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Brookhaven National Laboratory

Particle Beam Lasers

U.S. DEPARTMENT OF ENERGY

A New Medium Field Superconducting Magnet for the EIC

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FY25 Nuclear Physics SBIR/STTR Phase II Exchange Meeting, July 30, 2025

Outline

- Optimum Integral Design: Why? What? Relevance to EIC?
- Goals of PBL/BNL STTR on the Optimum Integral Dipole B0ApF:
  - ➢ Meet key technical specs: integral field, field quality, cross-talk
  - ➢ Field integral = 1.98 T.m, B_o = 3.9 T, coil i.d. = 114 mm

    (higher “field & aperture” than RHIC arc dipole: 3.45 T, i.d. 80 mm)
- Design, construction and test results
- Application to other magnets (in EIC, and beyond)
- Summary

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)

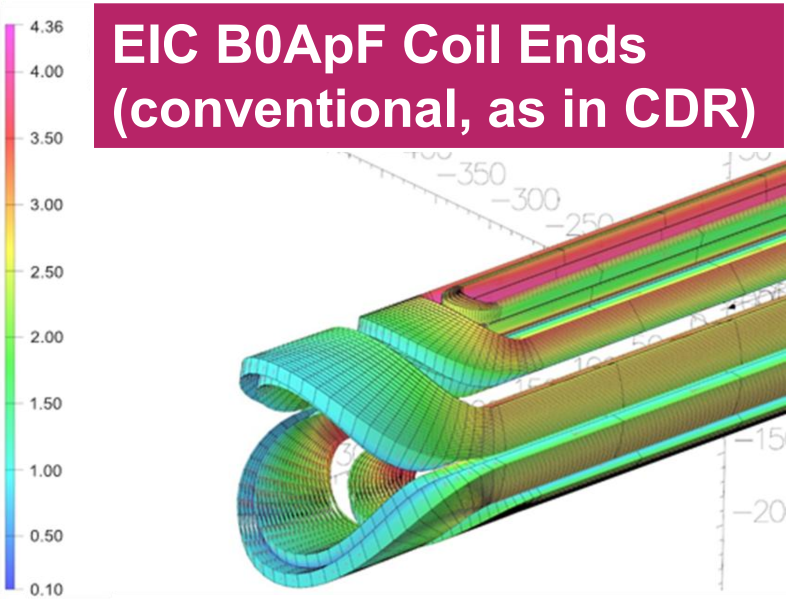
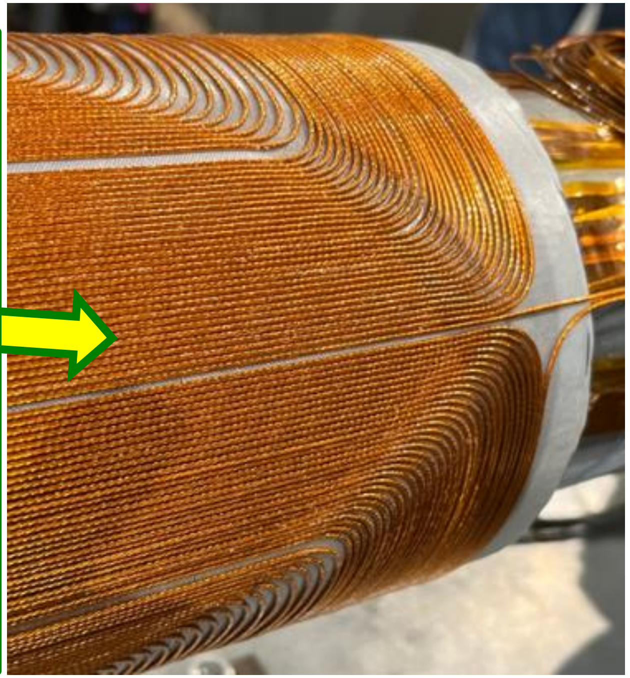


Figure 5: B0APF coil with field contour

Optimum Integral Design:

- End turns at midplane run full length of the coil => almost no loss in space due to Ends
- Gain in magnetic length => about a coil diameter in dipole. A significant fraction in short magnets (as some in EIC)



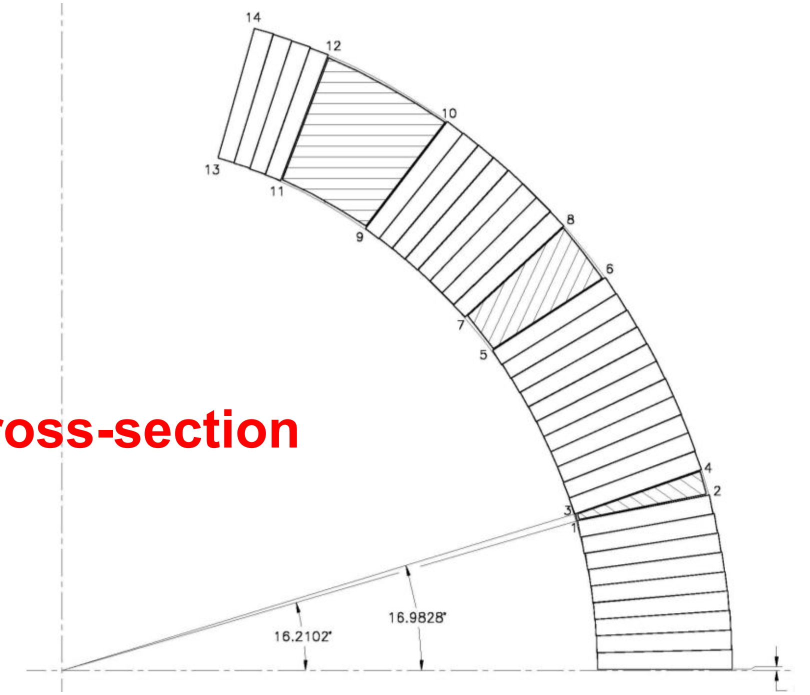
Conventional Design Approach

A two-step process of designing magnets:

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

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

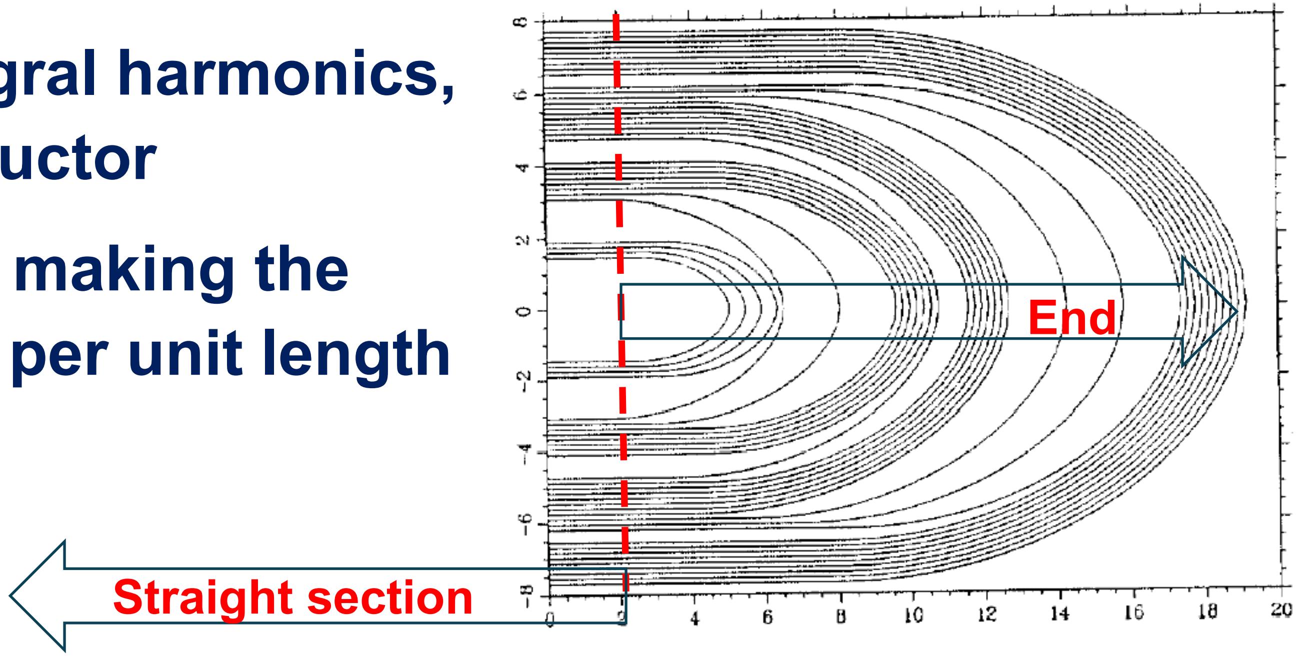
- This limits the number of turns in straight section



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

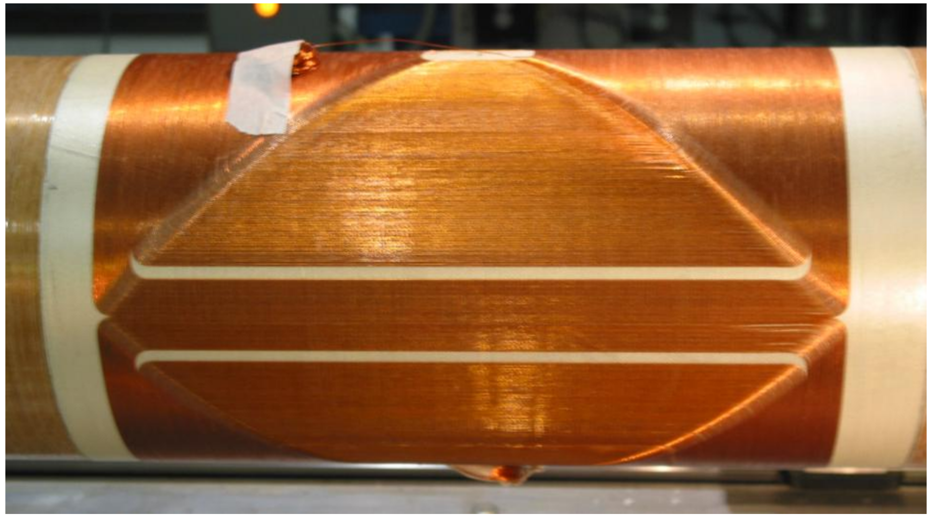
- This spreads out turns in the ends, making the ends longer, and reducing the field per unit length

Each step shapes the field and reduces the integral field



Optimum Integral Design Approach

Extend midplane turns to full coil length & optimize cross-section and ends together in a single step to obtain an overall cosine theta distribution in the integral sense:

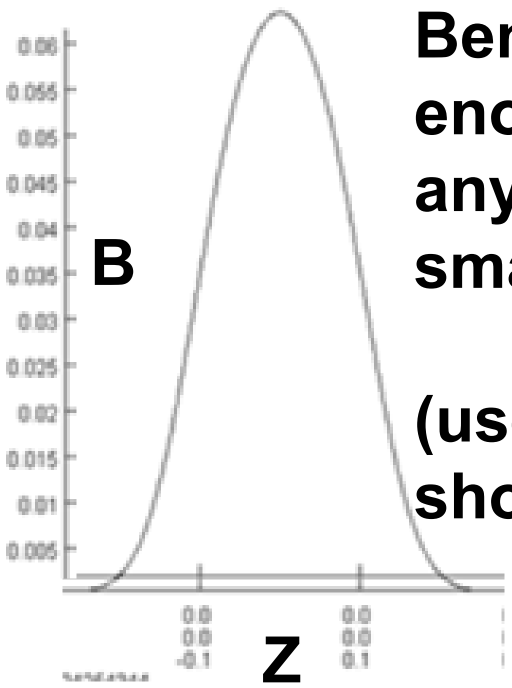


$$I(\theta) . L(\theta) = I_o . L_i(\theta) \propto I_o . L_o . \cos(n\theta)$$

Length of coil ends, which determine the loss in magnetic length, made nearly zero

- ✓ **Loss due to ends essentially eliminated**

Higher fill factor - both in the body and in the ends

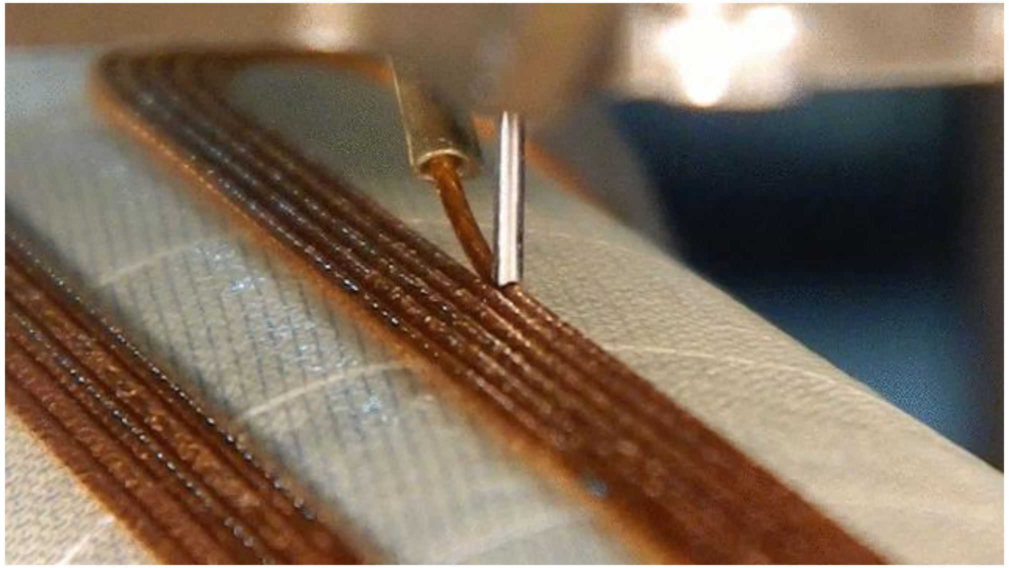


Benefits are enormous in any magnet with small flat-top

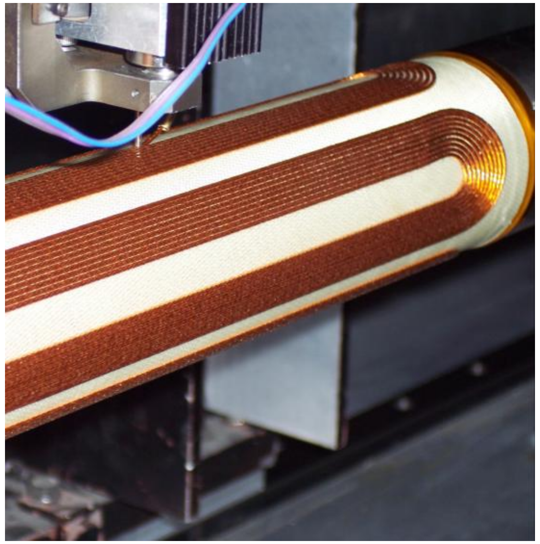
(useful in all short magnet)

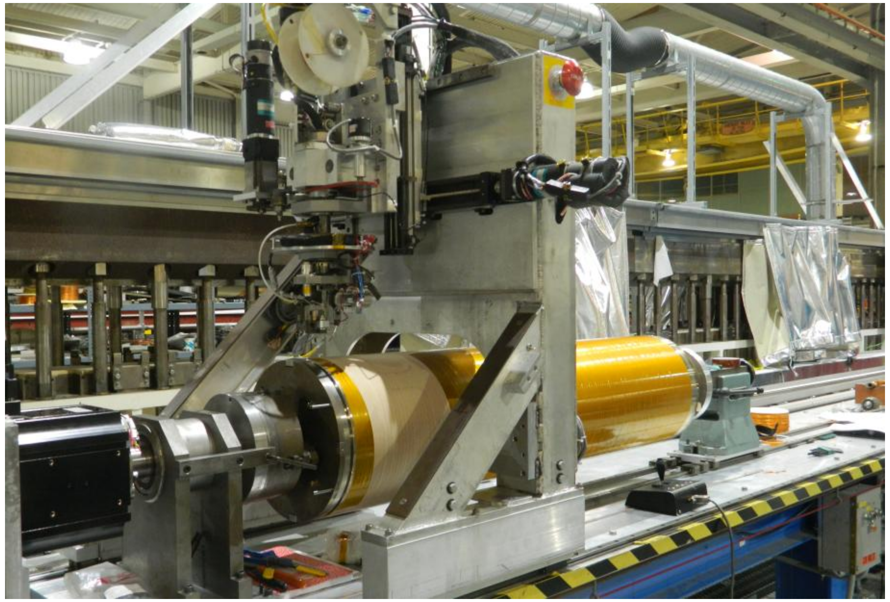
AGS dipole

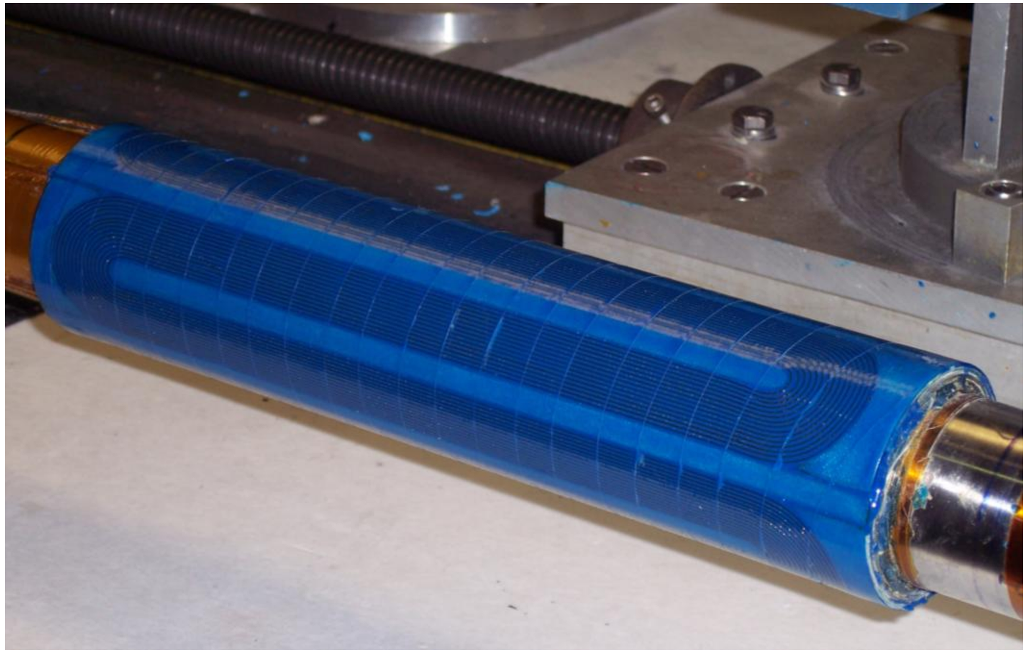
A Key Component of this STTR – the Direct Wind Technology



- **Wire is laid directly on the tube and bonded using ultrasound onto a substrate (plus other steps)**
- **This is an inexpensive technology for one-off magnets. It doesn't require tooling, and detailed design. It has been reliable for low field magnets**
- **Question: Can this technology be taken to higher fields as needed in EIC? To be tested in this STTR**

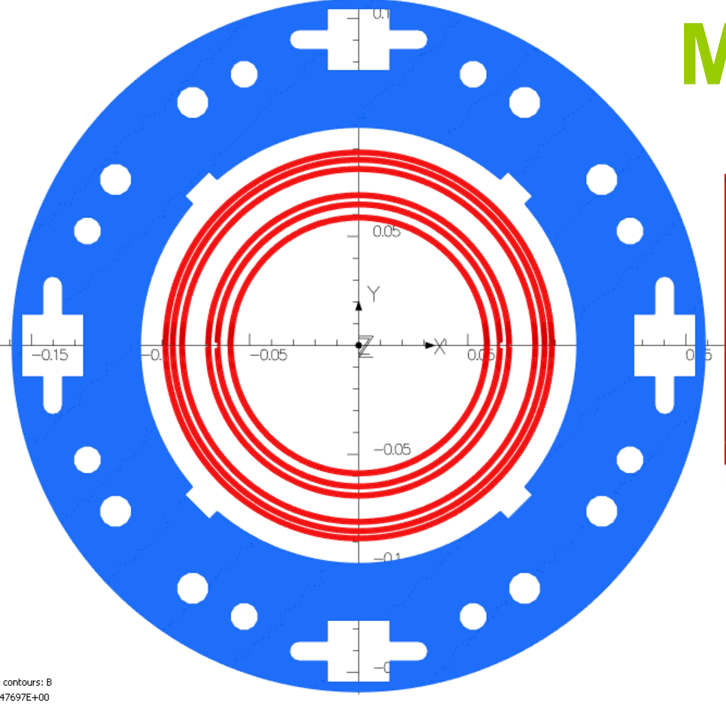


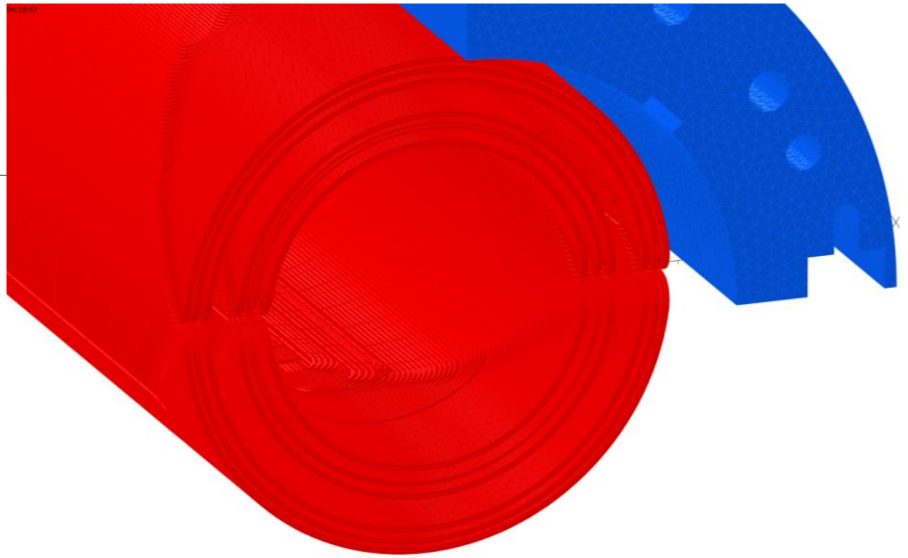




R&D Magnet Design for EIC IR Dipole B1apF

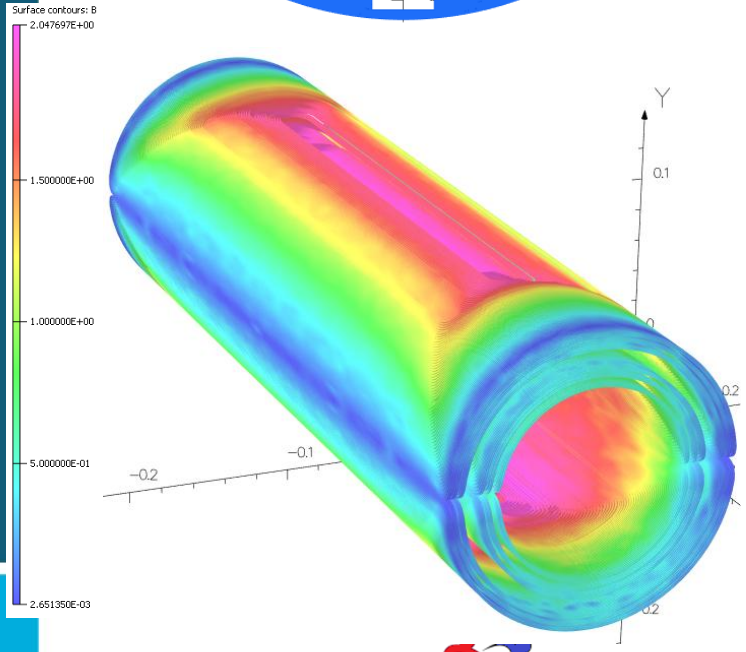
Magnetic Design of the 12 Layer OID B0ApF



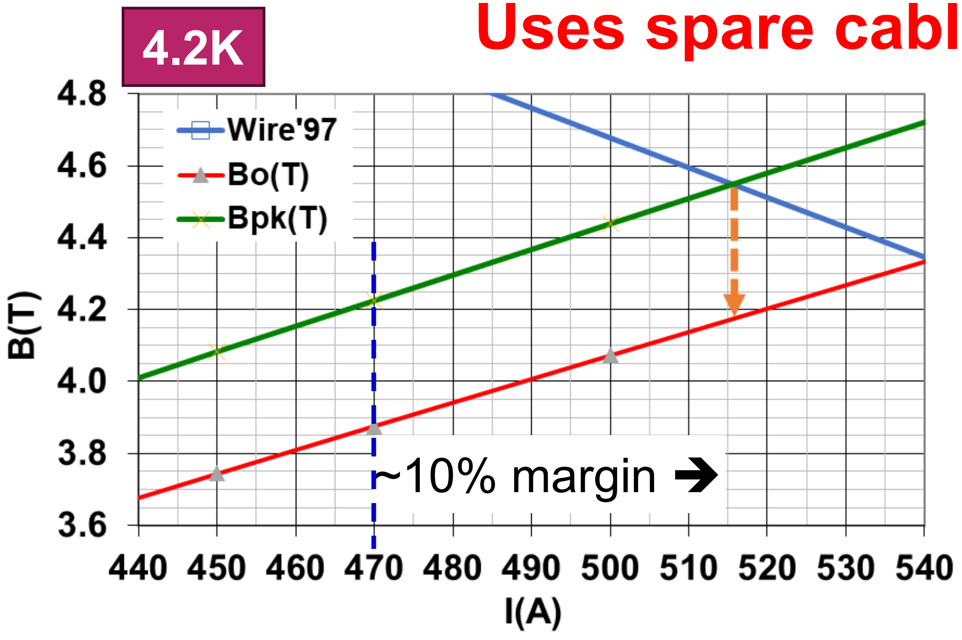


Key Parameters:

- Coil id, od: 114, 183 mm
- Coil length: 600 mm
- B_o, B_{pk}: 3.9T, 4.3T @470A
- Integral field: 1.98 T.m
- Inductance: ~700 mH
- 12 Layers (6 + 6)
- Intermediate SS tube

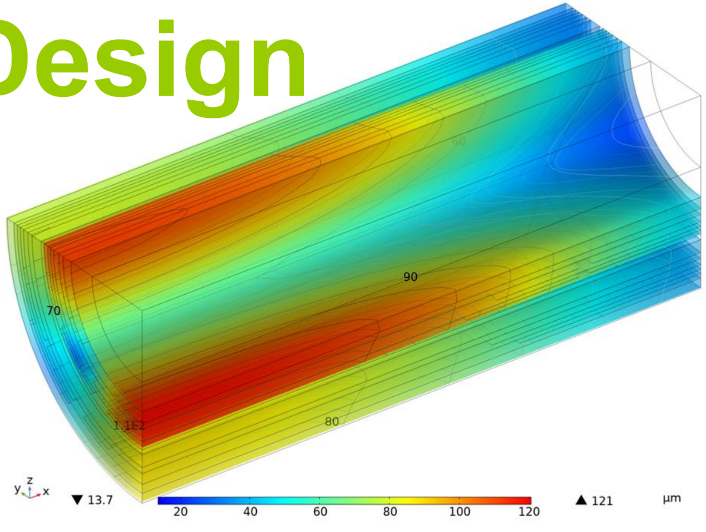


Uses spare cables from a previous project



- Superconducting wire diameter: 0.33 mm
- Filament diameter: 10 μm
- Cable type: 6-around-1
- Cable diameter (bare): 1 mm
- Cable diameter (Kapton insulated): 1.1 mm
- Critical current (4.2K, 5T): > 421 A
- Copper to superconductor ratio: 2.25
- Cable used in the magnet: 1.7 km
- Computed quench current at 4.2 K: ~500 A

Mechanical Design of the 12-layer Design



Analysis with COMSOL

<u>Primary components of mechanical structure:</u>

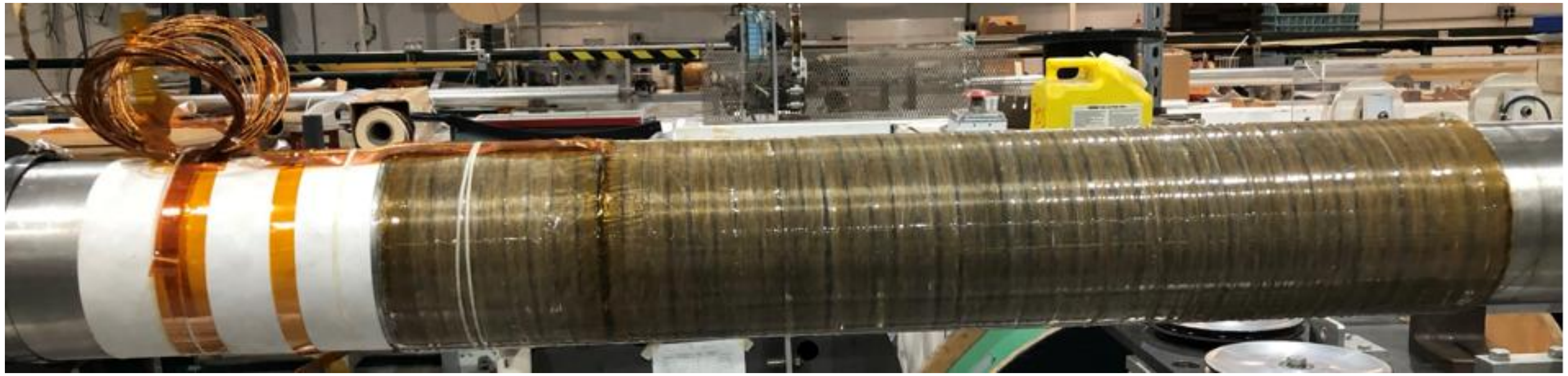
- **Tension roving after every two layers**
- **Two stainless steel tubes**
  - ➢ **2 instead of 1 to reduce stress/strain buildup**

Three Phases of the PBL/BNL STTR Program

- **Phase I:** **Two layers**
- **Phase II (year 1):** **Six layers**
- **Phase II (final):** **Twelve layers (six layers each on two tubes)**

➢ **An ambitious undertaking with a field and aperture higher than that in the RHIC arc dipoles !**

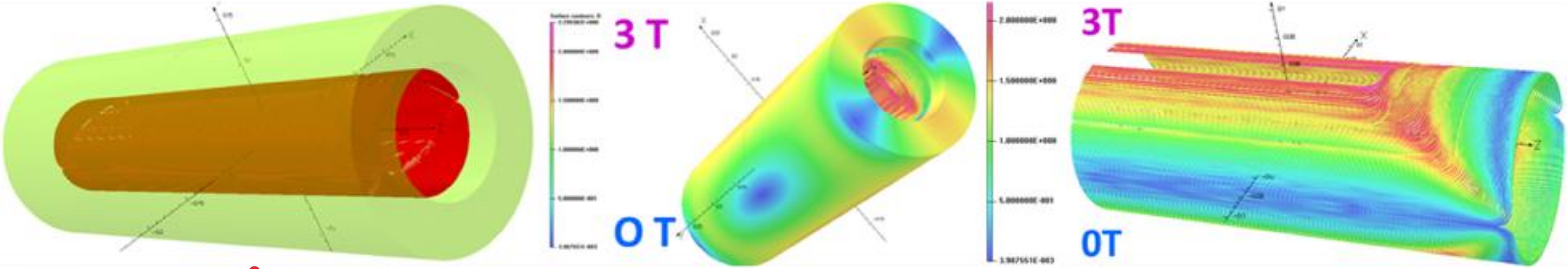
Optimum Integral Dipole in Phase I (two layers in a yoke)



Tension rowing over two layers to contain forces (inner SS tube also has a role in the mechanical structure)

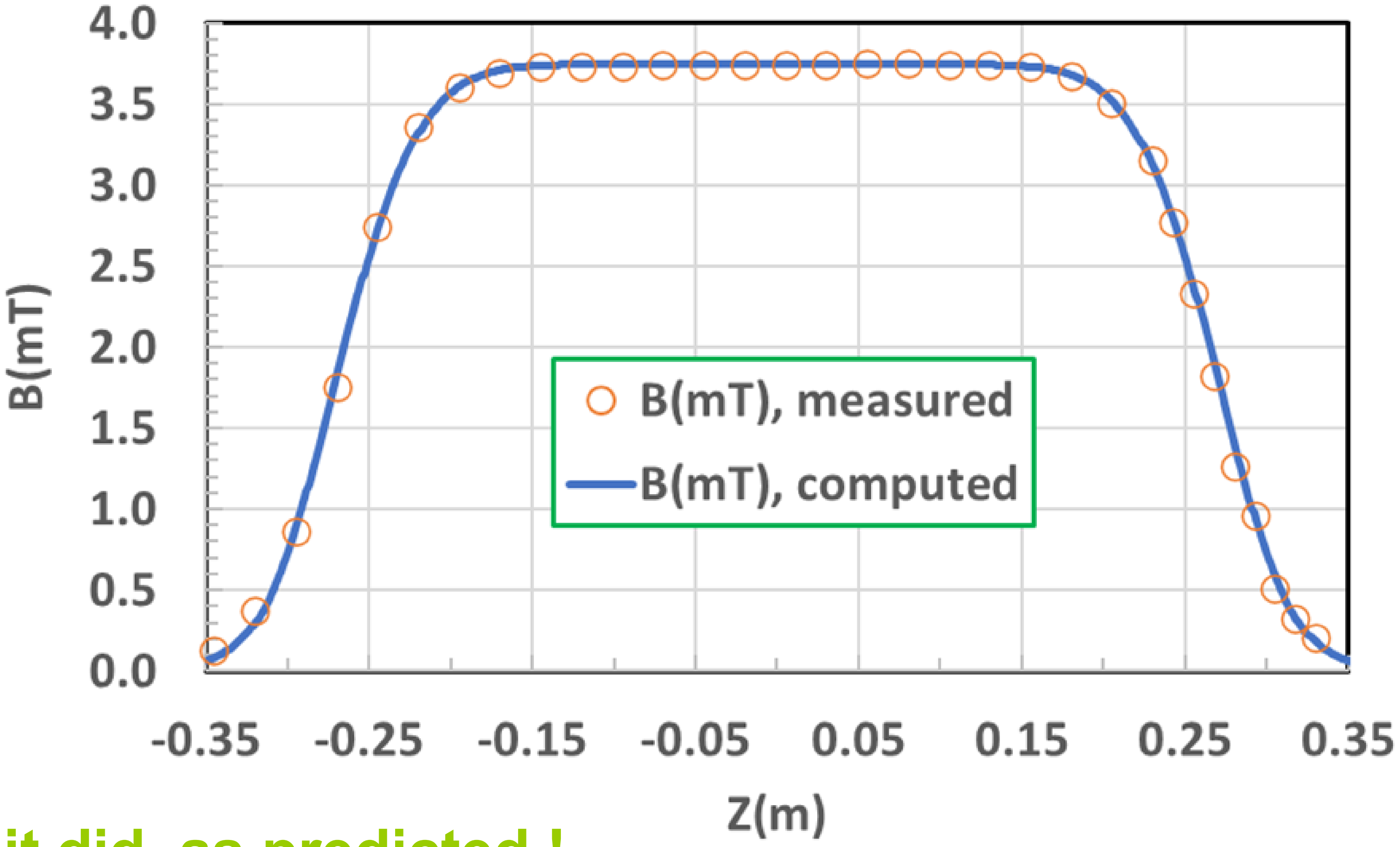
Coil in the yoke (ready for the testing)

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



Question #1: Will optimum integral design extend the magnetic length?

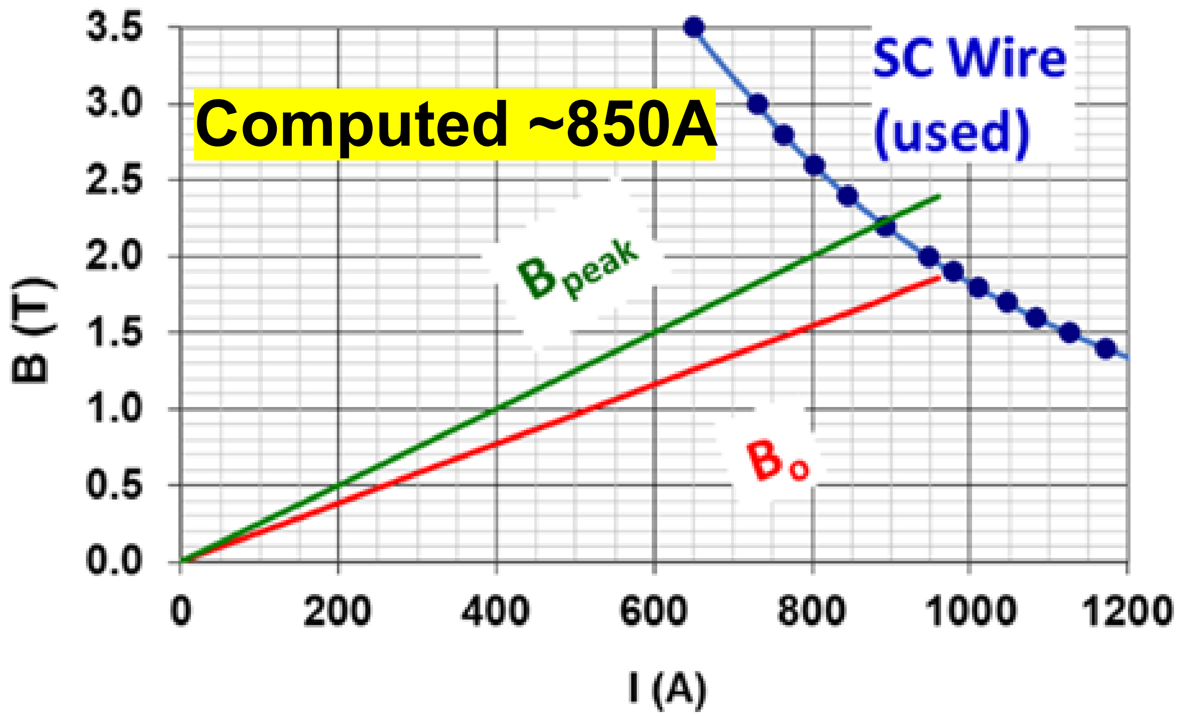
Major motivation of the optimum integral design demonstrated

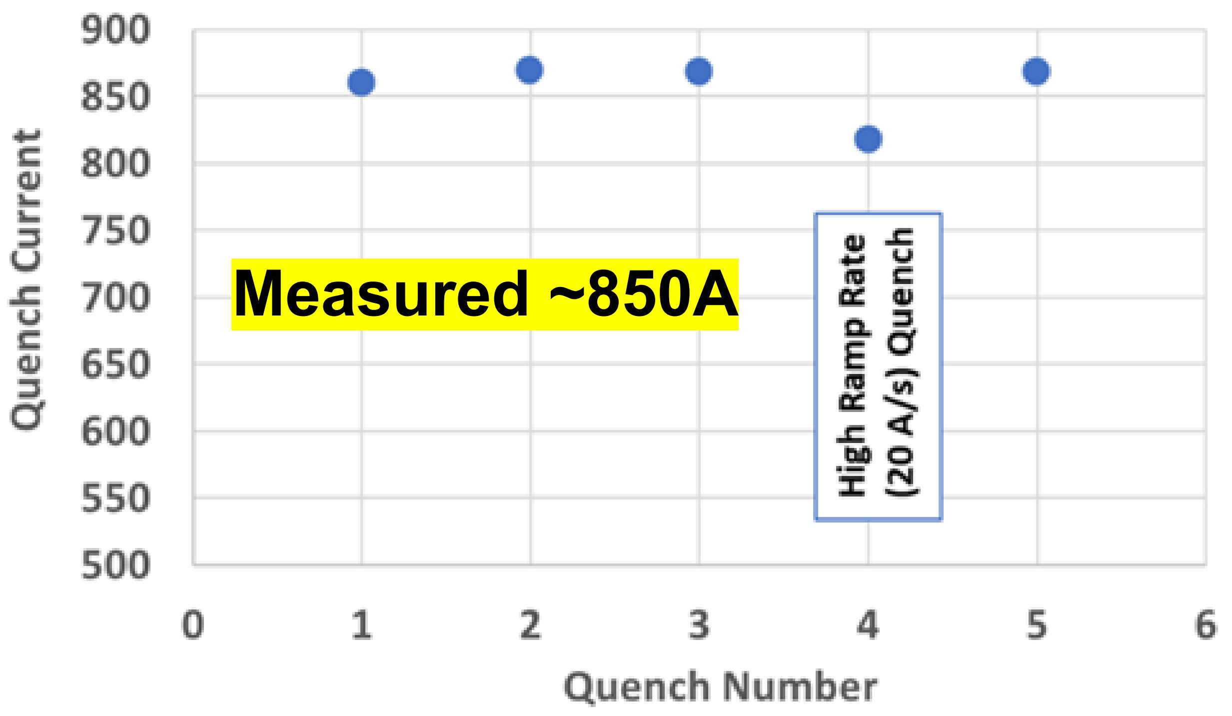


✓ **Answer: Yes, it did, as predicted !**

Good agreement between calculations & measurements.

Question #2: Will the direct wind coil based on the optimum integral have a good quench performance?





✓ **Answer: Quench performance remains excellent to this field/bore (reached computed short sample without any training)**

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

These two are significant demonstration for a Phase I (in <1 year)

Goals of the Phase II Magnet

a) Demonstrate field quality with warm magnetic measurements

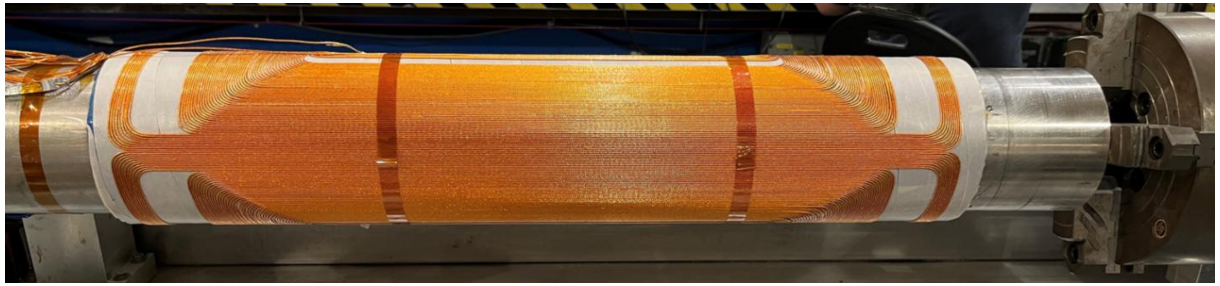
- Validation of the optimum integral design and the special software developed

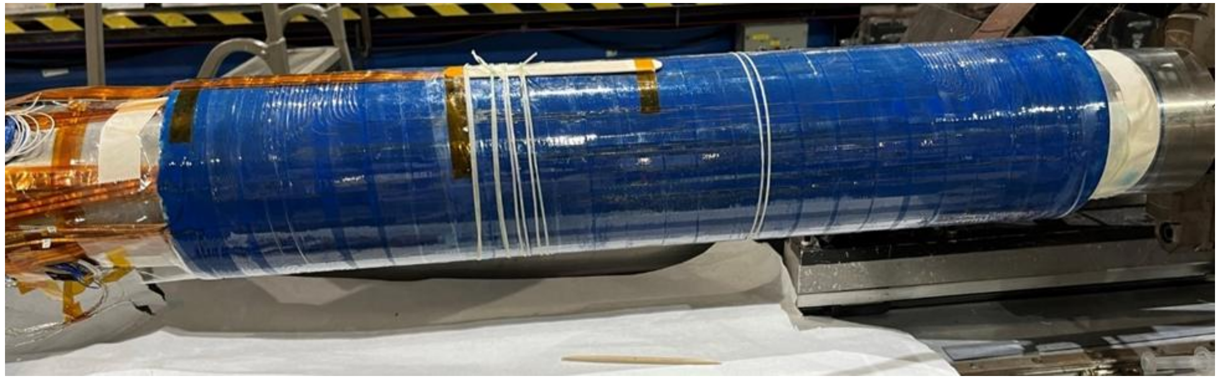
b) Intermediate test with six layers and final test with twelve layers

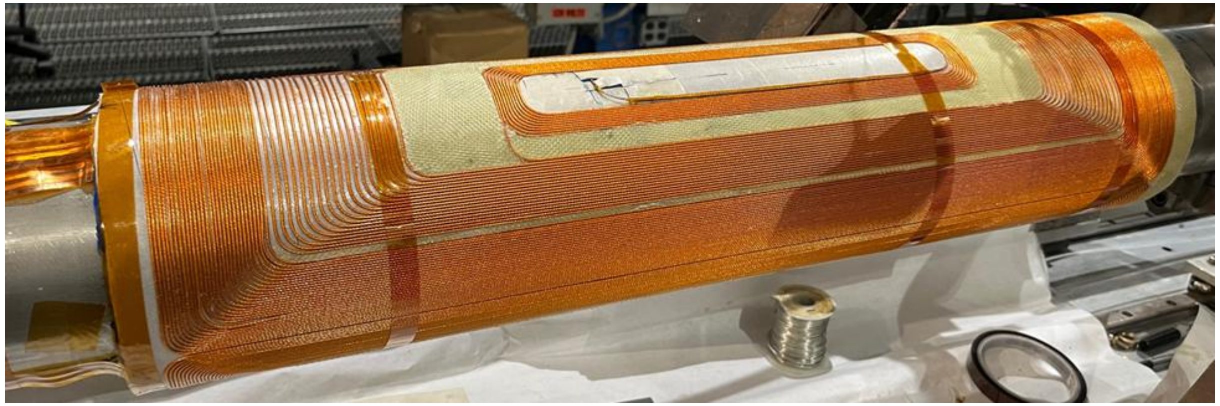
- 6-layer: B_o=~2.9 T, B_{pk}=~3.5 T, B_{int} =~1.5 T.m
- 12-layer: B_o= ~3.9 T, B_{pk}=~4.3 T, B_{int} =1.98 T.m (+margin)

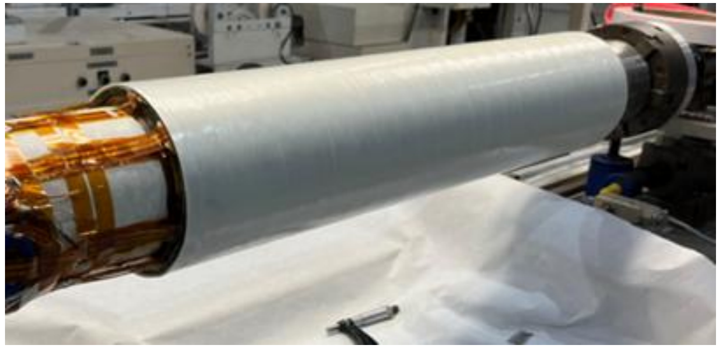
c) Demonstration of the superconducting shielding in a geometric and magnetic configuration as faced by the electron beam in EIC

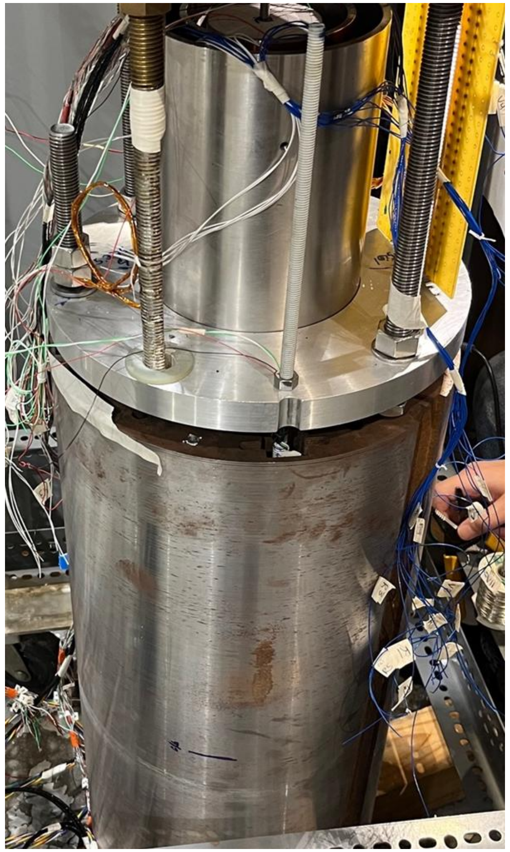
Coil Winding, Magnet Construction (Phase II, Year 1)

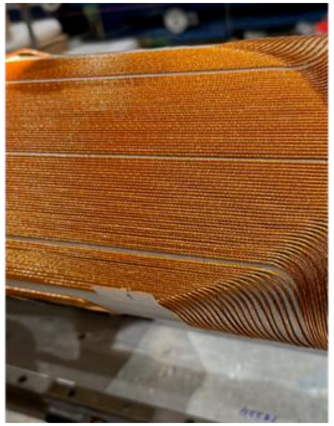


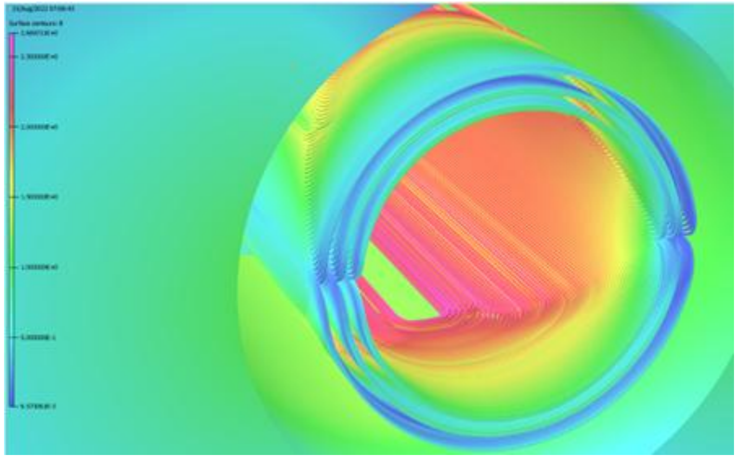












Six layers (3 coil sets)

Field Quality Demonstration of the Design, and of the Code

(code uses a new method)

Warm harmonic measurements after the 6 layers of B0ApF OID

Success: A good field quality in the 1st attempt itself, despite changes.

Optimum Integral Dipole B0ApF 6-layers		
ITF (NO Fe	1.860	mT.meter/A
Measured Integral Harmonics@25mm		
No.	bn	an
2	0.62	2.83
3	3.98	2.81
4	0.23	-0.52
5	0.39	0.21
6	0.07	-0.21
7	0.51	0.16
8	0.00	0.05
9	-0.12	-0.03
10	0.00	-0.01
11	0.02	0.01
12	0.00	0.00
13	-0.01	0.00

(in 10^{-4} units)

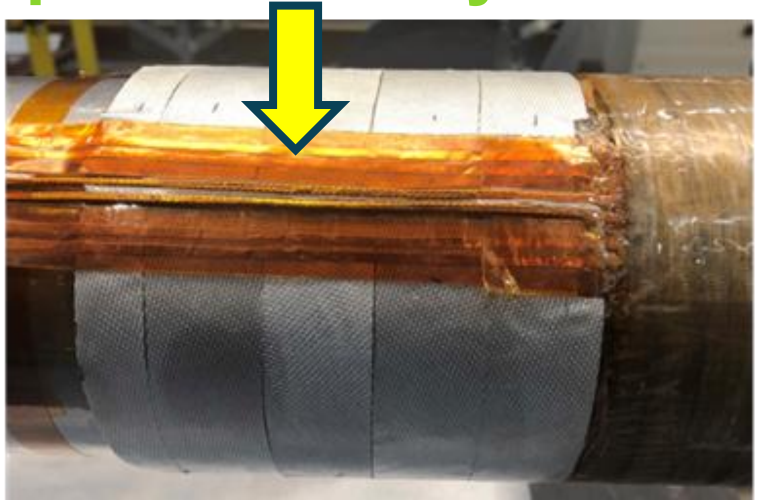
Lower order terms from the external leads (not real).

All other harmonics are <2 units (meets the spec).

Small measured harmonics are corrected in the outer coil.

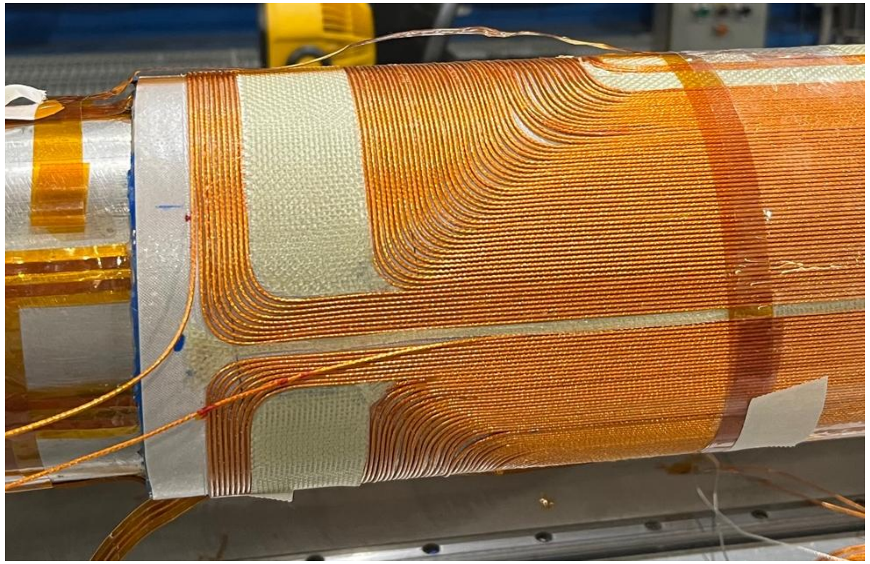
A Change in Design to Eliminate Loss in Radial Space Used by Leads

- Phase I "Optimum Integral Design" used extra radial space for bringing leads out "over the coil" at the pole.
- Used in the first two layers.



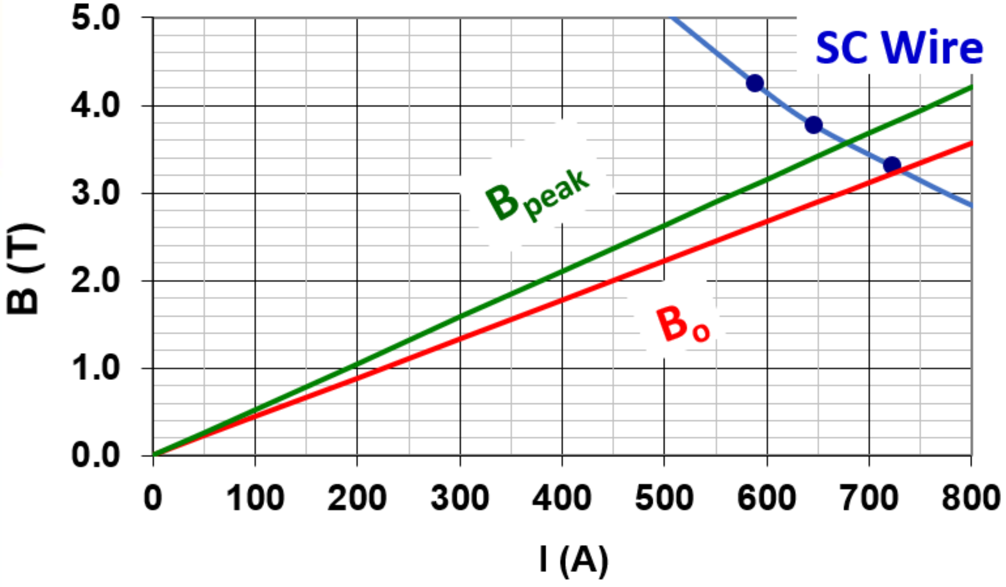
Phase I configuration

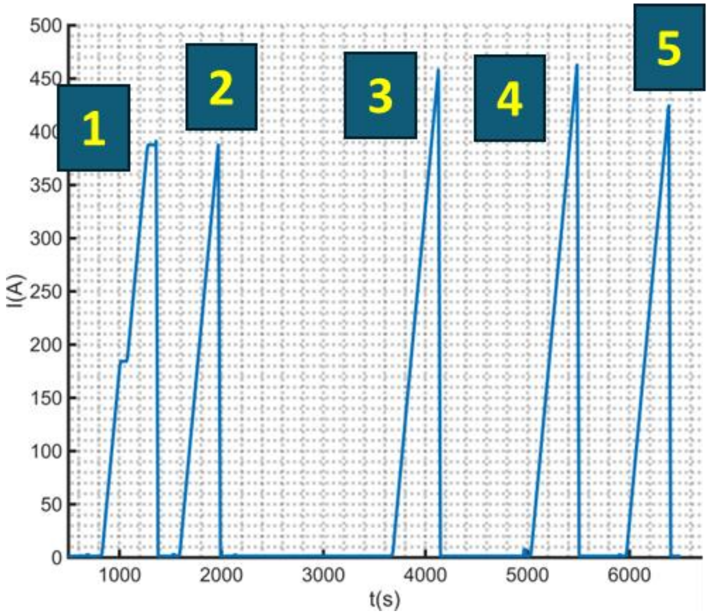
- An innovation was implemented to remove extra radial space. Leads out at midplane.
- This solution required a splice at the pole in high field region, and additional routing of leads in an area outside the end of coil.
- This was used in the next four layers.

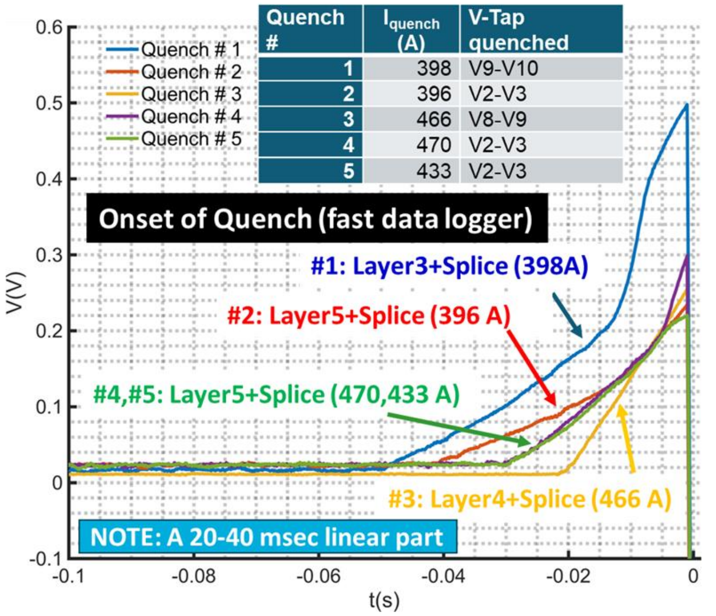


Phase II configuration

Quench Test of the 6-layer Optimum Integral Dipole







B_o:2.4T@470A

- **First quench at ~60% and highest at ~70% of the short sample (670A).**
- **All quenches were in the coil sets where the lead routing was modified to eliminate the use the extra radial space.**

Issue that limited the performance seems to have been resolved now (next slide)

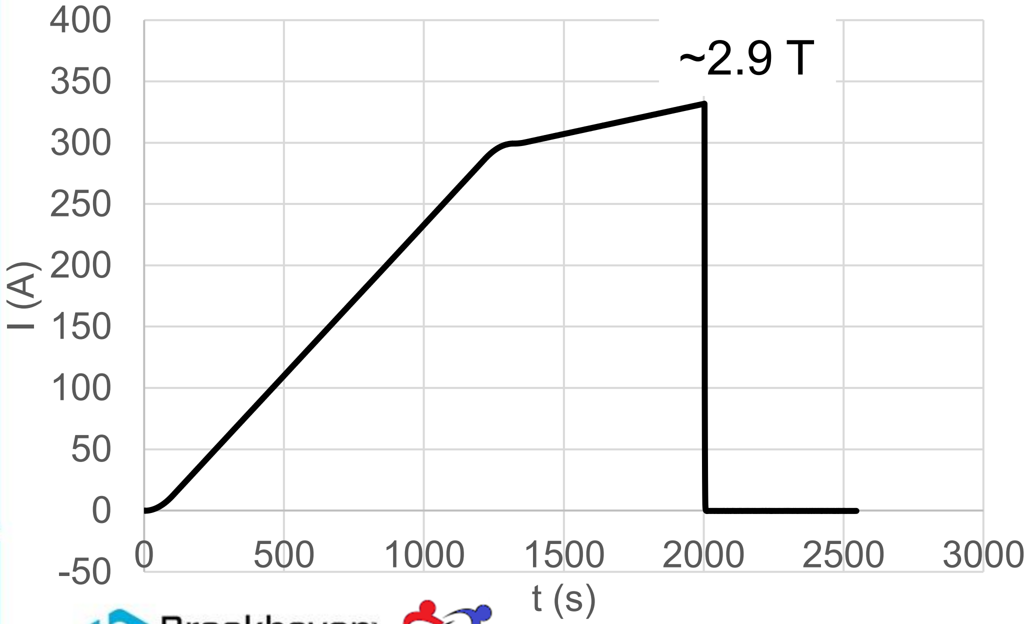
Investigation and Resolution of What Limited the Performance of Phase II, Year 1

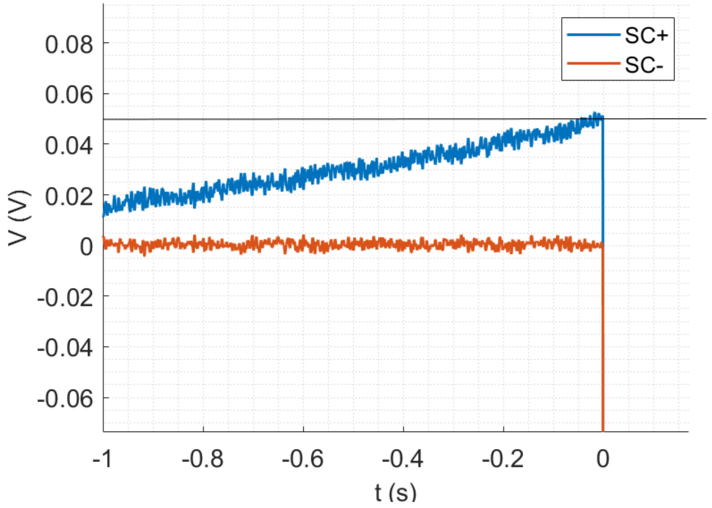
- **Weakness found in routing of the leads outside the magnet.**
- **Improved support to make the lead routing more robust.**

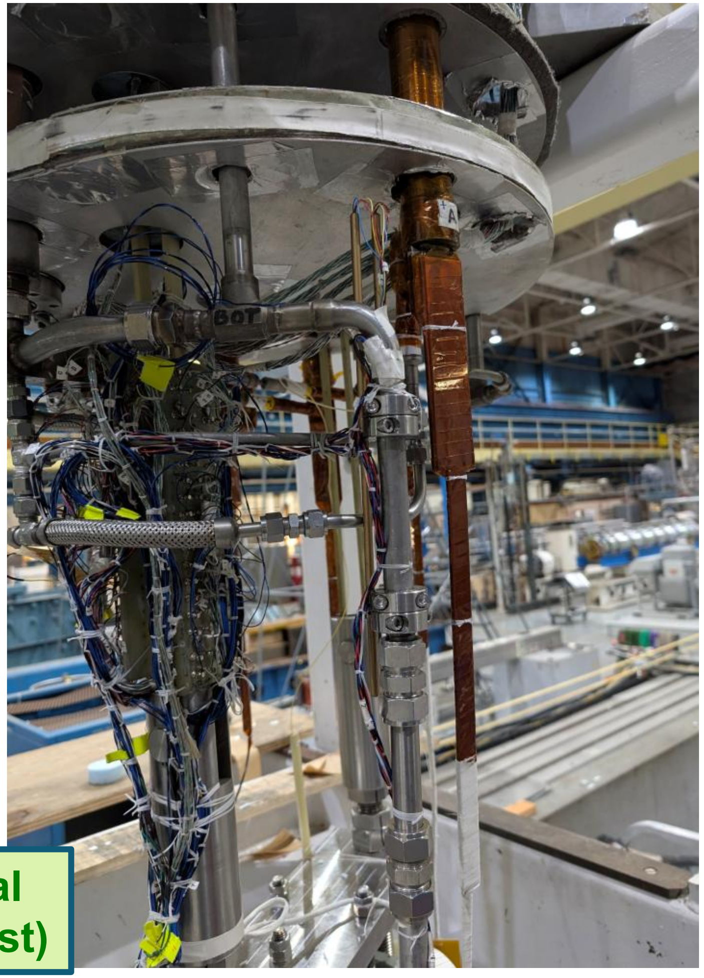
Test Results of the 12-layer Direct Wind Optimum Integral Dipole B0ApF

- **Magnet energized to ~2.9 T or 1.49 T.m (~75% of the required field integral) with NO spontaneous quenches.**
- **A significant and promising test result for direct wind**
- **Innovation to reduce radial buildup appears to work**
  (since the magnet was energized to higher fields and the splices were subjected to larger forces, issue that limited the performance seems to have been resolved now)
- **Test was limited by the difference voltage in sc leads exceeding 50 mV, either from a joint or a signal mix-up.**

~84% of the design field of RHIC 80mm dipole, in 114mm aperture





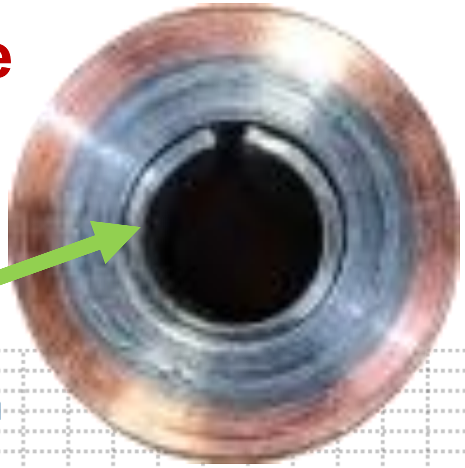


(magnet seems to be good, external issue to be fixed before the next test)

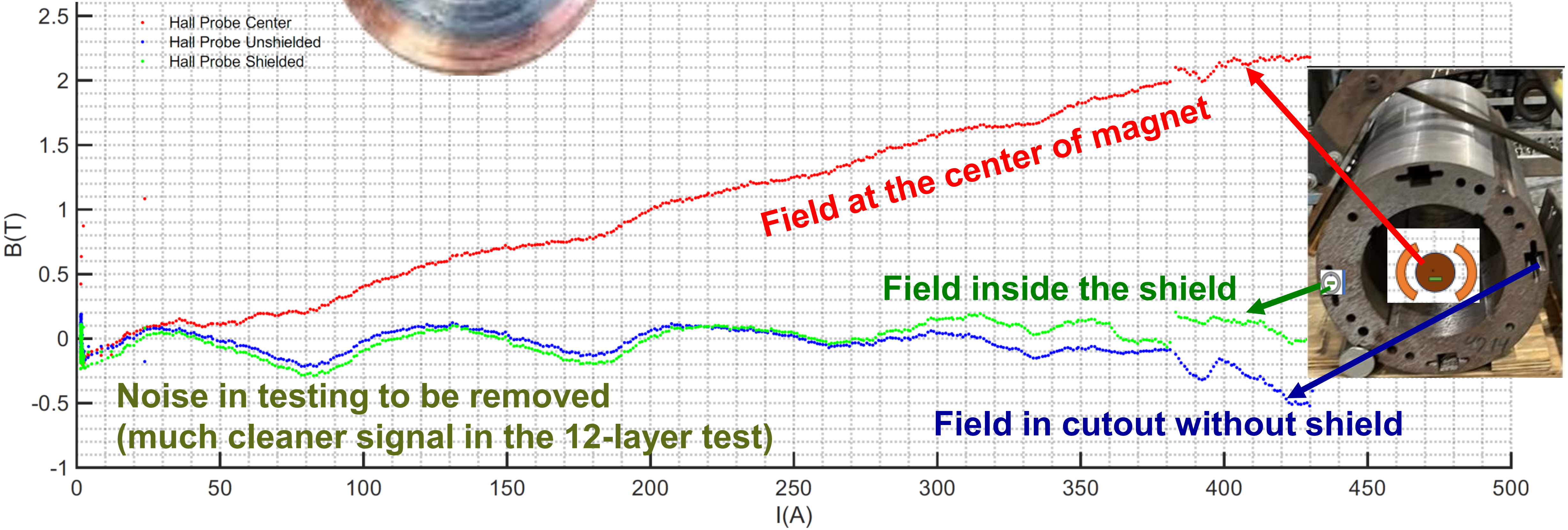
Demonstration of Superconducting Shielding in 6-layer Magnet

NbTi Tube

High permeability *A4K to shield persistent field

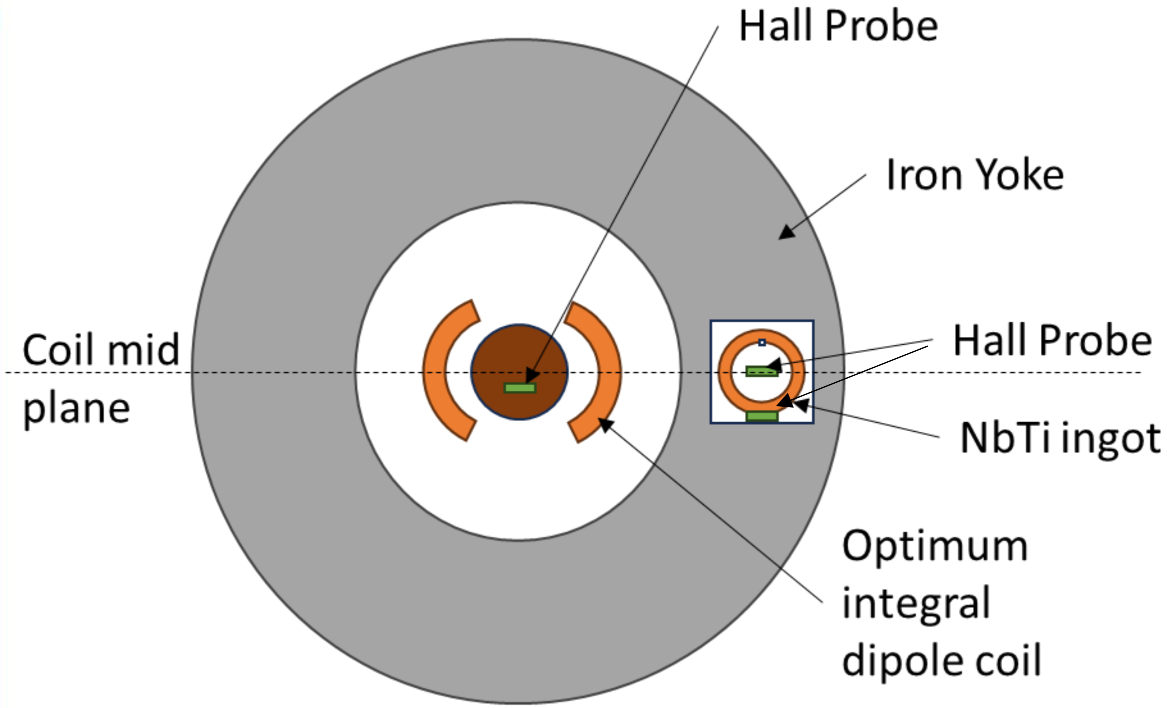


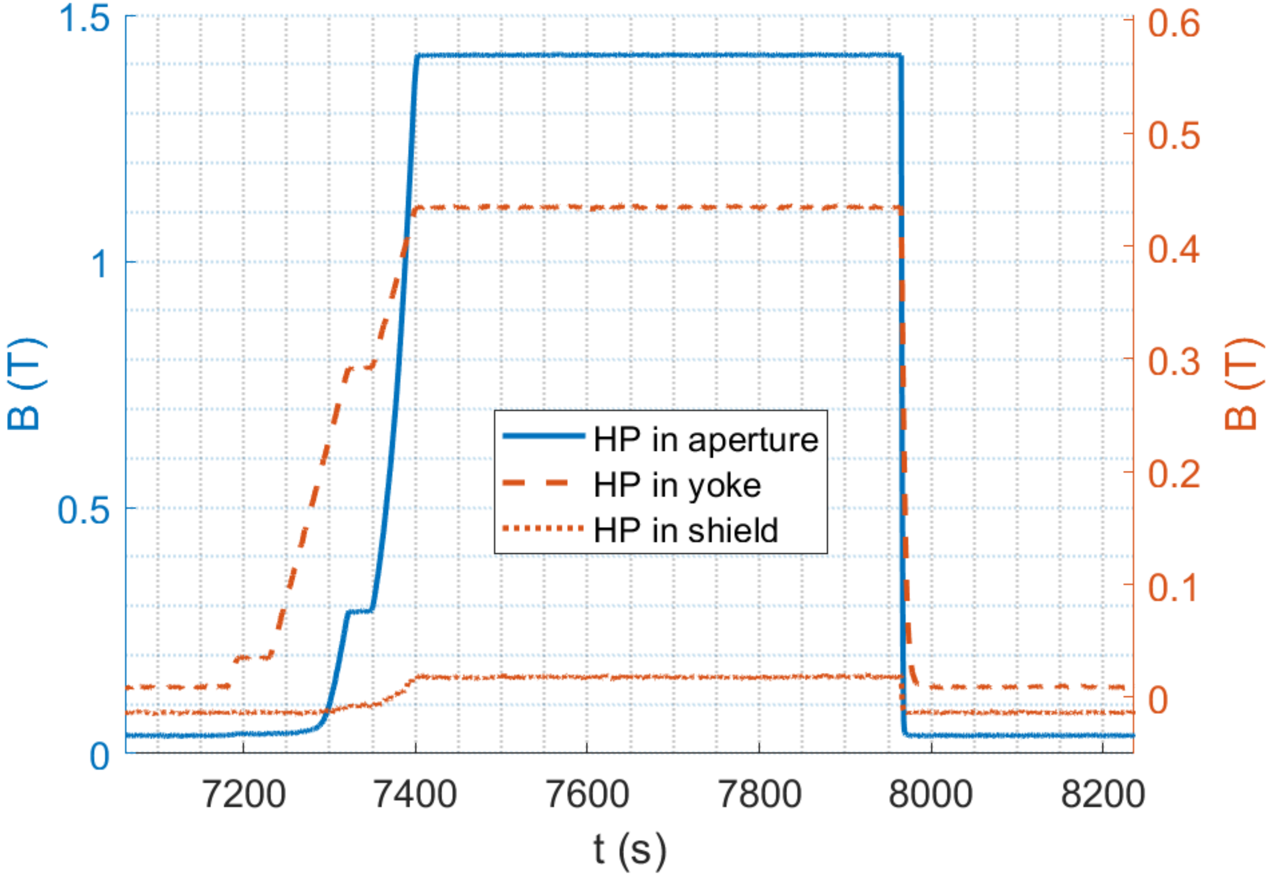
Superconducting shielding works



*A4K: High permeability Amumetal 4K (A4K) from Amuneal Manufacturing Corporation

Passive Shielding Experiment in 12-layer higher field dipole





(cleaner Hall probe signal, data still being examined)

Possible Application of the Optimum Integral Design in Other EIC Magnets

Possibility of Optimum Integral Design for Short EIC Magnets

- Typical mechanical length of end: ~ 2 coil diameter each in dipole. Total ends in dipole: ~four diameter (~2 coil diameter in quad).
- Compare coil length (L) to coil i.d. (id) ratios. Relative loss will be significant when the ratio is <8 in dipoles and <4 in quadrupoles.

Coil length to coil diameter ratios in some EIC magnets:

- B0ApF (*L* = 600 mm, i*d* = 114 mm): ~5.3
- B1ApF (*L* = 1600 mm, i*d* = 370 mm): ~4.3
- B1pF/B1ApF (L = 2500 mm, id = 363 mm): ~6.9
- B0pF/Q0eF (L = 1200 mm, id = 656 mm): ~1.8

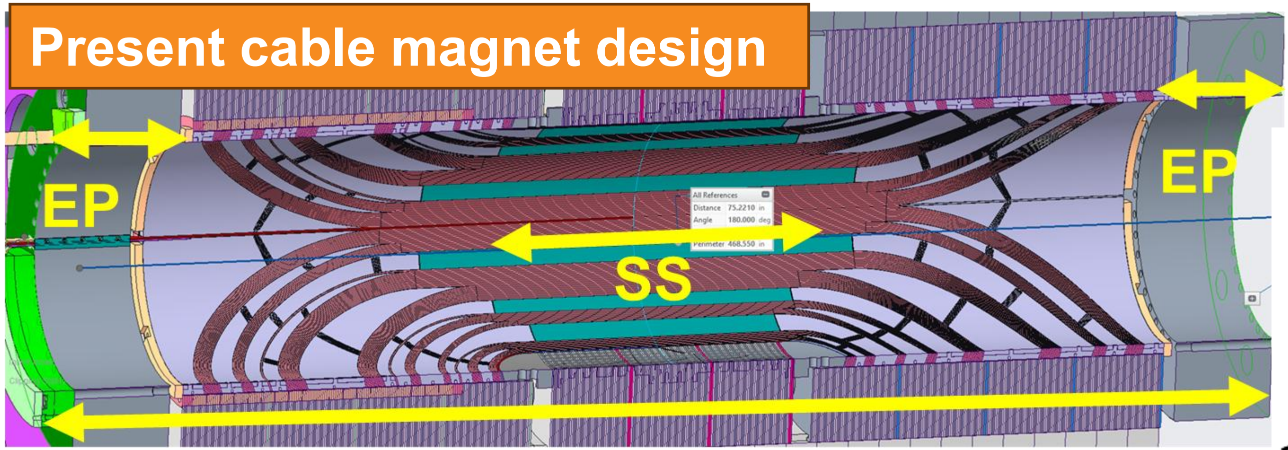
(compare this to quadrupole, not to dipole)

Reference guide
~8 in dipole
~4 in quads

Value of the Optimum Integral Design in B1ApF

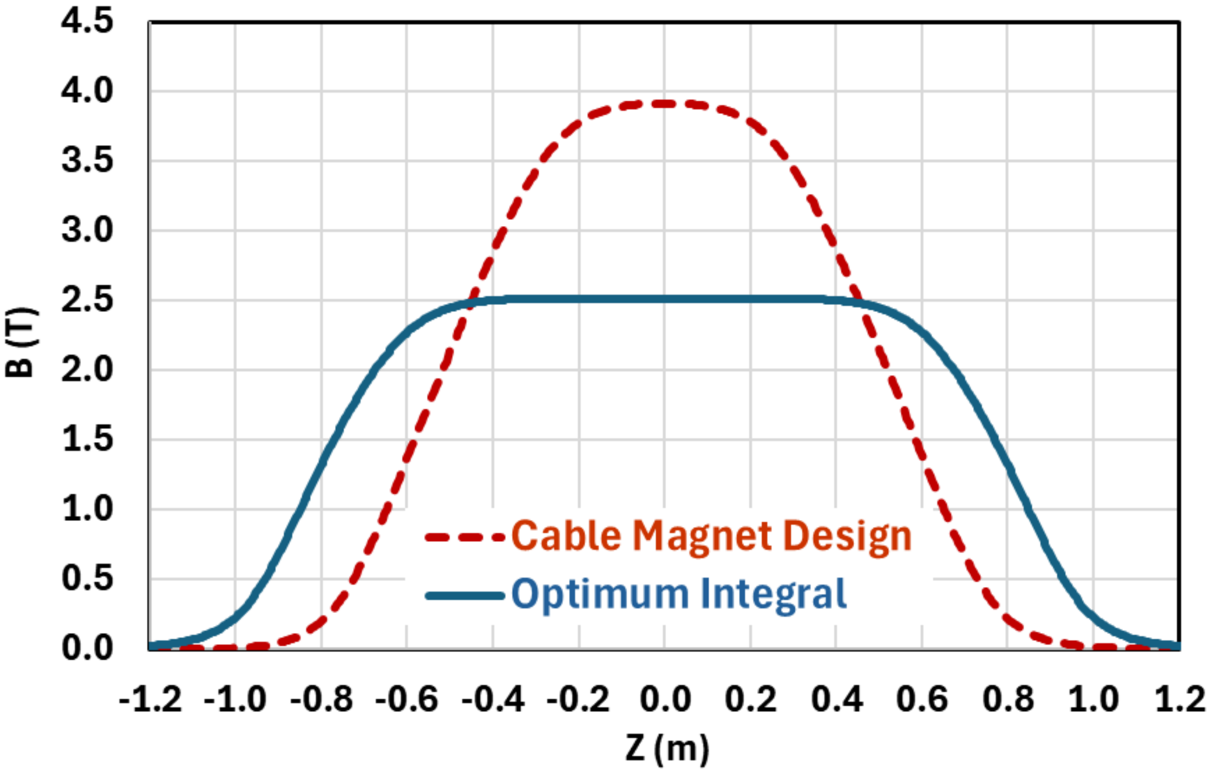
(comparison with the cable magnet design–current baseline)

Present cable magnet design



Direct wind optimum integral design

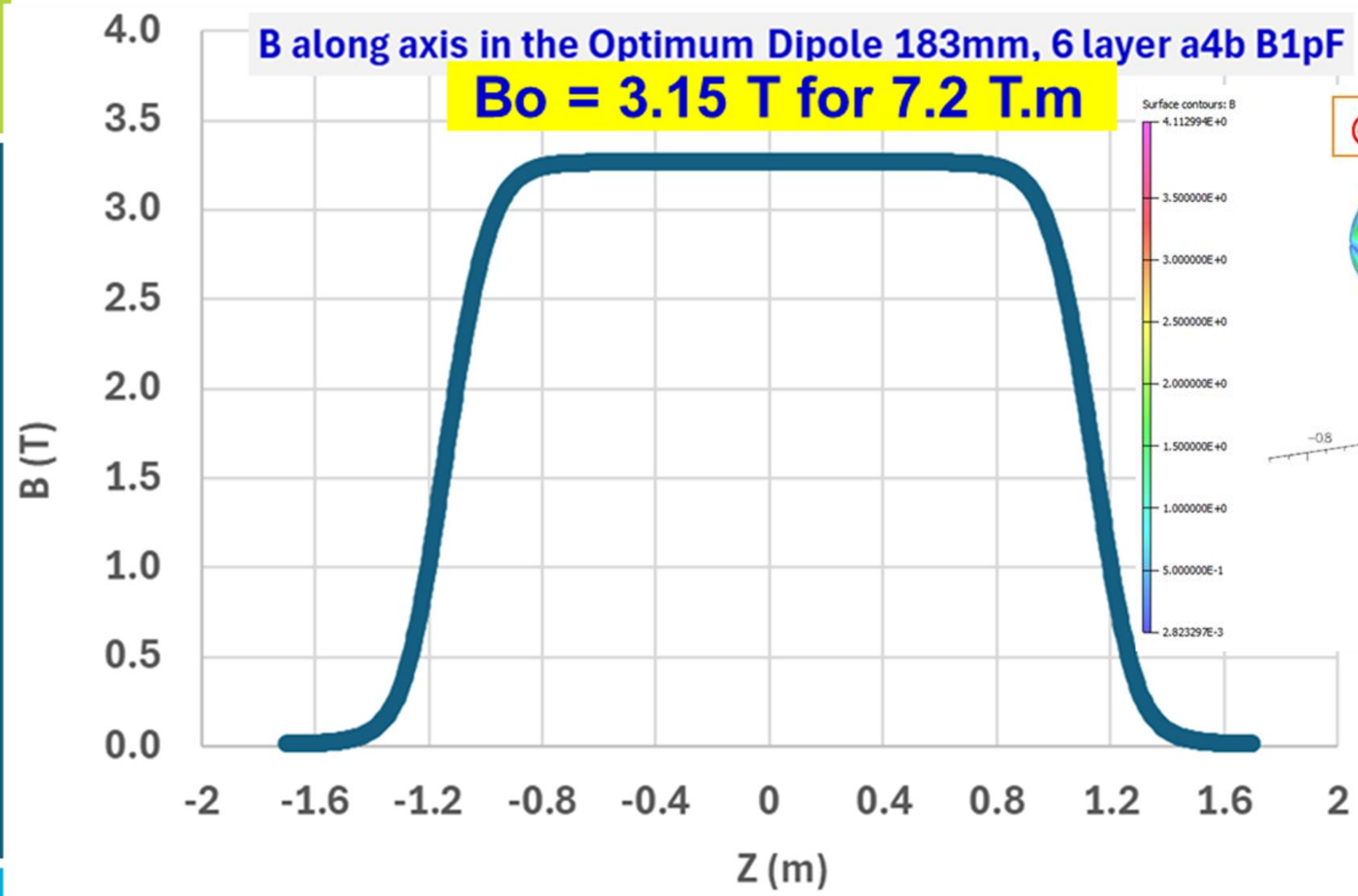
A wider flap-top in Optimum Integral

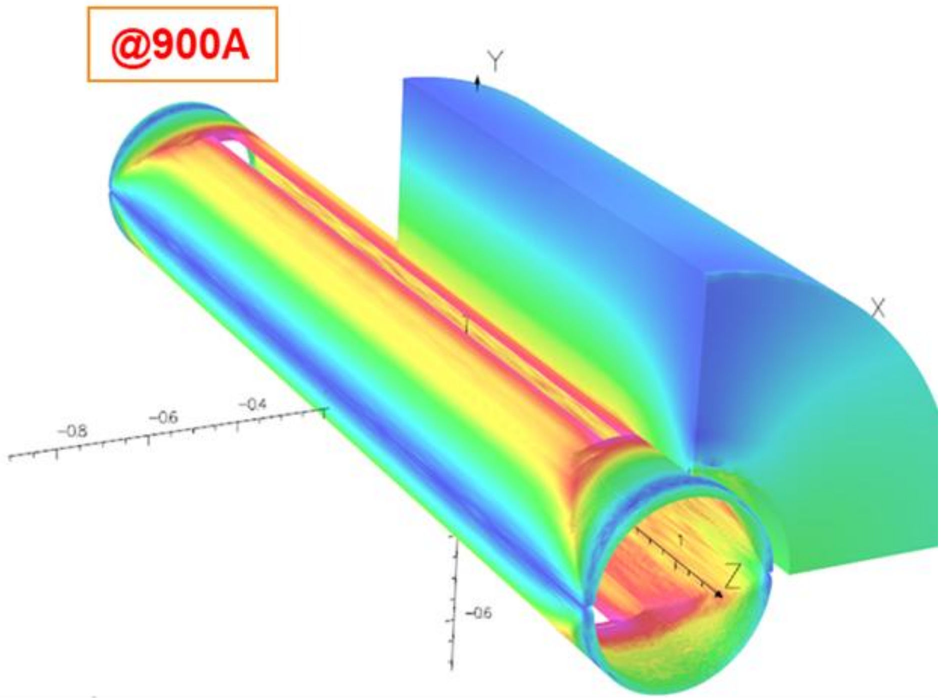


Technical benefit: B_o goes down from ~3.9 T to ~2.5 T; forces/stresses go down as B^2

- **Required Field Integral: 4.05 T.m**

B1pF/B1ApF Common optimum integral 6-layer design (1)

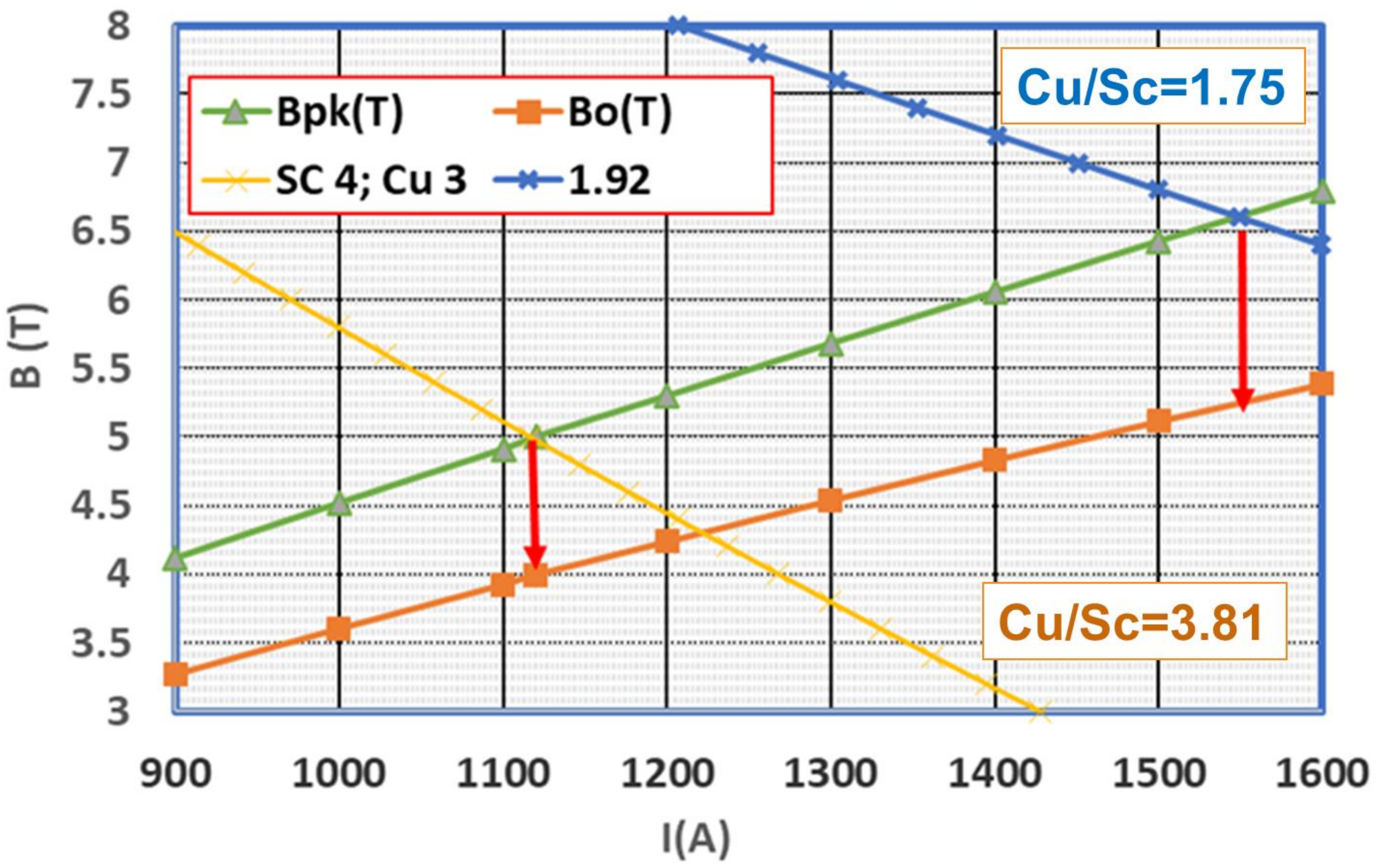




- **Coil id: 363 mm**
- **Coil length: 2,500 mm**
- **Integral field: 7.2 T.m**
- **Magnetic length: 2.25 m**
- **Design current: 885 A**

B1pF/B1ApF Common optimum integral 6-layer design (2)

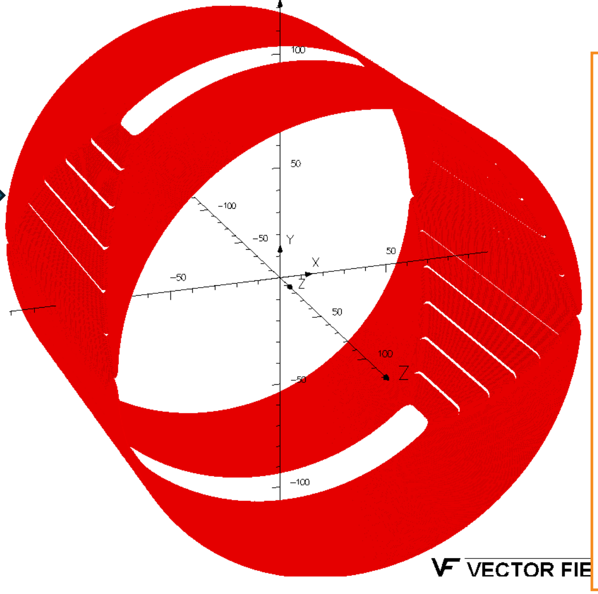
- **Coil id: 363 mm**
- **Coil length: 2,500 mm**
- **Length/Aperture: 6.9**
- **Number of layers: 6**
- **Field at the center: 3.2 T**
- **Integral field: 7.2 T.m**
- **Magnetic length: 2.25 m**
- **Design current: 885 A**
- **Wire dia: 0.47 mm**
- **Cable: 6-around-1 (not all Superconductor)**
- **Temperature: 1.92 K**



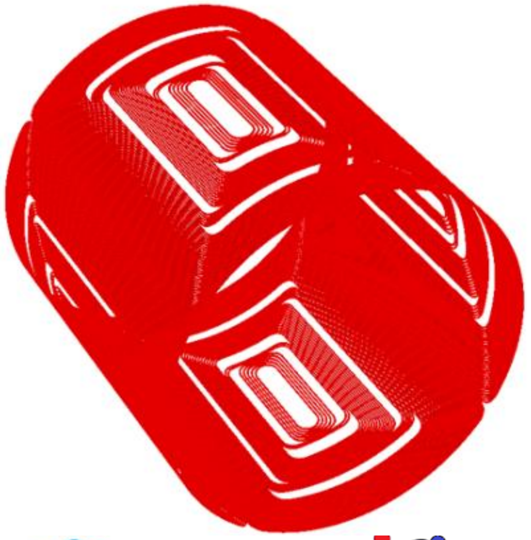
Optimum Integral Design Opens a New Parameter Space

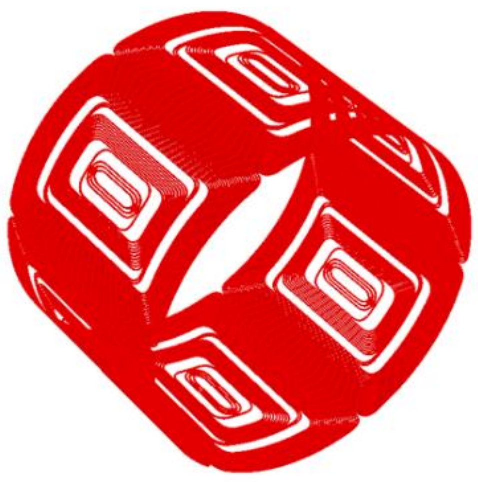
(not considered practical for superconducting magnets before)

- **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**



- ***Model of a "really" short length dipole.***
- ***Coil length 175 mm; Coil diameter 200 mm.***
- ***Coil length < diameter (much less than 8, the earlier figure of merit)!***





Very Good Field Quality

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

Potential uses of this design and technology go well beyond the EIC or NP; e.g., fusion, etc, ...

- **Real challenge is how to make it be known?**

Acknowledgments

- We acknowledge the contributions of our technicians who worked hard and long hours. The outcome of R&D like this, carried out with a limited engineering, depends on their skills, experience and practical solutions.

- We wish to acknowledge support from various lab programs.

- Demonstration of the "Optimum Integral Design" and its likely application to various EIC magnets, and hopefully to many other future projects would not have been possible without the DOE SBIR/STTR program and the encouragement and understanding from the program manager.

Summary (1)

- Optimum integral design reduces the maximum field required for the desired integral field by reducing the loss in magnetic length due to ends.
- Relative benefits of this design are significant in short magnets. This could be relevant in several EIC IR magnets and beyond, where the length of the body becomes comparable to the length of the ends. This also makes some short magnets possible that were not practical before.
- This program was proposed to demonstrate these benefits in the dipole B0ApF using the direct wind technology and evaluate them for others.
- The program has already demonstrated (a) the extension of magnetic length, (b) demonstration of a good field quality for hadron beam, and (c) superconducting shielding for ensuring field quality for electron beam.

Summary (2)

- PBL/BNL direct-wind, optimum integral, full-length EIC B0ApF dipole was energized to ~2.9 T, reaching ~75% of the required integral field at 4.2 K (~84% of the RHIC dipole design field), with no spontaneous quenches in the magnet. Margin at ~1.92K will be higher with appropriate structure.
- Testing to the required integral field was interrupted due to issues external to the magnet. It is likely to resume soon after resolving the issues to demonstrate the design to the design integral field.
- This STTR has already resulted in a significant demonstration of the optimum integral design and of the direct wind technology.
- Development of the optimum integral design to this level would not have been possible without the support of the DOE SBIR/STTR office. Thanks.

BACKUP Slides

List of Tasks in Phase II Proposal

Task 1: Enhancement of Code to Optimize the Phase II Design

Task 2: Magnetic Design and Analysis of the Phase II EIC IR Dipole B0ApF

Task 3: Mechanical Structural Design and Analysis of the Phase II Dipole

Task 4a: Winding of Phase II Inner Coils

Task 4b: Winding of Phase II Outer Coils and Construction of the Dipole

Task 5: Quench Protection and Analysis of the Phase II Dipole

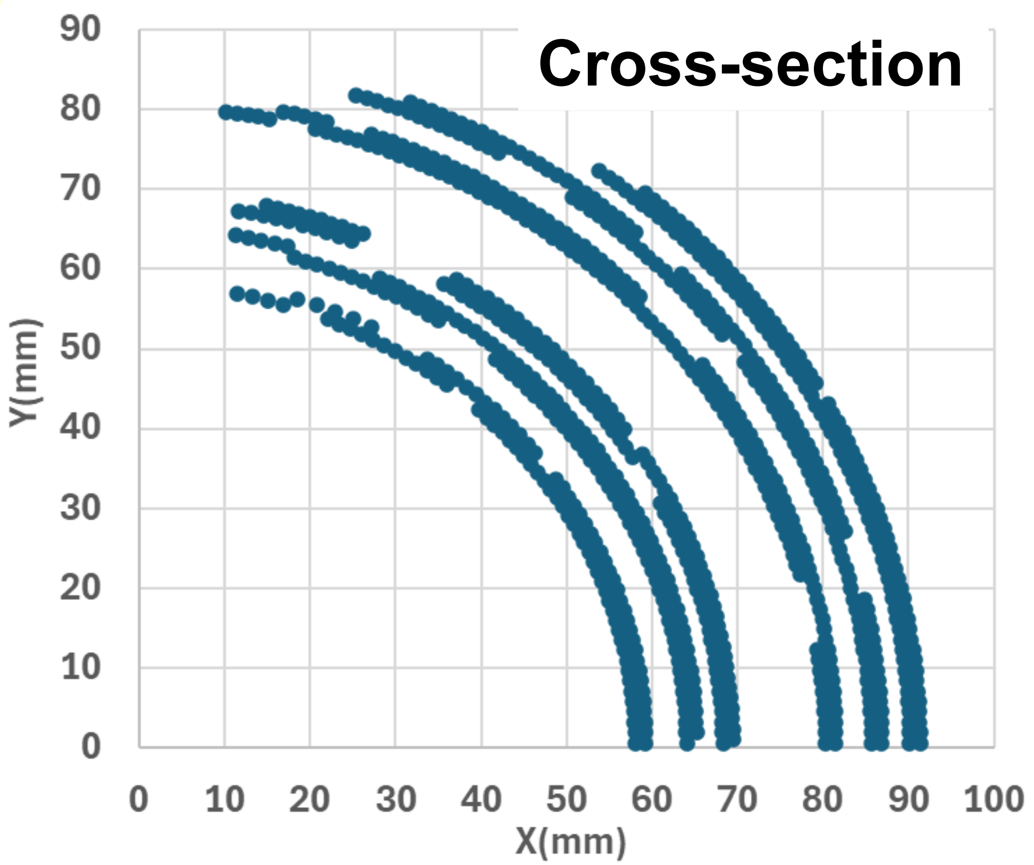
Task 6: Phase II Dipole Field Quality and Quench Tests

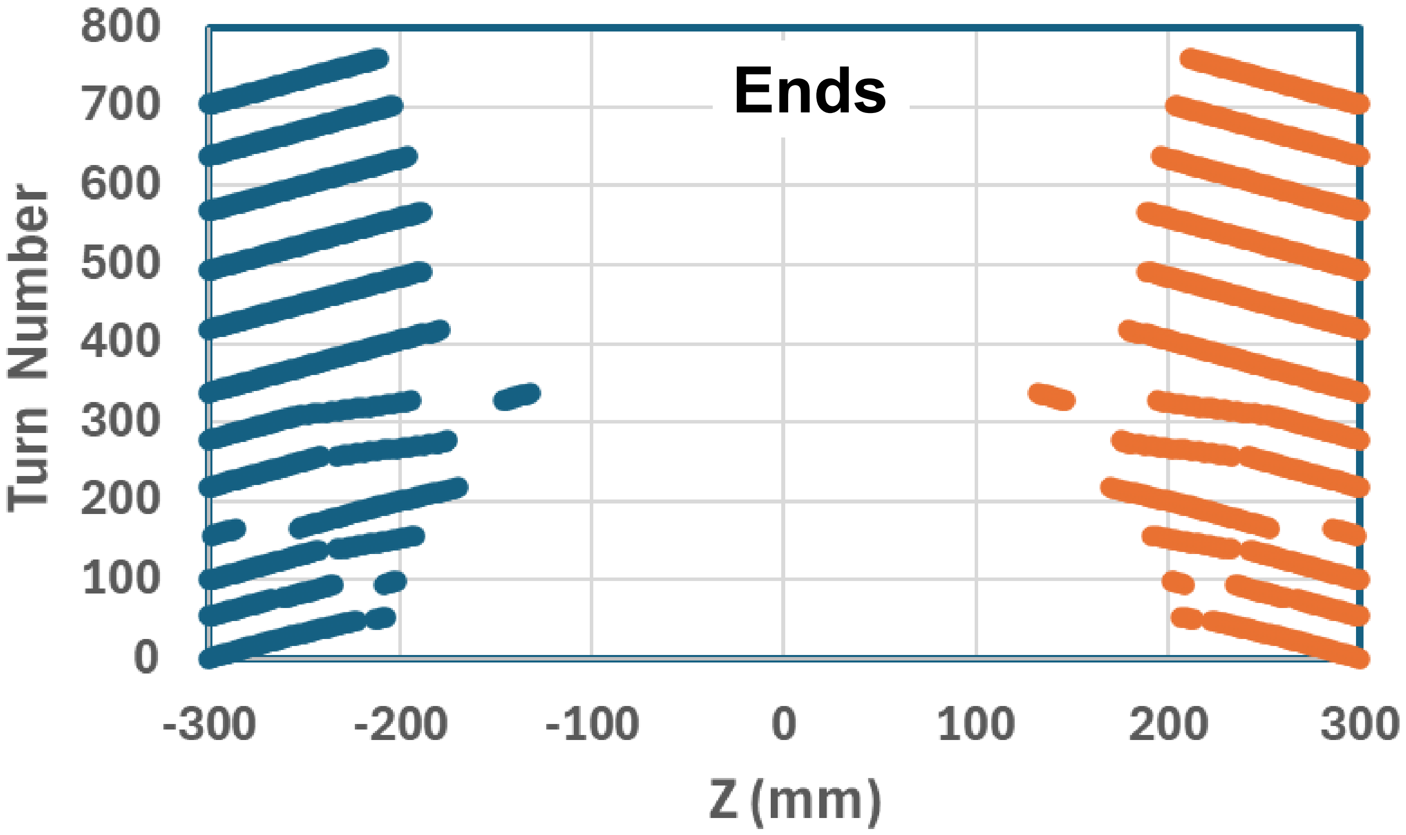
Task 7: Ensuring Field Quality in the Phase II Dipole

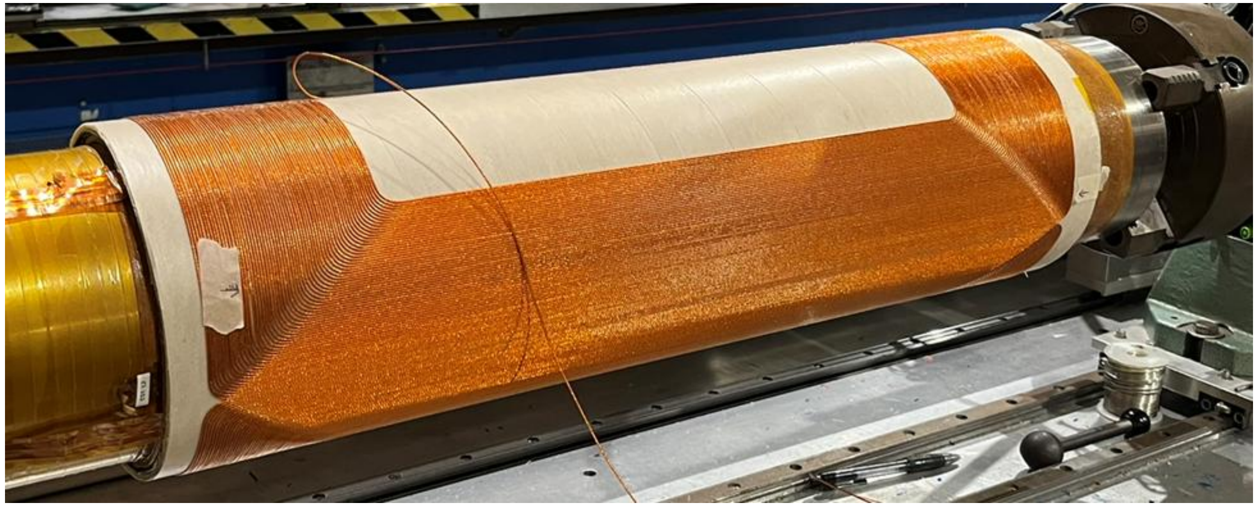
Task 8: Evaluation of the *Optimum Integral Design* for Other Applications

Task 9: Preparation of Phase II Report and Plans beyond Phase II

Coil Geometry



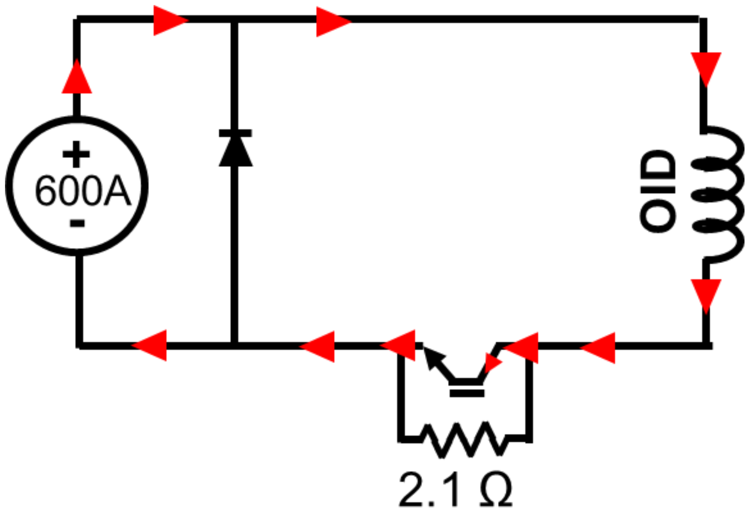




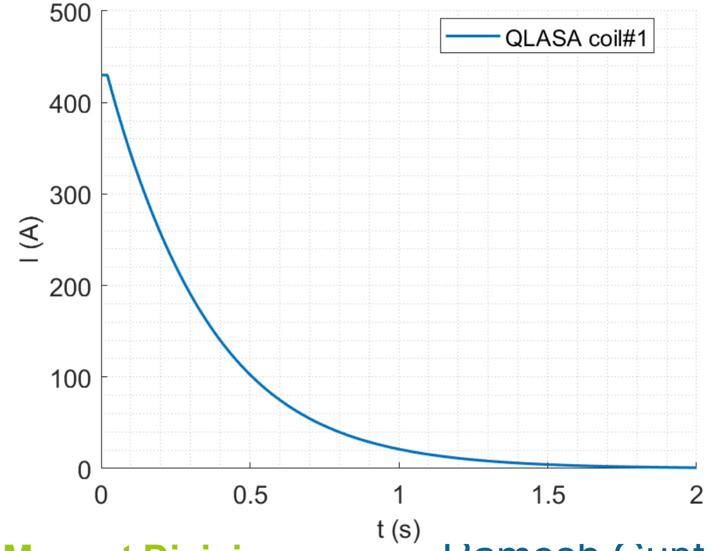
Total cable used in 12 layers: 1.73 km
(121 meter to 175 meter used in a layer)

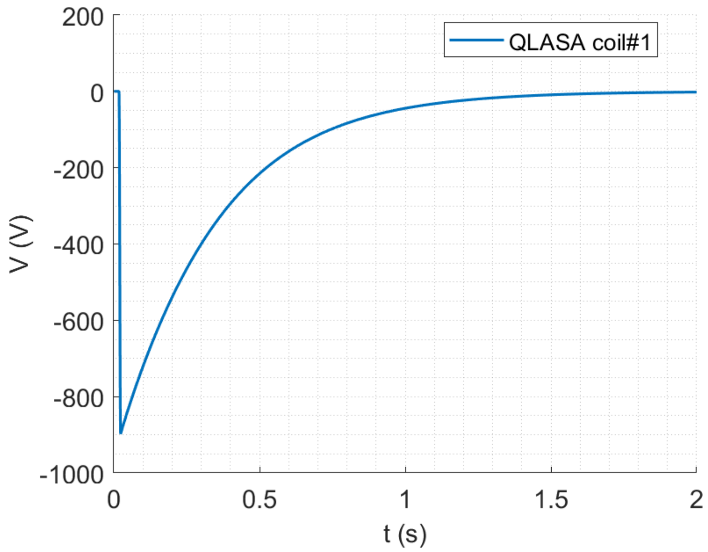
Quench Protection

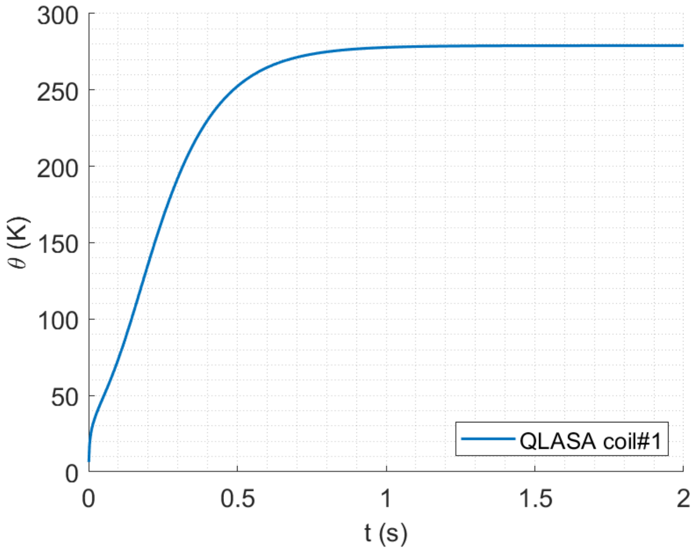
QLASA simulation
@ I = 430 A
L = ~0.7 H
R_{dump}=2.1 Ω



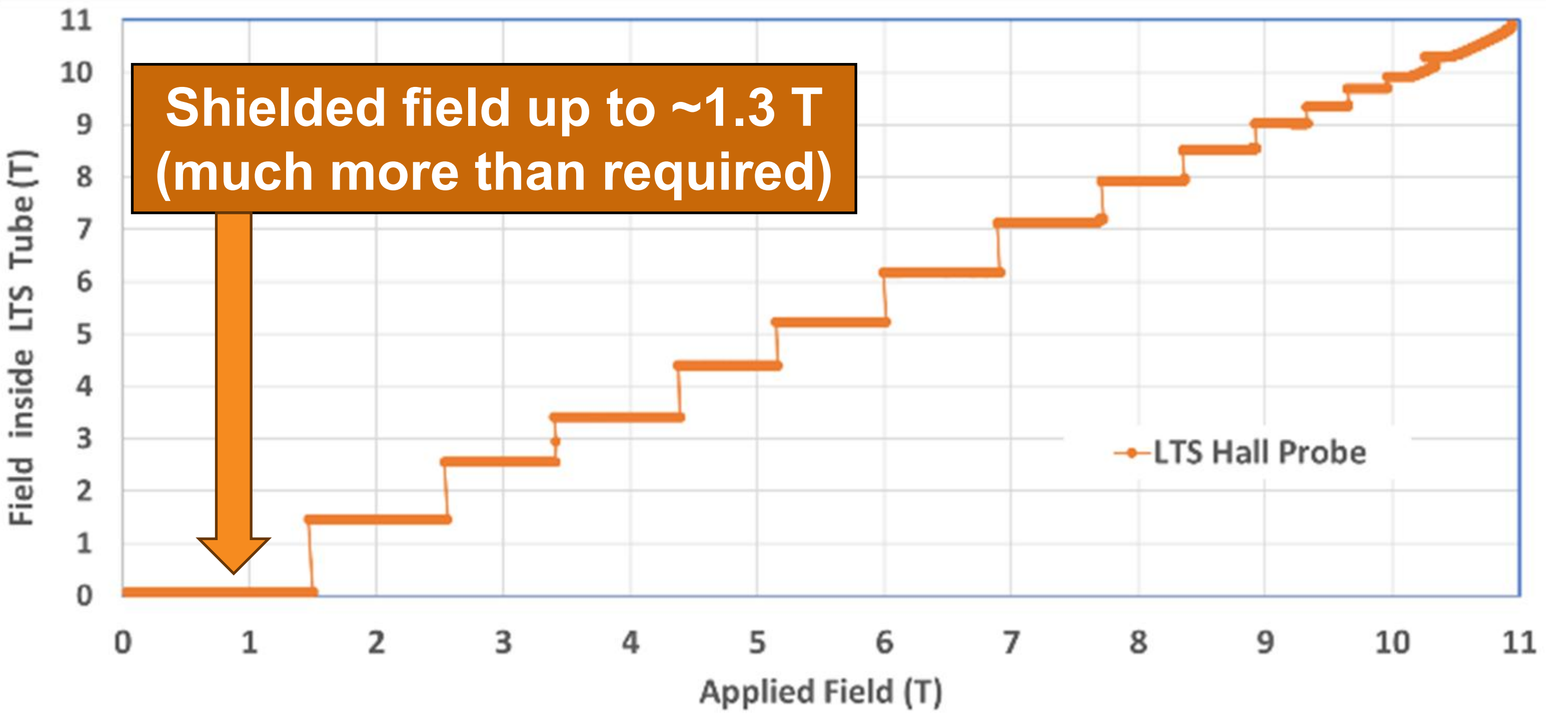
Parameter	Value
MIITs	0.0353
Hotspot temperature	279 K
Voltage total	898 V
Voltage to GND	449 V
Decay time constant	337 ms



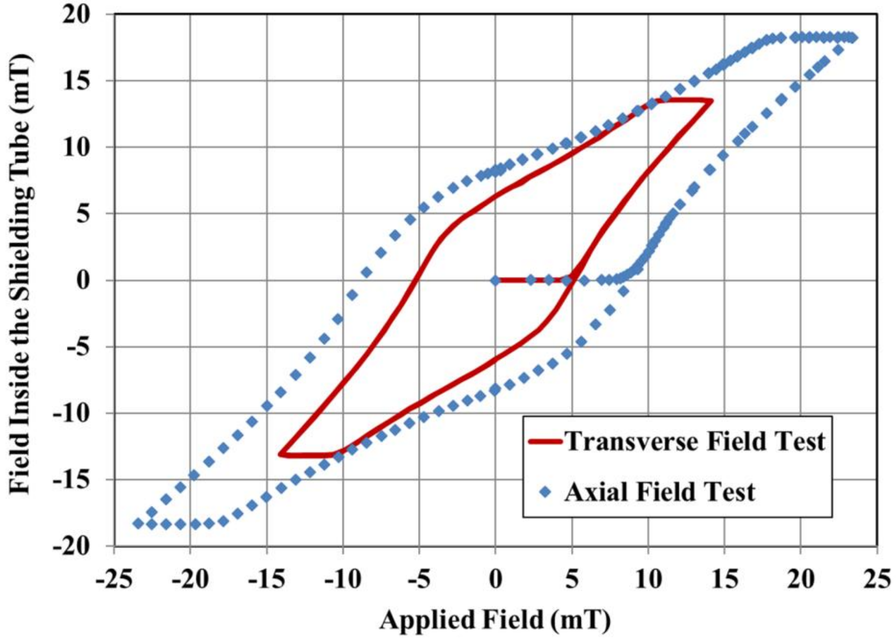




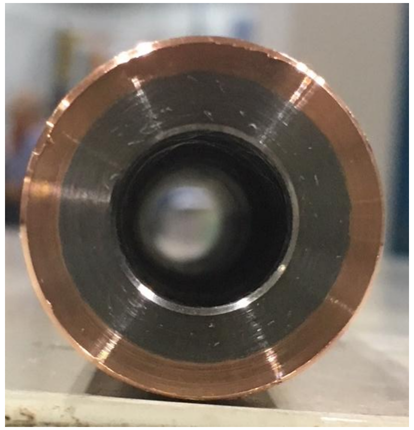
Demonstration of Superconducting Shield in a Previous SBIR



HTS@77K



LTS@4K



can superconductors

Brookhaven National Laboratory

Magnet Division

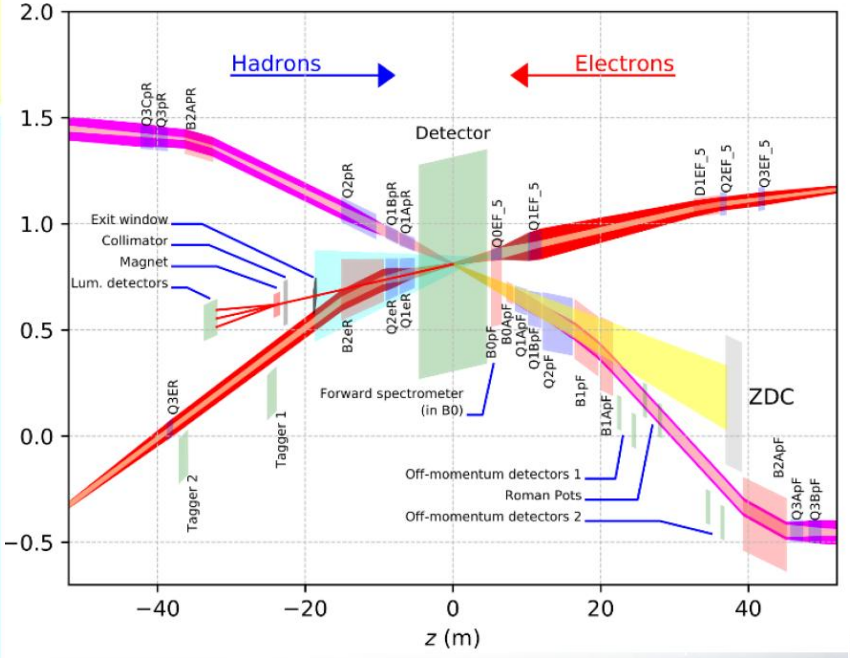
PBL

Luvata

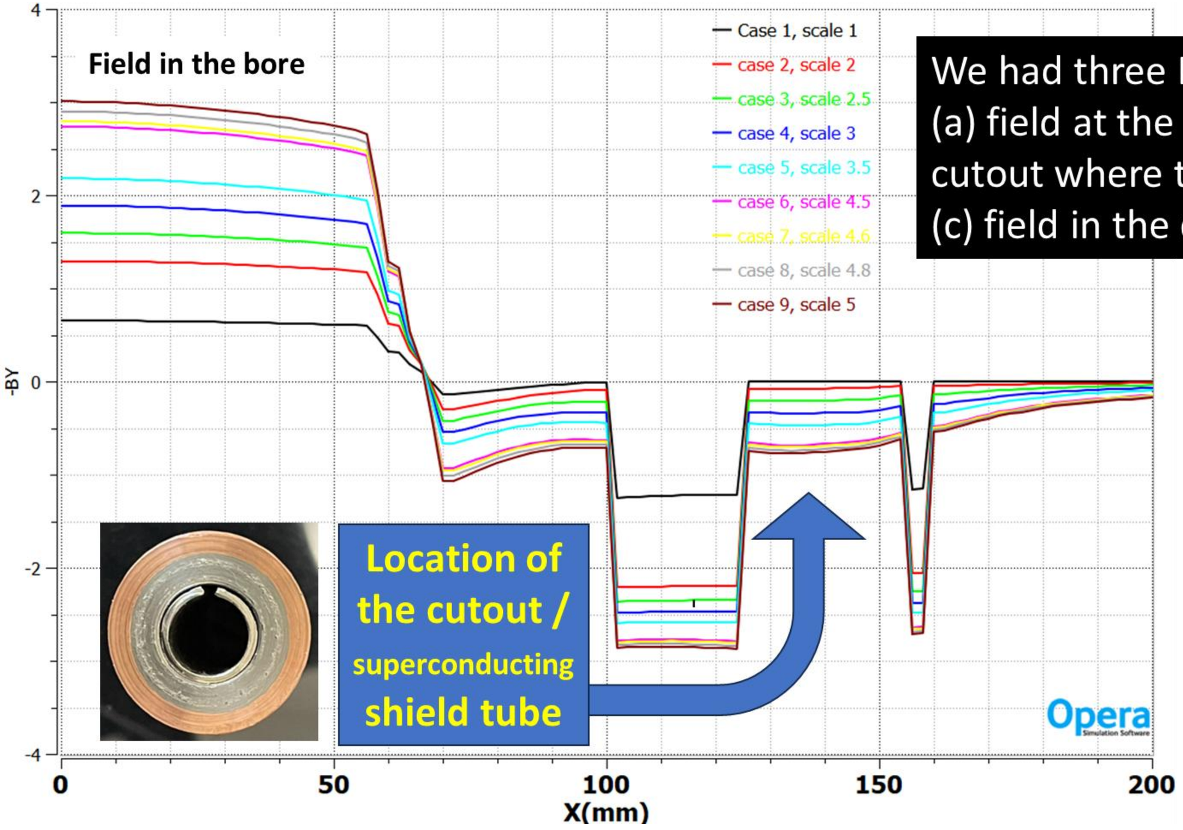
Bruker/Oxford

Test of Superconducting Shielding for EIC Magnets

A major challenge in EIC IR: e-beam traverses very close to Ion beam in EIC IR region



- ➢ This test run provided an opportunity to test the potential benefit of superconducting shield in EIC.
- ➢ The topic was part of an earlier PBL/BNL Phase I SBIR



We had three Hall probes to measure (a) field at the center, (b) field in the cutout where the SC shield is (+x) and (c) field in the cutout with no shield (-x).

Field from the high field magnets for ion beams must be shielded on the path of e-beam

Homepage on the Optimum Integral Design

Optimum Integral Design:

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

Selected papers, presentations, and SBIR/STTRs on the Optimum Integral Design:

- Optimum Integral Design and It's Application to EIC Magnets, Magnet Steering Group Meeting, July 25, 2025.
- Design, Construction, and Test of a Direct Wind Dipole B0ApF based on the Optimum Integral Design (https://mt29-conf.org/), Thu-Mo-Or1-03, Boston, July 1 – 6, 2025 (abstract).
- Optimum Integral Design for EIC Dipole B1pF/B1ApF, MT29 – International Conference on Magnet Technology (https://mt29-conf.org/), Fri-Mo-Po.05-04, Boston, July 1 – 6, 2025 (poster).
- Optimum Integral Dipole B0ApF, Magnet Steering Group Meeting, June 6, 2025.
- Optimization Strategy and Code for the Optimum Integral Design, May 29, 2025 (design manual).
- A Proposed Value Engineering Design for B1ApF, January 7, 2025.
- **A New Medium Field Superconducting Magnet for the EIC**, FY24 Nuclear Physics SBIR/STTR Phase II Exchange Meeting, August 14, 2024.
- Optimum Integral Magnet Design (includes work performed under PBL/BNL STTR), US MDP general meeting, October 25, 2023
- A Novel, Medium-field Optimum Integral Dipole, Presented at MT28 – International Conference on Magnet Technology (https://mt28.aoscongres.com/home!en), September 14, 2023
- A new medium field superconducting magnet for the EIC, FY23 DOE SBIR/STTR Phase II Exchange Meeting, August 15, 2023
- Optimum Integral Dipole STTR for EIC, internal presentation to BNL EIC magnet team, October 5, 2022
- STTR Phase II with Particle Beam Lasers, Inc. (PBL), "A New Medium Field Superconducting Magnet for the EIC", (2022-ongoing), DE-SC0021578, (Summary, Narrative, Report)
- A new medium field superconducting magnet for the EIC, FY21 Phase I PI meeting, June 28, 2021
- STTR Phase I with Particle Beam Lasers, Inc., "A New Medium Field Superconducting Magnet for the EIC", (2021, Phase I completed), DE-SC0021578, (Summary, Narrative, Report)
- **R. Gupta, "Optimum Integral Design for Optimizing Field in Short Magnets", Presented at the Applied Superconductivity Conference during October 3-8, 2024 at Jacksonville, FL, USA (2004). ****Click Here for Poster******
- R. Gupta, **Optimum Integral Design for Maximizing Field in Short Magnets**. Magnet Division Note No. MDN-634-37 (AM-MD-334) (February 2004). https://wpw.bnl.gov/rgupta/wp-content/uploads/sites/9/2023/03/MDN-634-37.pdf

Magnet Experts in the PBL Team

Current staff of Particle Beam Lasers, Inc. (PBL):

- Erich Willen (Ex-head, BNL magnet division, retired)
- Ron Scanlan (Ex-head, LBNL magnet group, retired)
- Al Zeller (Ex-head FRIB/MSU magnet group, retired)
- James Kolonko (President, UCLA retired)
- Delbert Larson (Vice President, Senior Scientist)
- Steve Kahn (Senior Scientist, BNL retiree)
- Bob Weggel (Senior Engineer, MIT/BNL retiree)

Well recognized experts providing the critical input

Previous PBL employees:

Bob Palmer, ex-head, BNL magnet division, retired

Albert Garren, ex-LBNL scientist, retired; David Cline, ex- Professor UCLA, retired
Harold Kirk, ex-BNL scientist (BNL), retired; Fred Mills ex-FNAL scientist, retired
Shailendra Chouhan, ex-MSU/FRIB scientist, and a few others.

PBL SBIR/STTR Awards with BNL (NP 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**

Major outcome of PBL/BNL team in backup slides

Major Outcome of PBL/BNL SBIR/STTR Awards

- **Record field in an all HTS solenoid: 16 T (2012)**

  Follow-on work:

  ✓ Led to (a) several other SBIR/STTR grants, (b) HTS SMES program at BNL with ARPA-E which produced record high field, high temperature SMES (12 T, @27 K), (c) synergy with DOE/NP's HTS prototype quadrupole for FRIB and other programs

- **Record field in an HTS/LTS hybrid accelerator dipole: 8.7 T (2017)**

  Follow-on work:

  ✓ Led to (a) several new SBIR/STTR grants, (b) Magnet Development Program with HEP producing another record hybrid field of 12.3 T, (c) created a unique Common Coil Test Facility (**CCTF**), in high demand by "Fusion", HEP and worldwide users

- **Patents and other follow-on work for both PBL and BNL Teams**