Grant Award Number: DE-SC0021578

Particle Beam Lasers

A New Medium Field Superconducting Magnet for the EIC

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@BrookhavenLab

FY24 Nuclear Physics SBIR/STTR Phase II Exchange Meeting, August 14, 2024

Overview

- **Main contributions of Particle Beam Lasers, Inc. (PBL)**
- **New Design and its benefits to Electron Ion Collider (EIC)**
- **Status and plans**
  - ➢**Collaborative R&D with other projects for creating experimental data on quench propagation, etc., and for allowing extended testing of the upcoming magnet despite the added tasks**
- **Application to other EIC magnets and beyond**
- **Summary**

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**

NOT include above: Other PBL Awards, Grants and Contracts

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

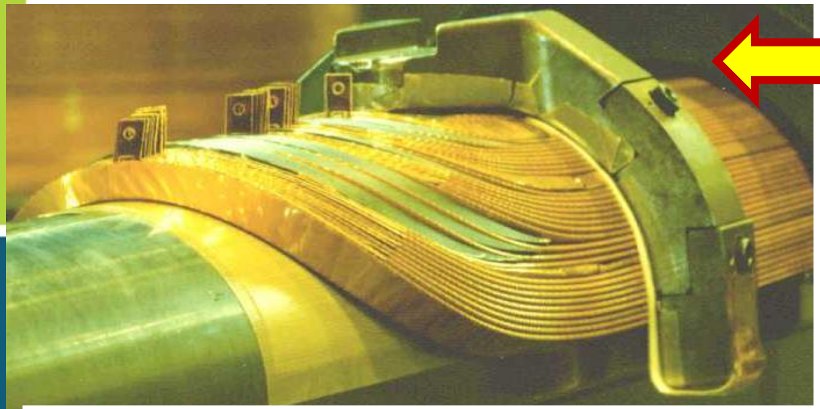
- **Record field in an HTS/LTS hybrid accelerator dipole: 8.7 T (2017)**

  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**

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)

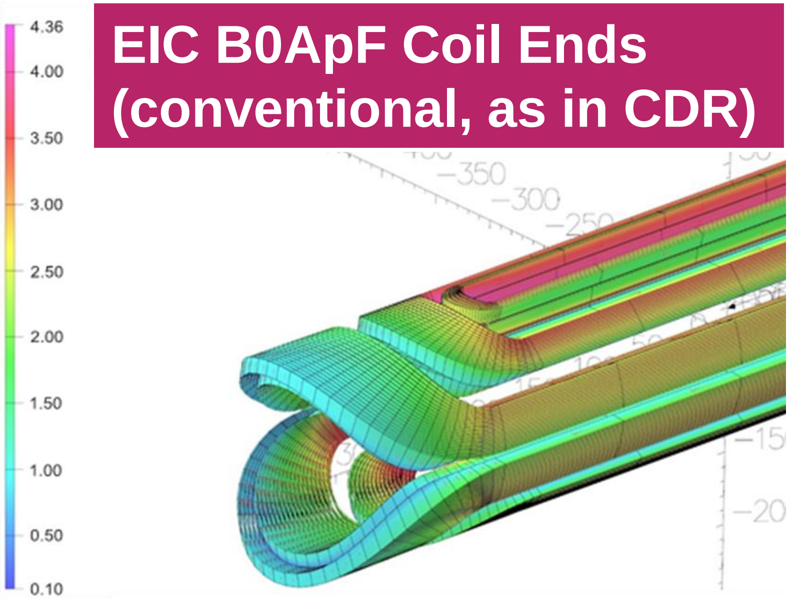
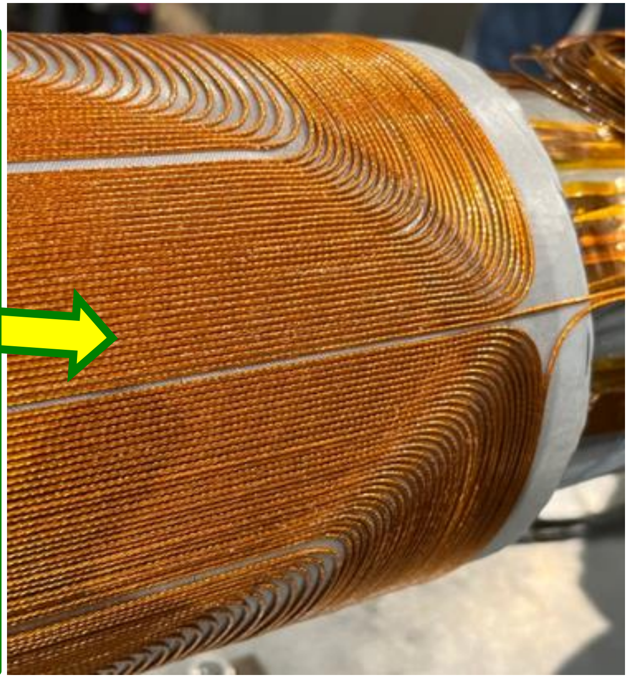


Figure 5: *B0APF coil with field contour*

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)



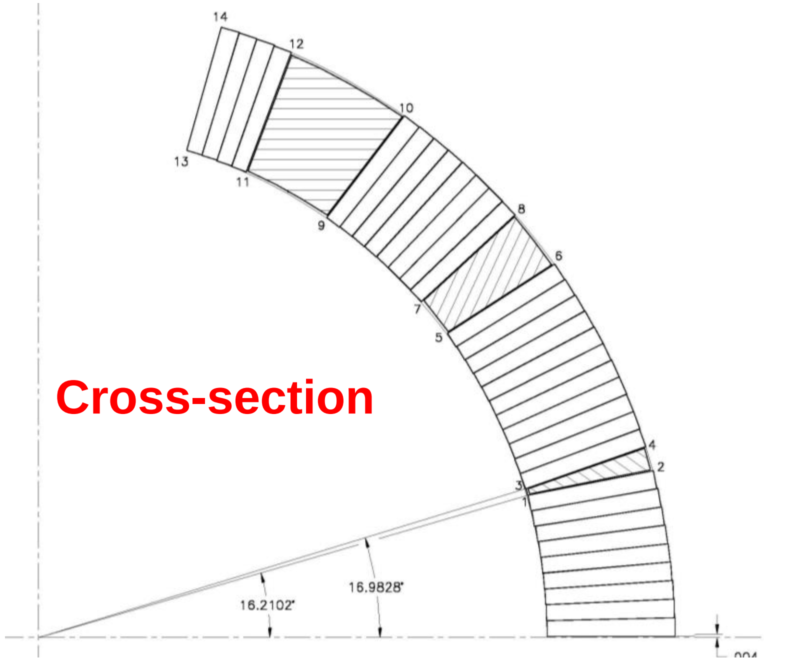
Conventional Design Approach

A two-step process of designing magnets:

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

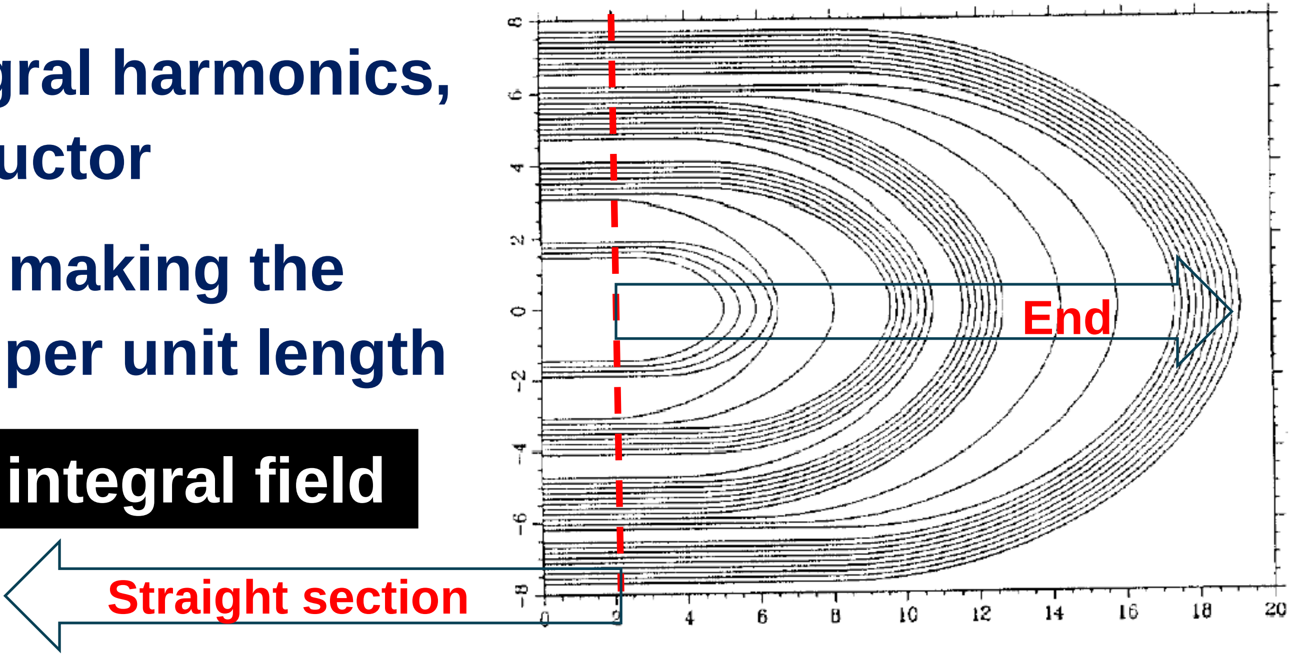
$$I(\theta) = I_o \, . \cos(n\theta)$$

- ➢ **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**



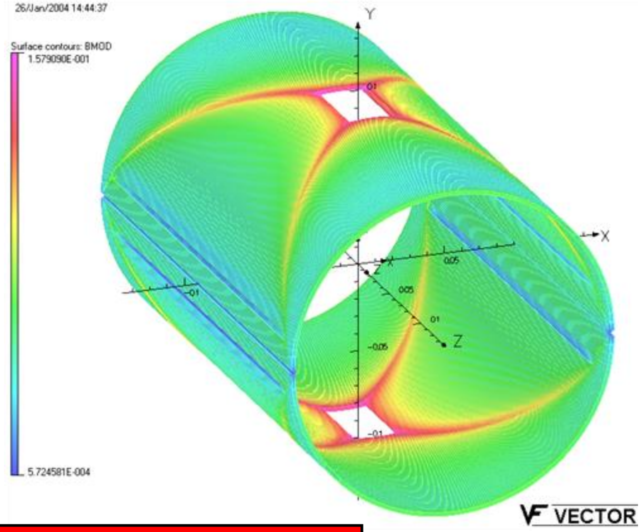
Each step reduces the maximum integral field

Optimum Integral Design Approach

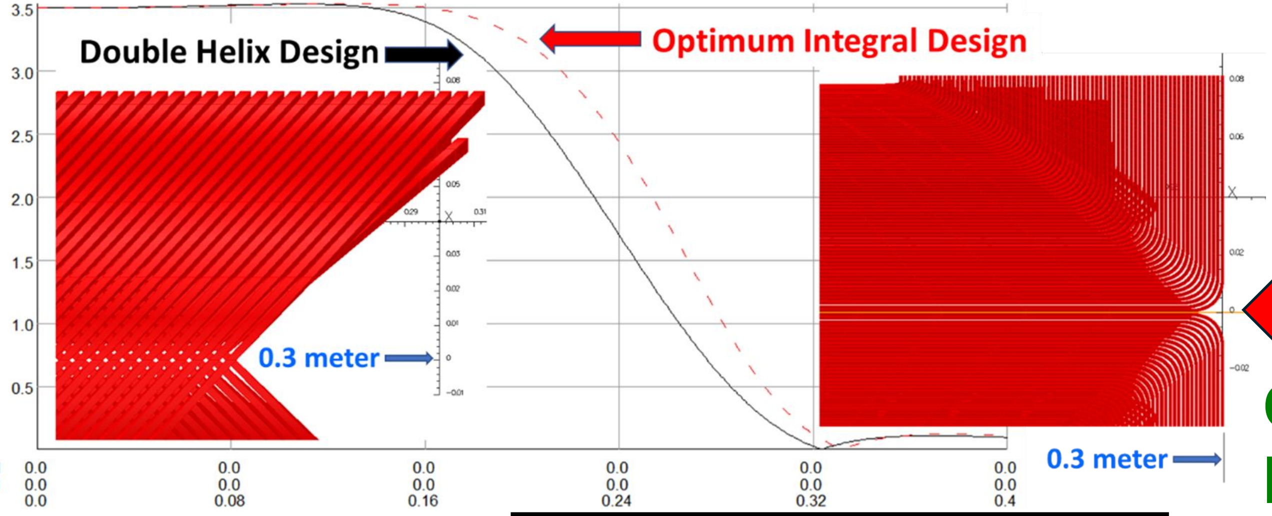
A one step integrated process:

Optimize cross-section and ends together to obtain an integrated cosine theta distribution:

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



- **A full-length midplane a zero-length pole produces a linear function. Conceptually modulate that to cos(θ).**



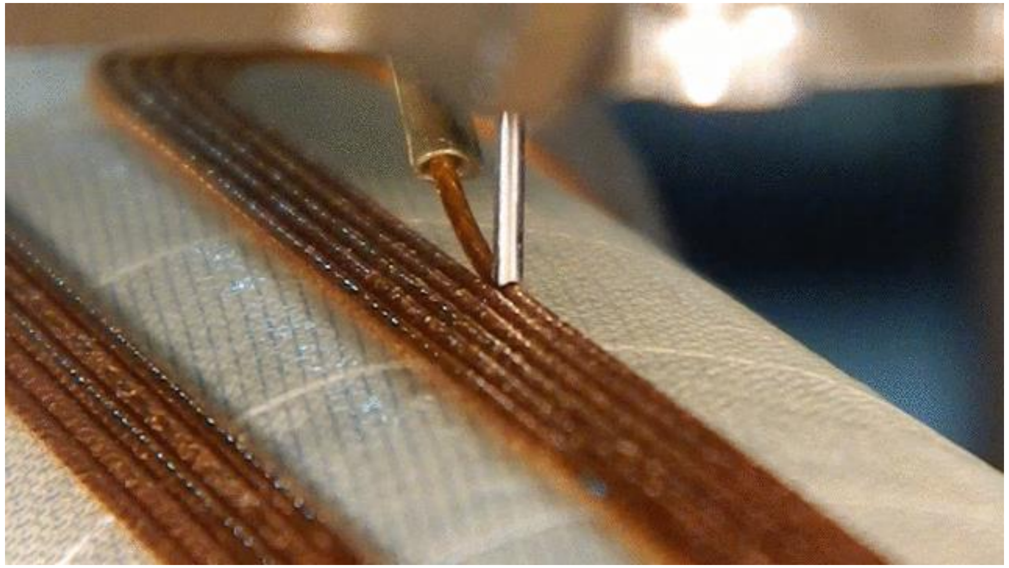
STTR Dipole EIC B0ApF

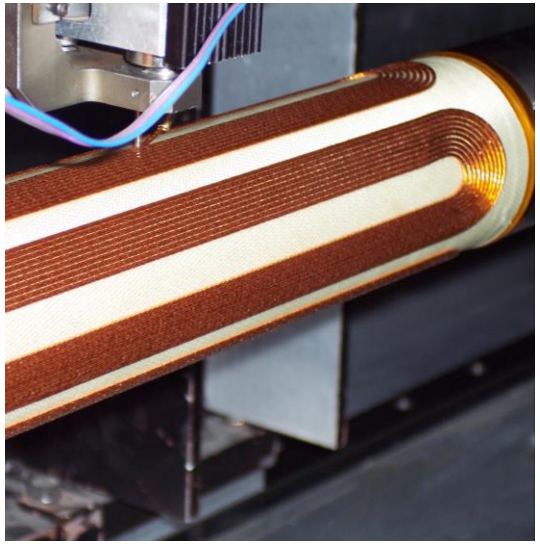
Larger integral field

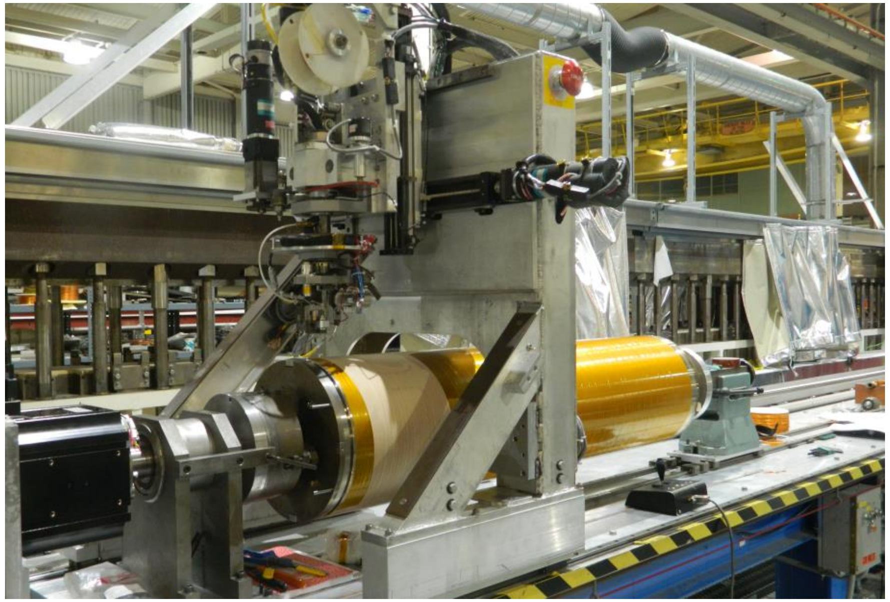
Coil length approaches the magnetic length. Ends help in shaping the integral field rather than causing a loss

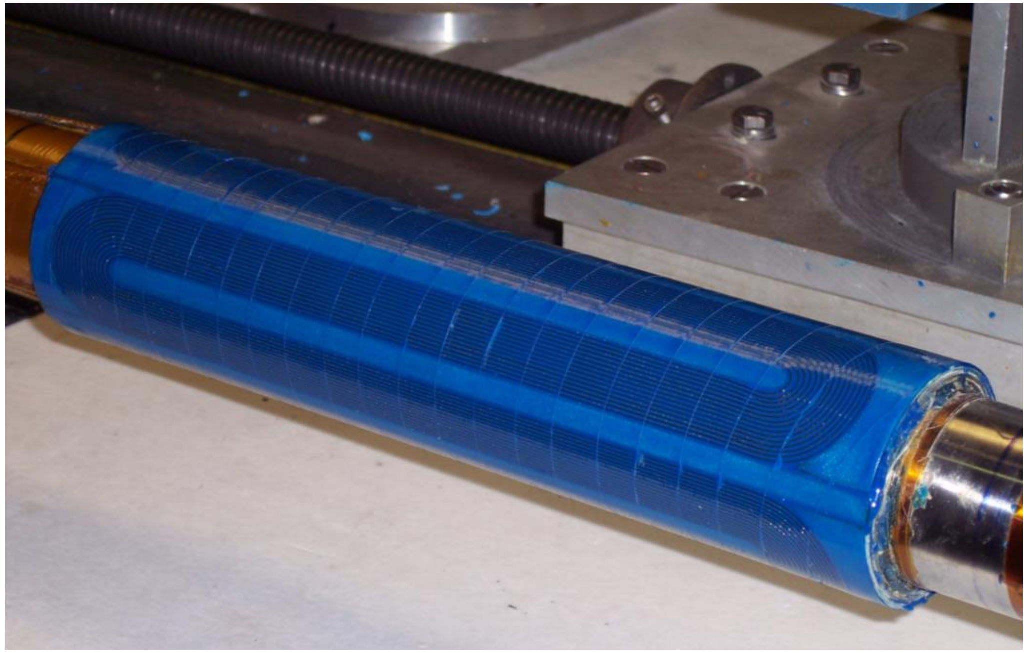
A Key Component of this STTR – the Direct Wind Technology

- **Wire is laid directly on the tube and bonded with 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**

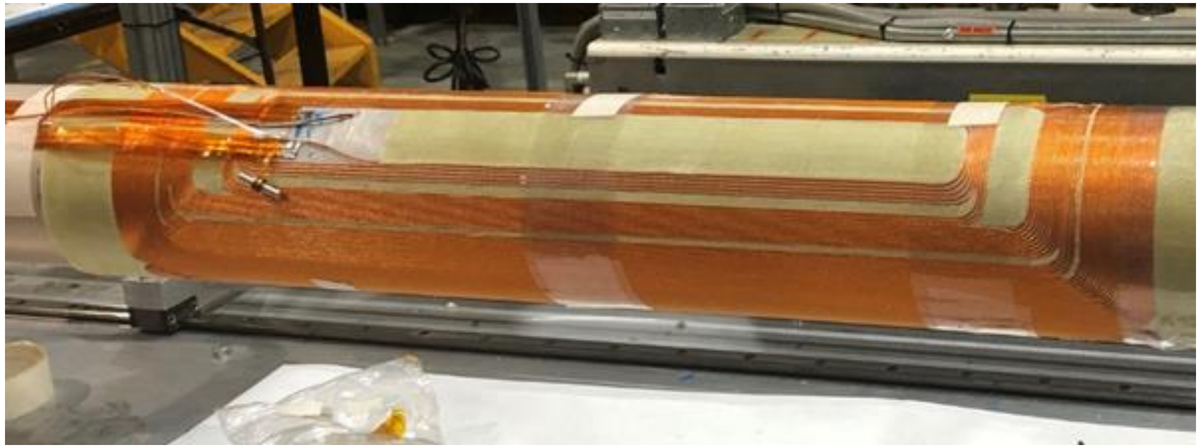


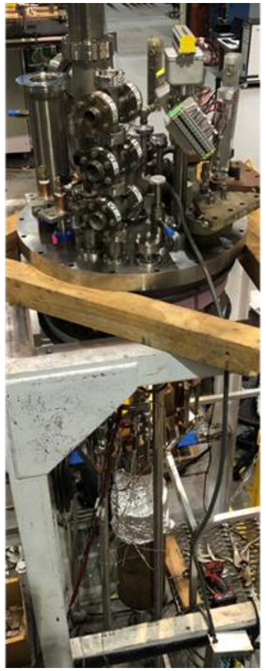


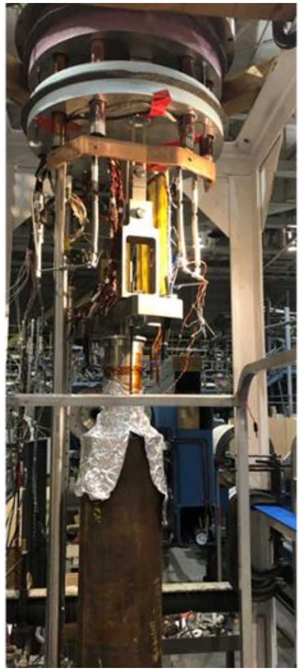




Optimum Integral Dipole for EIC B0ApF (Phase I construction and testing)



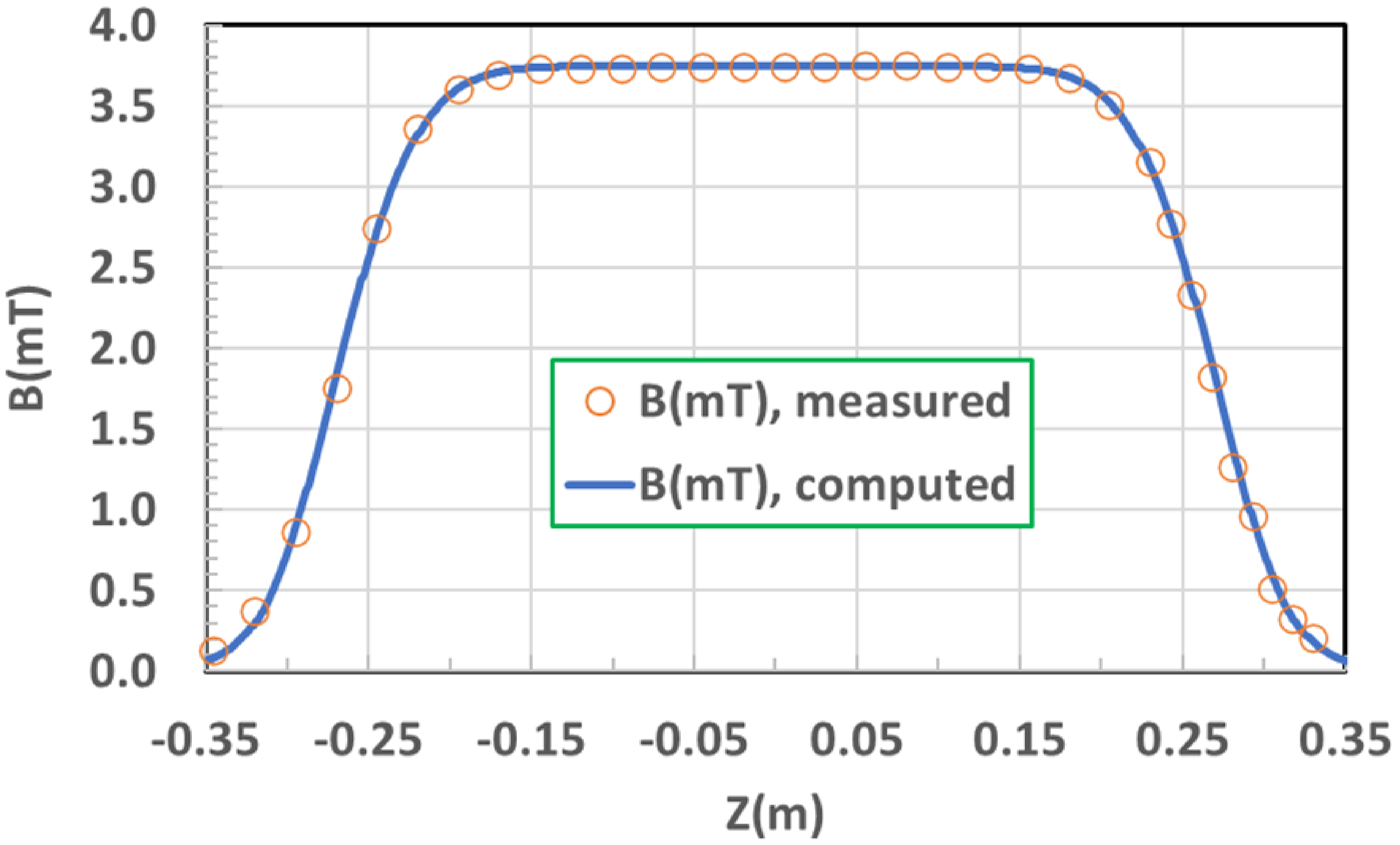




Question #1 for Phase 1:

Will optimum integral design extend the magnetic length, as promised?

Major motivation of the optimum integral design

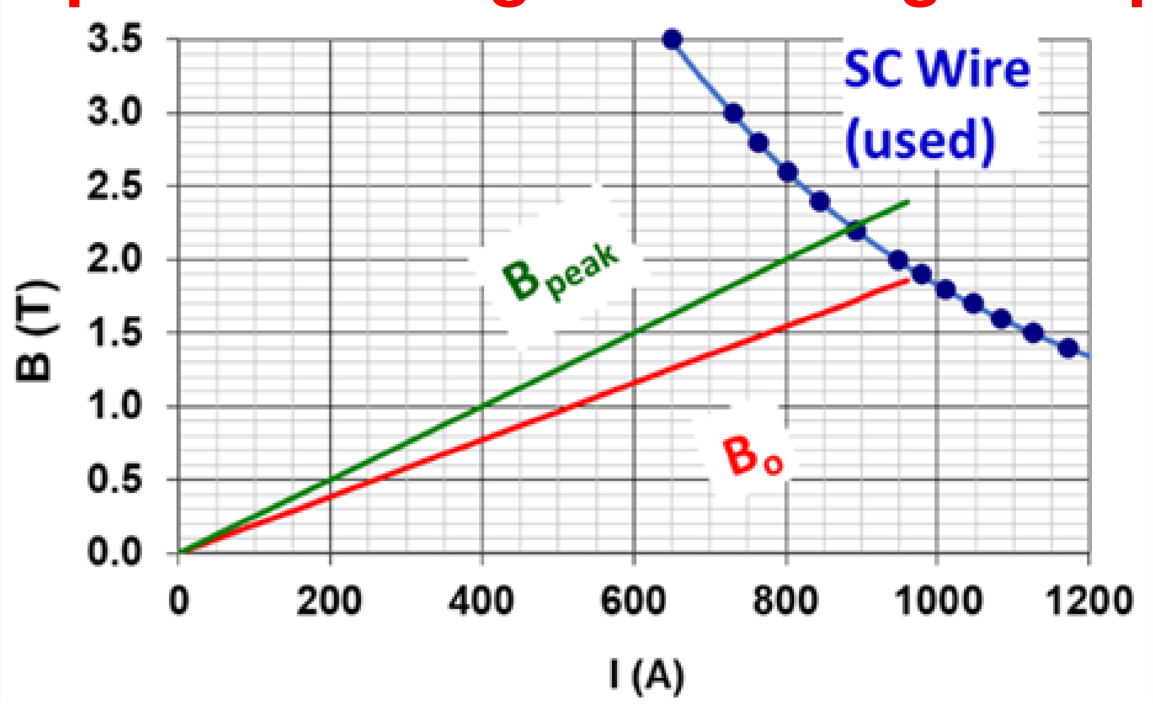


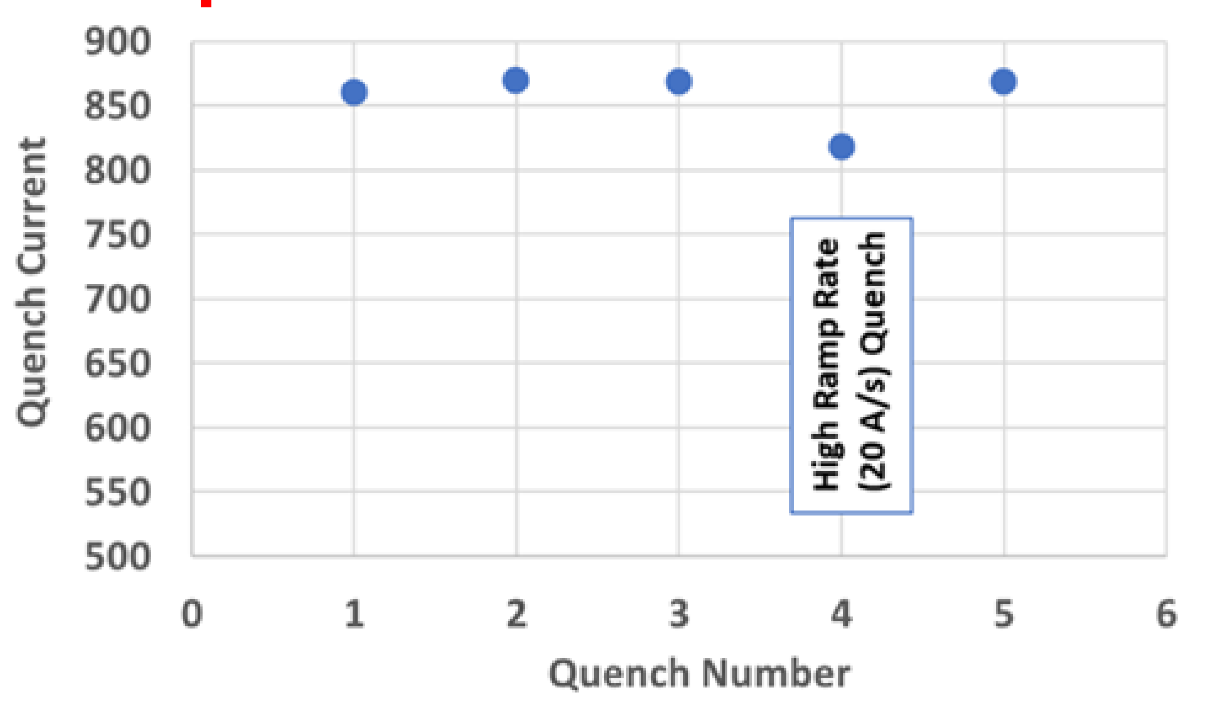
Answer:

✓ **Yes, it does.**

A good agreement between calculations & measurements

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





✓ **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?

Status and Plans of Phase II

Overall Plan and Goals of Phase II
(2-year program, following 1 year of Phase I)

Final Goal:

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

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

Intermediate Goal (~1 year):

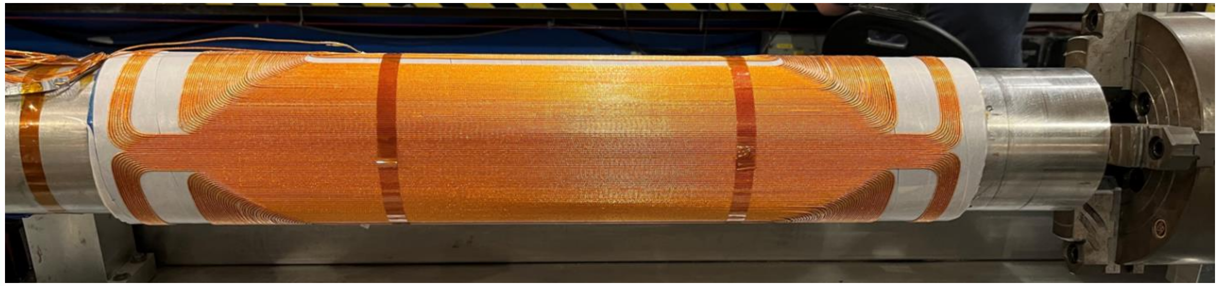
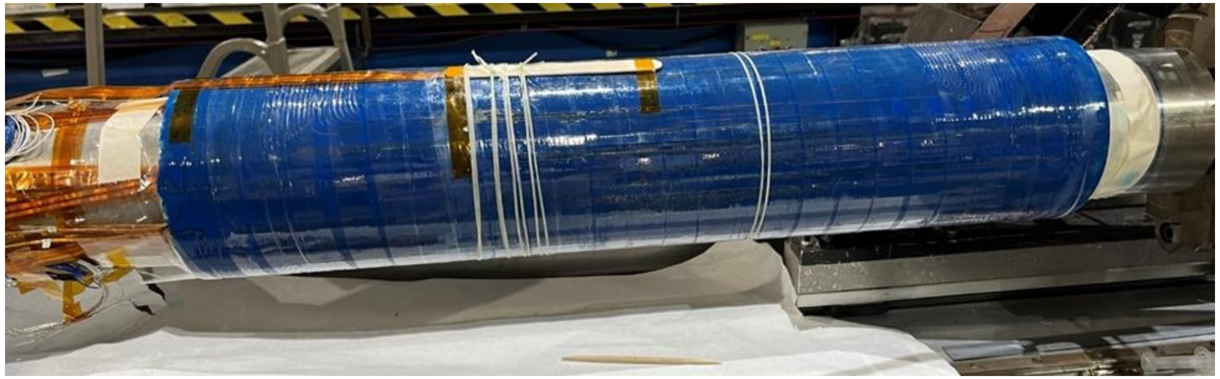
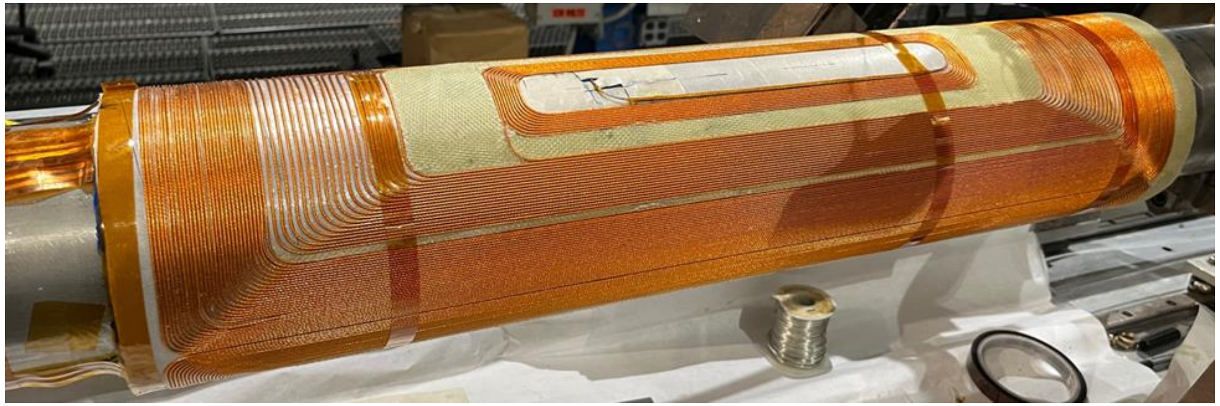
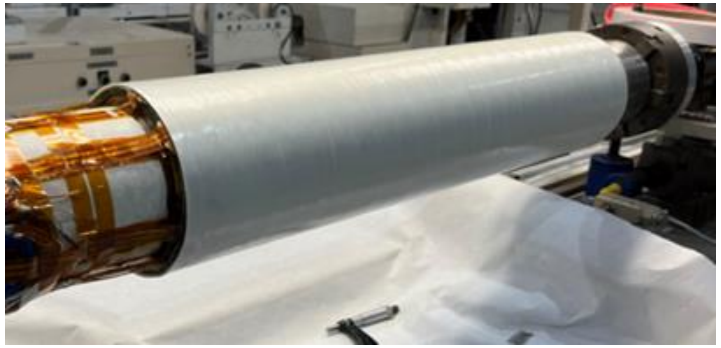
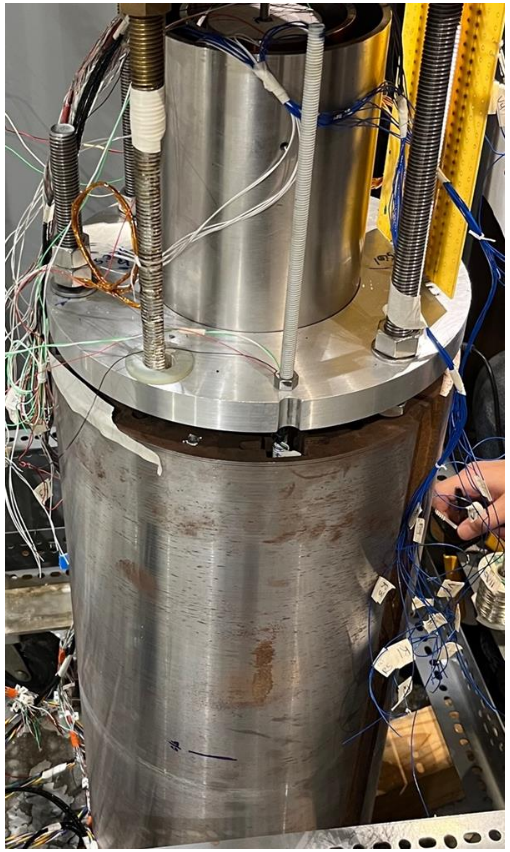
1. Demonstration of a good field quality:

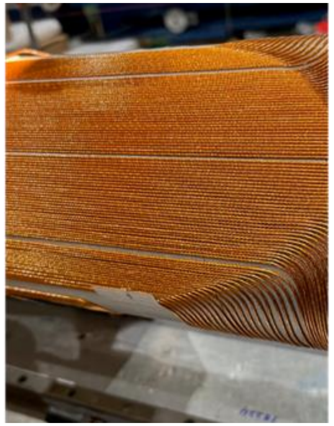
- **Validation of the optimum design and of the 3-D design software**

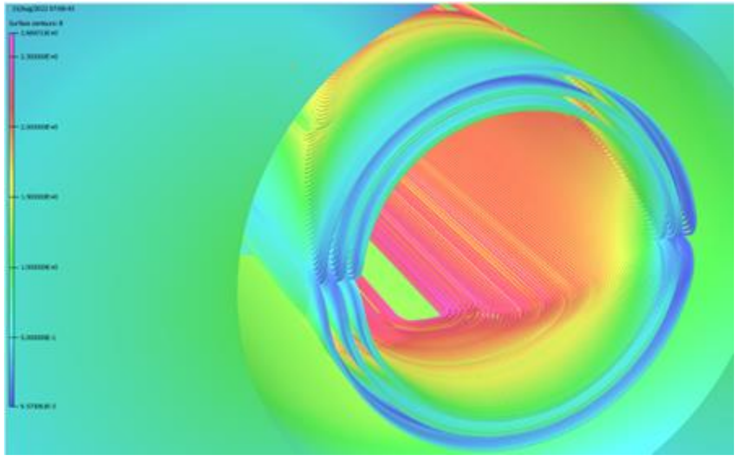
2. Quench performance of the direct wind technology at higher fields

- **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)





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

- Good field quality despite several changes on the fly (as in any R&D project)
- Next layers to compensate these harmonics, however small

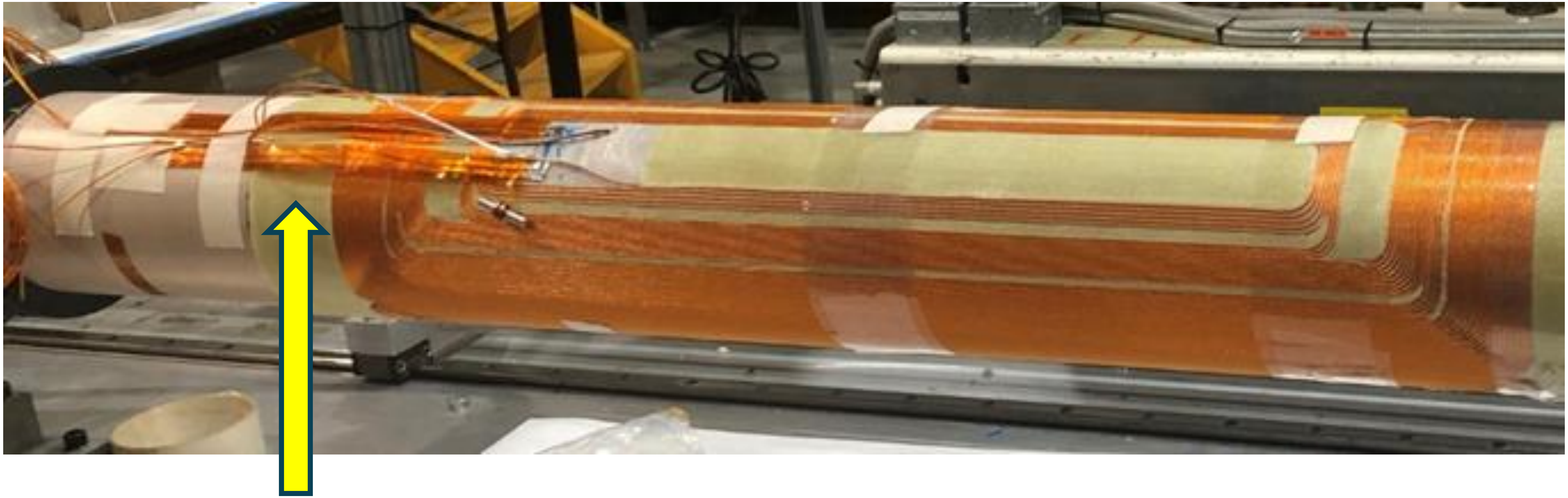
Innovations in SBIR/STTR Programs

SBIR/STTR programs offer a unique opportunity to innovate and test out those innovations, and commercialize, if successful

- PBL/BNL team had been very fortunate that innovations it tried in previous grants worked successfully (all of them)
- However, one must be prepared that not all ideas will work (otherwise, perhaps we are not bold enough)
- This STTR is an example where one innovation for added improvements did not work 100% and see how the team is recovering from that partial success/failure
- The optimum integral design, as outlined in the SBIR/STTR, didn't depend on that innovation or require that. With that change removed, we are back on track.

A Change in Design to Eliminate Radial Space Used by Leads

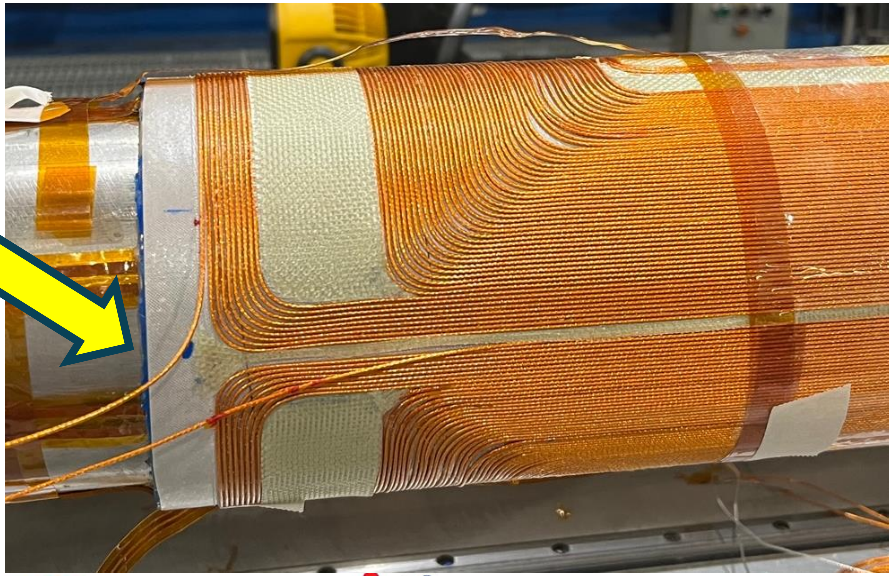
- Phase I design used extra radial space for bringing leads out "over the coil" at the pole.
- Can this use of extra radial space be saved to make design more efficient?



Phase I configuration

A Change in Design to Eliminate Radial Space Used by Leads

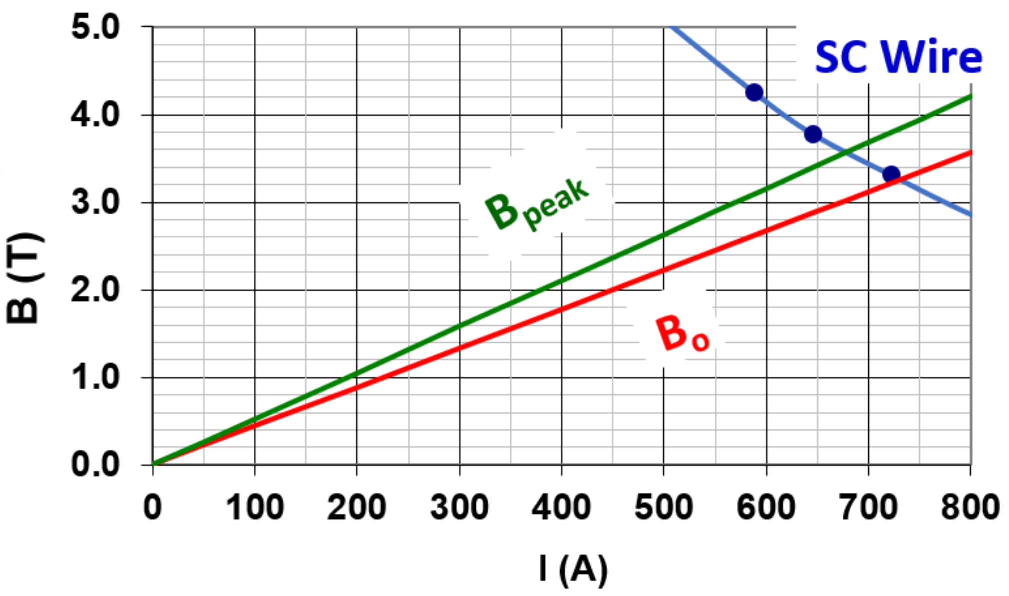
- A new idea was found to eliminate the above-mentioned extra radial space.
- Bring leads out at the midplane (as in the picture) – avoid extra radial space.
- Everyone then thought that it was a brilliant idea, at that time.
- However, this meant adding a splice at pole – a high field region.
- Such 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.

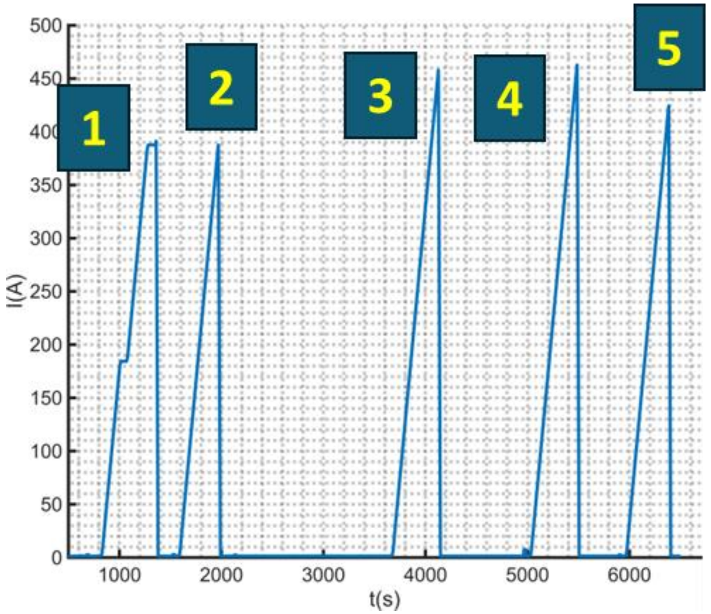


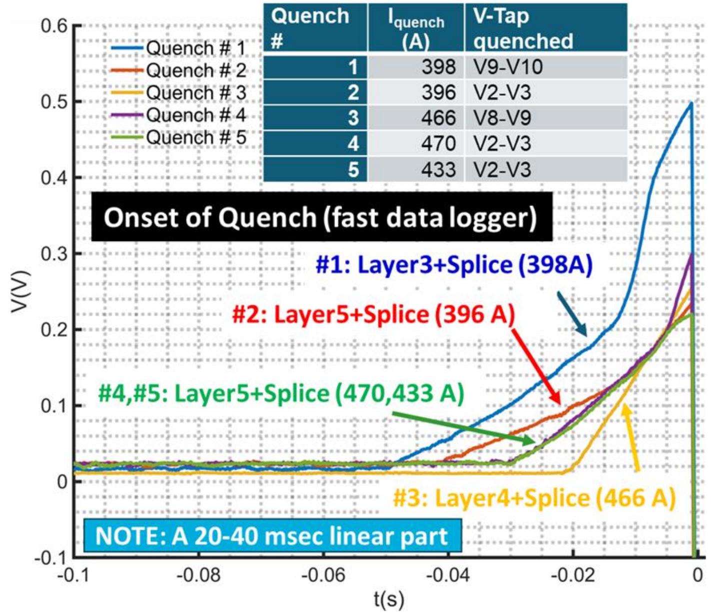
Internal Splice is here

Phase II configuration

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

- **Magnet reached only ~70% of the short sample.**
- **All quenches were in the outer four layers where the new splice was used (to save radial space) and were distributed over new coils.**
- **Limited cooling (1st test run in <2 hours, and subsequent runs with ~20 minutes or less wait) didn't help.**
  - ➢ **This splice was not part of the original or baseline EIC design.**

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.

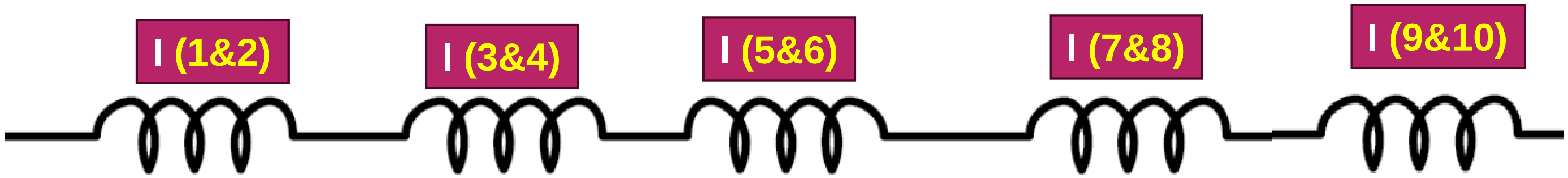
➢ Coordinate this program with other programs to overcome the budgetary challenges.

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

Updated Plan for the Phase II Dipole

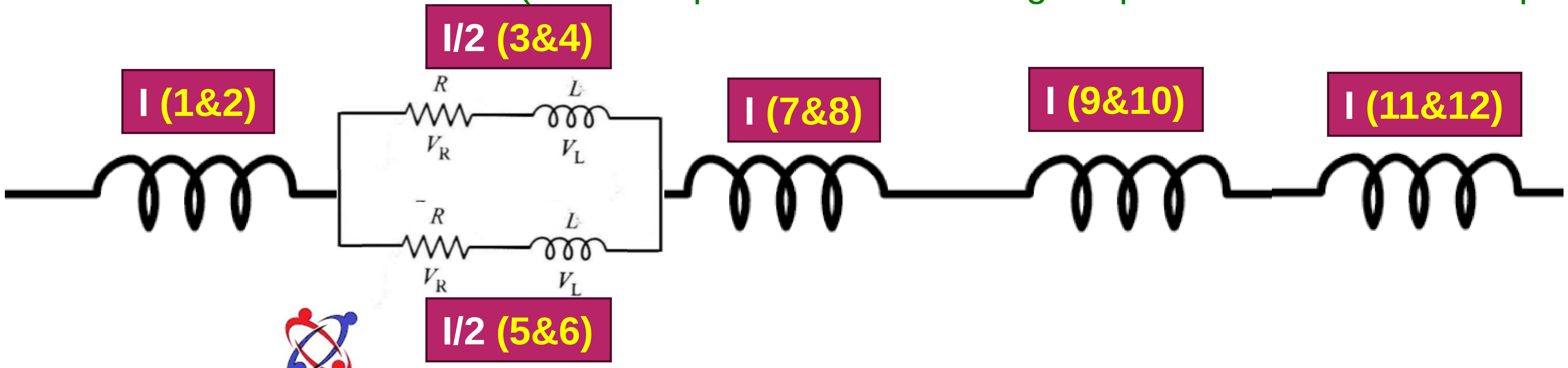
- **The original plan was for 5 double-layer (10 single-layer), all connected in series.**
- **The revised plan is for 6 double-layer (12 single-layer). Double layers 3&4 and 5&6 will be in parallel to each other. They will be in series to the rest of the four double layer. This will make it effectively (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**



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

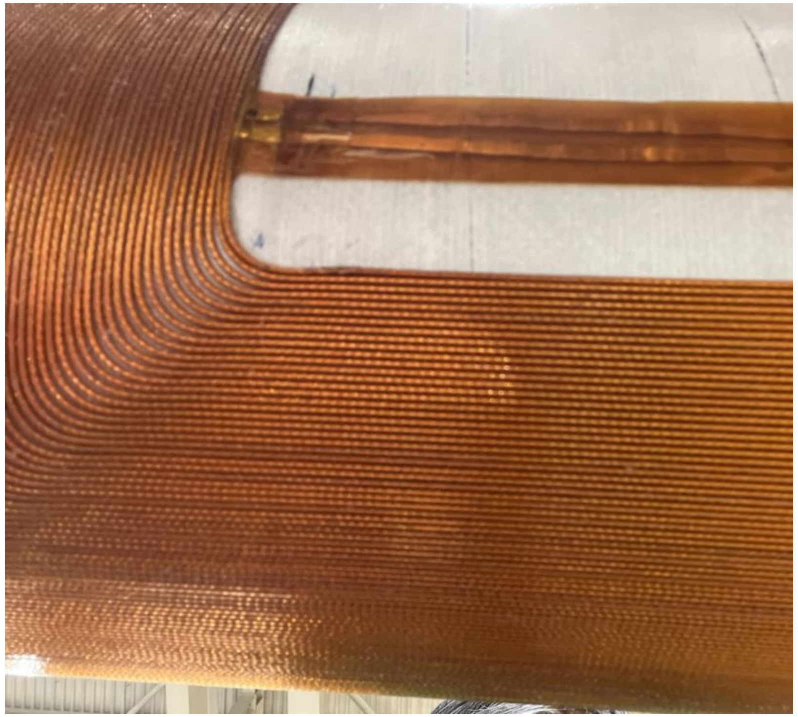
(same Amp-turns as in the original plan with the troubled splice running at ½ current)

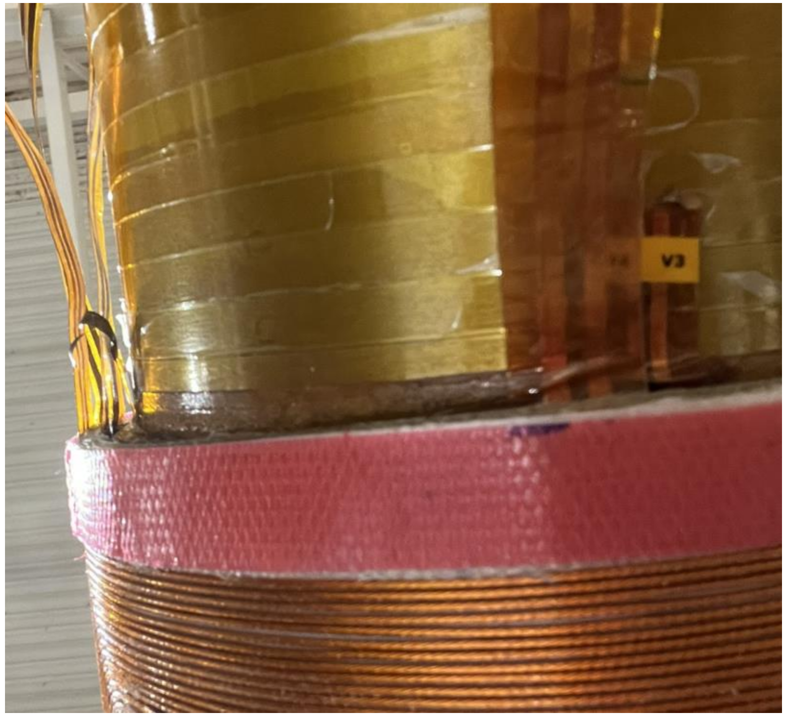


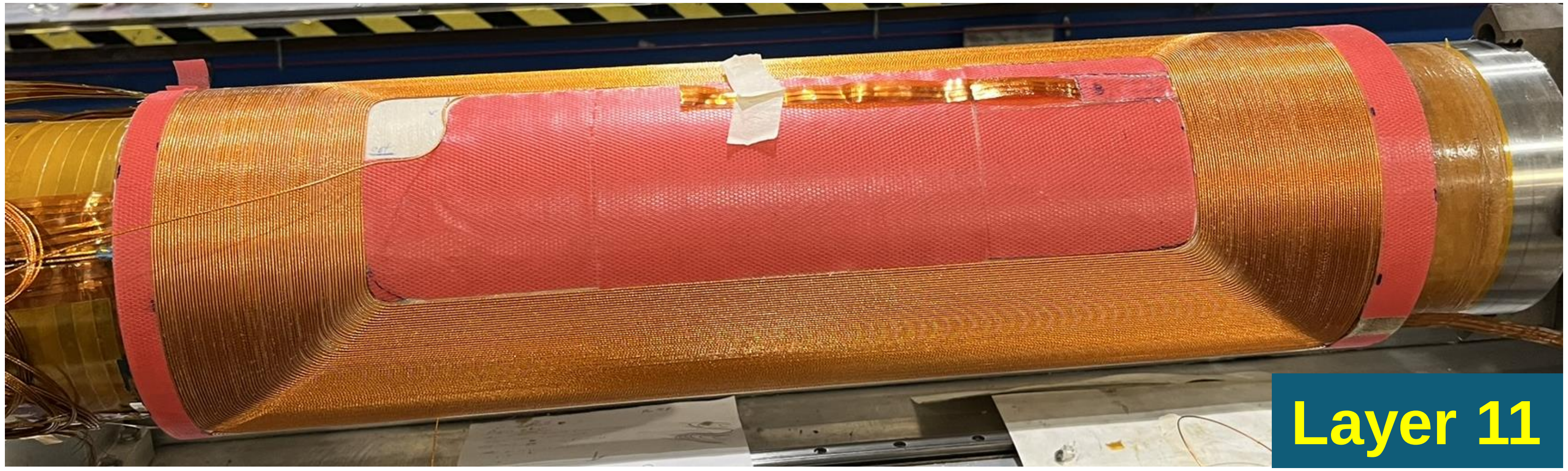
Two extra layers wound

Quench Propagation Studies in Direct Wind Magnets with Laboratory Directed Research and Development (LDRD) Program

- **A BNL LDRD is studying for quench propagation studies in Direct Wind magnets.**
- **Funding is too limited to allow a full-scale magnet to be built, fully instrumented and tested.**
- **Add extra instrumentations in layers 11 &12 of the STTR coils and validate quench models in a full-scale magnet for LDRD.**
- **A "win-win" situation for both - the STTR magnet gets tested, and for LDRD, a real magnet becomes available for quench studies (otherwise it would have been just a tiny coil for limited validation).**

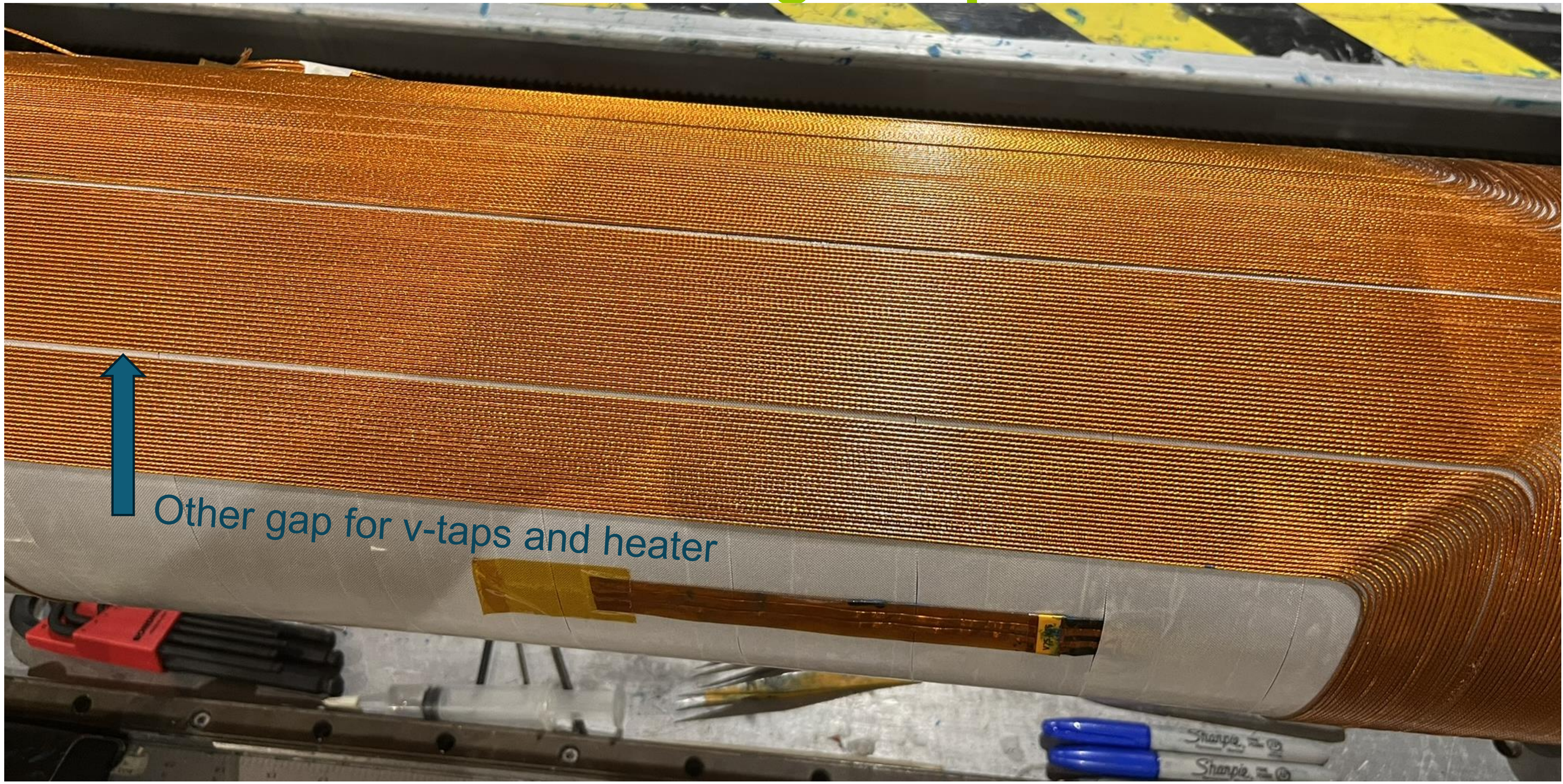






Modified Design of Layer 12 to provide a better access to instrumentation without sacrificing the performance

Layer 12

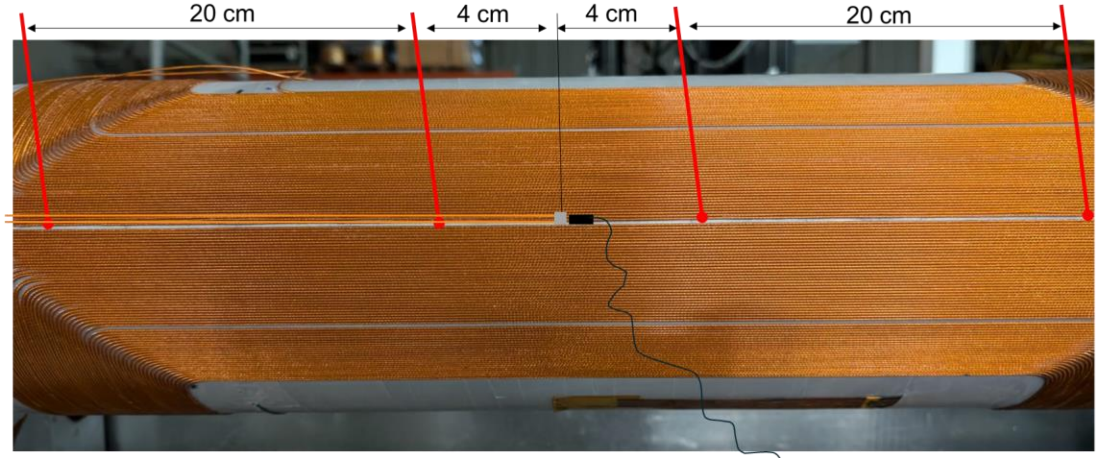


Space added/managed for instrumentation: heaters, v-taps, temperature sensors and Fiber Optics) to be installed in Layers 11&12 of the STTR coils

Space added for instrumentation

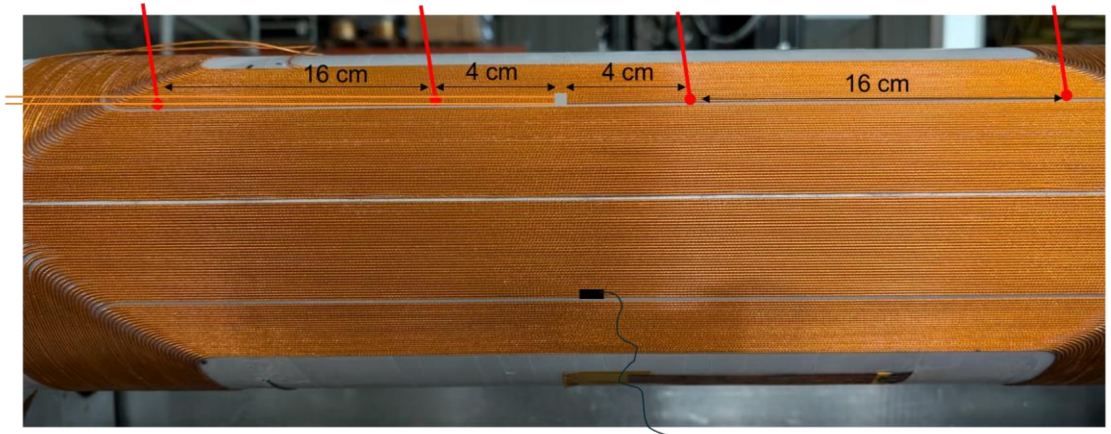
Instrumentation for Quench Propagation Studies

12th layer instrumentation: midplane



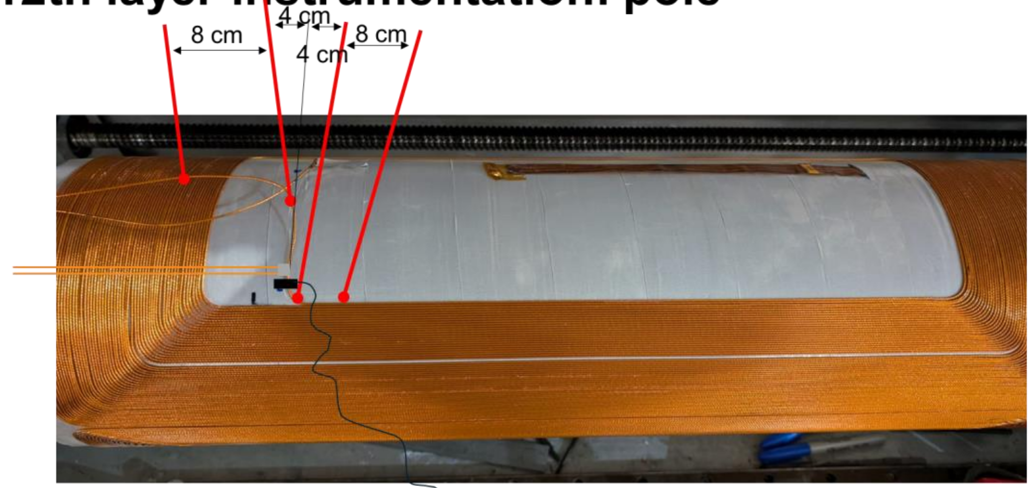
CX 1050 temperature sensor

12th layer instrumentation: BLOCK2



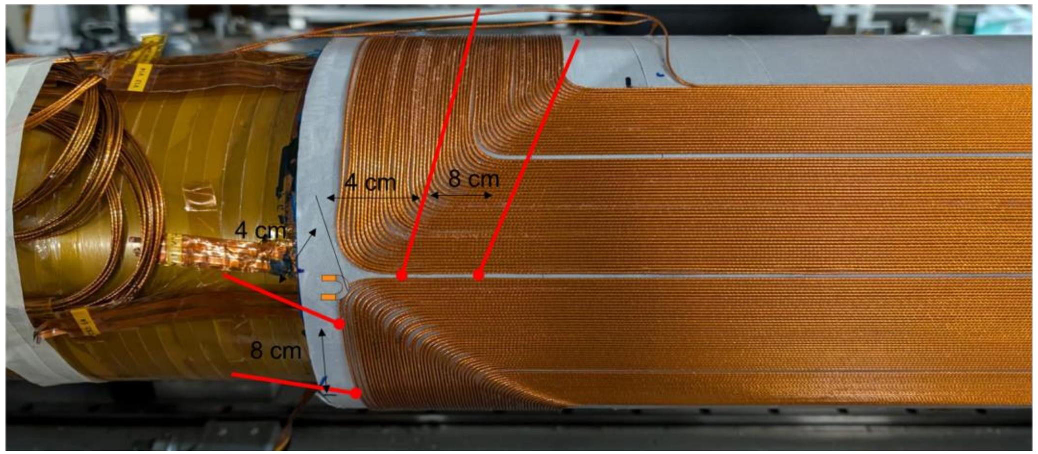
CX 1050 temperature sensor

12th layer instrumentation: pole



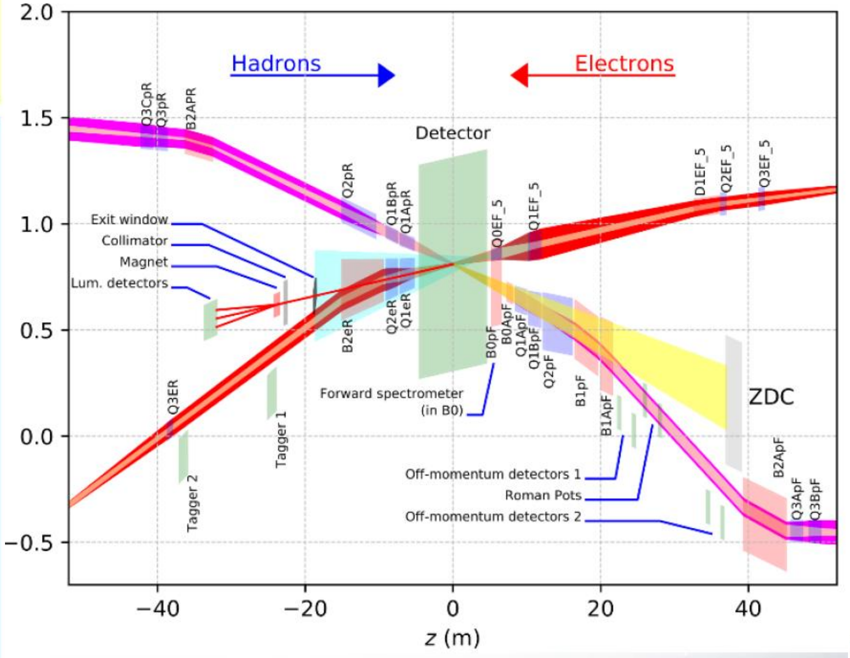
CX 1050 temperature sensor

12th layer instrumentation: corner

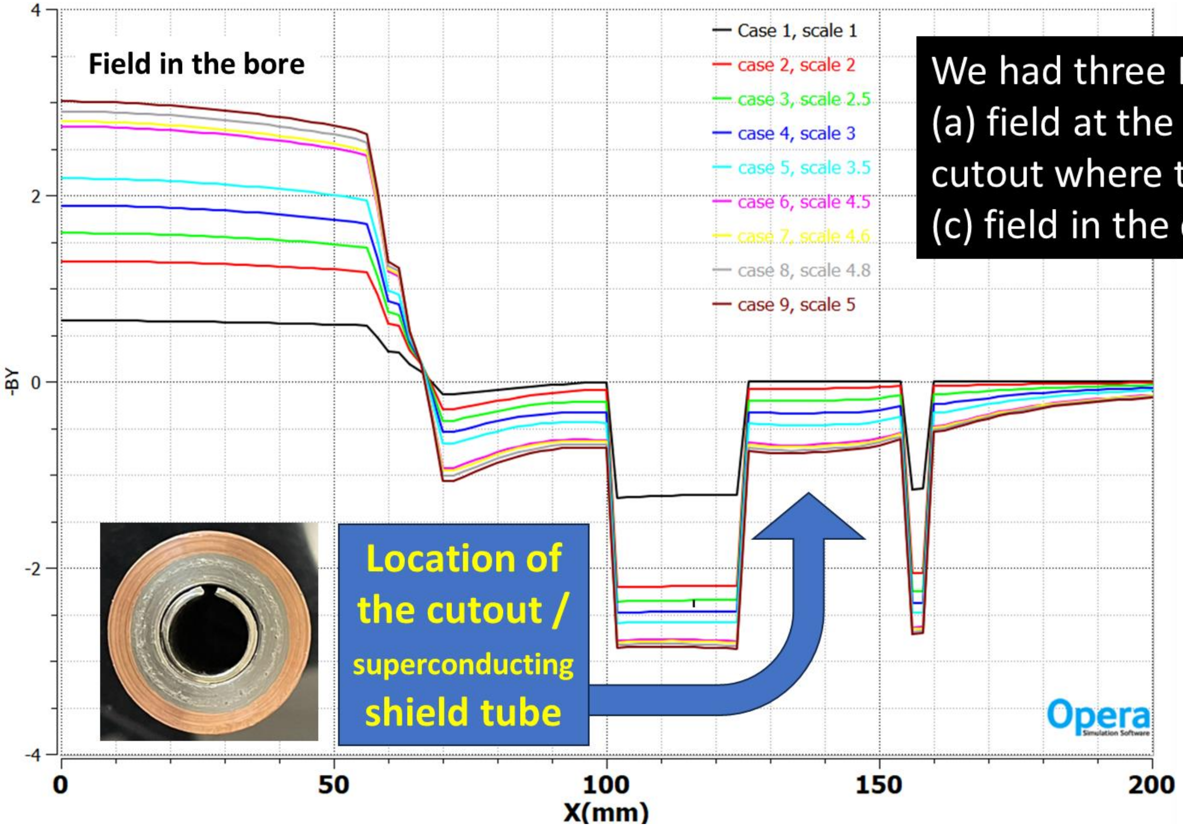


Test of Superconducting Shielding for EIC Magnets

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

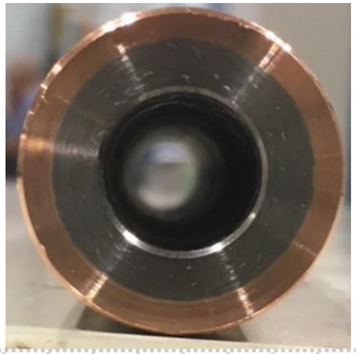


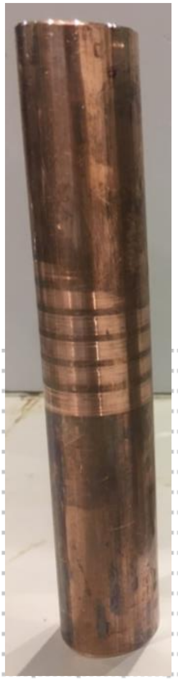
We had three Hall probes to measure (a) field at the center, (b) field in the cutout where the SC shield is (+x) and (c) field in the cutout with no shield (-x).

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

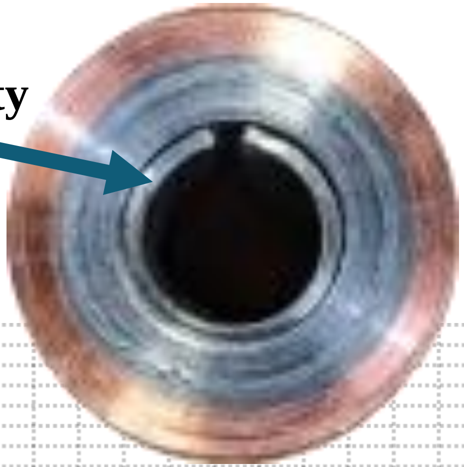
Demonstration of Superconducting Shielding (with Additional A4K)

NbTi tube from Luvata

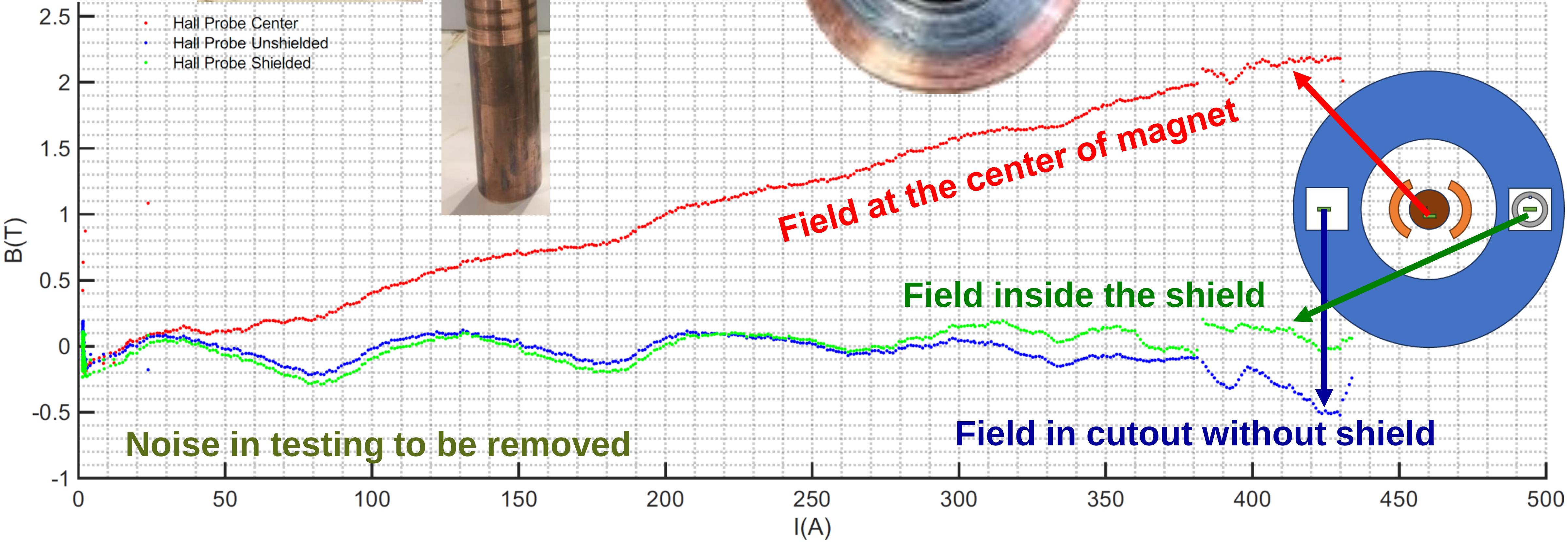




High permeability *A4K to shield persistent field



Superconducting shielding works



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

Development of Software

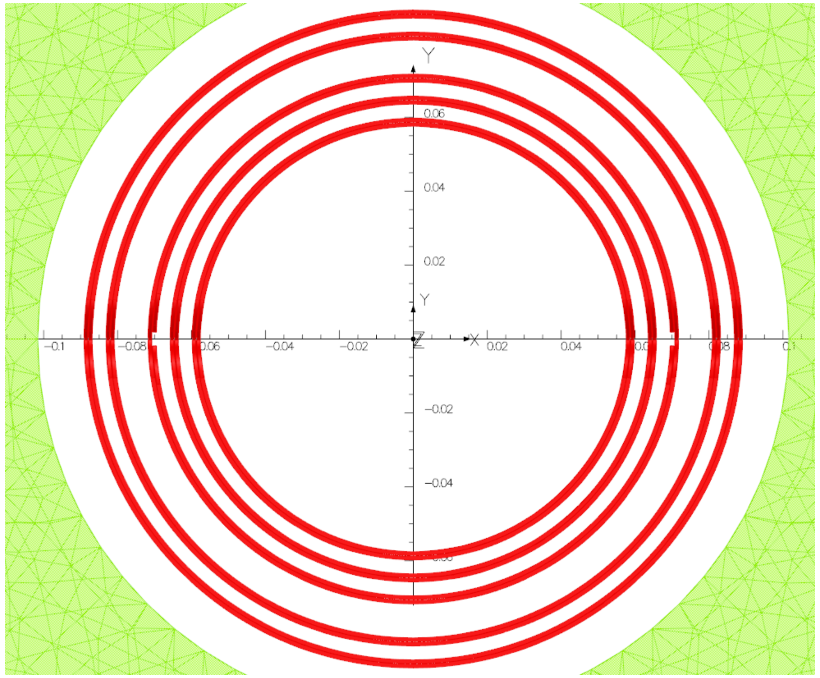
Development of Software OptIntegral (a part of this STTR)

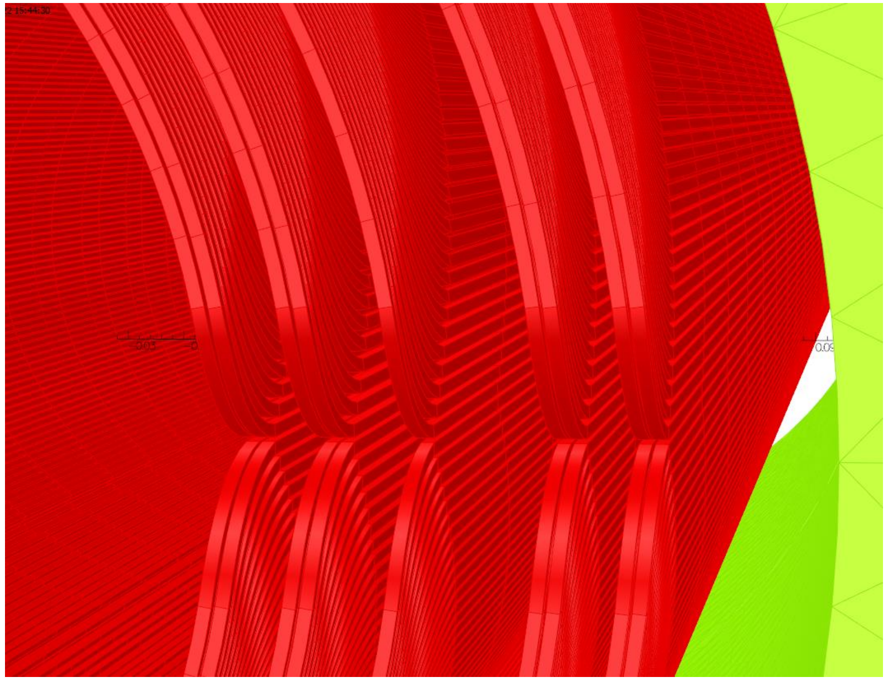
- Developed specifically for rapid optimization of 3-d design
  - ✓ Typical software takes hours to fully optimize 3-d design per case. Not suitable when we want to examine a large number. **OptIntegral** takes minutes.
  - ✓ **OptInegral** also writes files to help create wiring file for DirectWind machine
  - ✓ **OptIntegral** also does several other tasks, such as 3-d EM model for other software such as OPERA3d. A user manual written.
  - ✓ **OptIntegral** code is being updated for patterns other than the Optimum Integral design, such as the Serpentine design (thanks to an internal funding from BNL)

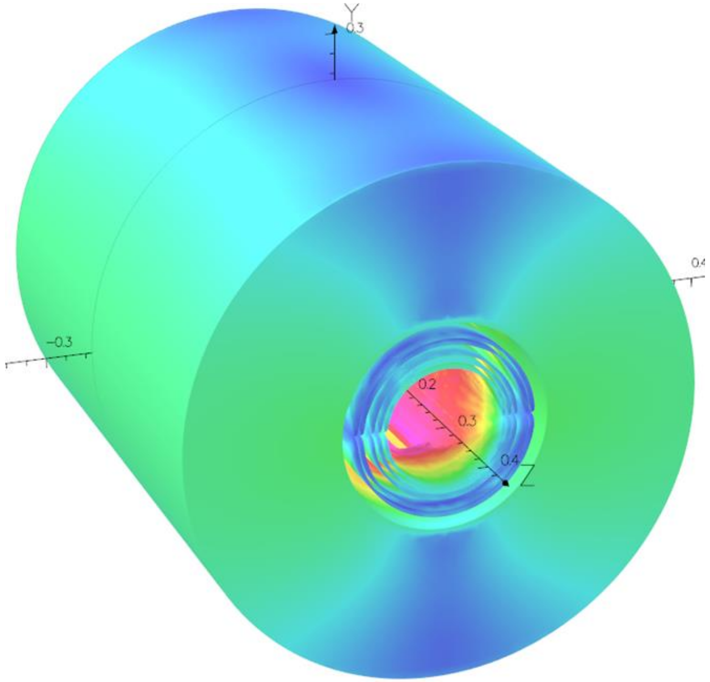
Another analytic approach based on COMSOL for high field-integral uniformity

Electro Magnetic (EM) Models of the Phase II Dipole

The design is optimized for low field harmonics with the ***OptIntegral*** *code*

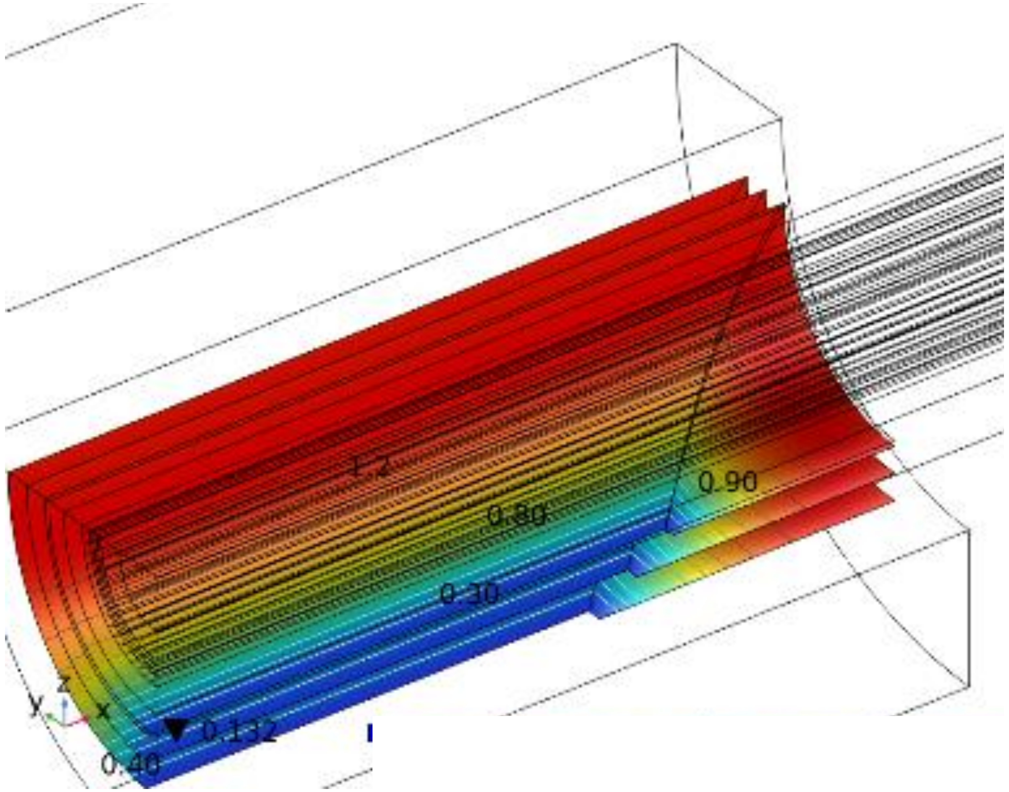


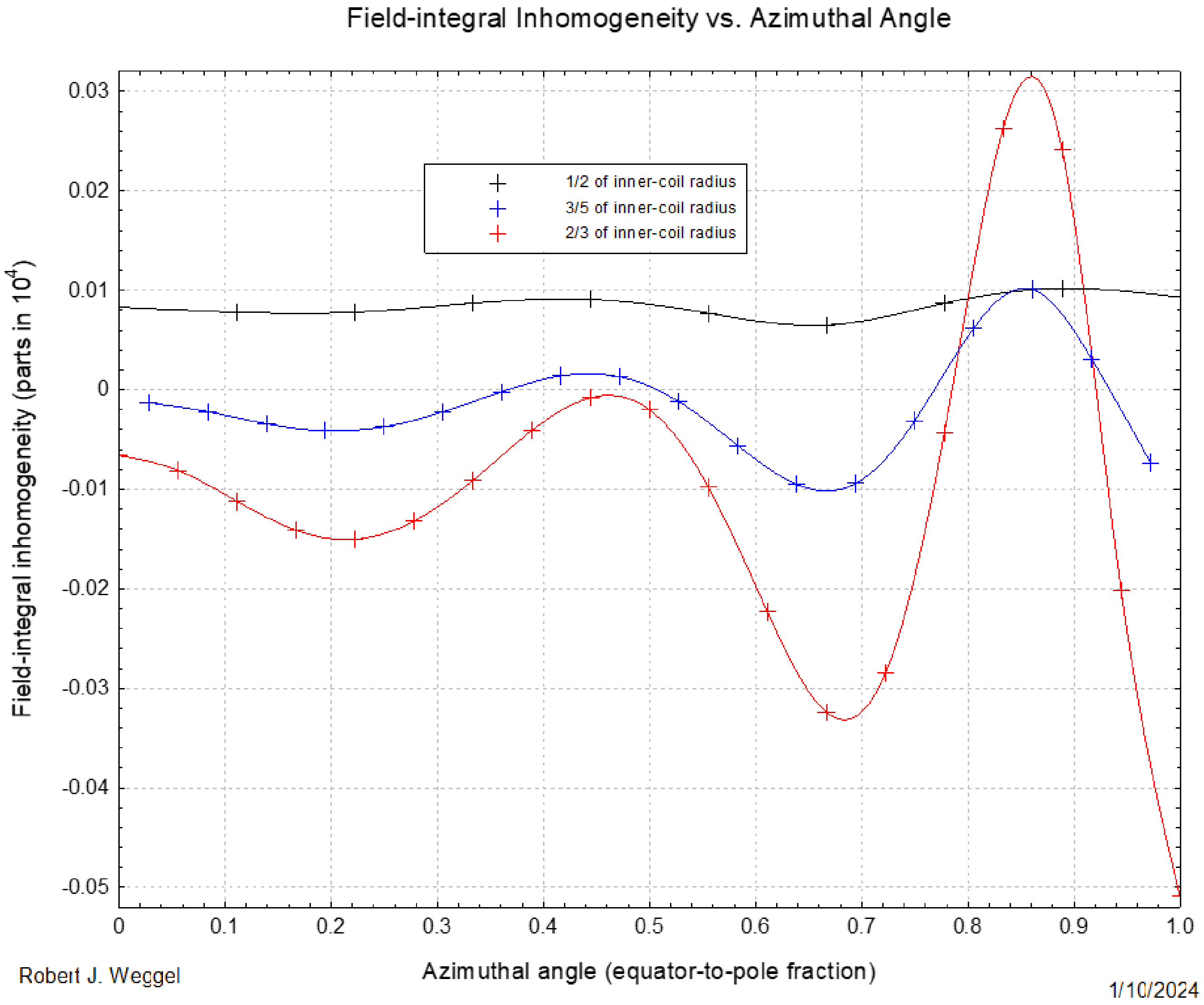


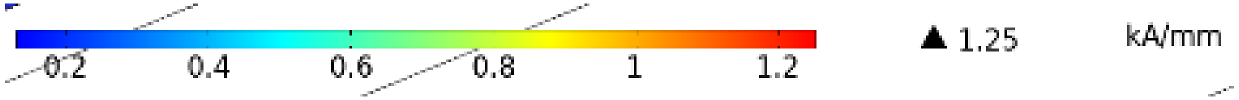


Field-Integral Homogenization of Current-Sheets with COMSOL MULTIPHYSICS

- **Electro-magnetic analysis**
- **Mechanical analysis**

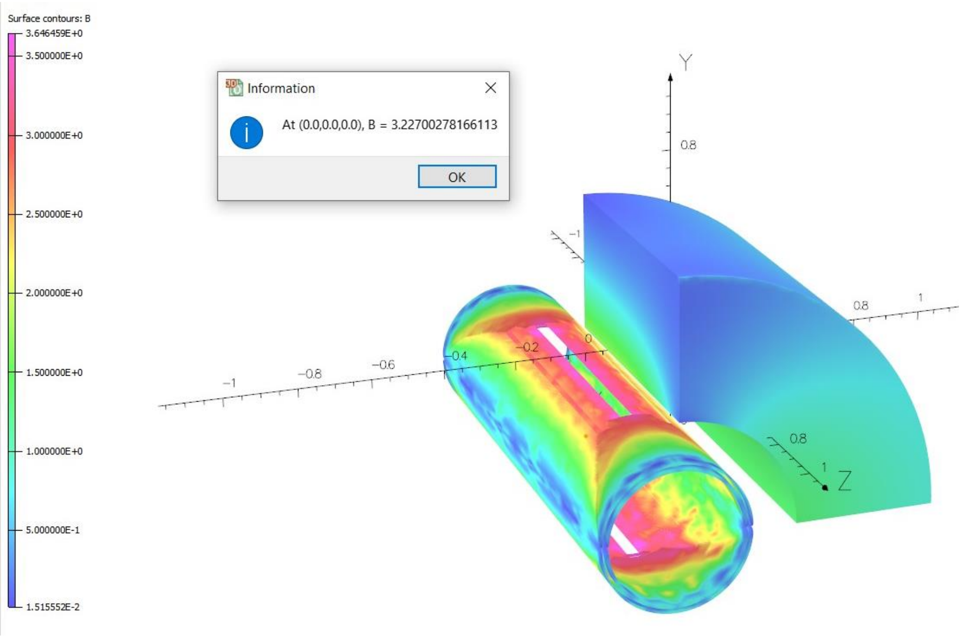


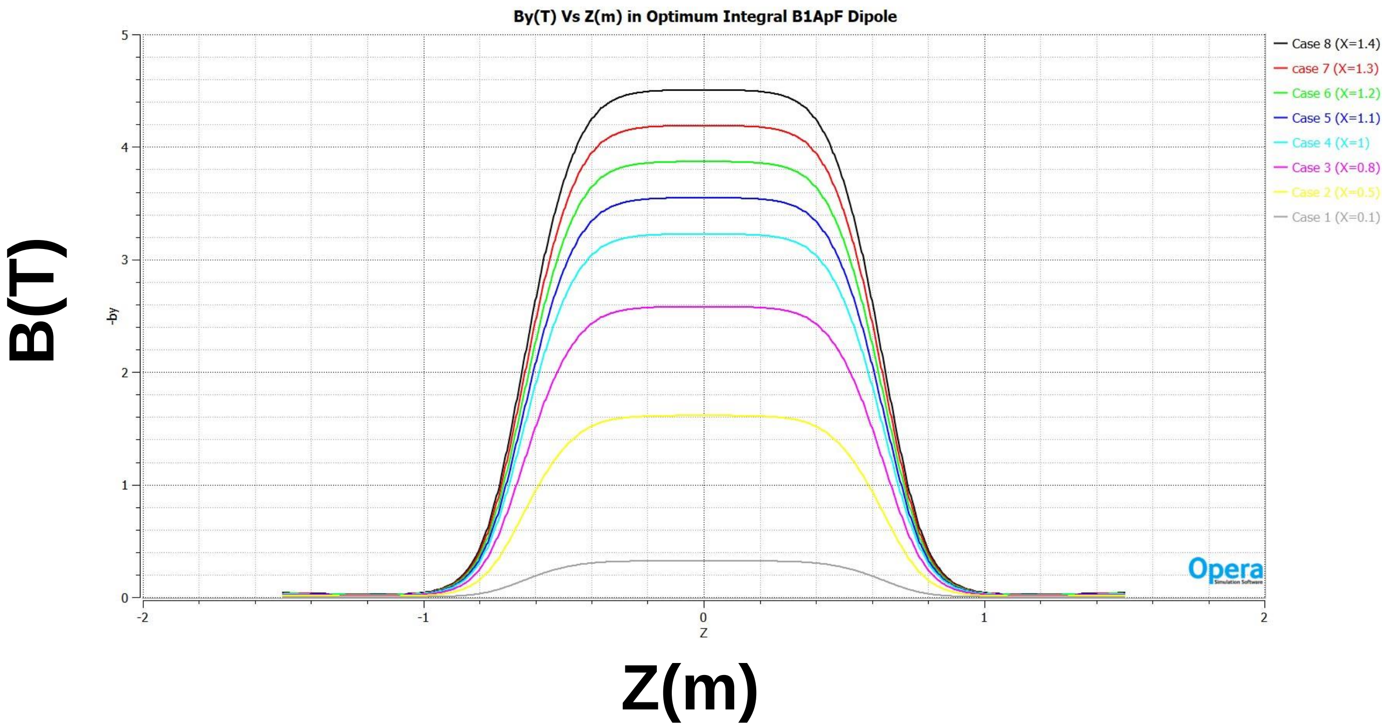




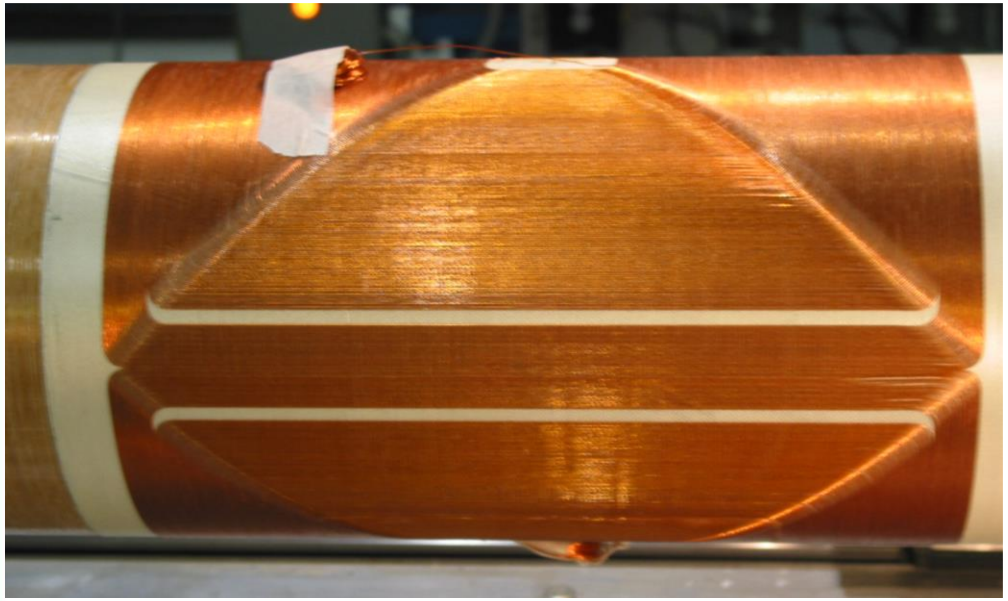
Investigation of Optimum Integral Design for Other EIC Magnets

- One of the tasks of this STTR is to investigate optimum integral design for other EIC magnets where it has potential to provide significant benefits
- B1ApF is a relatively short dipole (1.6 m) with large aperture (370 mm). Length to aperture ratio is even smaller than in B0ApF, and therefore a good candidate.
- Current design of 3^{+} T B1ApF is based on the cable magnet (expensive for one off).
- Initial design is very promising. It shows that an optimum integral magnet coil having only 6 layers will satisfy the requirement. This will be a cheaper and faster option.





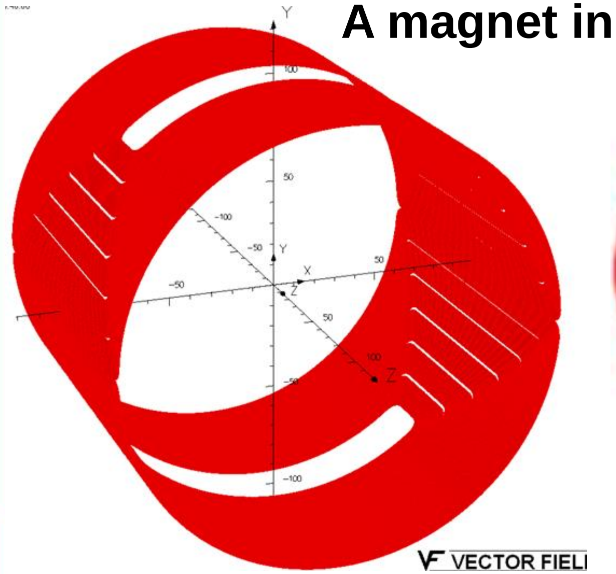
More Examples of Short Optimum Integral Multi-pole Magnets



A magnet in BNL AGS Tunnel

- **dipole with coil length < coil diameter**
- **quadrupole with coil length < coil radius**
- **sextupole with coil length < 2/3 of coil radius**
- **…**

Such short-length superconducting magnets with significant integral fields are possible only with the optimum integral design



Summary (1)

- Optimum integral design minimizes the loss in magnetic length due to the ends is demonstrated via this STTR program for EIC Dipole B0ApF.
- Benefits of this approach are significant in short magnets.
- Good field harmonics and validation of the codes are demonstrated.
- Results have been positive, except for the limited success in one case.
- A setback occurred, likely due to implementation of a new design for saving the radial space. This was not part of the original proposal. This is now eliminated from the next layers (back to the original design).

Summary (2)

- Promising results with the superconducting shielding experiment. This is an additional contribution of this SBIR/STTR (not part of the original proposal).
- Two additional layers have been added (not part of the original design) to compensate for the loss in performance caused by the splice in new design.
- Coordinating this STTR with a BNL LDRD on quench propagation in direct wind magnets provides technical and budgetary benefits. A “win-win” for both, as the magnet gets tested, and quench studies gets performed in a magnet.
- Demonstration of the “Optimum Integral Design” in this specific EIC dipole (B0ApF) should have a wider impact on the other EIC IR magnets as well, such as B1ApF, and in other applications beyond DOE/NP.