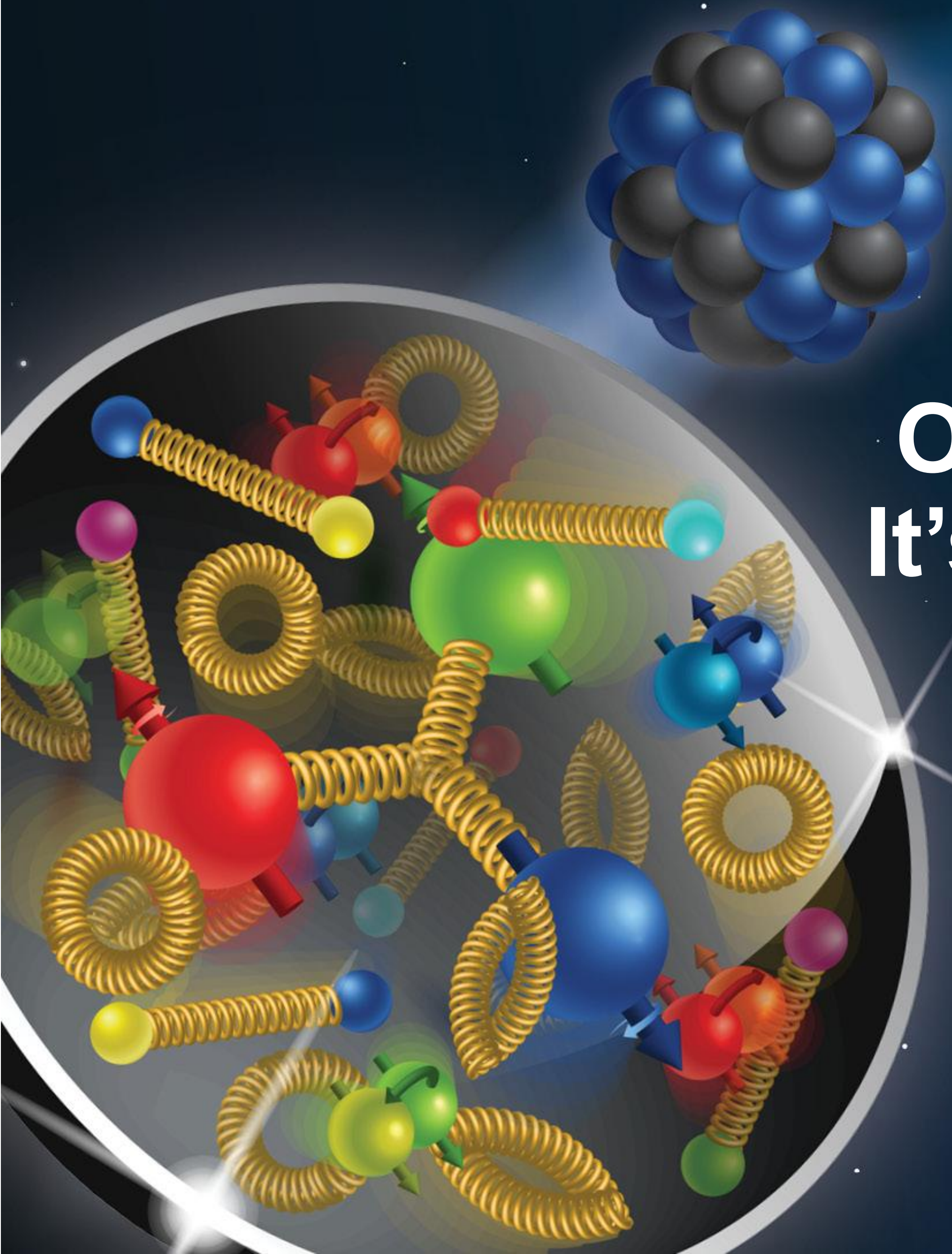


Optimum Integral Design and It's Application to EIC Magnets

Ramesh Gupta

Magnet Steering Group Meeting

July 25, 2025

Electron-Ion Collider

PBL · BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY | Office of Science

Background

- Optimum Integral Design was proposed for a short, low field magnet in 2004. A dipole was built and installed in AGS tunnel – the only direct wind magnet in a BNL machine.
- Particle Beam Lasers, Inc. (PBL) and BNL made a couple of SBIR/STTR proposals to apply the optimum integral design with direct technology to high field EIC IR magnets.
- Phase I and Phase II proposals were funded to (a) demonstrate the optimum integral design for EIC dipole B0ApF, and (b) to explore this design for other magnets in EIC.
- Another proposal to develop "tapered optimum integral design" was deferred till the above is demonstrated. "Tapered optimum integral design" is efficient and flexible.
- Mechanically "optimum integral" is like the "serpentine"; demo of one is demo of other.
- As such DOE office has awarded several SBIR/STTR to PBL/BNL team, including a few exclusively in support of the EIC. Program managers like when a positive outcome of those awards gets applied to projects. This should, of course, be based on the merit.

Outline

- A brief introduction to PBL team
- 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
- Remaining tasks
- Summary

Magnet Experts in the PBL Team

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

- **Erich Willen (Ex-head, BNL magnet division)**
- **Ron Scanlan (Ex-head, LBNL magnet group)**
- **Al Zeller (Ex-head FRIB/MSU magnet group)**
- **James Kolonko (President, UCLA retiree)**
- **Delbert Larson (Senior Scientist, Vice President)**
- **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 (BNL)
Albert Garren (LBL)
David Cline (UCLA)
Harold Kirk (BNL)
Fred Mills (FNAL)
Shailendra Chouhan (MSU)
And a few others

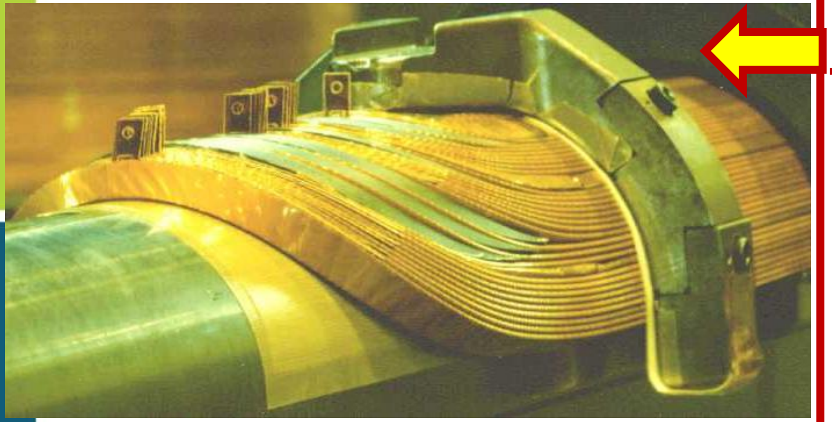
PBL SBIR/STTR Awards with BNL (EIC awards highlighted)

	Title	Contract	Date	Amount
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 extra slides

Optimum Integral Design

Motivation for the Optimum Integral Design in Short Magnets

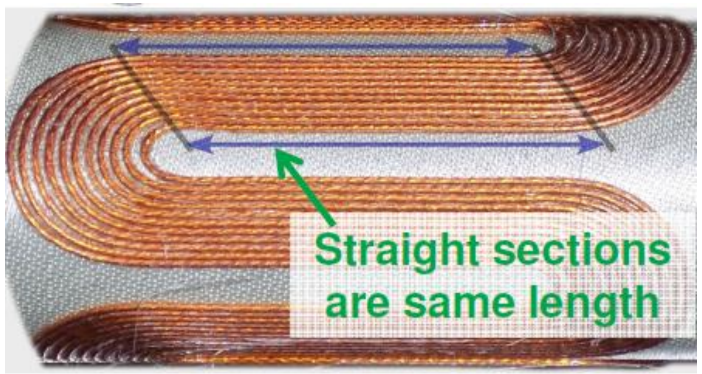


RHIC Cosine(θ) Coil Ends

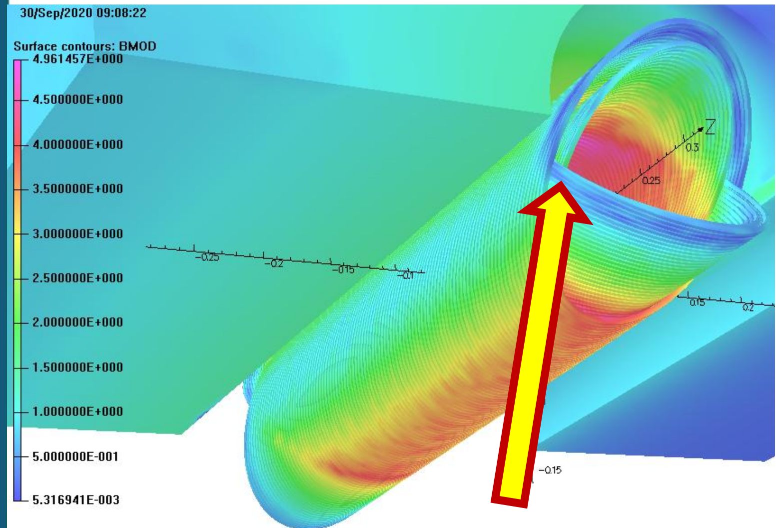
Conventional End Designs:

- Conventional ends take large space (~2X coil ID in dipole)
- Field per unit length in ends is ~1/2 of that in the body.

=> A large loss in integral field in most designs for short magnets.



Serpentine



Double helix

Midplane turns end here

Optimum Integral Design:

- Midplane turns run almost full length of the coil in the ends.
- Turns near midplane contribute most to the field integral. They also determine the length of straight section. This implies almost no loss due to Ends.

Optimum Integral

Loss in Integral Field Due to Ends and Some Short EIC Magnets

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

Coil length to coil diameter ratios in some EIC magnets:

- B0ApF (*L* = 600 mm, 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 (refer to quad)

Reference guide
~8 in dipole
~4 in quads

Conventional Design Approach

A two-step process:

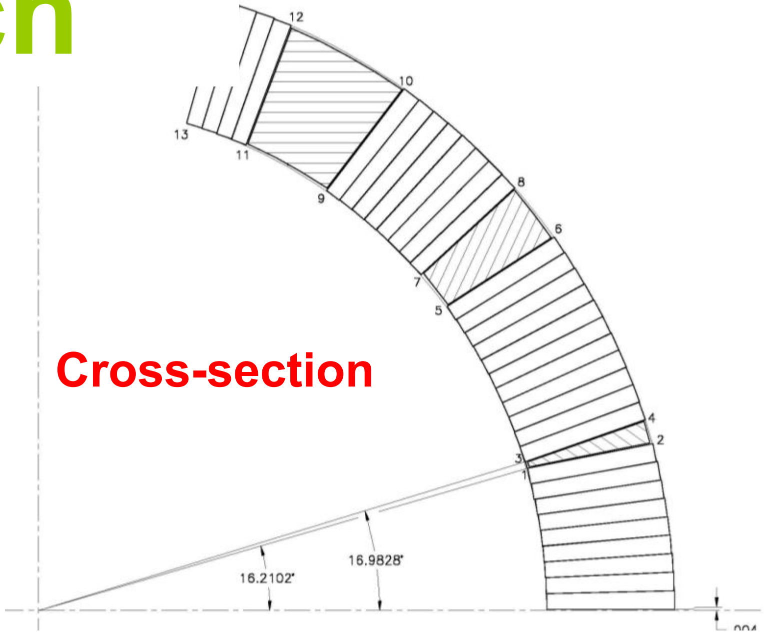
Step 1: Optimize coil cross-section to obtain cosine theta like distribution:

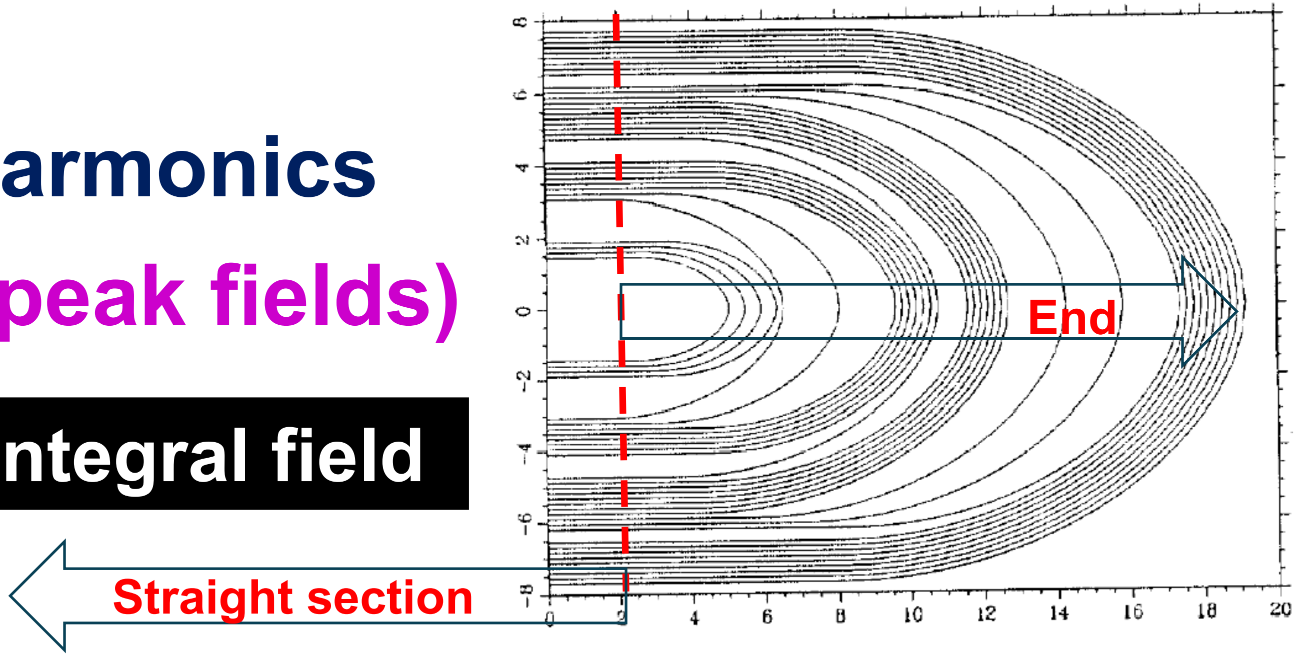
$$I(\theta) = I_o \cdot \cos(n\theta)$$

Step 2: Optimized ends for harmonics

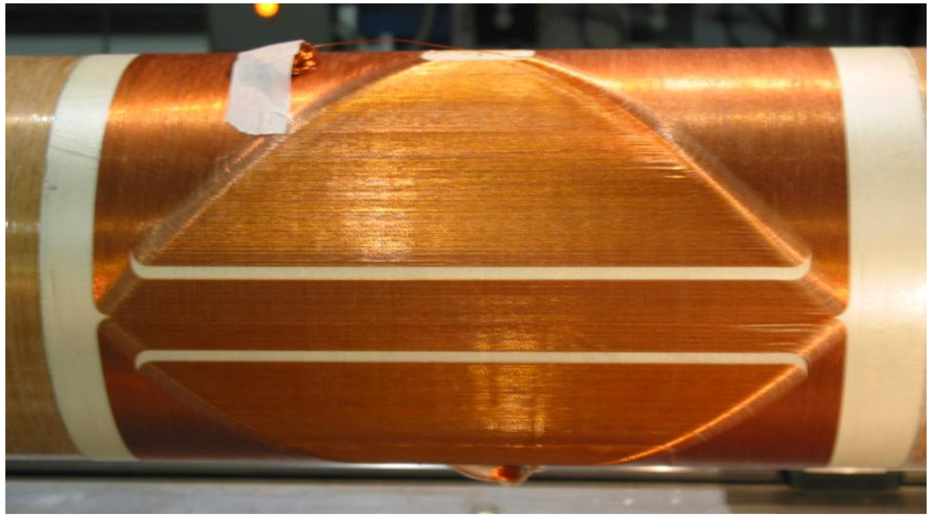
(also, optimize both for low peak fields)

Each step limits the packing & integral field





Optimum Integral Design Approach



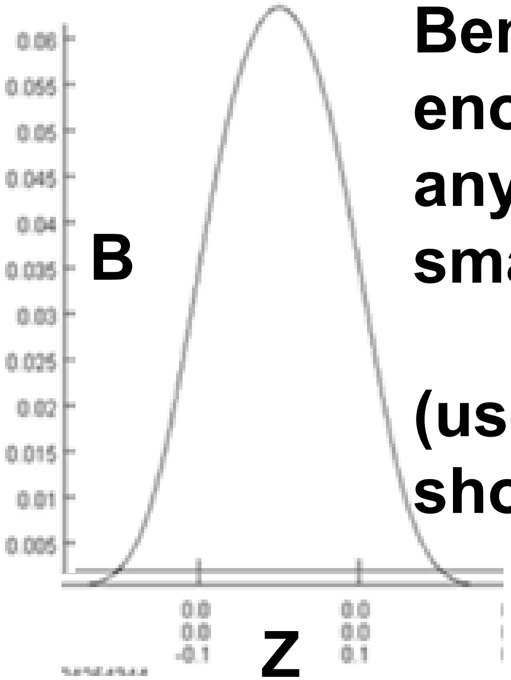
Extend midplane turns to full coil length & optimize cross-section and ends together in a single step to obtain an overall cosine theta distribution in the integral sense:

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

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

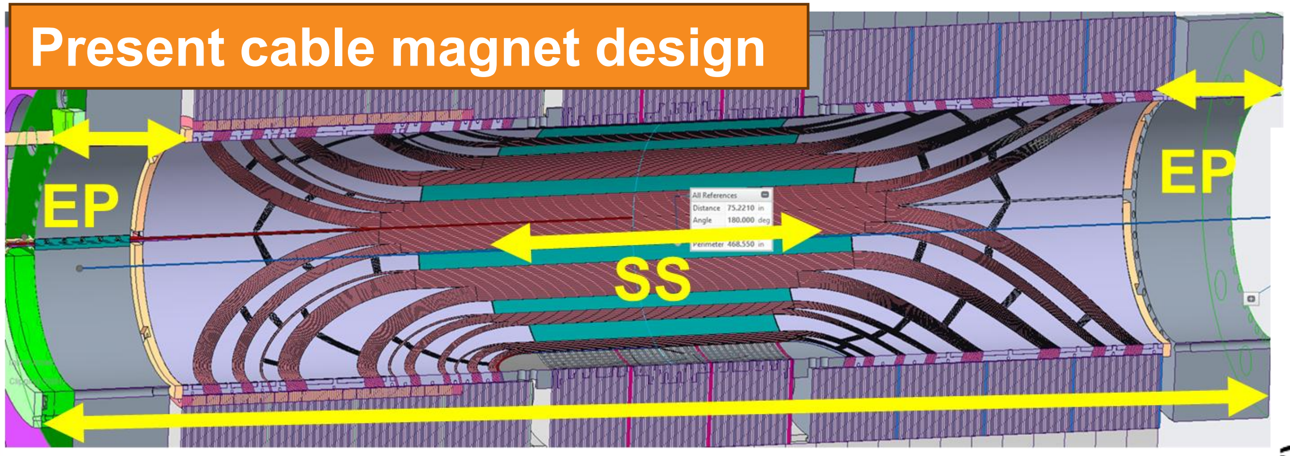
(useful in all short magnet)

AGS dipole

Value of the Optimum Integral Design in B1ApF

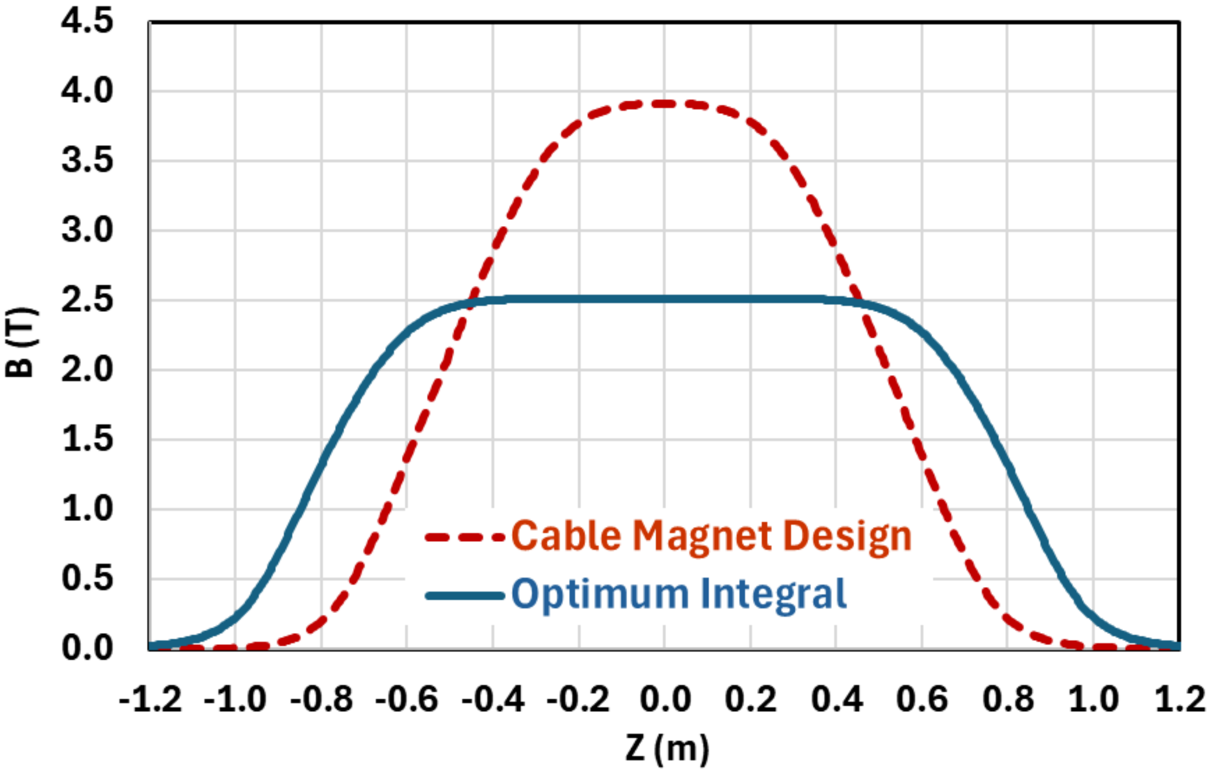
(midplane turn extends full length to minimize the loss due to ends)

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

*Calculations for the cable magnet design from Mithlesh Kumar

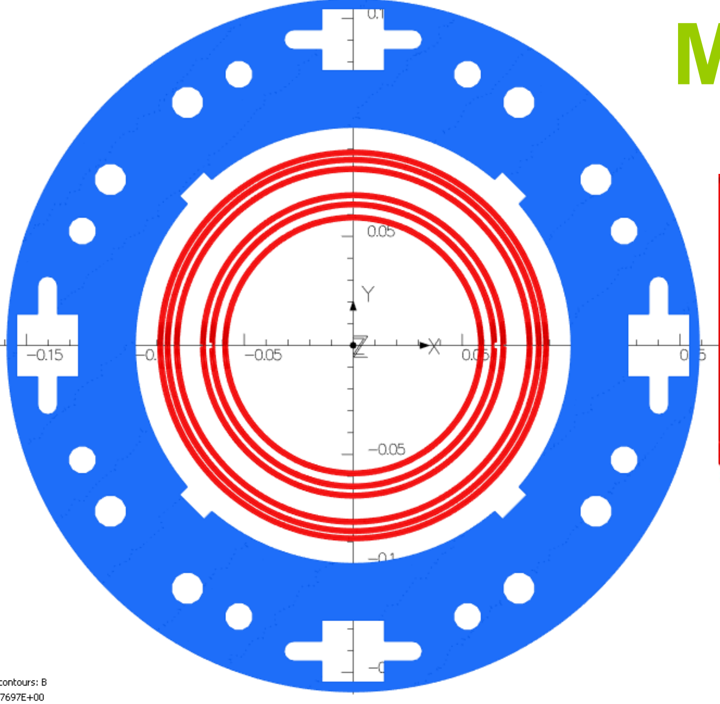
PBL/BNL STTR

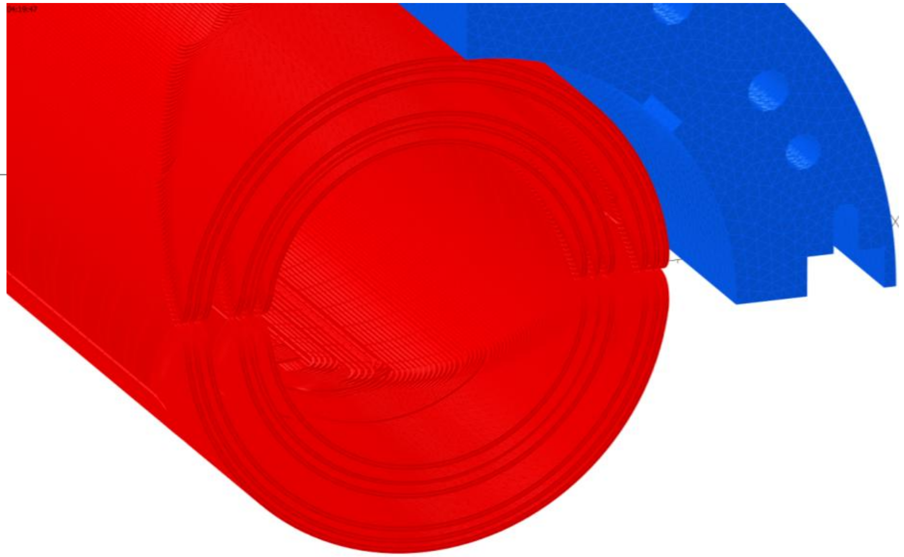
Goal: A Proof-of-Principle Optimum Integral Dipole B0ApF for EIC

- ➢ **Demonstrate that it meets all key technical specifications**
  - ✓ **Integral field, field quality and cross-talk**

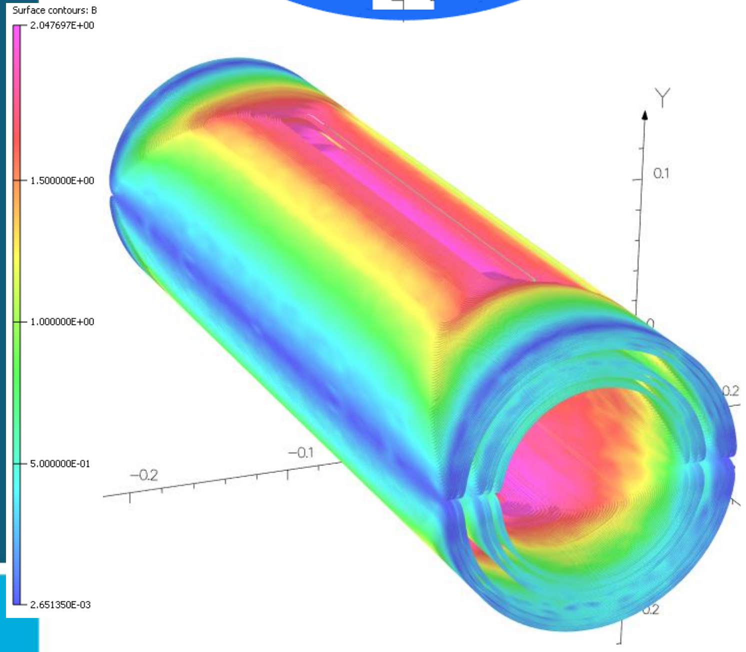
*(budget and schedule constraints drove certain design and programmatic choices)

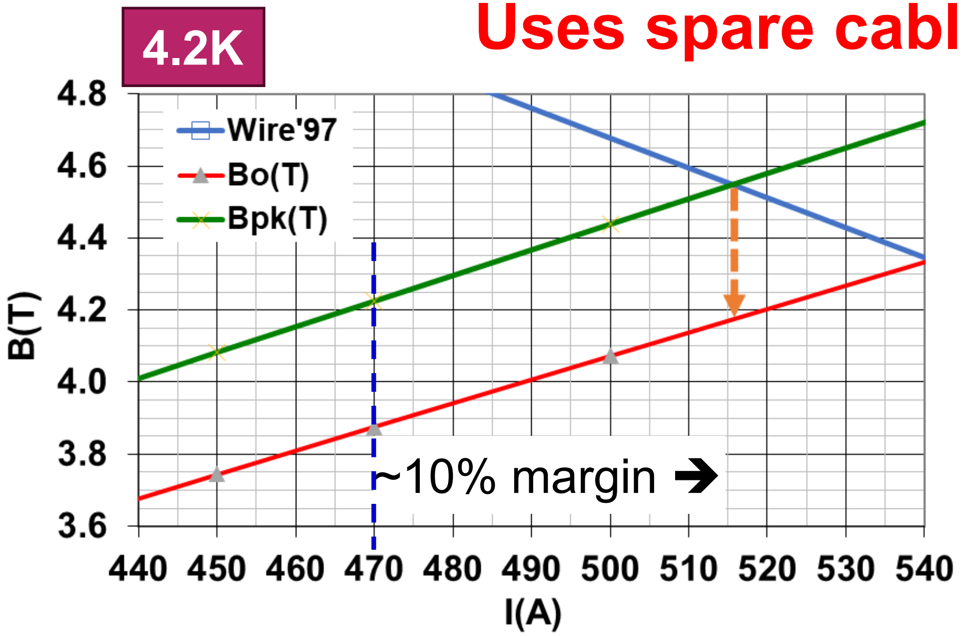
Magnetic Design of the 12 Layer OID B0ApF





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

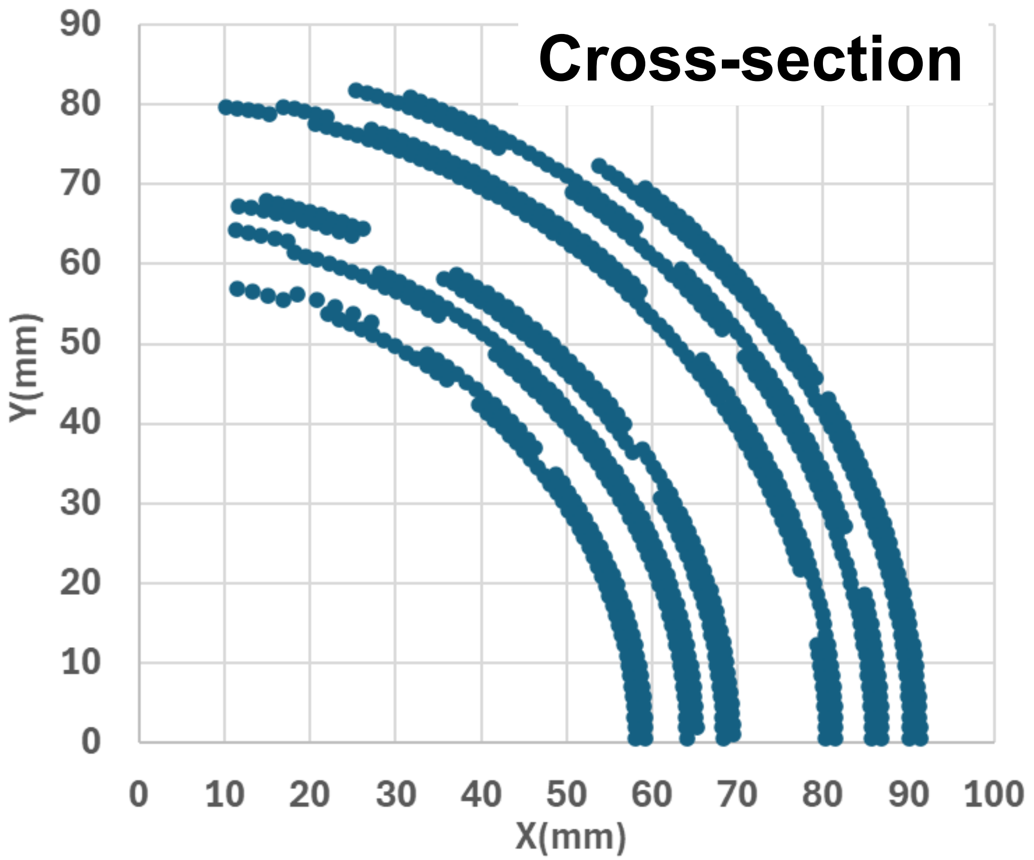


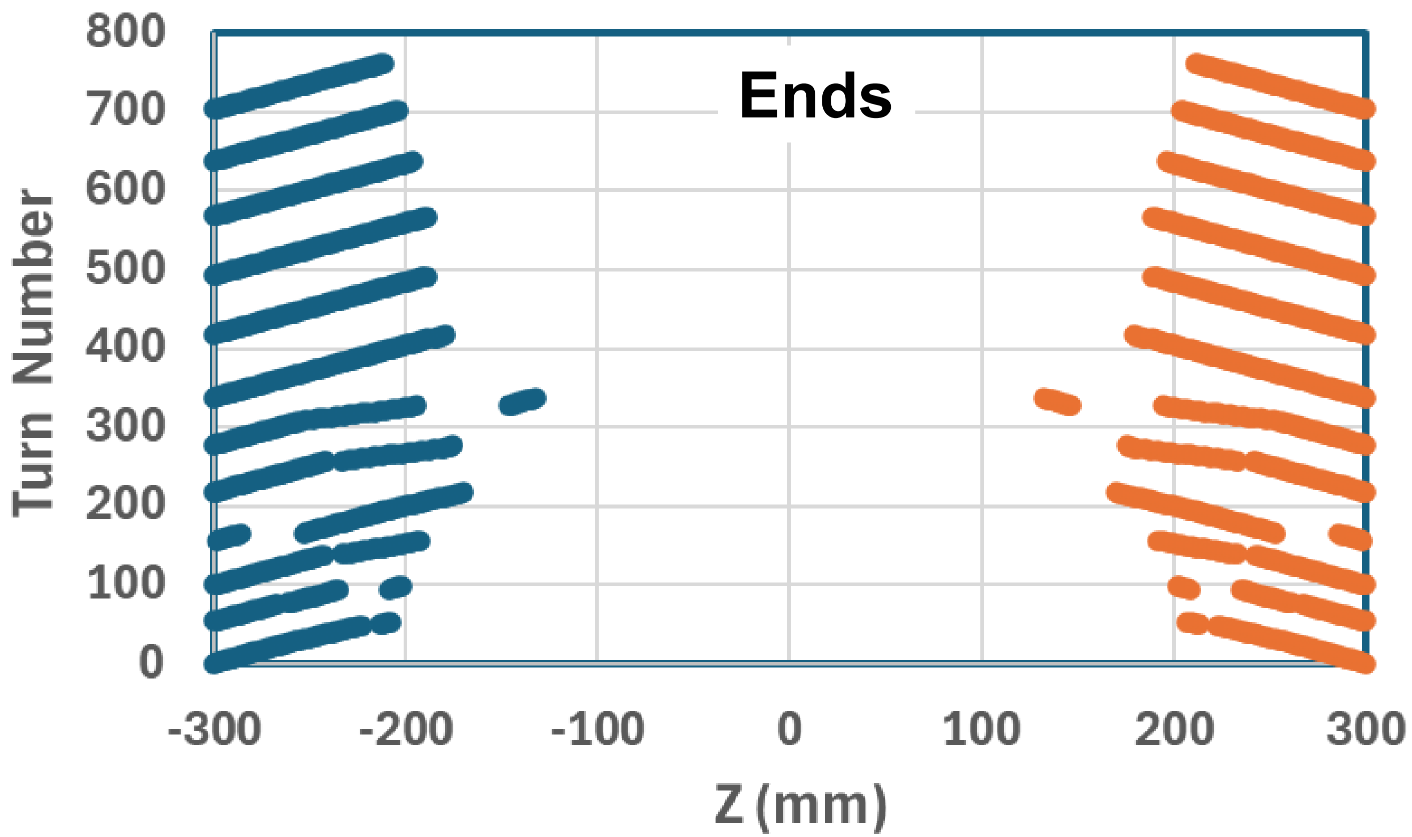


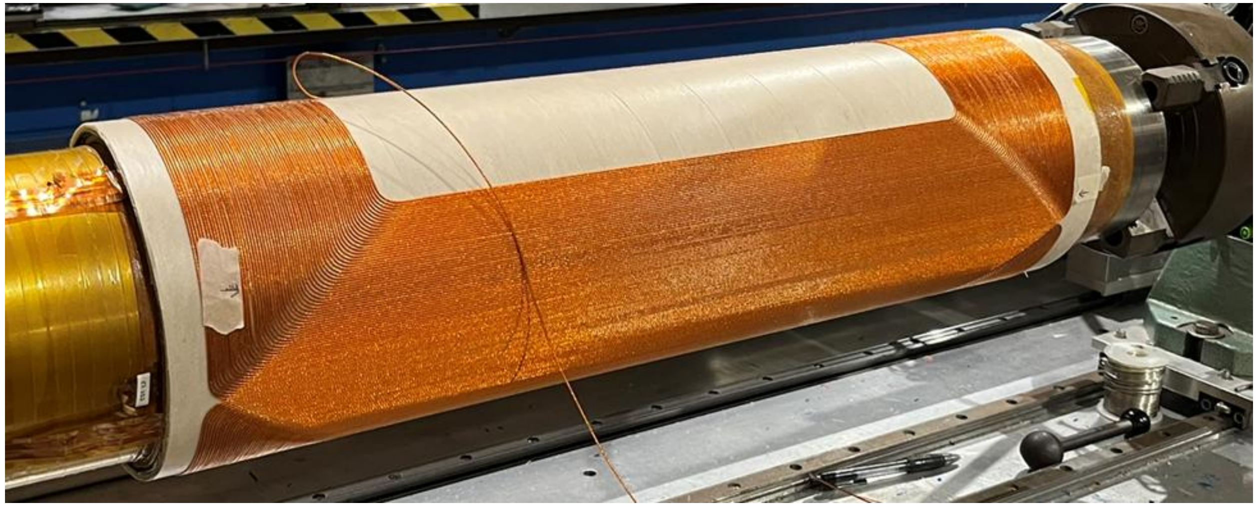
Uses spare cables from a previous project

- 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

Coil Geometry

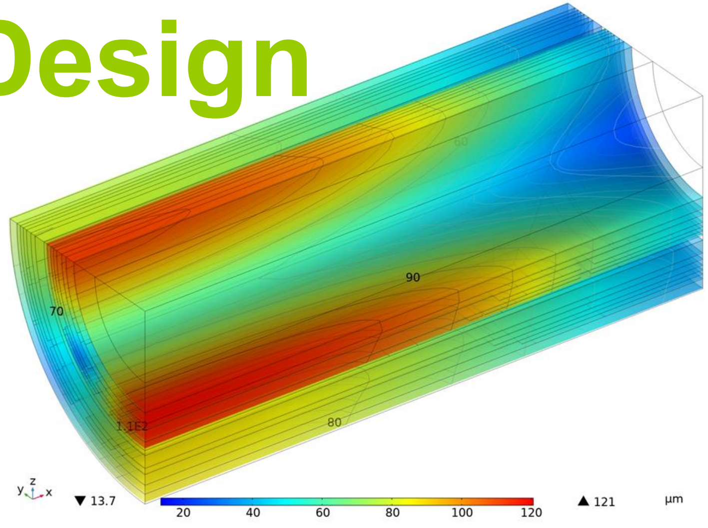






Total cable used in 12 layers: 1.73 km
(121 meter to 175 meter used in a layer)

Mechanical Design of the 12-layer Design



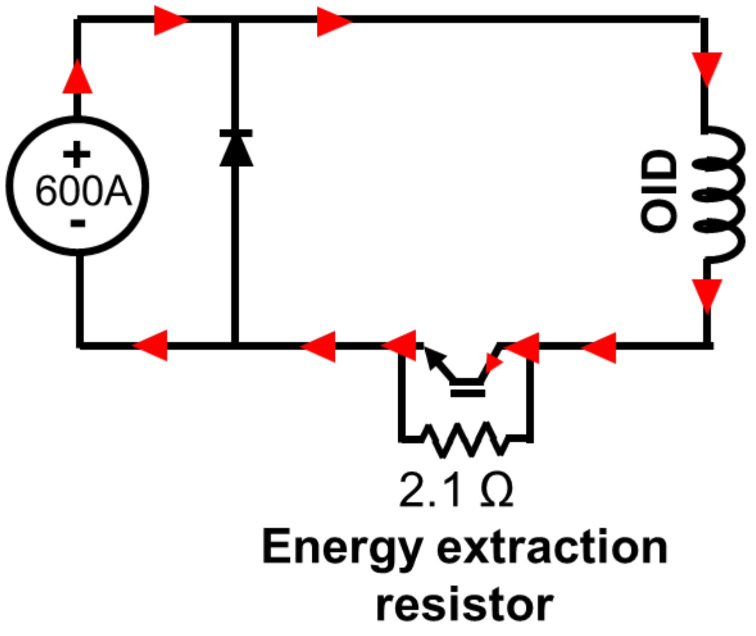
Analysis with COMSOL

Primary components of mechanical structure:

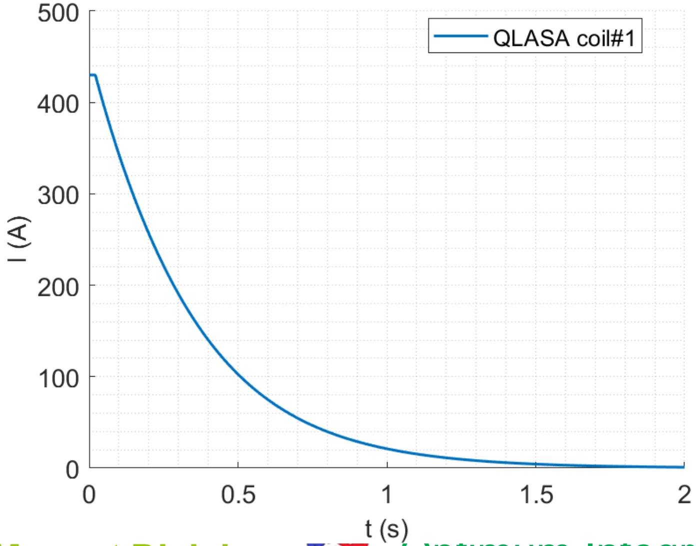
- **Tension roving after every two layers**
- **Two stainless steel tubes**
  - ➢ **2 instead of 1 to reduce stress/strain buildup**
  - ➢ **Original design had an outer SS tube also. As built, has only tension roving on outside.**

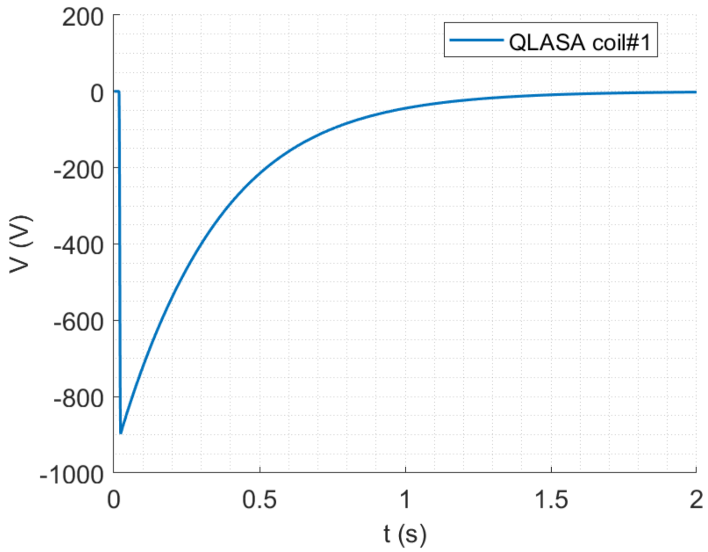
Quench Protection

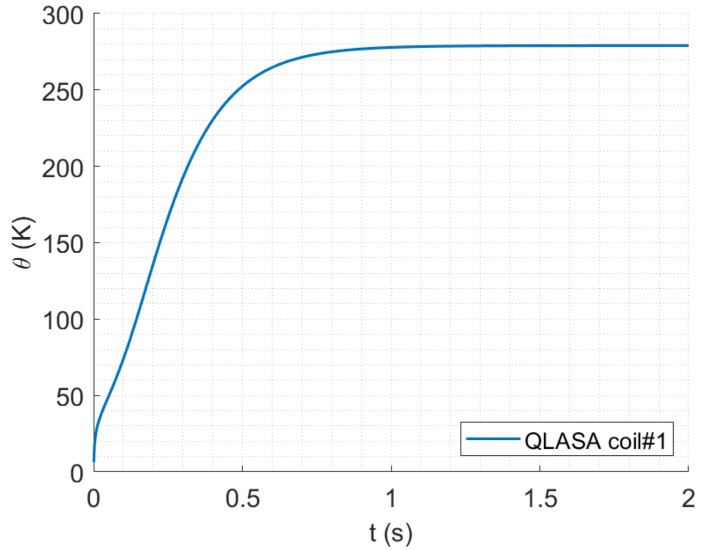
QLASA simulation
@ I = 430 A
L = ~0.7 H
R_{dump}=2.1 Ω



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







Quench Protection

Like in many other EIC magnets, quench protection needs attention here also.
- **large inductance, large dump resistor, high temperature rise, high voltage, ...**

Key parameters for quench protection for various EIC magnets:

	B0ApF	Q1ABpF	B0pF/Q0eF
Inductance	~0.7H	~0.08H	~1.3H
No. of layers	12	12	8+2
Design current	470A	1360A	1143 A
Dump resistor	2.1Ω	0.6Ω	1.6Ω

For I <600 A, one can use cold diodes, as used in e-lens solenoid (460 A, 1.4 MJ, 14 H)

A Comparison with the Serpentine Design of B0ApF Dipole

Parameter	Serpentine Design	Optimum Integral
Integrated Field	1.98 T.m	
Operating Temperature	1.92 K	
Coil aperture	Ø114 mm	
Nominal Current	1100 A	470 A
Central Field / Peak Field	4.5 T / 4.9 T	3.9 T / 4.3 T
Stored energy	70 KJ	

Optimum Integral Design requires a significantly lower bore field for the same integral field, since it increases the effective magnetic length.

OID has ~10% margin at 4.2K even with a Swiss cheese yoke (will have ~35% at 1.9K with real yoke)

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)**

This, by far, is, in the most advanced stage of any magnet in EIC:

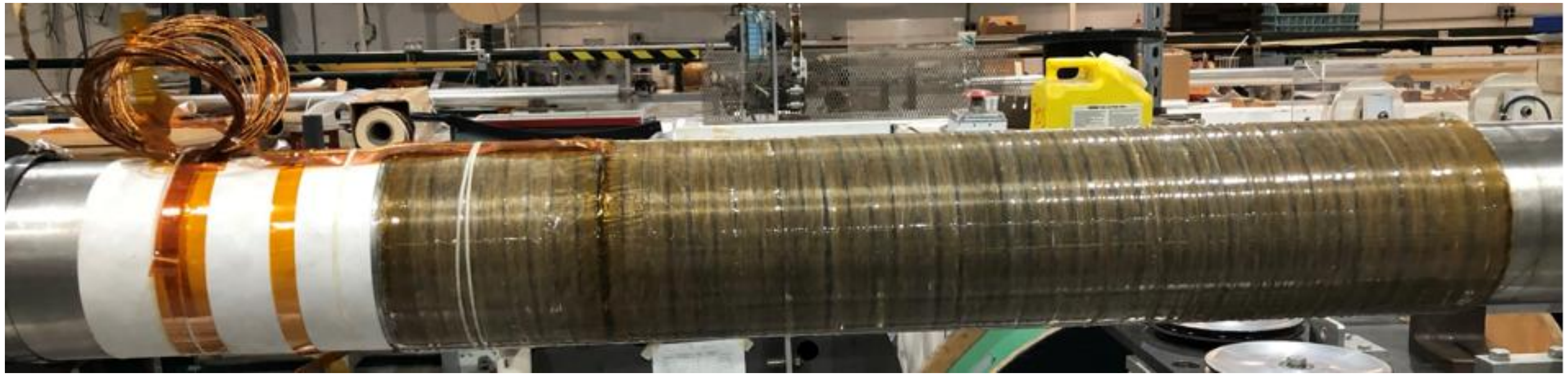
A full-length R&D dipole designed to meet all key technical specs

- ➢ **Plus, more: ~10% margin at 4.2 K (EIC operates@1.92K)**

… while recognizing the technically challenging requirements

"3.9 T, 114 mm" in B0ApF Vs. "3.45 T, 80 mm" in RHIC dipoles

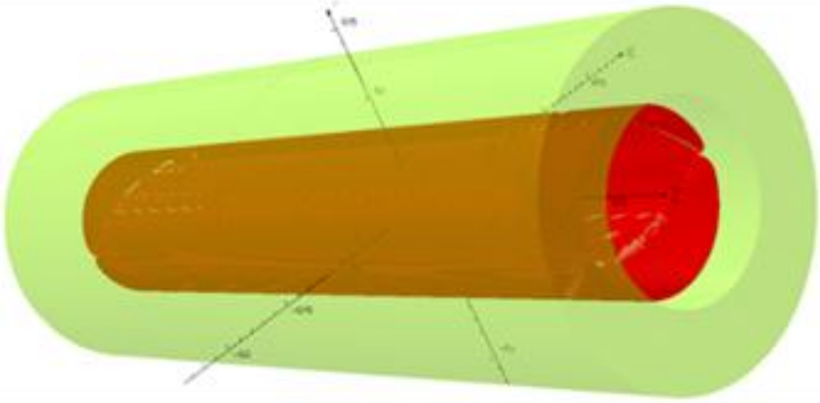
Optimum Integral Dipole in Phase I (two layers in a yoke)

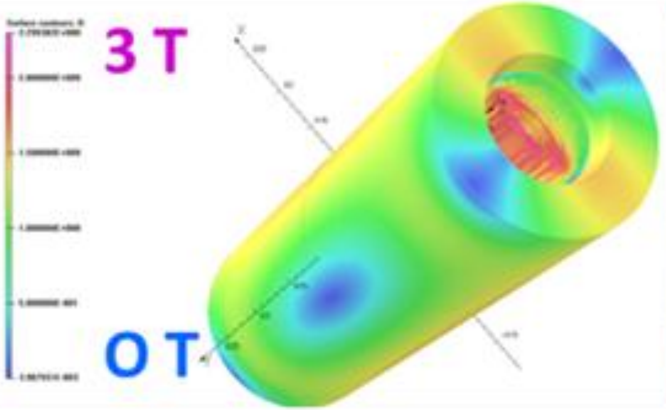


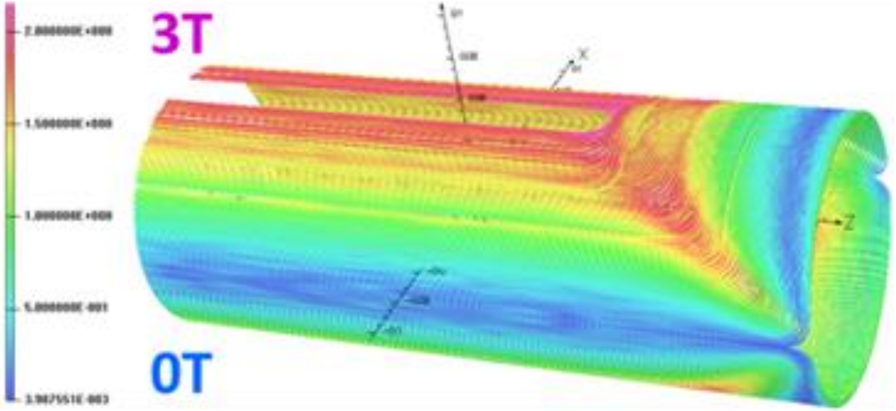
Tension rowing over two layers to contain forces (inner SS tube also has a role in the mechanical structure)

Coil in the yoke (ready for the testing)

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

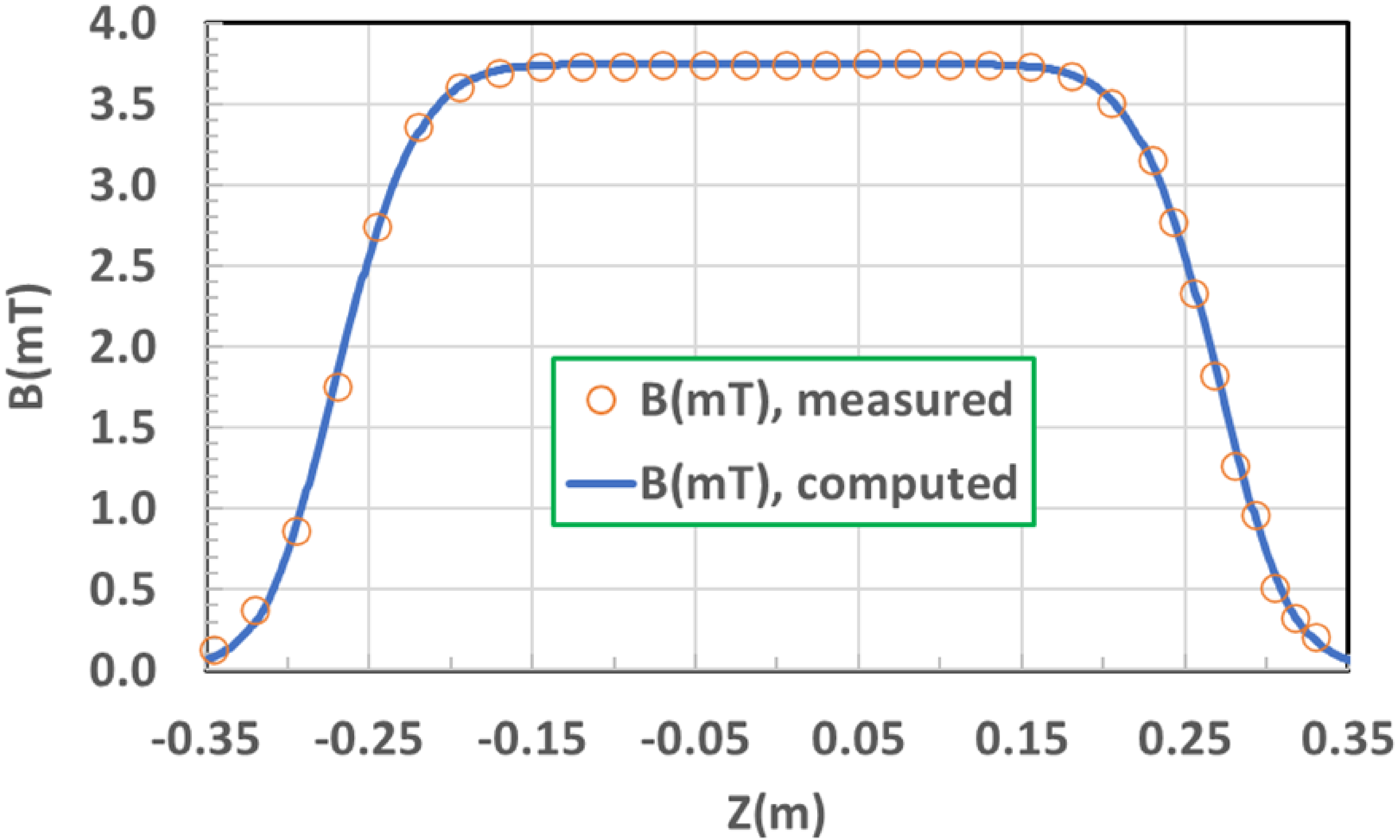






Question #1: Will optimum integral design extend the magnetic length?

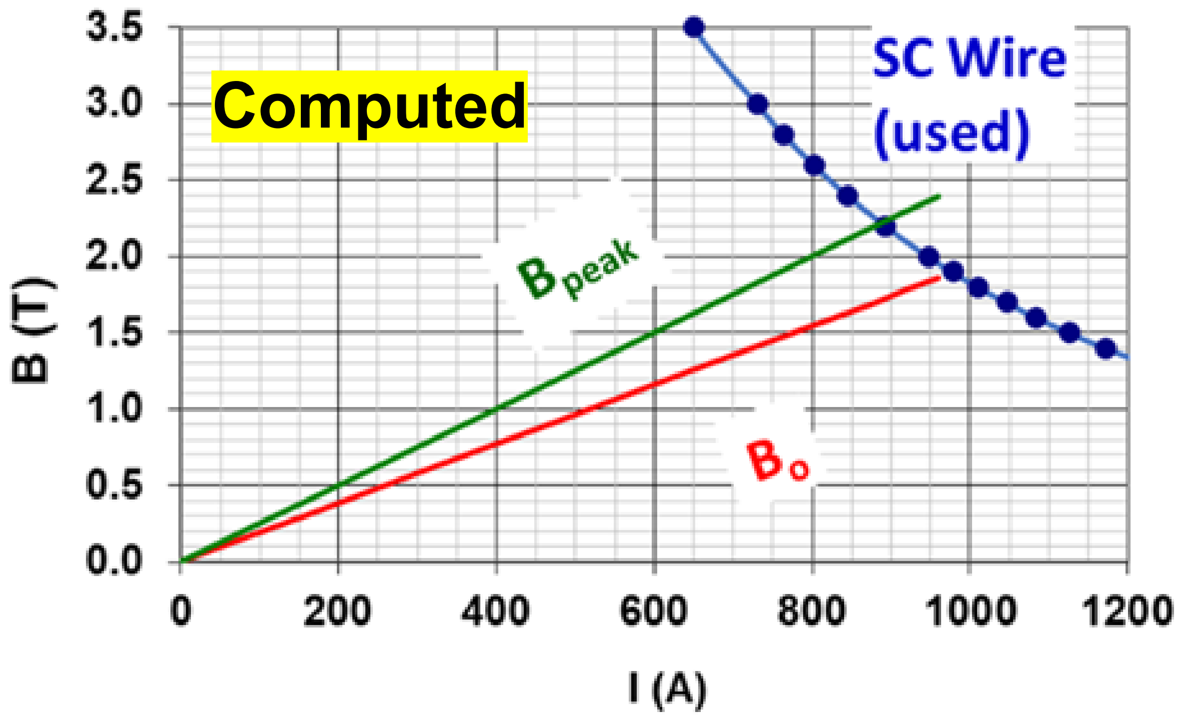
Major motivation of the optimum integral design demonstrated

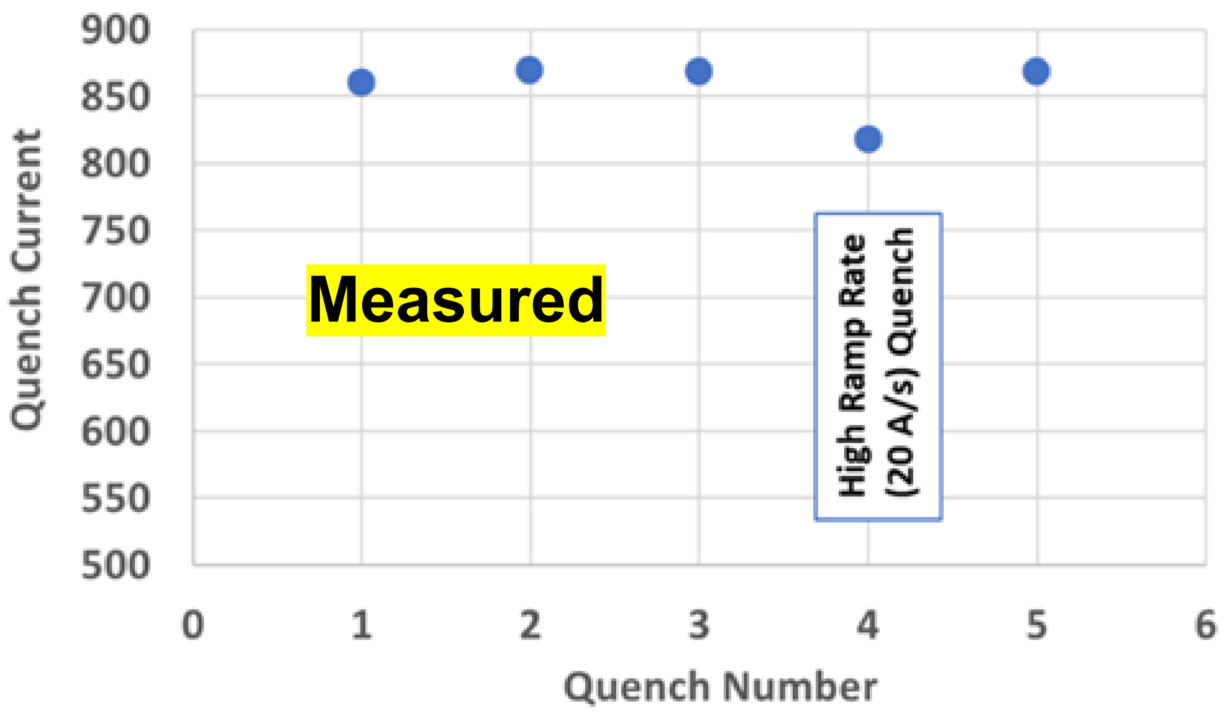


✓ **Answer: Yes, it did, as predicted !**

Good agreement between calculations & measurements.

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





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

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

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

Goals of STTR Phase II Year 1 (with 6 layers)

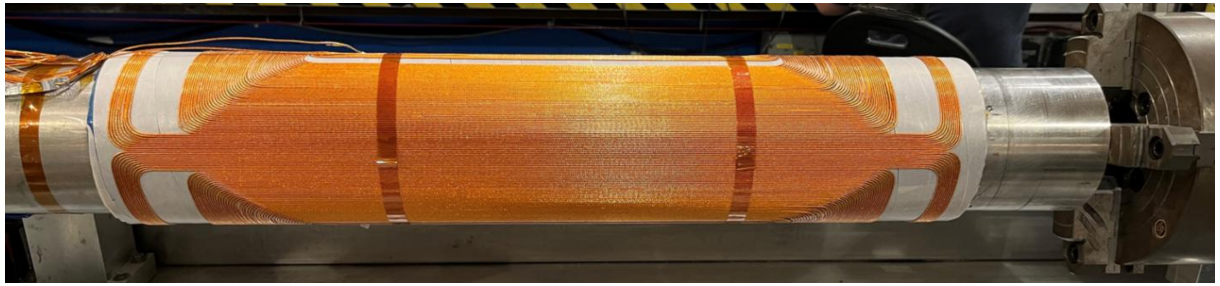
a) **Demonstrate good field quality based on the warm magnetic measurements**

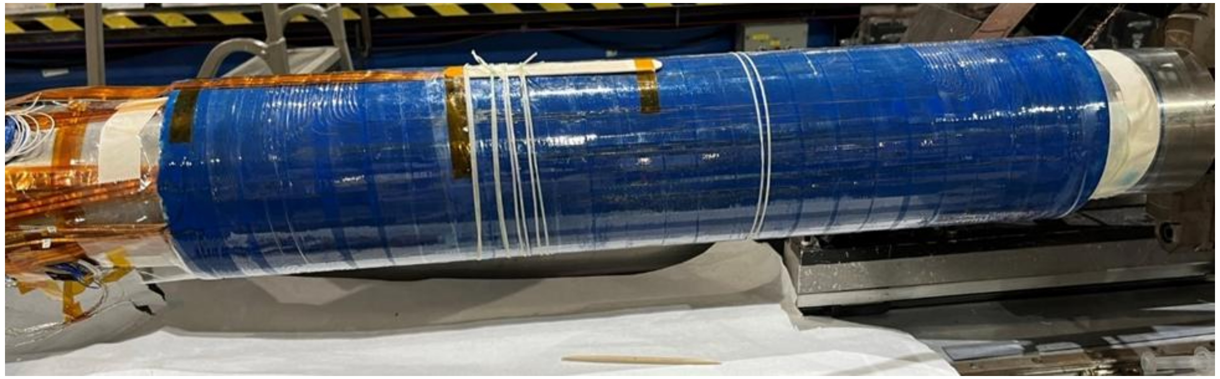
- **Validation of the optimum integral design and the special software developed**

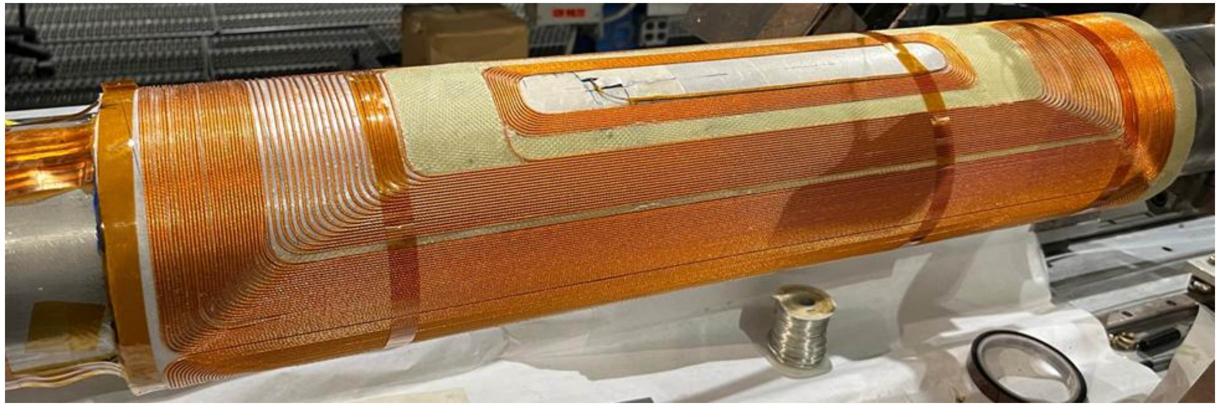
b) **Test six coils with an outer SS support tube in a yoke**

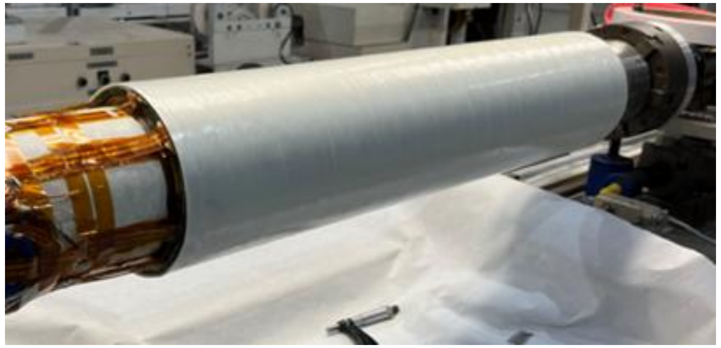
- **Computed performance: B_o = ~2.9 T, B_{pk} ~3.5 T**

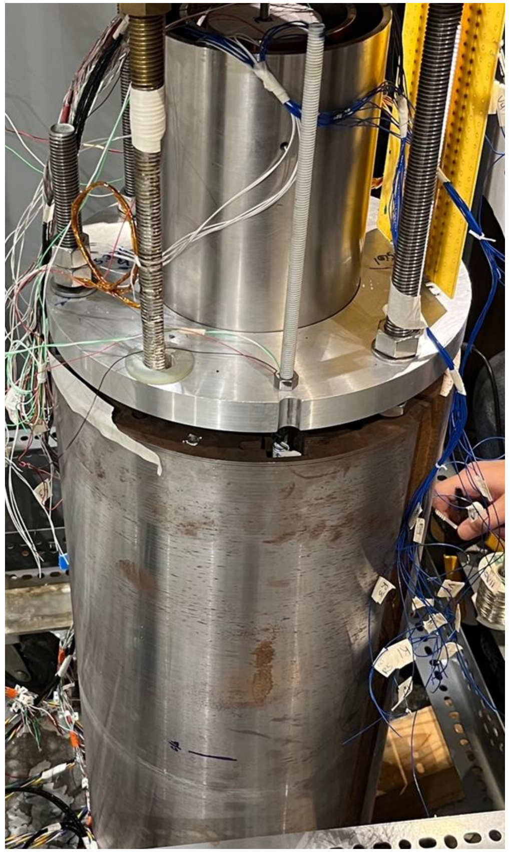
Coil Winding, Magnet Construction (Phase II, Year 1)

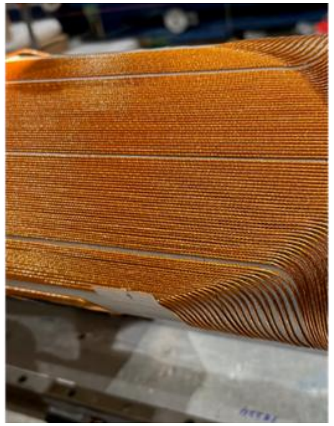


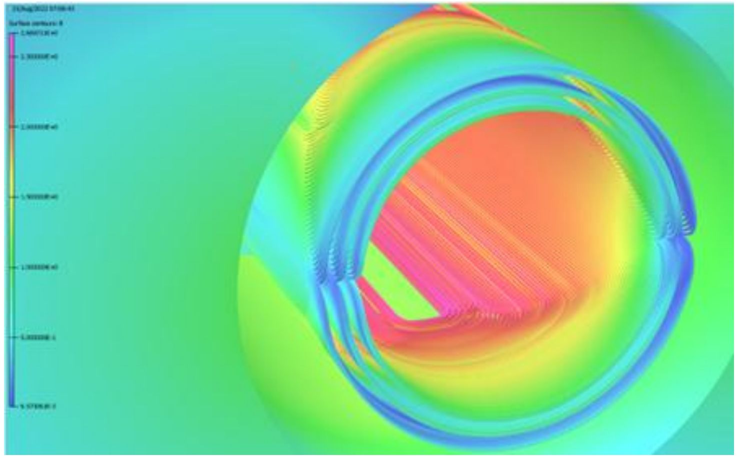












Six layers (3 coil sets)

Field Quality Demonstration of the Design, and of the Code

Warm harmonic measurements after the 6 layers of B0ApF OID

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

Large radius helps, keep track of changes and adjust.

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

(code uses a new method)

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

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

Measured harmonics corrected in the outer coil.

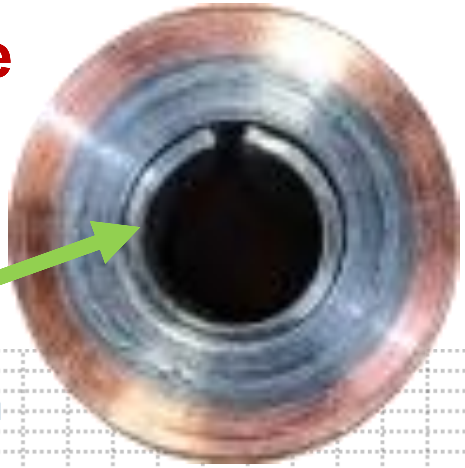
Meeting Requirement of Low Field in Electron Hole (cross-talk)

- The impact of leakage field from high field proton magnets on to the nearby electron beam was recognized as a major driver in the EIC early on.
- DOE SBIR/STTR office funded two proposals on the passive superconducting shielding (rare in a highly competitive area where typically 1 in 7 to 10 gets funded).
- The first funded SBIR was for using LTS tube, as well HTS tube. Both options were experimentally demonstrated to work, however, in a different geometry (extra slide).
- The second funded SBIR was on modelling work and on MgB_2 shielding. MgB_2 tube from HyperTech was obtained, and good progress was made on the modelling.
- **In this STTR, we decided to demonstrate the NbTi shielding in the EIC dipole B0ApF. We made the test much more demanding than required in the machine, by reducing the size of the yoke to increase the leakage field in the e^- cutout.**
- As such the techniques used in other magnets should work here as well. The use of superconducting shielding is likely to be “must” in the Fermilab design of Q2pF.

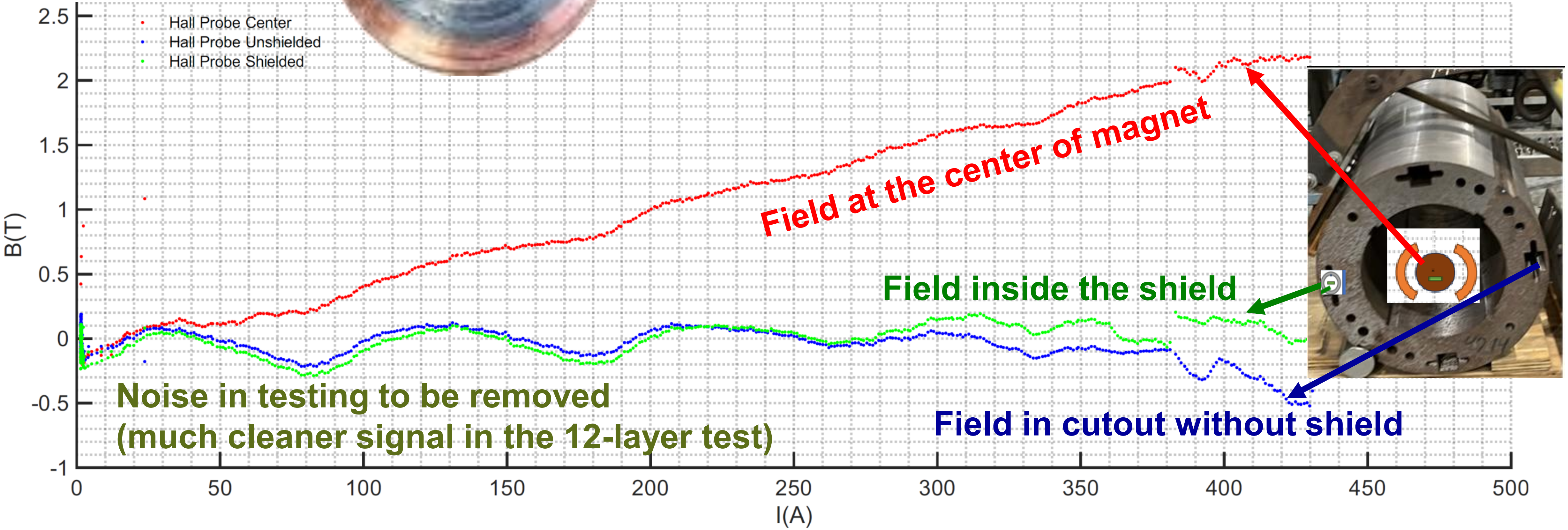
Demonstration of Superconducting Shielding (A4K inside)

NbTi Tube

High permeability *A4K to shield persistent field



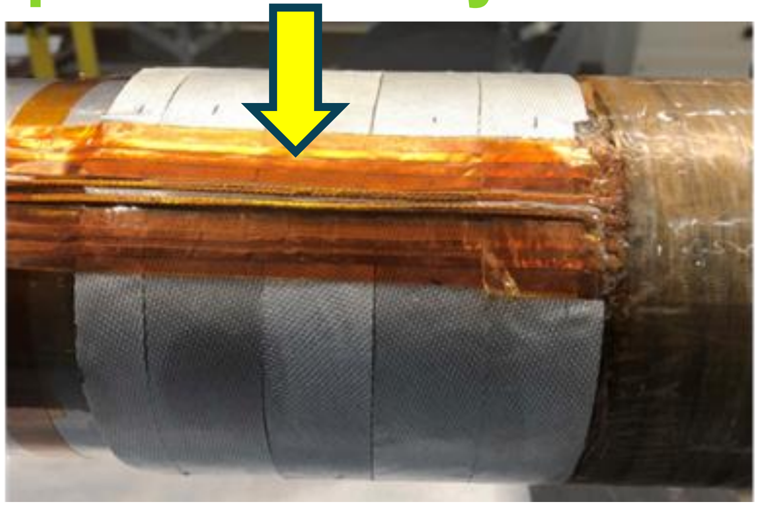
Superconducting shielding works



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

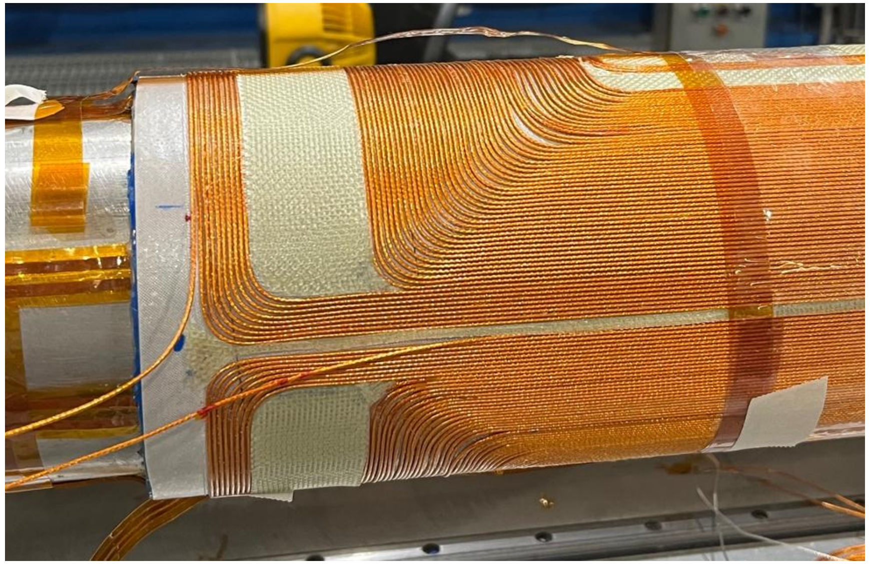
A Change in Design to Eliminate Loss in Radial Space Used by Leads

- 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.



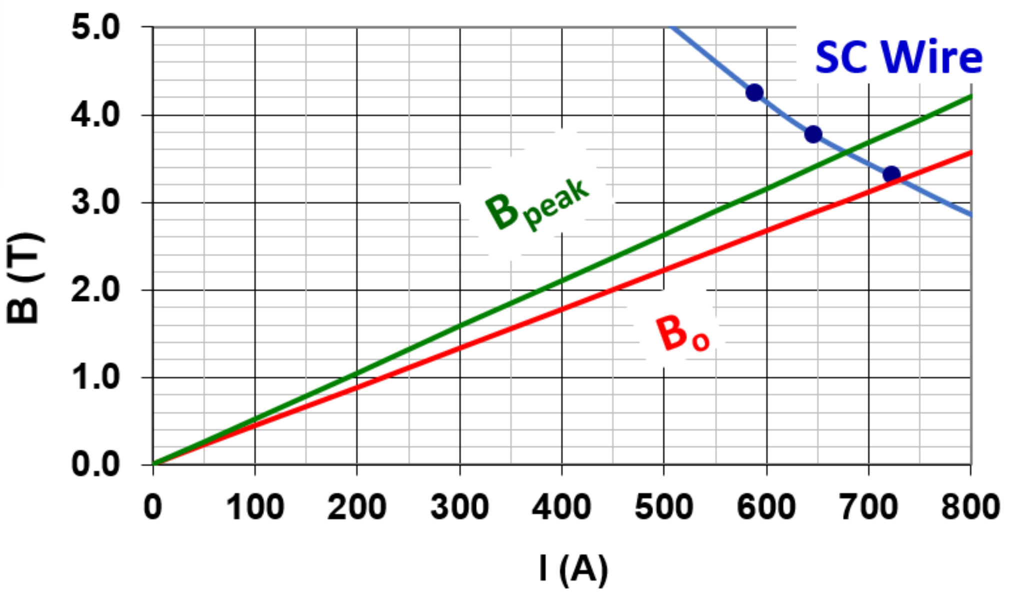
Phase I configuration

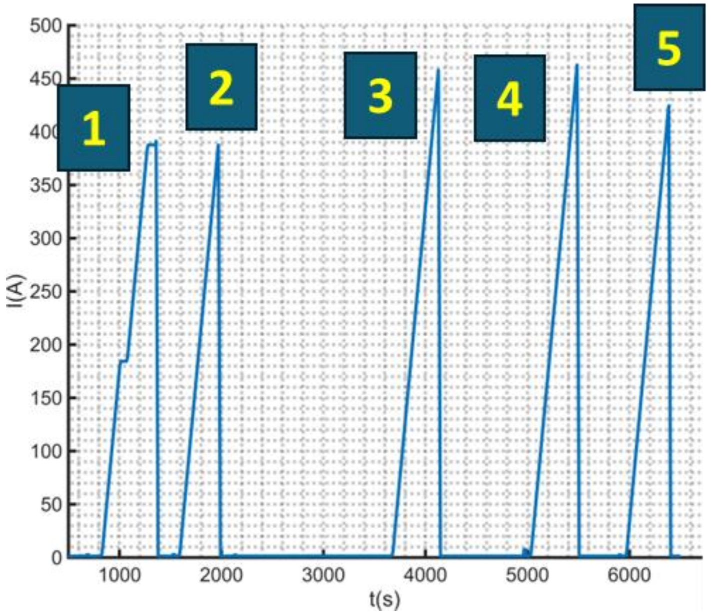
- An innovation was implemented to remove extra radial space. Leads out at midplane.
- This solution required a splice at the pole in high field region, and additional routing of leads in an area outside the end of coil.
- This was used in the next four layers.

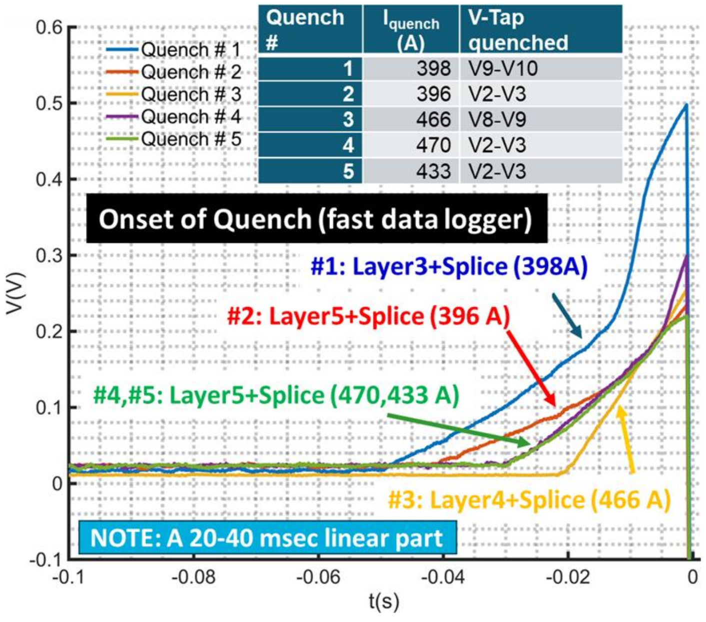


Phase II configuration

Testing of the Intermediate 6-layer Optimum Integral Dipole







- **Magnet reached 470 A (~70% of the short sample).**
- **All quenches were in the coil sets where the lead routing was changed to eliminate the need to use the extra radial space.**

This issue has now been resolved !

Updated Goals of the Phase II (12 layers on two tubes)

First address the issue that limited the performance of the Phase II, year 1 construction.

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

<u>Project goal of the OID B0ApF (full-length, field integral)</u>

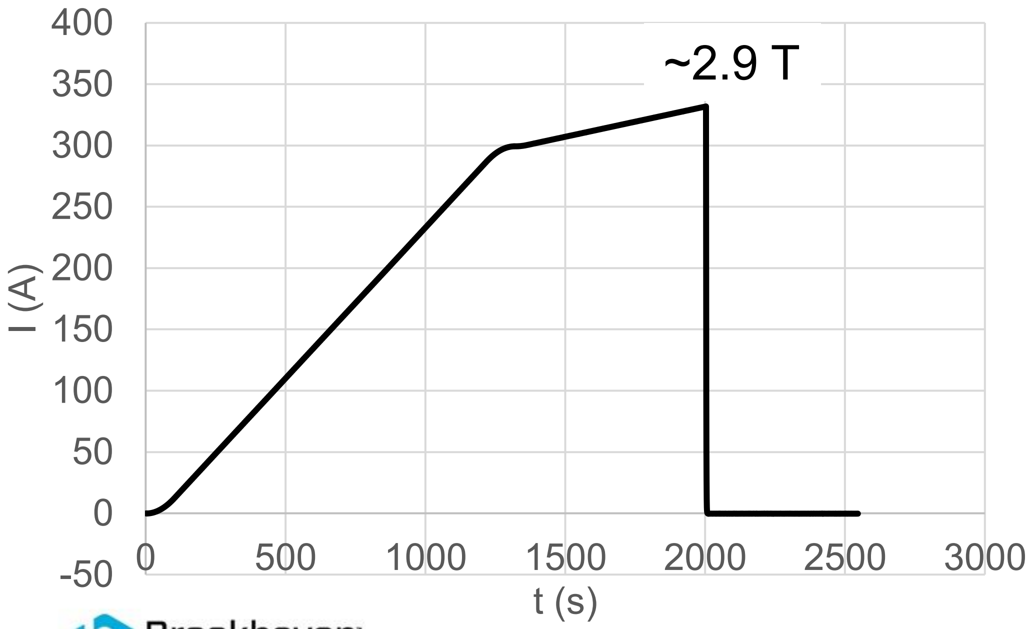
Coil i.d. 114 mm, L = 600 mm to generate 1.98 T.m integral

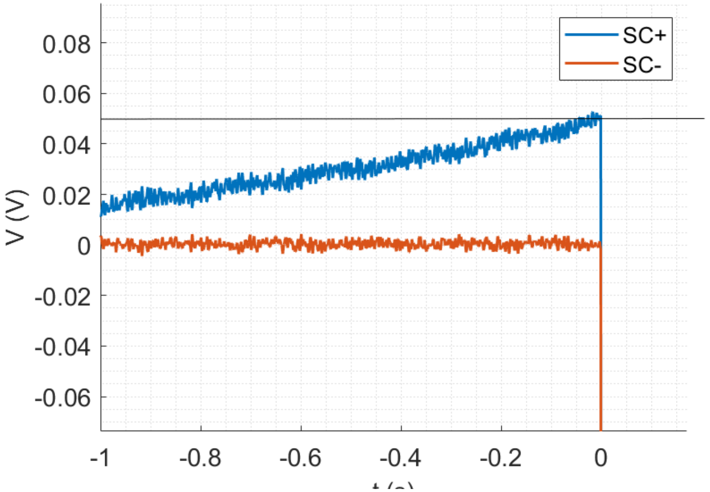
Model computation: I = 470 A, B_o~3.9 T, B_{peak} ~4.3 T

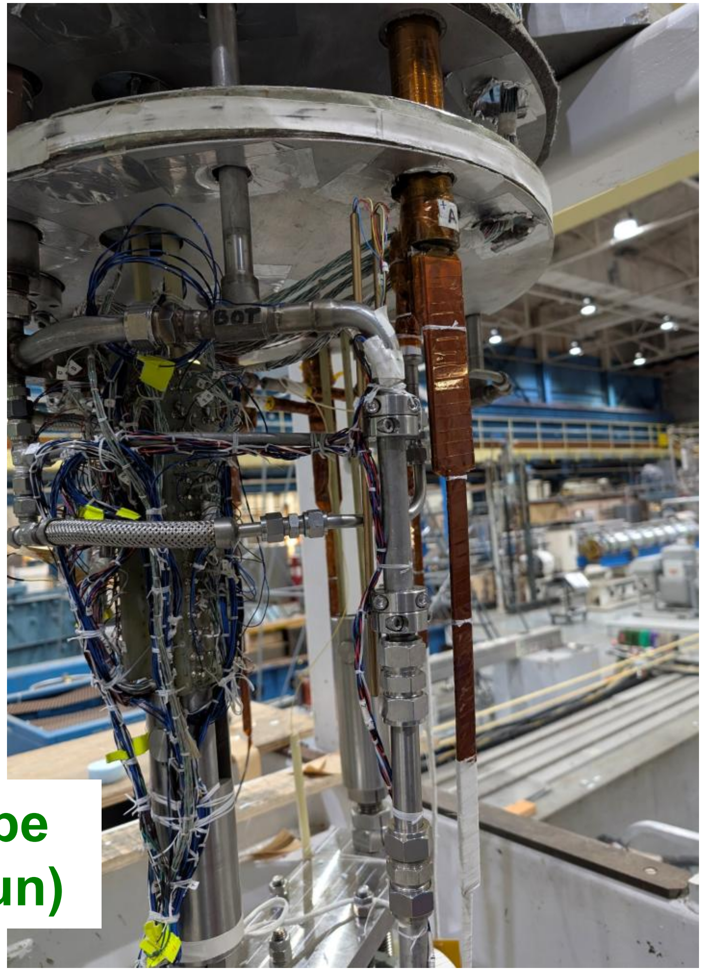
Test Results of the 12-layer Direct Wind Optimum Integral Dipole B0ApF

- **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 worked, as planned (issue that limited performance last year is resolved)**
- **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 is good, issue to be resolved before the next run)

*Required field integral in an alternate lattice ~1.7 T.m

Steps for Possibly Making Optimum Integral as the Baseline Design for B0ApF and Making it Ready for MSG and PDR

- Fix the issue external to the magnet and perform the test to its design integral field.
- Even though the issue reported are external to the magnet and the magnet did not quench to a significant fraction (~75%) of the design field, we are pushing the direct wind technology where it has yet to demonstrated.
- We can move as there is little mechanical difference between the serpentine & OID.
- We still need to complete the following tasks:
  - ➢ Model real iron with a large diameter yoke which includes electron hole and other features
  - ➢ Include skew quad and vertical dipole corrector in the overall design
  - ➢ Investigate other options. However, if the design is demonstrated, why change it?
  - ➢ There is enough spare wire. Make the cable and plan to use it in the actual magnet.
  - ➢ Perform quench analysis and look for reliable options.
  - ➢ Perform mechanical analysis and other necessary engineering before the review.

➢ **We need "go ahead" from the project management to proceed.**

Summary

- Optimum integral design significantly reduces the field requirement in short magnets by reducing the loss in magnetic length due to the ends.
- Benefits are enormous in many EIC magnets, including but not limited to B0ApF.
- Extension of magnetic length, good field quality and suppression of field on electron beam due to cross-talk of proton magnet have been demonstrated in B0ApF.
- PBL/BNL direct-wind, optimum integral, full-length B0ApF dipole, was energized to ~2.9 T for ~75% of the required integral field at ~4.2 K (extra margin at ~1.92 K) and ~84% of the RHIC dipole design field, with no spontaneous quench in the magnet.
- The test is planned to be continued after fixing the issues external to the magnet.
- The design can be adapted for B0ApF. Some design work required before the review.
- A limited EM design work is in order to examine this design in other EIC magnets.

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

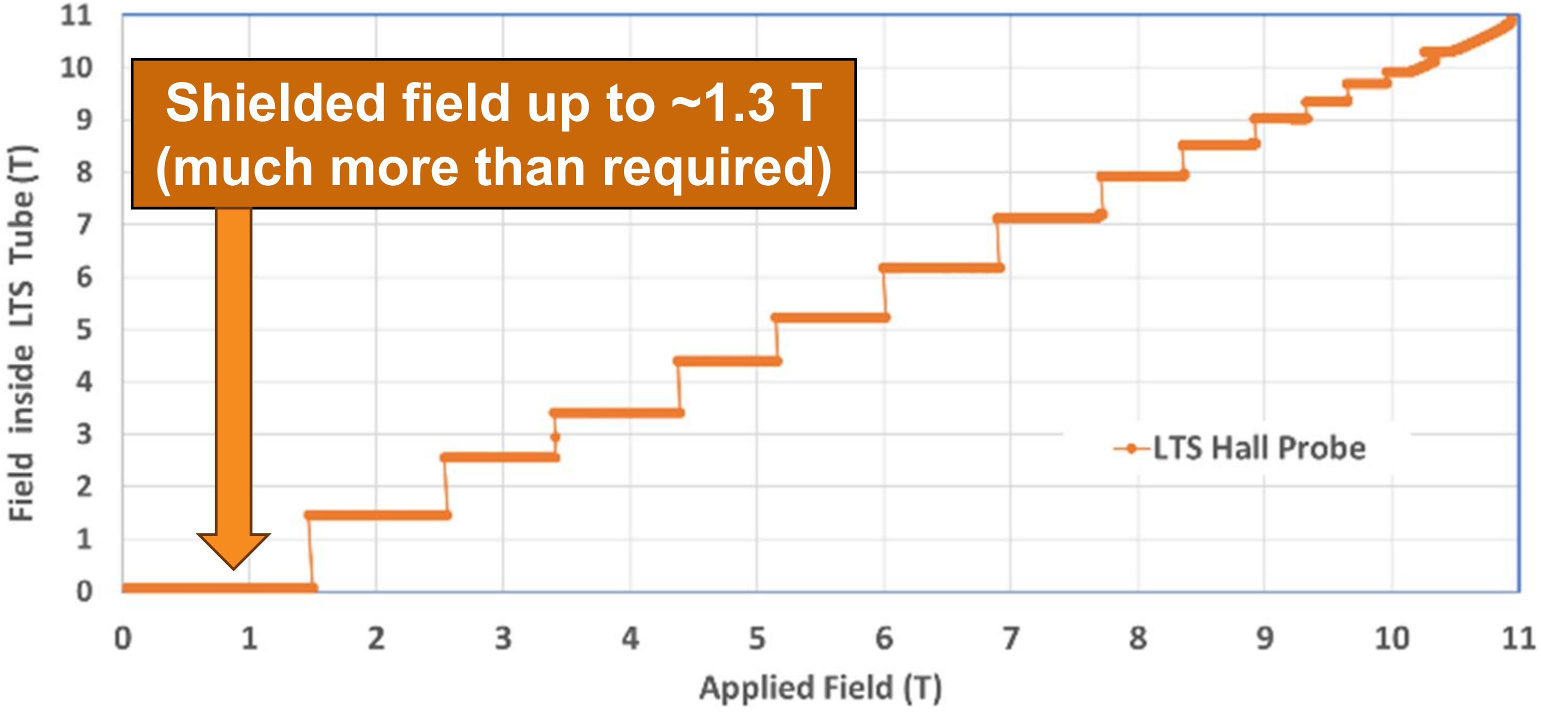
- **Record field in an HTS/LTS hybrid accelerator dipole: 8.7 T (2017)**

  Follow-on work:

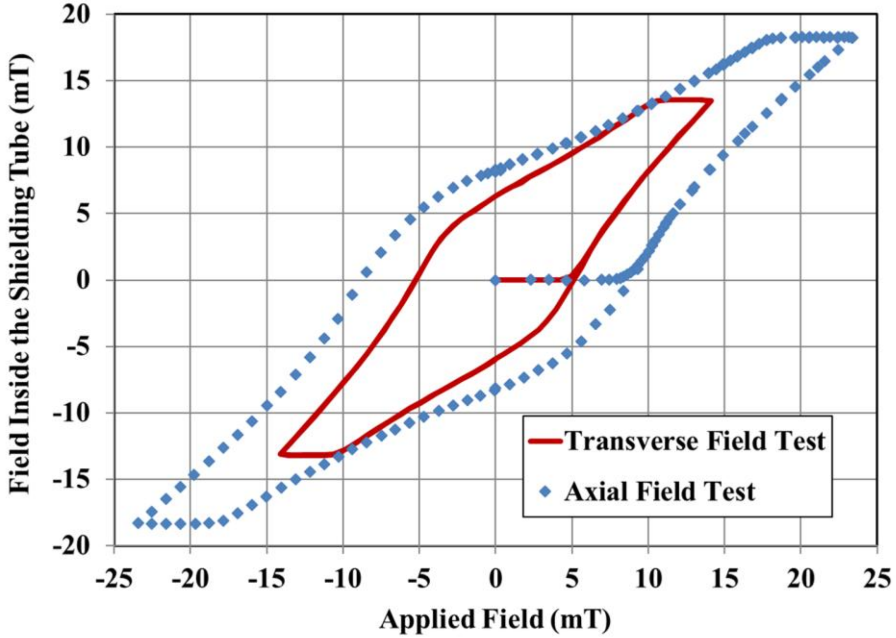
  ✓ Led to (a) several new SBIR/STTR grants, (b) Magnet Development Program with HEP producing another record hybrid field of 12.3 T, (c) created a unique Common Coil Test Facility (**CCTF**) for HEP and "Fusion" cable and magnet R&D.

- **Useful R&D by PBL/BNL SBIRs which got applied to BNL programs**

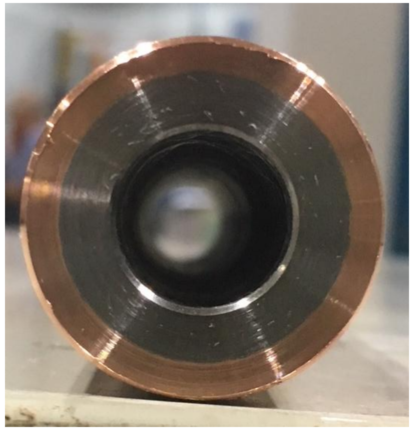
Demonstration of Superconducting Shield in a PBL/BNL SBIR



HTS@77K



LTS@4K



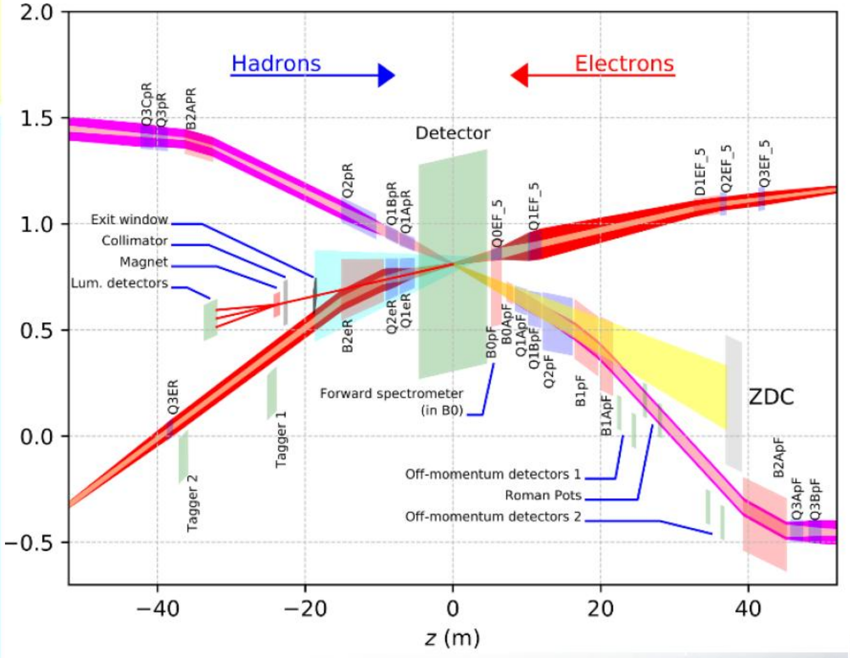
Luvata

Bruker/Oxford

can superconductors

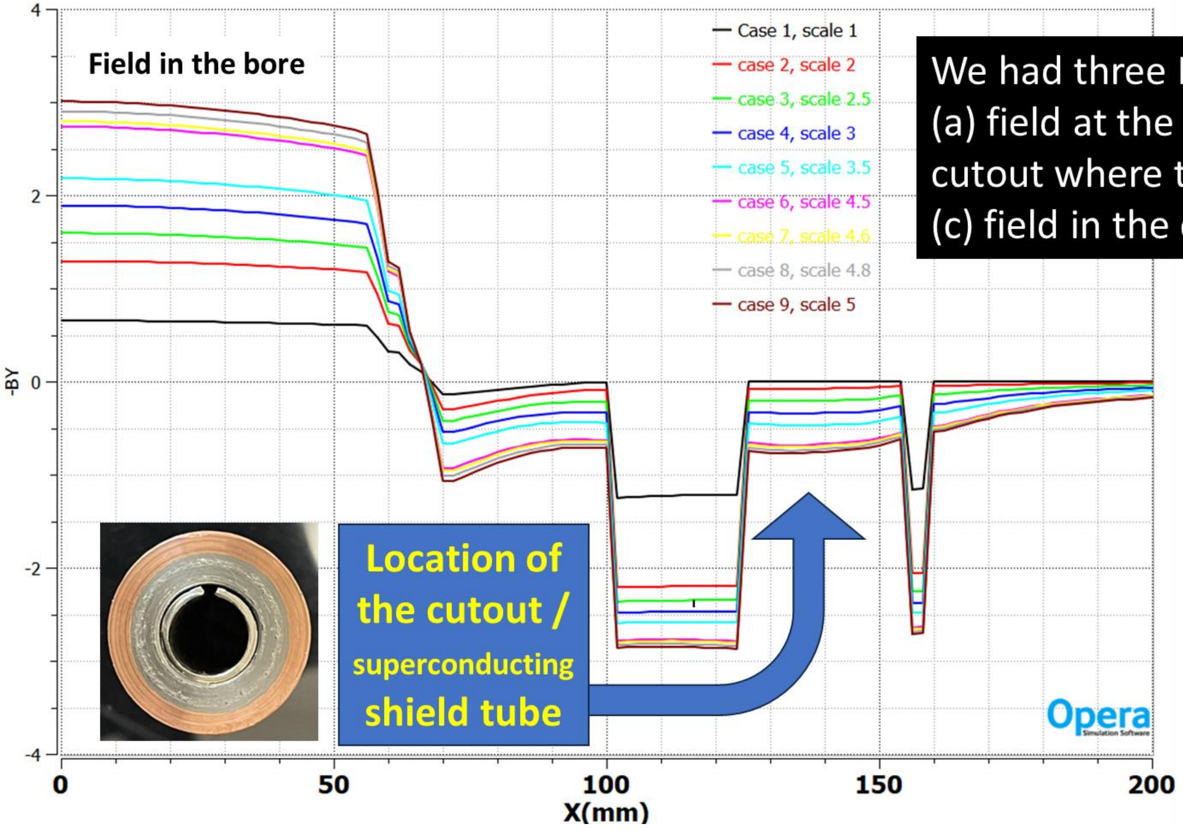
Test of Superconducting Shielding for EIC Magnets

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



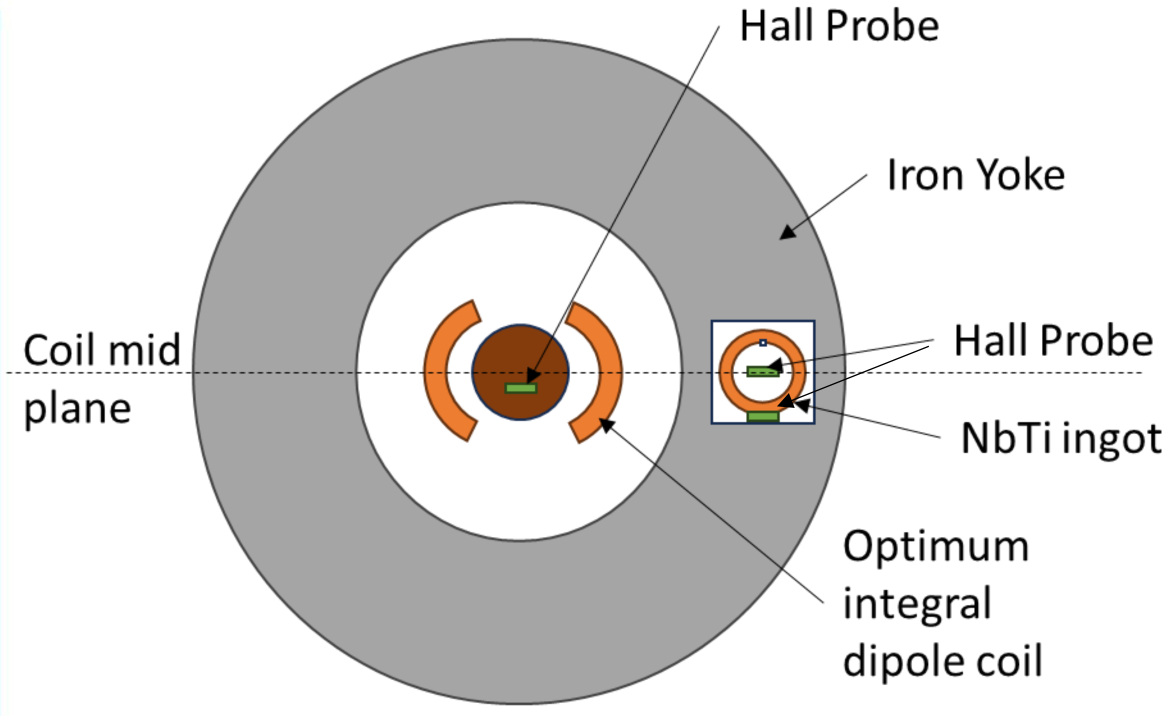
Field from the high field magnets for ion beams must be shielded on the path of e-beam

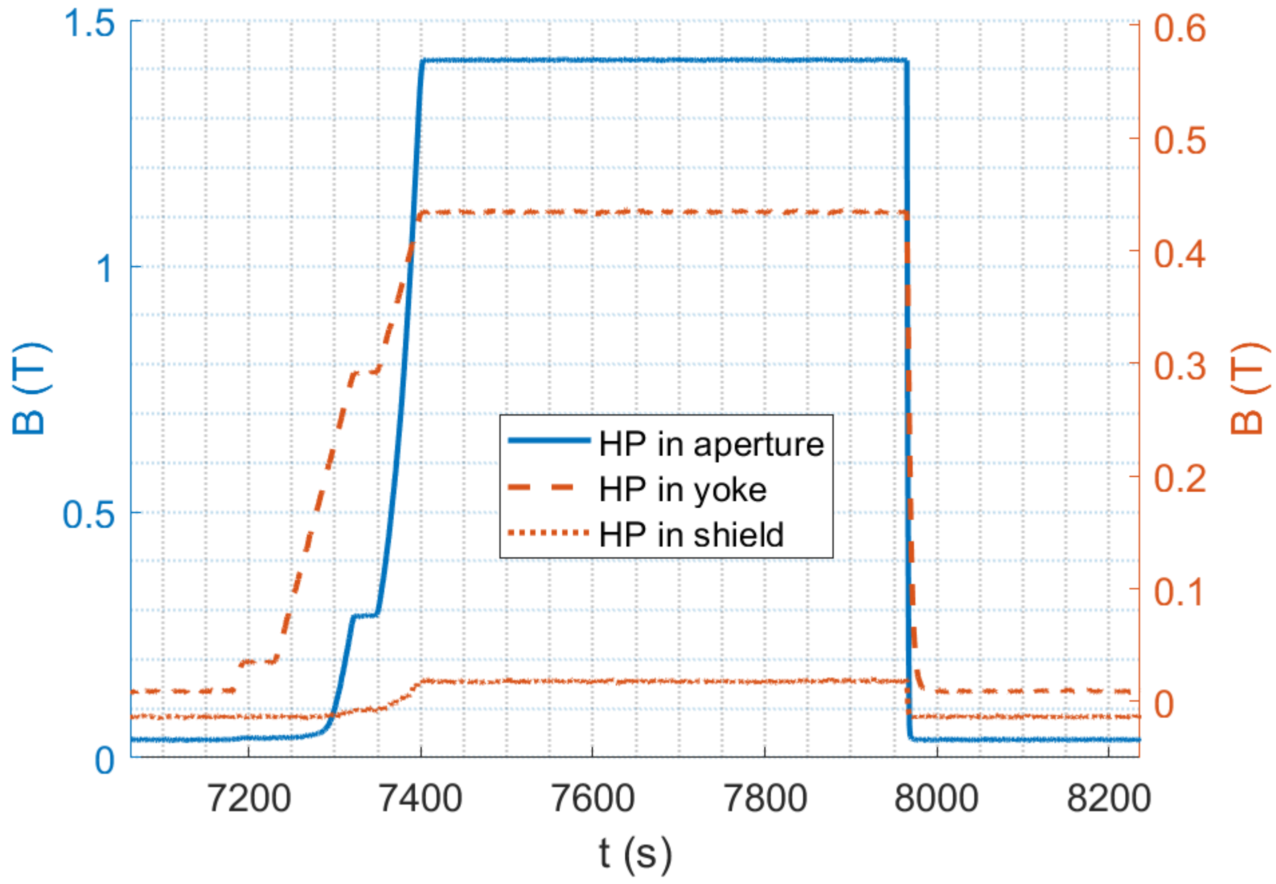
- ➢ This test run provided an opportunity to test the potential benefit of superconducting shield in EIC.
- ➢ The topic was part of an earlier PBL/BNL Phase I SBIR



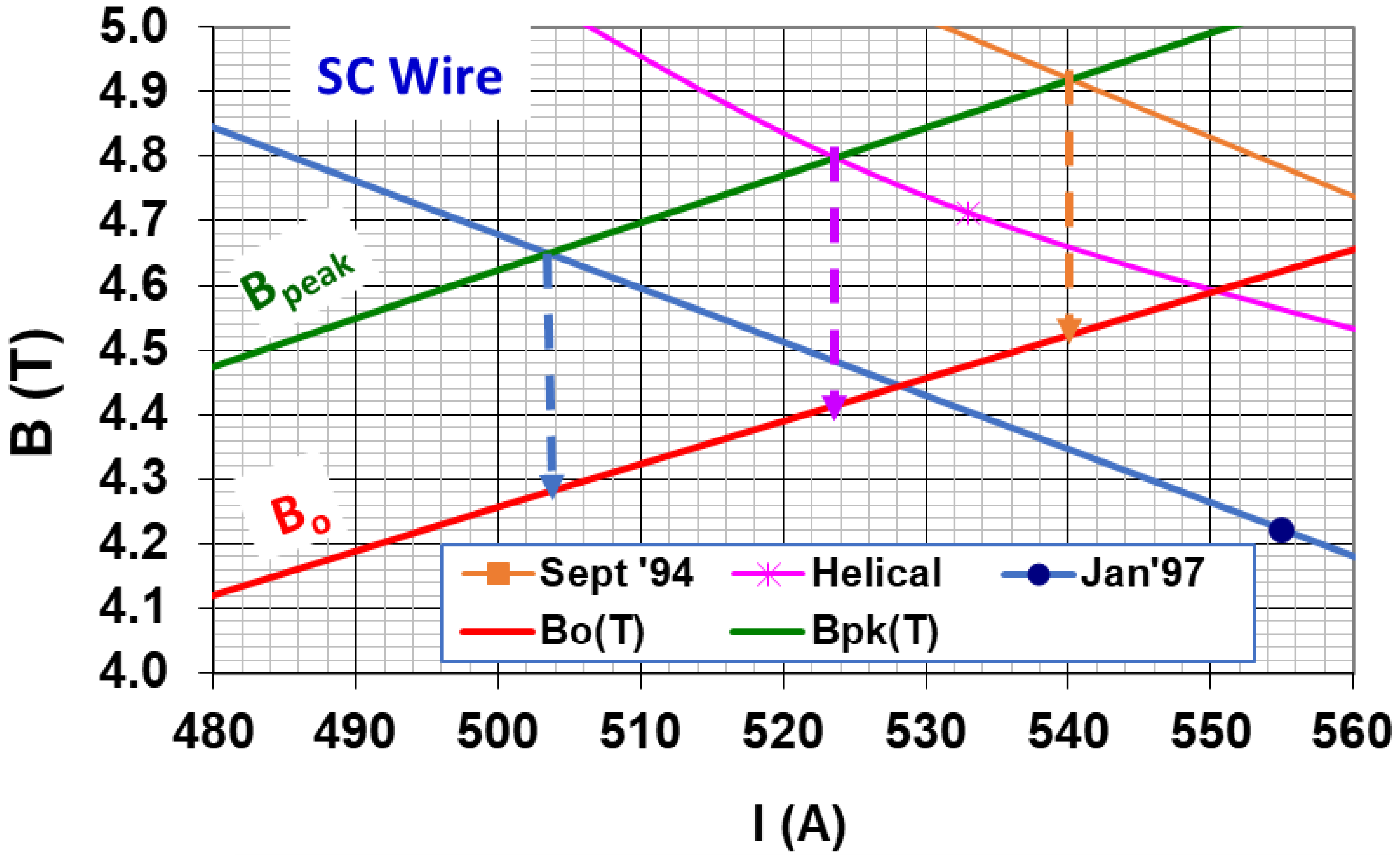
We had three Hall probes to measure (a) field at the center, (b) field in the cutout where the SC shield is (+x) and (c) field in the cutout with no shield (-x).

Passive Shielding Experiment in 12-layer higher field dipole





(cleaner Hall probe signal. Data still being examined.



4.22 K

Optimum Integral 114 mm id, L=600 mm, 12 (6+6) Layers

Model Calculations (OPERA3d)			eic-pbl-12lyrs-as-built-yoke.op3				
Scale	B-Integral (T.m)	**Case #**	**Current (A)**	**Bo(T)**	**Bpk(T)**	**B/I (T/kA)**	**Bpk/Bo**
0.01	0.025	1	5	0.048	0.051	9.560	1.075
0.1	0.246	2	50	0.478	0.514	9.567	1.074
0.2	0.491	3	100	0.956	1.028	9.558	1.076
0.3	0.726	4	150	1.42	1.54	9.456	1.087
0.4	0.946	5	200	1.86	2.05	9.304	1.100
0.5	1.16	6	250	2.29	2.54	9.151	1.109
0.6	1.36	**7**	300	2.69	3.01	8.962	1.120
0.7	1.55	8	350	3.06	3.46	8.743	1.129
0.8	1.73	9	400	3.41	3.72	8.523	1.091
0.9	**1.91**	**10**	**450**	**3.74**	**4.08**	8.320	**1.090**
0.94	**1.98**	**…yoke-470A**	**470**	**3.88**	**4.23**	**8.247**	**1.090**
1	**2.08**	**11**	**500**	**4.07**	**4.44**	**8.145**	**1.090**
1.1	2.25	**12**	550	4.40	4.79	7.996	1.089
1.2	2.42	13	600	4.72	5.14	7.869	1.089
1.3	2.59	14	650	5.04	5.49	7.760	1.089
1.4	2.75	15	700	5.37	5.84	7.665	1.088
1.5	2.92	16	750	5.69	6.19	7.582	1.088
1.6	3.09	17	800	6.01	6.54	7.509	1.088
1.7	3.26	18	850	6.33	6.88	7.445	1.088
1.8	3.42	19	900	6.65	7.23	7.387	1.088

Summary of Test Results

- We carried out several quench experiments by initialing several heater induced quenches at different currents and with different dump resistors. We got a lot of useful data but not a complete set of data in a limited time and instrumentation.
- Preliminary test results show that the superconducting shield worked well in suppressing field for e-beam more than what would be present anywhere in EIC IR.
- Fiber optics wire picked up signal (even though the wire was not designed and procured for this experiment), implying that this tiny wire could be a good fit for the direct wind coils with small gaps between the turns.
- Only two attempts were made to energize the magnet to quench. The maximum current was limited by one of the superconducting lead developing resistive voltage. Though we need to verify this but it appears to be either a bad joint or not properly stabilized superconductor between the magnet and the current leads at the top-hat.
- The test results are still impressive, as we were able to energize a large aperture EIC IR R&D magnet without any quench to ~2.9 T, which is ~74% of ~3.9 T for 1.98 T.m.

Latest on the Optimum Integral Design

Optimum Integral Design : https://wpw.bnl.gov/rgupta/optimum-integral/

At MT29:

Oral:

Design, construction, and test of a superconducting dipole based on the Optimum Integral Design (https://mt29-conf.org/), Thu-Mo-Or1-03, Boston (abstract).

Poster:

Optimum Integral Design for EIC Dipole B1pF/B1ApF, (https://mt29-conf.org/), Fri-Mo-Po.05-04, Boston, July 1 – 6, 2025 (poster).

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

- 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 Nuclear Physics 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