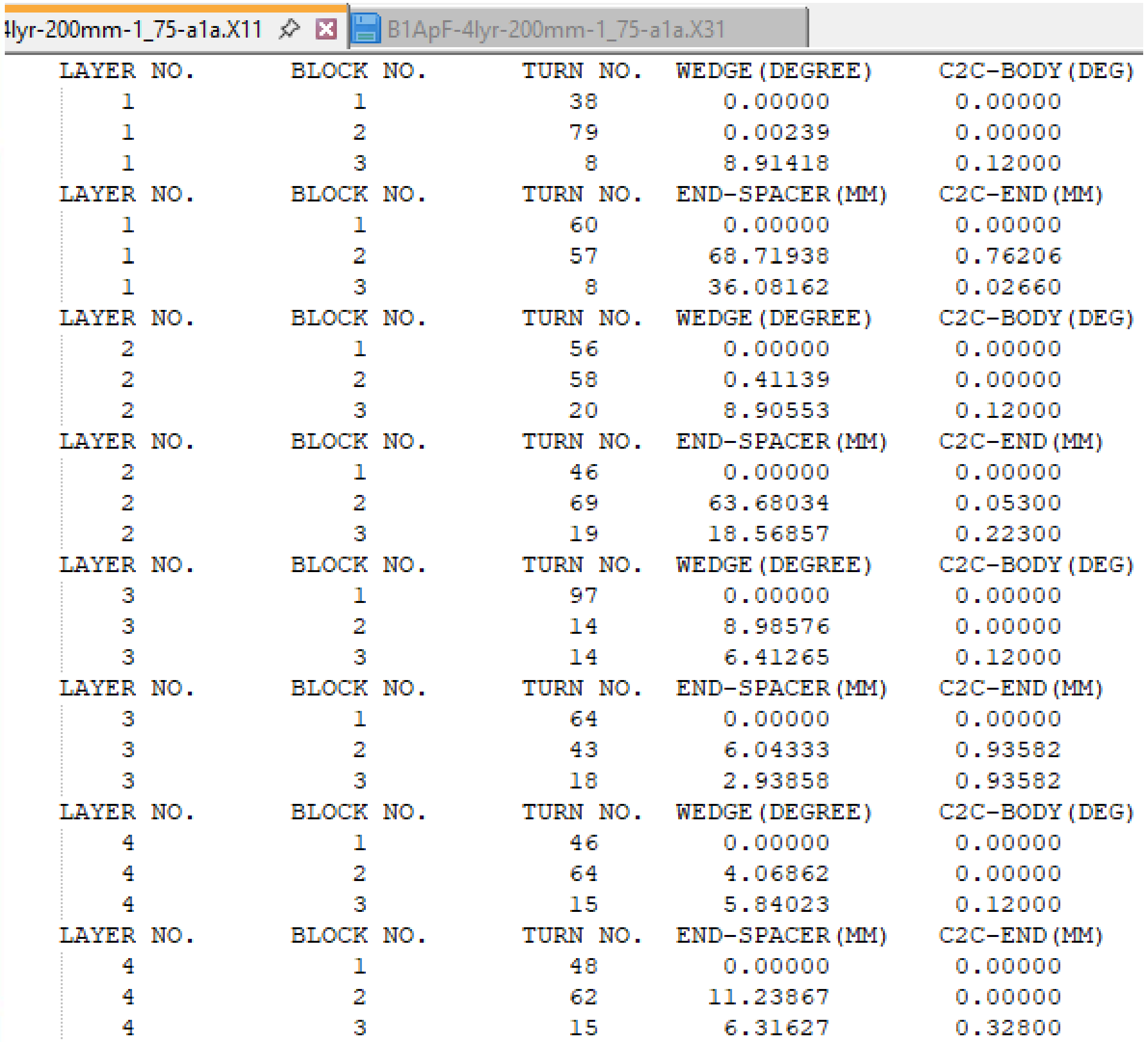


Tc=4.5K
Iss=1340 A
Bss=2.75T
Bpk=3.36T

Tc=1.92K
Iss=1815 A
Bss=4.66T
Bpk=5.55T

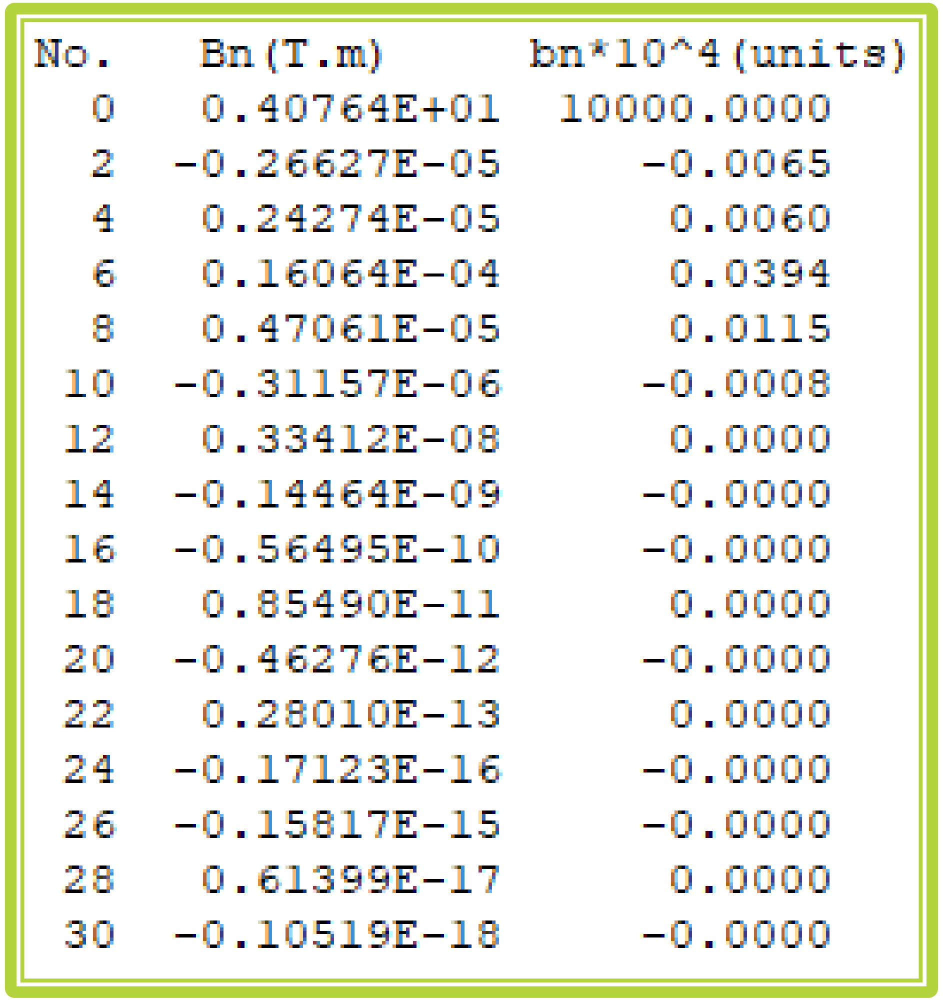
4-layer Type II Wire Design Optimized with the Optimum Integral Code

(two B1Apf >> One B1pF option)



```
LAYER NO.        BLOCK NO.        TURN NO.  WEDGE(DEGREE)     C2C-BODY(DEG)
     1                1              38        0.00000          0.00000
     1                2              79        0.00239          0.00000
     1                3               8        8.91418          0.12000
LAYER NO.        BLOCK NO.        TURN NO.  END-SPACER(MM)    C2C-END(MM)
     1                1              60        0.00000          0.00000
     1                2              57       68.71938          0.76206
     1                3               8       36.08162          0.02660
LAYER NO.        BLOCK NO.        TURN NO.  WEDGE(DEGREE)     C2C-BODY(DEG)
     2                1              56        0.00000          0.00000
     2                2              58        0.41139          0.00000
     2                3              20        8.90553          0.12000
LAYER NO.        BLOCK NO.        TURN NO.  END-SPACER(MM)    C2C-END(MM)
     2                1              46        0.00000          0.00000
     2                2              69       63.68034          0.05300
     2                3              19       18.56857          0.22300
LAYER NO.        BLOCK NO.        TURN NO.  WEDGE(DEGREE)     C2C-BODY(DEG)
     3                1              97        0.00000          0.00000
     3                2              14        8.98576          0.00000
     3                3              14        6.41265          0.12000
LAYER NO.        BLOCK NO.        TURN NO.  END-SPACER(MM)    C2C-END(MM)
     3                1              64        0.00000          0.00000
     3                2              43        6.04333          0.93582
     3                3              18        2.93858          0.93582
LAYER NO.        BLOCK NO.        TURN NO.  WEDGE(DEGREE)     C2C-BODY(DEG)
     4                1              46        0.00000          0.00000
     4                2              64        4.06862          0.00000
     4                3              15        5.84023          0.12000
LAYER NO.        BLOCK NO.        TURN NO.  END-SPACER(MM)    C2C-END(MM)
     4                1              48        0.00000          0.00000
     4                2              62       11.23867          0.00000
     4                3              15        6.31627          0.32800
```

Computed harmonics @55 mm (good field quality in coil geometry) low harmonic contents:



```
No.     Bn(T.m)         bn*10^4(units)
  0    0.40764E+01      10000.0000
  2   -0.26627E-05        -0.0065
  4    0.24274E-05         0.0060
  6    0.16064E-04         0.0394
  8    0.47061E-05         0.0115
 10   -0.31157E-06        -0.0008
 12    0.33412E-08         0.0000
 14   -0.14464E-09        -0.0000
 16   -0.56495E-10        -0.0000
 18    0.85490E-11         0.0000
 20   -0.46276E-12        -0.0000
 22    0.28010E-13         0.0000
 24   -0.17123E-16        -0.0000
 26   -0.15817E-15        -0.0000
 28    0.61399E-17         0.0000
 30   -0.10519E-18        -0.0000
```

Toal number of turns: 509

Computed Parameters of Optimum Integral B1ApF Dipole (4-layer Type II design @1.92K and @ 4.5K)

Bint(T.m)	Iwire(A)	Bo(T)	Bpk(T)	B/I*1000	Bpk/Bo	Leff(m)
	0	0	0			
0.410	100	0.278	0.349	2.783	1.255	1.473
2.050	500	1.391	1.747	2.783	1.256	1.473
3.677	900	2.4952	3.080	2.772	1.234	1.474
4.070	**1000**	**2.753**	**3.414**	**2.753**	**1.240**	**1.478**
4.820	**1200**	**3.261**	**3.931**	**2.718**	**1.205**	**1.478**
5.287	1340	3.5721	4.2807	2.666	1.198	1.480
5.533	1400	3.736	4.467	2.668	1.196	1.481
5.879	1500	3.965	4.731	2.644	1.193	1.483
6.219	1600	4.190	4.992	2.619	1.191	1.484
6.551	1700	4.411	5.251	2.595	1.190	1.485
6.873	1800	4.627	5.508	2.571	1.190	1.485
6.9245	1815	4.6591	5.5465	2.567	1.190	1.486

B1ApF Design @1000 A

B1pF Design @1200 A

SS(4.5K) @1340 A

SS(1.92K) @1815 A

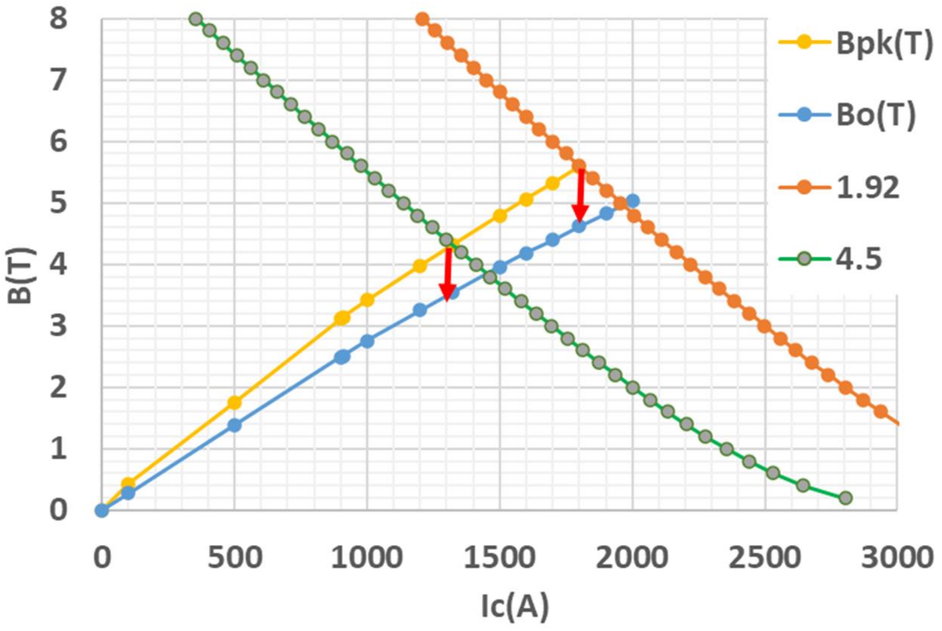
- Required integral gradient: 4.05 T.meter

Selected Direct Wind Optimum Integral Dipole Options for B1ApF

Design	No. of Layers	Wire Type	No. of Turns	Length (m)	Current (A)	B_o (T)	Integral B.dL (T.m)	B_{pk} (T)	Inductance (H)	Load line Margin (%) 1.92K / 4.5K	Operating Margin (%) 1.92K / 4.5K
B1ApF-0	4	I	509	1.91	910	2.51	4.05	3.14	1.3	49/31	92/45
B1ApF-1	2	I	258	1.91	1870	2.63	4.06	3.67	0.32	13/xx	16/xx
B1ApF-2	4	II	758	1.91	625	2.54	4.06	3.23	2.8	41/20	70/25
B1ApF 3*B1ApF=>B1pF+B1ApF	4	I	509	1.75	1000 1200	3.41 3.93	4.07 4.82	3.41 3.93	1.2	45/25 34/10	82/34 34/12

Required field integral for B1ApF : 4.05 T.meter

Required field integral for the three B1ApF replacing B1pF and B1ApF: 4.8 T.meter



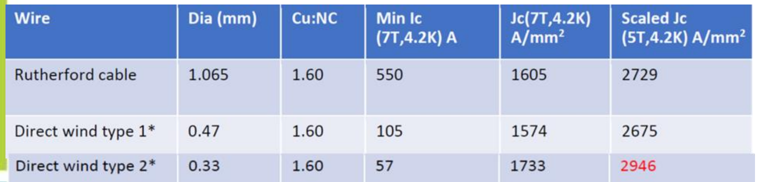
Summary

- **Work under the STTR has shown that an optimum integral direct wind dipole is an alternative to the current design of B1ApF based on the Rutherford cable.**
- **A 4-layer direct wind optimum integral B1ApF will be much cheaper and faster to build and test than the cable magnet. A proof-of-principle B1ApF based on this design should be available in ~1 year and in ~1M$ (?), with reusable coils.**
- **The central field in this design is significantly smaller than that in the cable magnet. This means lower Lorentz and a technically less demanding design. All 4-layer designs have comfortable margin, and they can be tested at ~4K.**
- **Furthermore, the length of B1ApF can be properly chosen so that two of these could replace one of B1pF.**
- **This provides an alternate design option for the B1pF dipole for no added cost.**
- **This is a prime example of value engineering. Given the large potential gains, we should examine this further now and build a PoP after appropriate reviews.**

Extra Slides

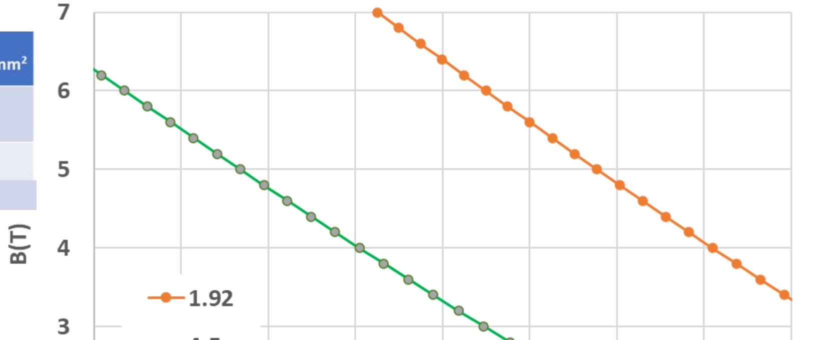
Cable Used in the Calculations (7 wires)

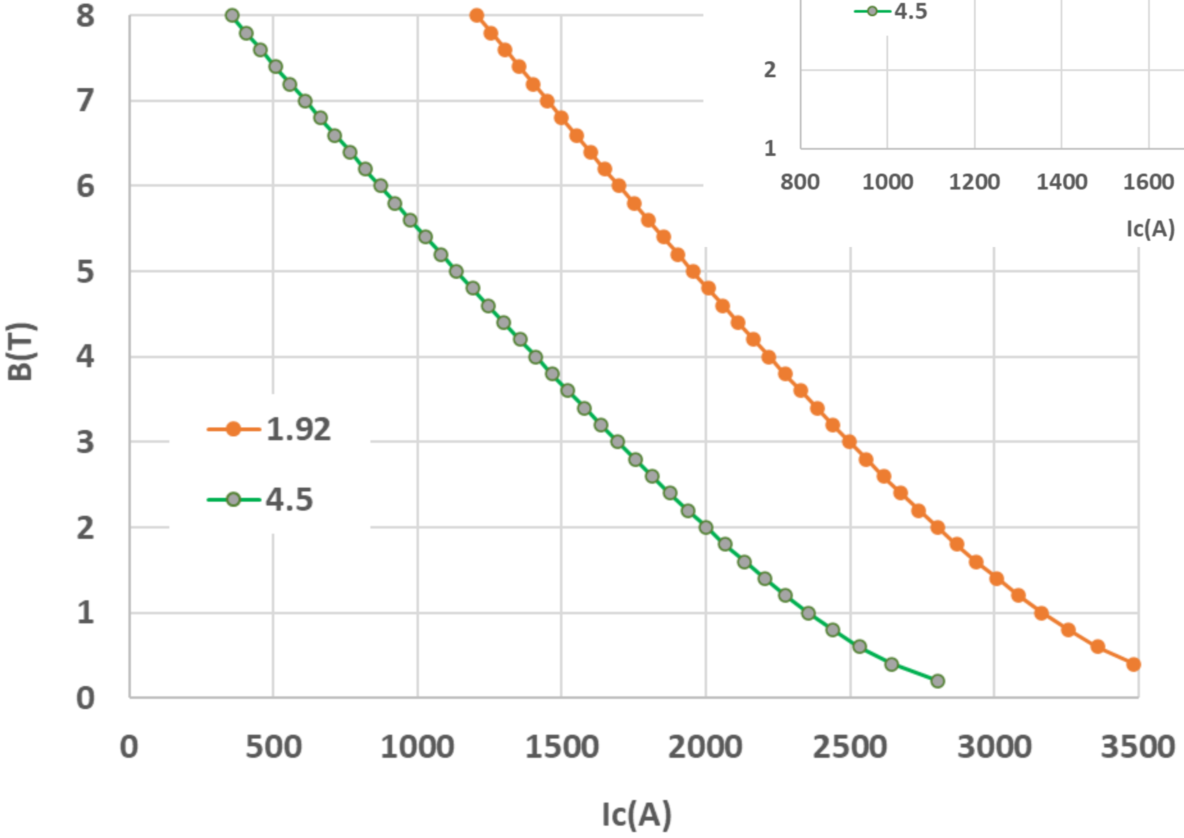
Performance computed at 1.92 K and 4.5 K



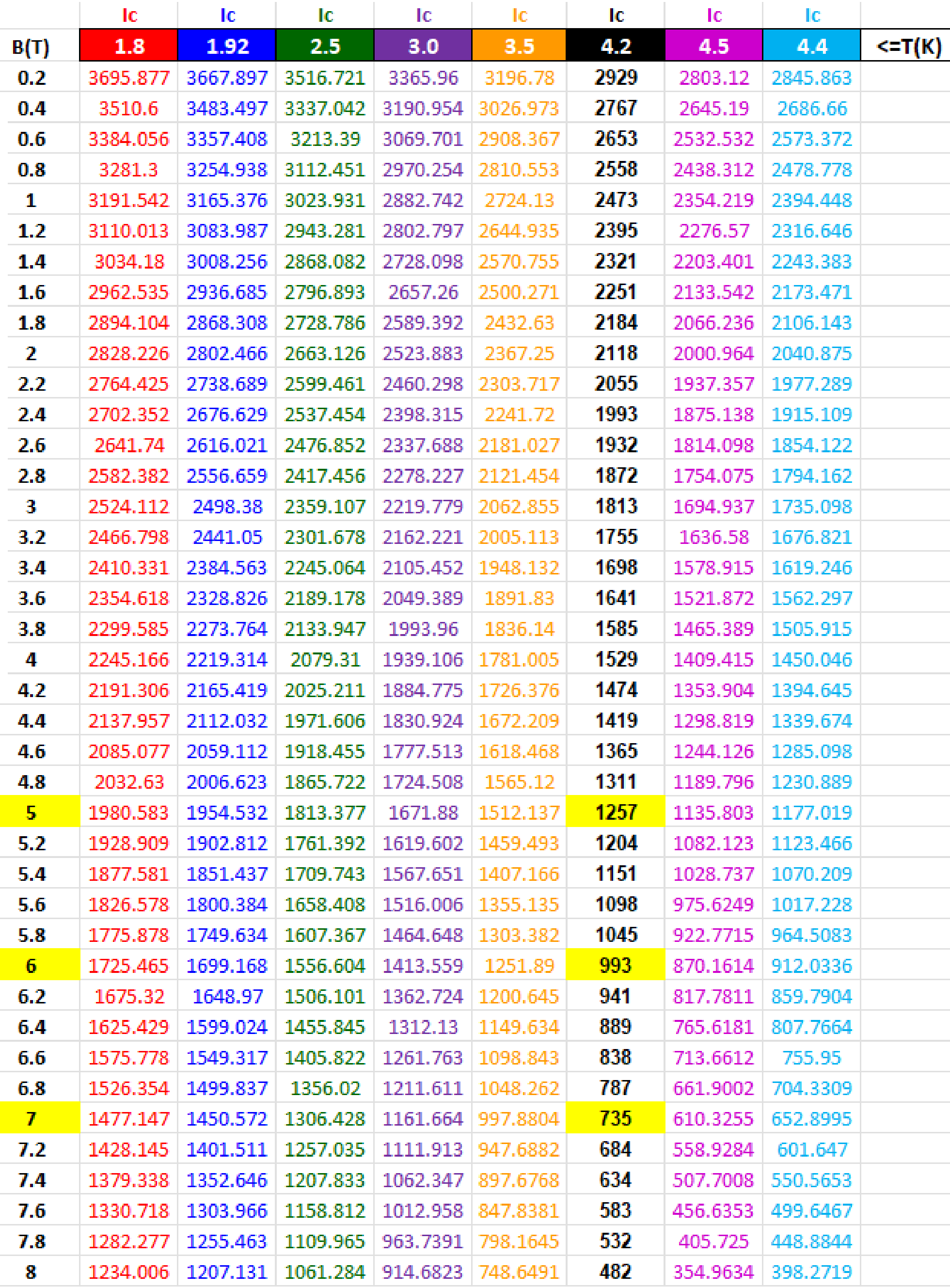
Wire	Dia (mm)	Cu:NC	Min Ic (7T,4.2K) A	Jc(7T,4.2K) A/mm²	Scaled Jc (5T,4.2K) A/mm²
Rutherford cable	1.065	1.60	550	1605	2729
Direct wind type 1*	0.47	1.60	105	1574	2675
Direct wind type 2*	0.33	1.60	57	1733	2946

TYPE I





There may be a slight degradation in going from wire to cable. However, past experience is that Ic of wires, as delivered, more than offsets that.



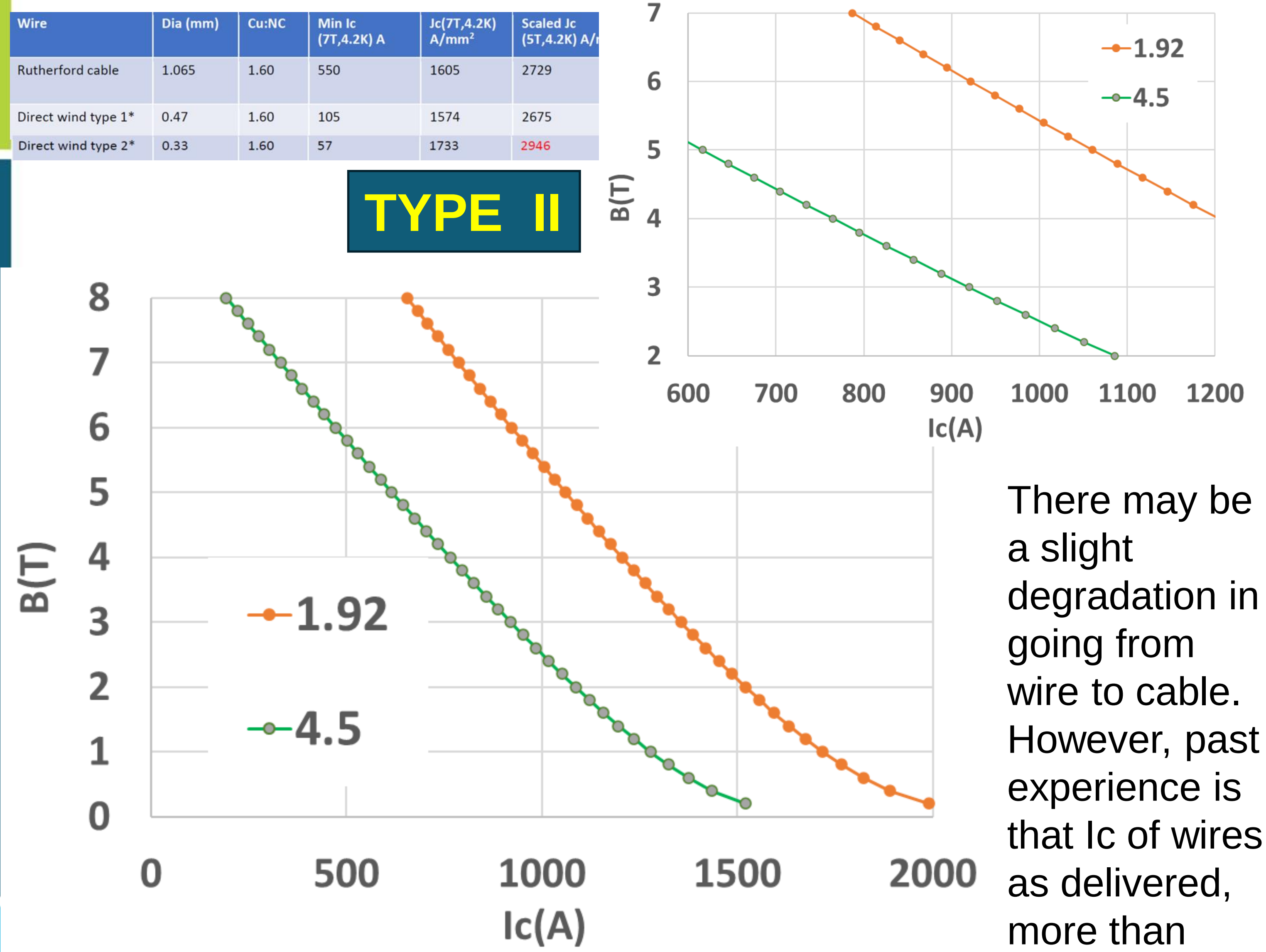
	Ic	Ic	Ic	Ic	Ic	Ic	Ic	Ic	
B(T)	**1.8**	**1.92**	**2.5**	**3.0**	**3.5**	**4.2**	**4.5**	**4.4**	**<=T(K)**
0.2	3695.877	3667.897	3516.721	3365.96	3196.78	2929	2803.12	2845.863	
0.4	3510.6	3483.497	3337.042	3190.954	3026.973	2767	2645.19	2686.66	
0.6	3384.056	3357.408	3213.39	3069.701	2908.367	2653	2532.532	2573.372	
0.8	3281.3	3254.938	3112.451	2970.254	2810.553	2558	2438.312	2478.778	
1	3191.542	3165.376	3023.931	2882.742	2724.13	2473	2354.219	2394.448	
1.2	3110.013	3083.987	2943.281	2802.797	2644.935	2395	2276.57	2316.646	
1.4	3034.18	3008.256	2868.082	2728.098	2570.755	2321	2203.401	2243.383	
1.6	2962.535	2936.685	2796.893	2657.26	2500.271	2251	2133.542	2173.471	
1.8	2894.104	2868.308	2728.786	2589.392	2432.63	2184	2066.236	2106.143	
2	2828.226	2802.466	2663.126	2523.883	2367.25	2118	2000.964	2040.875	
2.2	2764.425	2738.689	2599.461	2460.298	2303.717	2055	1937.357	1977.289	
2.4	2702.352	2676.629	2537.454	2398.315	2241.72	1993	1875.138	1915.109	
2.6	2641.74	2616.021	2476.852	2337.688	2181.027	1932	1814.098	1854.122	
2.8	2582.382	2556.659	2417.456	2278.227	2121.454	1872	1754.075	1794.162	
3	2524.112	2498.38	2359.107	2219.779	2062.855	1813	1694.937	1735.098	
3.2	2466.798	2441.05	2301.678	2162.221	2005.113	1755	1636.58	1676.821	
3.4	2410.331	2384.563	2245.064	2105.452	1948.132	1698	1578.915	1619.246	
3.6	2354.618	2328.826	2189.178	2049.389	1891.83	1641	1521.872	1562.297	
3.8	2299.585	2273.764	2133.947	1993.96	1836.14	1585	1465.389	1505.915	
4	2245.166	2219.314	2079.31	1939.106	1781.005	1529	1409.415	1450.046	
4.2	2191.306	2165.419	2025.211	1884.775	1726.376	1474	1353.904	1394.645	
4.4	2137.957	2112.032	1971.606	1830.924	1672.209	1419	1298.819	1339.674	
4.6	2085.077	2059.112	1918.455	1777.513	1618.468	1365	1244.126	1285.098	
4.8	2032.63	2006.623	1865.722	1724.508	1565.12	1311	1189.796	1230.889	
5	1980.583	1954.532	1813.377	1671.88	1512.137	1257	1135.803	1177.019	
5.2	1928.909	1902.812	1761.392	1619.602	1459.493	1204	1082.123	1123.466	
5.4	1877.581	1851.437	1709.743	1567.651	1407.166	1151	1028.737	1070.209	
5.6	1826.578	1800.384	1658.408	1516.006	1355.135	1098	975.6249	1017.228	
5.8	1775.878	1749.634	1607.367	1464.648	1303.382	1045	922.7715	964.5083	
6	1725.465	1699.168	1556.604	1413.559	1251.89	993	870.1614	912.0336	
6.2	1675.32	1648.97	1506.101	1362.724	1200.645	941	817.7811	859.7904	
6.4	1625.429	1599.024	1455.845	1312.13	1149.634	889	765.6181	807.7664	
6.6	1575.778	1549.317	1405.822	1261.763	1098.843	838	713.6612	755.95	
6.8	1526.354	1499.837	1356.02	1211.611	1048.262	787	661.9002	704.3309	
7	1477.147	1450.572	1306.428	1161.664	997.8804	735	610.3255	652.8995	
7.2	1428.145	1401.511	1257.035	1111.913	947.6882	684	558.9284	601.647	
7.4	1379.338	1352.646	1207.833	1062.347	897.6768	634	507.7008	550.5653	
7.6	1330.718	1303.966	1158.812	1012.958	847.8381	583	456.6353	499.6467	
7.8	1282.277	1255.463	1109.965	963.7391	798.1645	532	405.725	448.8844	
8	1234.006	1207.131	1061.284	914.6823	748.6491	482	354.9634	398.2719	

Cable Used in the Calculations (7 wires)

Performance computed at 1.92 K and 4.5 K

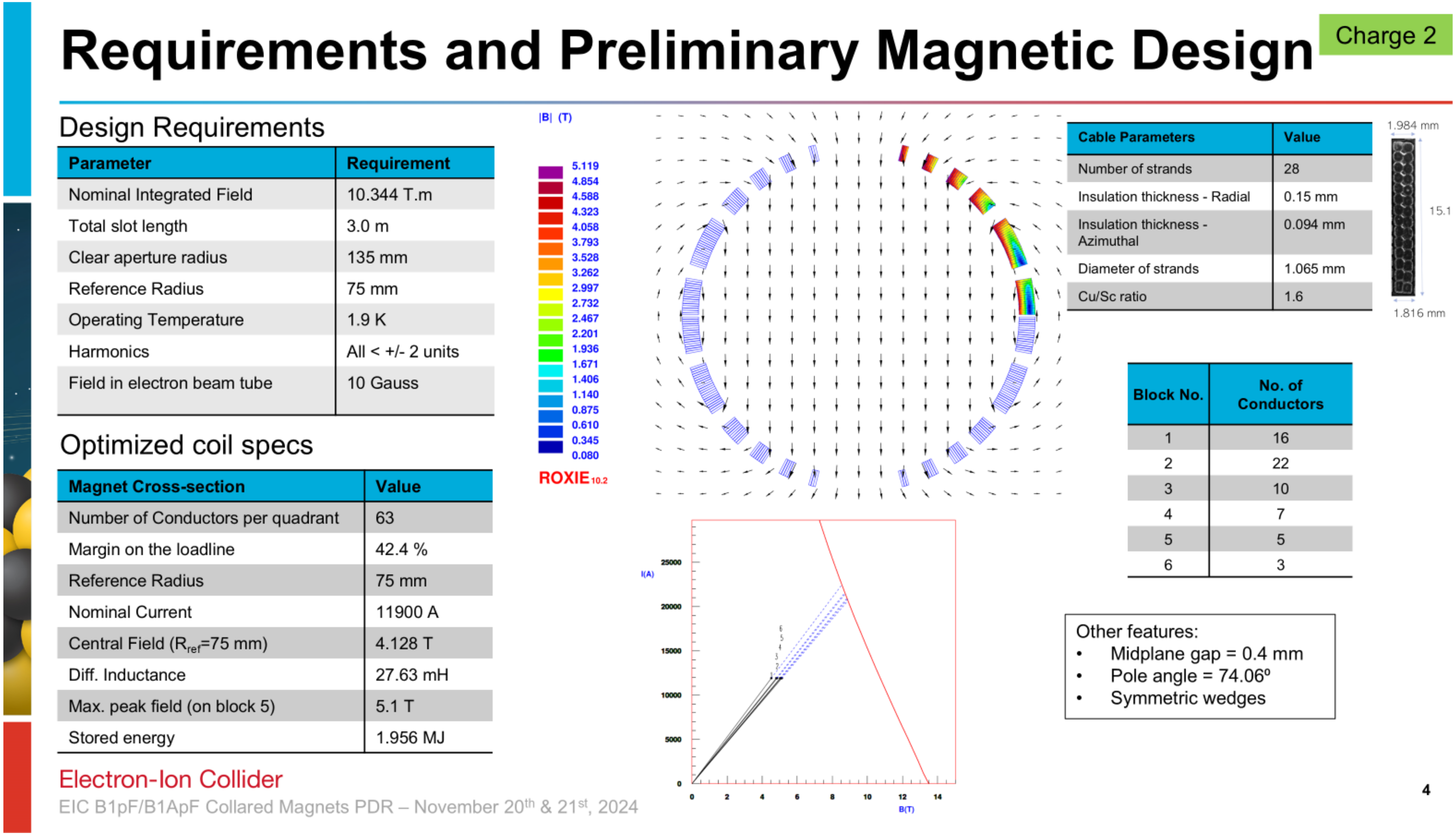
Wire	Dia (mm)	Cu:NC	Min Ic (7T,4.2K) A	Jc(7T,4.2K) A/mm²	Scaled Jc (5T,4.2K) A/
Rutherford cable	1.065	1.60	550	1605	2729
Direct wind type 1*	0.47	1.60	105	1574	2675
Direct wind type 2*	0.33	1.60	57	1733	2946

TYPE II



There may be a slight degradation in going from wire to cable. However, past experience is that Ic of wires as delivered, more than offsets that.

	Ic	Ic	Ic	Ic	Ic	Ic	Ic	Ic	
B(T)	1.8	1.92	2.5	3.0	3.5	4.2	4.5	4.4	<=T(K)
0.2	2005.24	1990.06	1908.04	1826.24	1734.45	1589	1520.87	1544.06	
0.4	1904.72	1890.01	1810.55	1731.29	1642.32	1501	1435.18	1457.68	
0.6	1836.06	1821.6	1743.46	1665.5	1577.97	1439	1374.05	1396.21	
0.8	1780.31	1766	1688.7	1611.55	1524.9	1388	1322.93	1344.89	
1	1731.61	1717.41	1640.67	1564.07	1478.01	1342	1277.31	1299.14	
1.2	1687.37	1673.25	1596.91	1520.69	1435.04	1299	1235.18	1256.92	
1.4	1646.23	1632.16	1556.11	1480.16	1394.79	1259	1195.48	1217.17	
1.6	1607.36	1593.33	1517.49	1441.73	1356.55	1221	1157.58	1179.24	
1.8	1570.23	1556.23	1480.53	1404.9	1319.85	1185	1121.06	1142.71	
2	1534.49	1520.51	1444.91	1369.36	1284.38	1149	1085.65	1107.3	
2.2	1499.87	1485.91	1410.37	1334.86	1249.91	1115	1051.14	1072.8	
2.4	1466.19	1452.24	1376.73	1301.23	1216.27	1081	1017.38	1039.06	
2.6	1433.31	1419.35	1343.85	1268.34	1183.34	1048	984.26	1005.98	
2.8	1401.1	1387.15	1311.62	1236.08	1151.02	1016	951.694	973.444	
3	1369.49	1355.53	1279.96	1204.37	1119.23	984	919.608	941.397	
3.2	1338.39	1324.42	1248.8	1173.14	1087.9	952	887.945	909.779	
3.4	1307.75	1293.77	1218.09	1142.34	1056.98	921	856.659	878.541	
3.6	1277.53	1263.53	1187.76	1111.92	1026.43	890	825.71	847.643	
3.8	1247.67	1233.66	1157.8	1081.85	996.219	860	795.064	817.052	
4	1218.14	1204.11	1128.15	1052.08	966.305	830	764.694	786.739	
4.2	1188.92	1174.87	1098.8	1022.61	936.665	800	734.577	756.681	
4.4	1159.97	1145.91	1069.72	993.389	907.277	770	704.69	726.856	
4.6	1131.28	1117.2	1040.88	964.41	878.119	740	675.015	697.245	
4.8	1102.83	1088.72	1012.27	935.652	849.174	711	645.538	667.833	
5	1074.59	1060.45	983.869	907.098	820.428	682	616.243	638.606	
5.2	1046.55	1032.39	955.664	878.734	791.865	653	587.118	609.55	
5.4	1018.7	1004.52	927.641	850.547	763.474	624	558.153	580.654	
5.6	991.031	976.819	899.788	822.527	735.244	596	529.337	551.909	
5.8	963.524	949.284	872.096	794.662	707.165	567	500.66	523.305	
6	936.171	921.903	844.554	766.943	679.228	539	472.116	494.834	
6.2	908.964	894.668	817.153	739.362	651.424	511	443.697	466.489	
6.4	881.895	867.569	789.886	711.911	623.747	483	415.395	438.263	
6.6	854.956	840.6	762.745	684.584	596.19	455	387.205	410.149	
6.8	828.141	813.754	735.724	657.374	568.747	427	359.122	382.143	
7	801.443	787.025	708.818	630.275	541.412	399	331.139	354.238	
7.2	774.856	760.406	682.019	603.281	514.179	371	303.253	326.431	
7.4	748.376	733.894	655.324	576.389	487.045	344	275.459	298.716	
7.6	721.997	707.482	628.727	549.592	460.004	316	247.753	271.089	
7.8	695.714	681.166	602.225	522.888	433.053	289	220.131	243.547	
8	669.524	654.943	575.812	496.272	406.188	262	192.59	216.087	



Requirements and Preliminary Magnetic Design

Charge 2

Design Requirements

Parameter	Requirement
Nominal Integrated Field	10.344 T.m
Total slot length	3.0 m
Clear aperture radius	135 mm
Reference Radius	75 mm
Operating Temperature	1.9 K
Harmonics	All < +/- 2 units
Field in electron beam tube	10 Gauss

Optimized coil specs

Magnet Cross-section	Value
Number of Conductors per quadrant	63
Margin on the loadline	42.4 %
Reference Radius	75 mm
Nominal Current	11900 A
Central Field (R_{ref}=75 mm)	4.128 T
Diff. Inductance	27.63 mH
Max. peak field (on block 5)	5.1 T
Stored energy	1.956 MJ

Cable Parameters	Value
Number of strands	28
Insulation thickness - Radial	0.15 mm
Insulation thickness - Azimuthal	0.094 mm
Diameter of strands	1.065 mm
Cu/Sc ratio	1.6

Block No.	No. of Conductors
1	16
2	22
3	10
4	7
5	5
6	3

Other features:

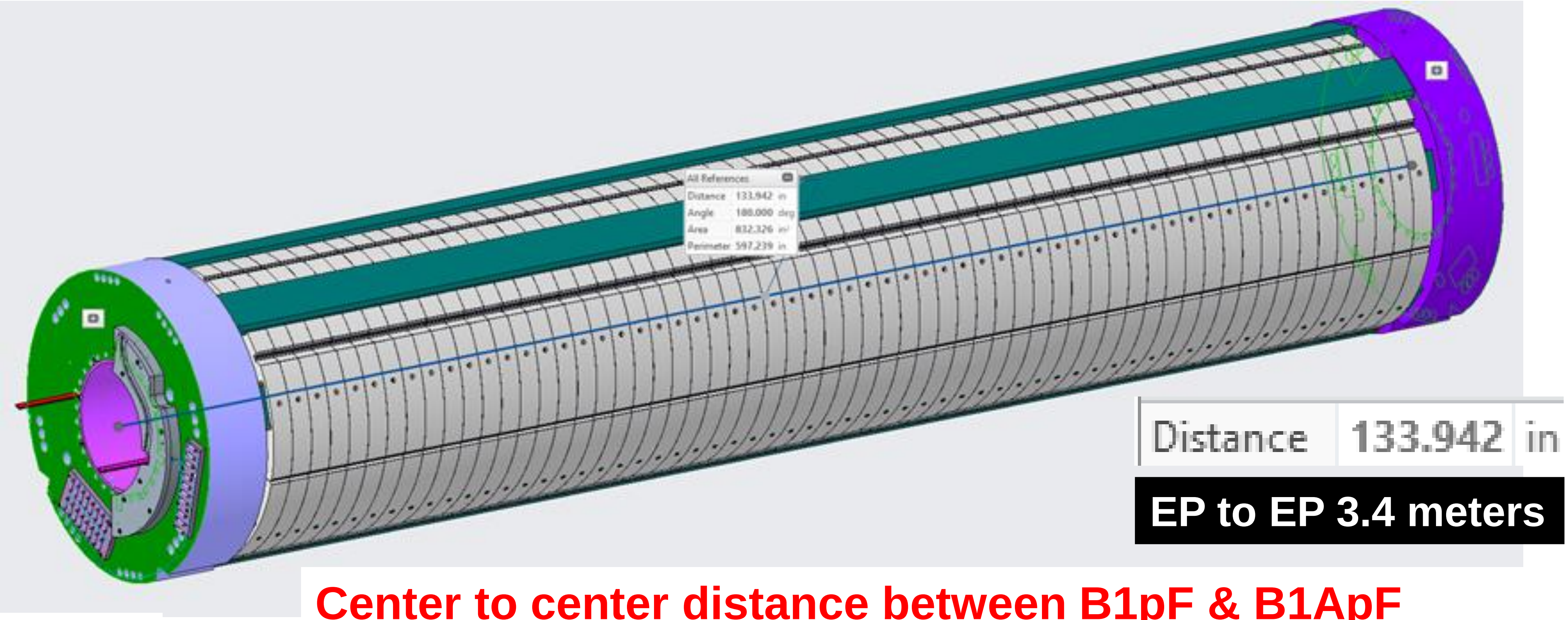
- Midplane gap = 0.4 mm
- Pole angle = 74.06°
- Symmetric wedges

Electron-Ion Collider

EIC B1pF/B1ApF Collared Magnets PDR – November 20th & 21st, 2024

4

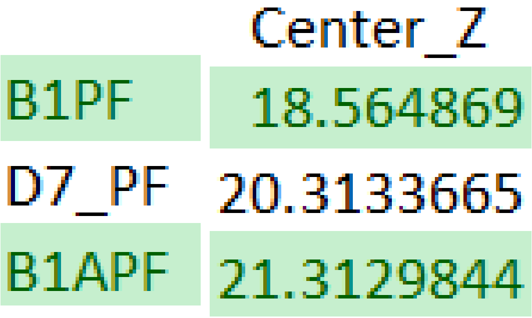
B1pF (and computation of length 3 B1ApF making B1pF+B1ApF)


All References

Distance	133.942	in
Angle	180.000	deg
Area	832.326	in²
Perimeter	597.239	in

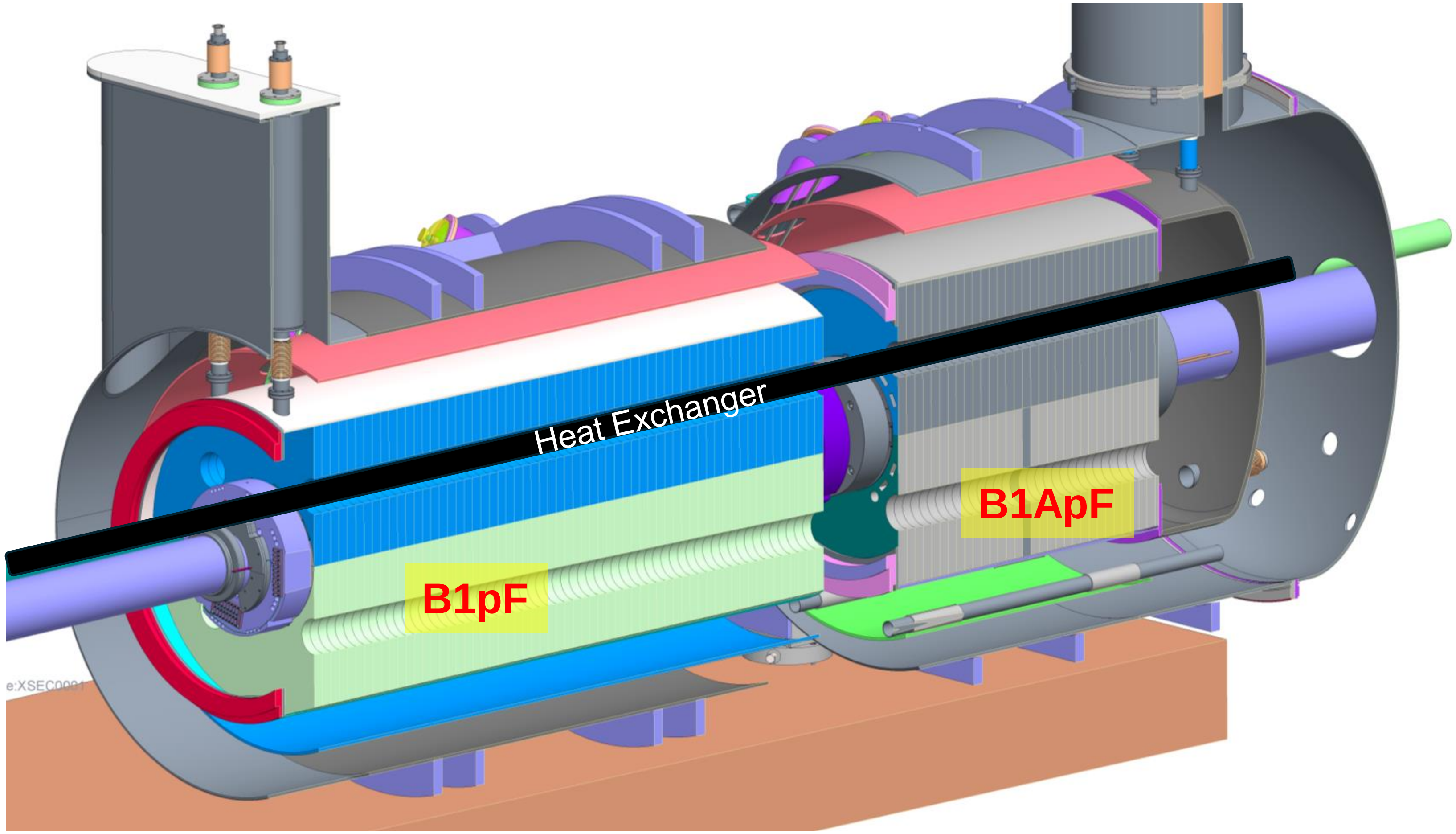
Distance	133.942	in

EP to EP 3.4 meters



	Center_Z
B1PF	18.564869
D7_PF	20.3133665
B1APF	21.3129844

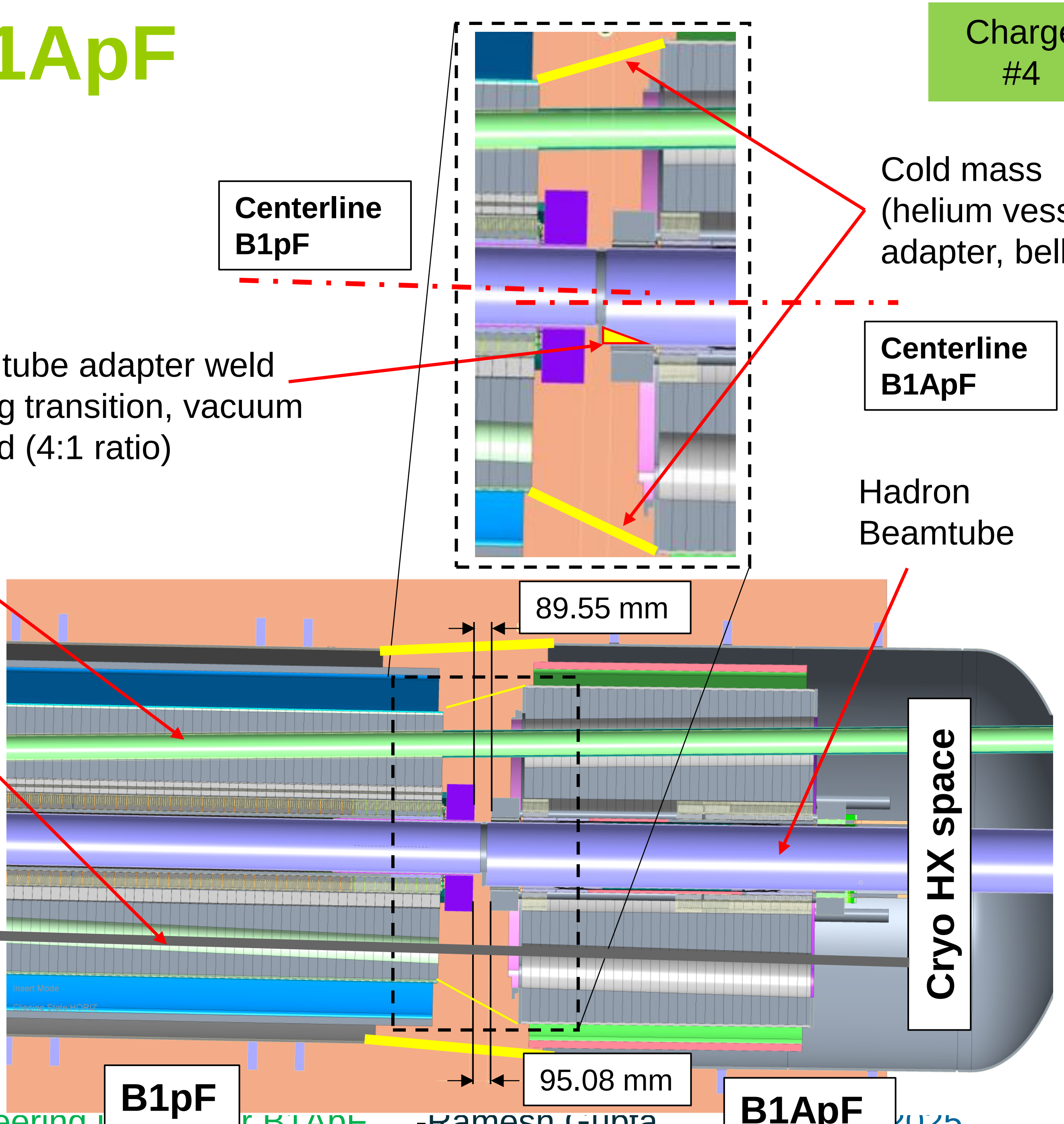
Center to center distance between B1pF & B1ApF
zd = 21.313-18.565 = 2.748 m
End Plate to End Plate in B1pF, B1ApF” 3.4 m, 1.91 m
End plate to End Plate between B1pF & B1ApF:
2.748+3.4/2+1.91/2=5.4 m (space for direct wind coil)
Length of B1ApF: 5.4/3=1.8 m;1.75 m leaves 100 mm gap


Heat Exchanger
B1ApF
B1pF
e:XSEC0001

Interfaces – B1pF & B1ApF

Charge #4

- Interconnects
  - Beam pipe welds
  - Cold mass welds
  - Heat shield interconnects
  - Cryostat interconnects
- EIC vacuum
  - HSR beam pipe
  - ESR beam pipe
  - Pump out ports
- EIC Cryogenics
  - 1.9K heat exchanger
  - Helium process lines
- EIC Power supplies
  - 300K lead connections
  - VCL helium return lines
- B1ApF only – "Valve Box" heat exchangers



Centerline B1pF

Centerline B1ApF

Cold mass (helium vessel) adapter, bellows

Hadron tube adapter weld including transition, vacuum can weld (4:1 ratio)

Electron Beamtube

Hadron Beamtube

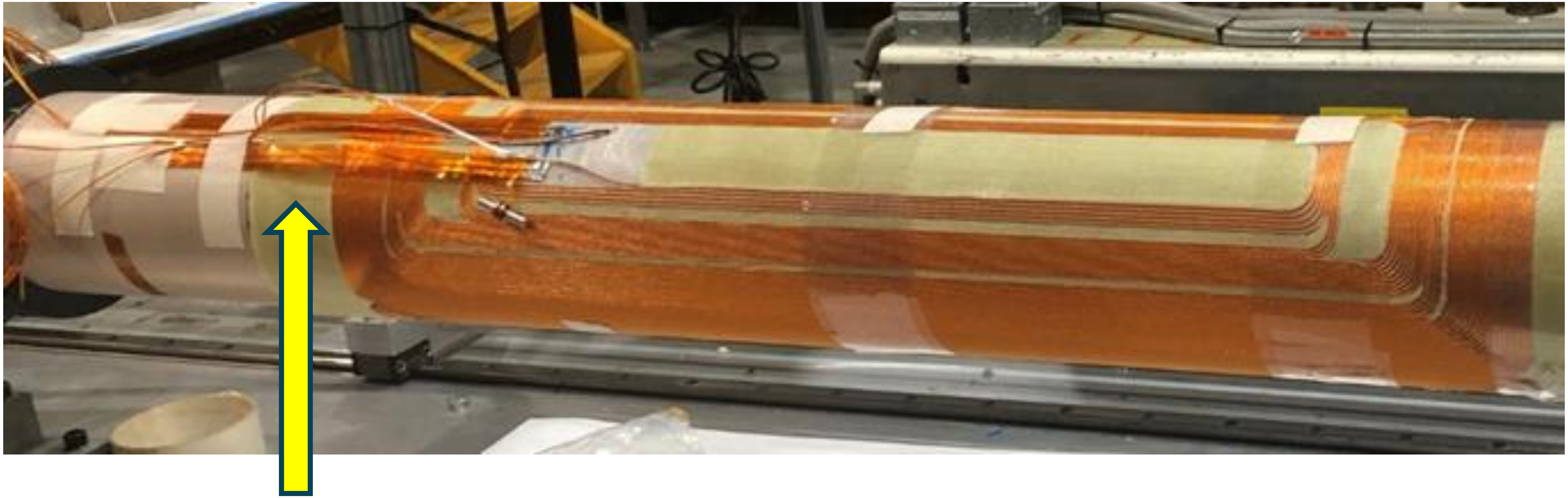
Heat Exchanger

More slides on

PBL/BNL STTR Phase II

A Change in Design to Eliminate Radial Space Used by Leads

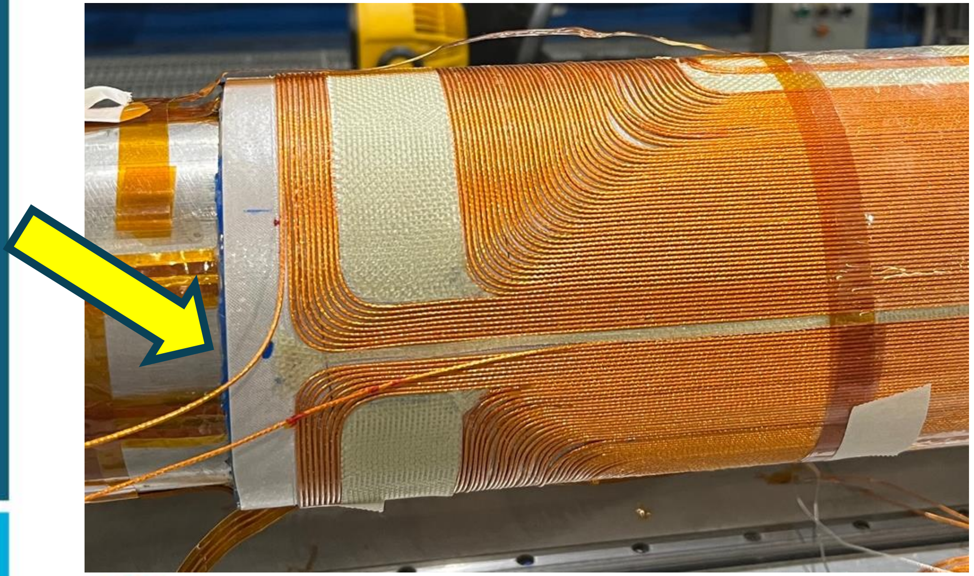
- **Phase I design used extra radial space for bringing leads out “over the coil” at the pole.**
- **Can this use of extra radial space be saved to make design more efficient?**



Phase I configuration

A Change in Design to Eliminate Radial Space Used by Leads

- A new idea was found to eliminate the above-mentioned extra radial space.
- Bring leads out at the midplane (as in the picture) – avoid extra radial space.
- Everyone then thought that it was a brilliant idea, at that time.
- However, this meant adding a splice at pole – a high field region.
- Such a splice had never been made before in any direct wind magnet with the 6-around-1 cable. Need to test this before implementing in the whole magnet.



Internal Splice is here

Phase II configuration

Recovery Plan for Remaining Phase II:

- Implement the lessons learned (go back to original splice).
- Operate compromised (innovative) coils at a safe (lower) current.
- Add extra layers to get the original amp-turns.

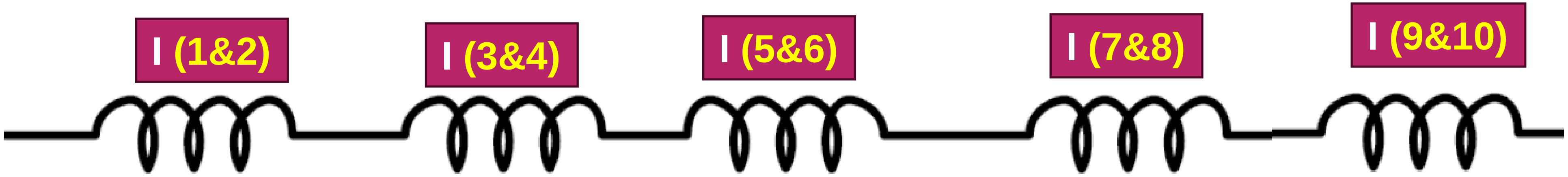
➢ Coordinate this program with LDRD on quench propagation study to overcome the budgetary challenges.

✓ This is essentially allowing us to test the original targets/goals.

Updated Plan for the Phase II Dipole

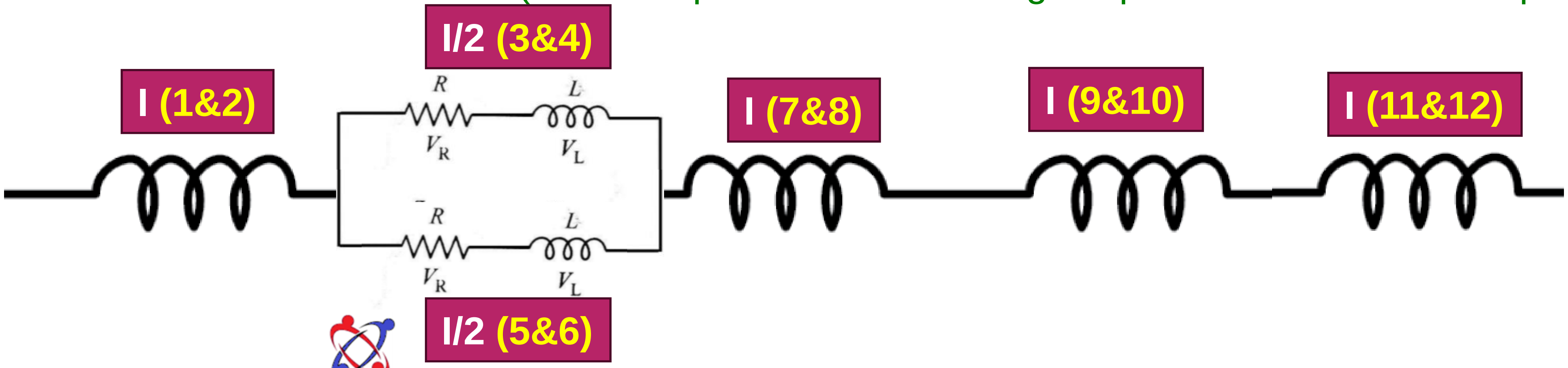
- The original plan was for 5 double-layer (10 single-layer), all connected in series.
- The revised plan is for 6 double-layer (12 single-layer). Double layers 3&4 and 5&6 will be in parallel to each other. They will be in series to the rest of the four double layer. This will make it effectively (to first order) a 5-layer coil again and will test the original design goals/principles.
- Double layers 3&4 + 5&6 can be safely used as both have reached >50% of the design current.

➢ Original plan: five double layers for certain Amp-turns


I (1&2)
I (3&4)
I (5&6)
I (7&8)
I (9&10)

➢ Revised plan: six double layers => two wired in parallel for a promising magnet

(same Amp-turns as in the original plan with the troubled splice running at ½ current)


I/2 (3&4)
I (1&2)
I (7&8)
I (9&10)
I (11&12)
I/2 (5&6)

Two extra layers wound