PBL

Particle Beam Lasers

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

A new medium field superconducting magnet for the EIC

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FY23 Nuclear Physics SBIR/STTR Phase II Exchange Meeting, August 15, 2023

Overview

- **Particle Beam Lasers, Inc. (PBL) and major contributions of the PBL/BNL team**
- **New Design and its benefits to Electron Ion Collider (EIC) and other short magnets**
- **Status and plans**
- **Summary**

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

	Title	Award No.	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**

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 other SBIR/STTR grants, (b) US Magnet Development Program (MDP) with DoE which produced another record hybrid field of 12.3 T, (c) created a novel background dipole field R&D program, now being used by "Fusion" and HEP

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

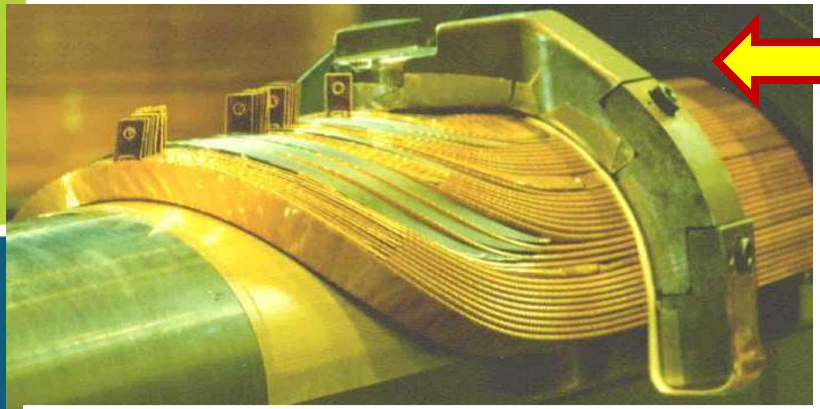
Current Phase II STTR

A new medium field superconducting magnet for the EIC

Chosen STTR Magnet: EIC Dipole B0ApF (114 mm Bore, ~3.8 T field, 600 mm long)

- For reference, parameters of RHIC arc dipole: 80 mm bore, 3.45 T field

What is new and why it is important?



RHIC Coil End (conventional)

EIC B0ApF Coil Ends (conventional, as in CDR)

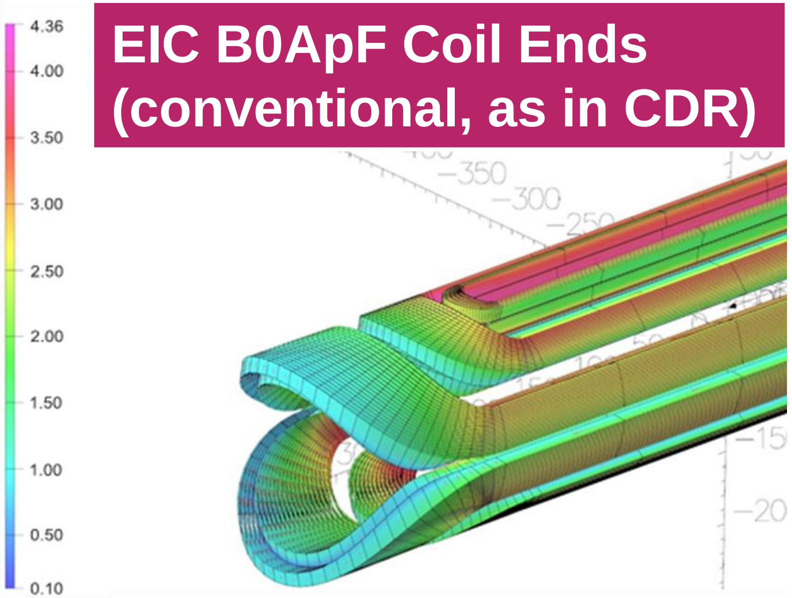
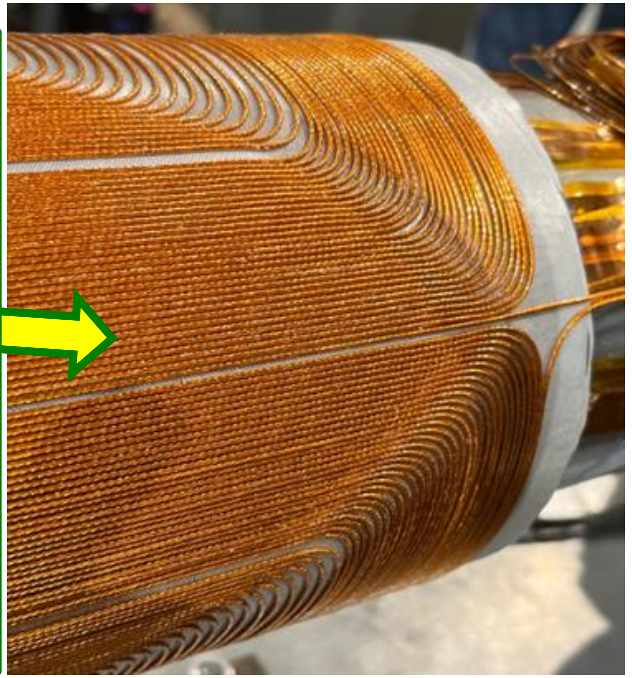


Figure 5: B0APF coil with field contour

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

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)

New B0ApF Ends (STTR) Optimum Integral Design



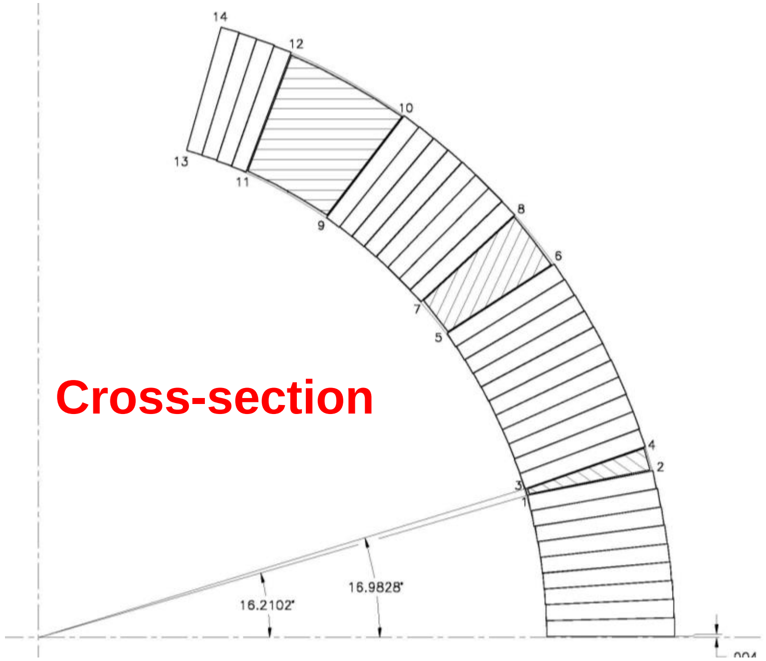
Conventional Design Approach

A two-step process of designing magnets:

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

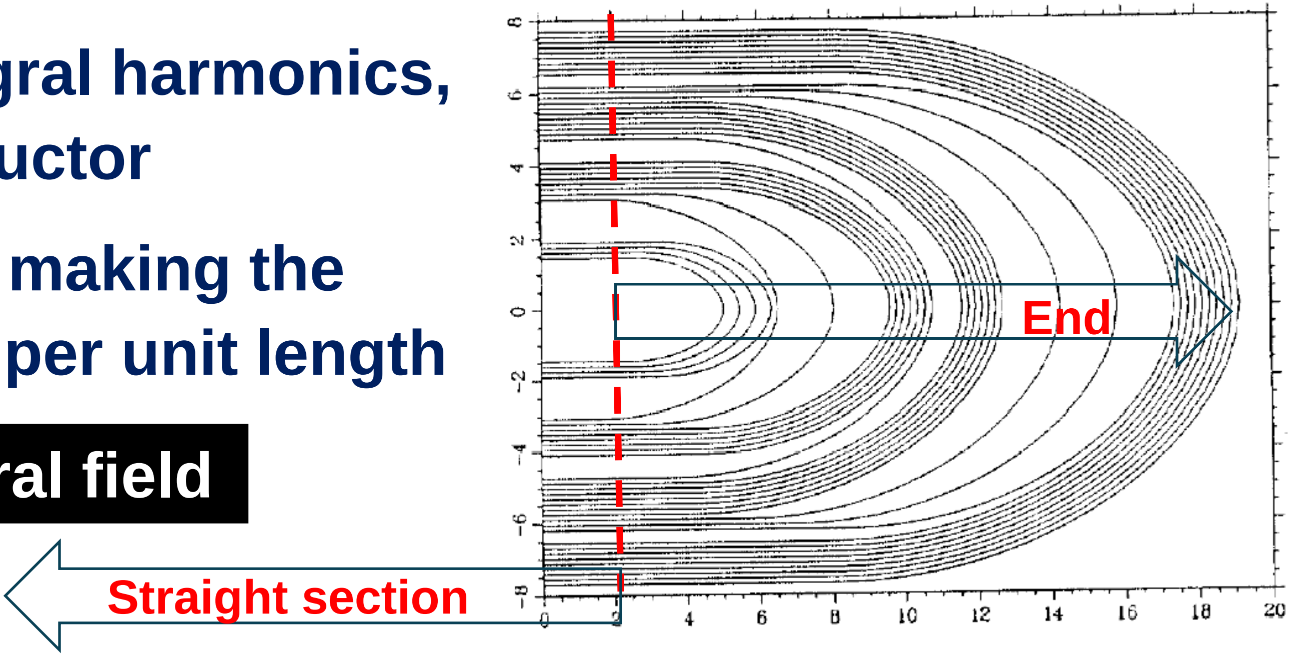
$$I(\theta) = I_o \,.\, \cos(n\theta)$$

- ➢ **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 limits the maximum integral field

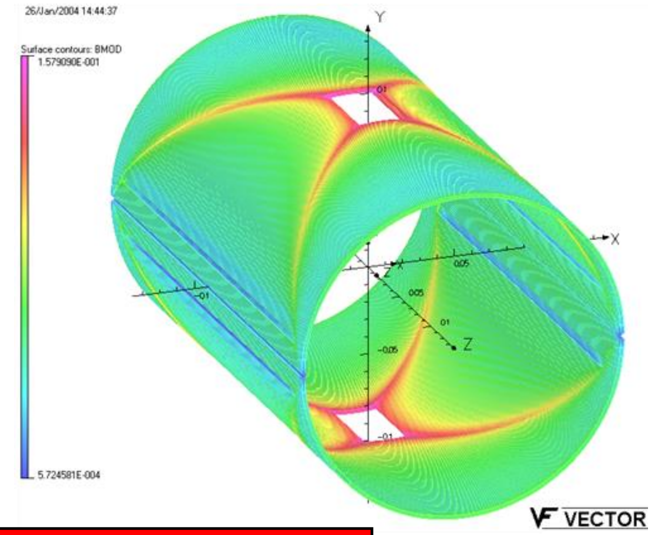
Optimum Integral Design Approach

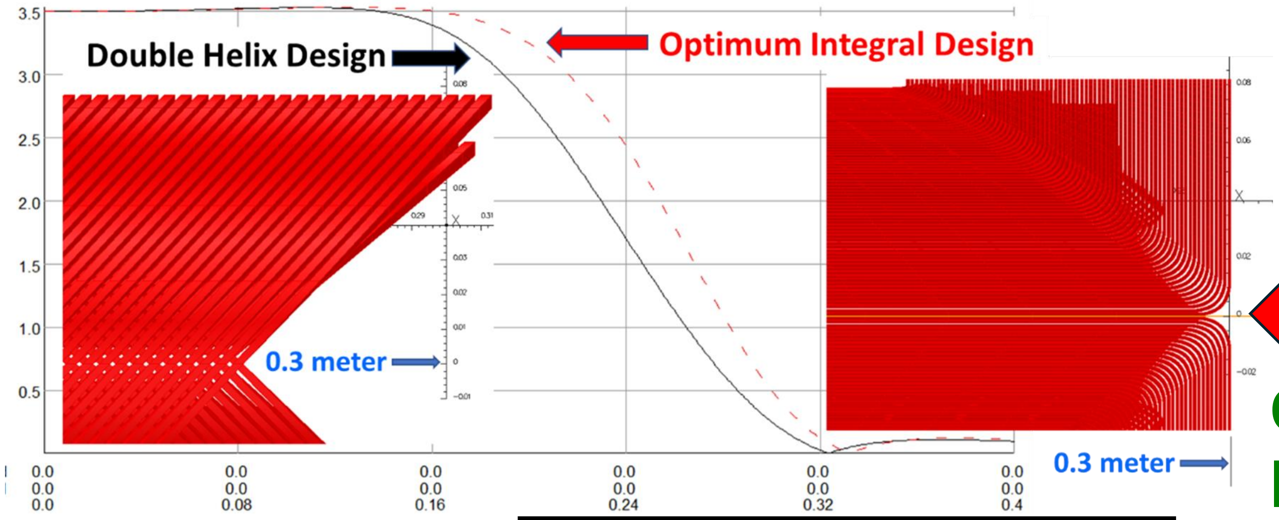
A one step process integrated process:

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).**





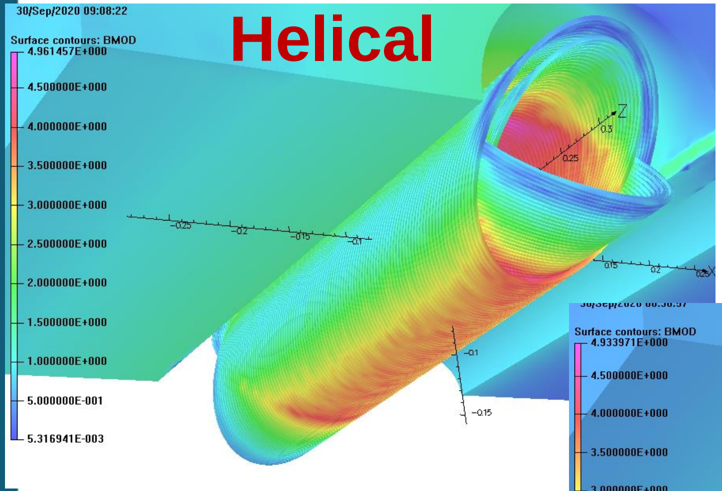
STTR Dipole EIC B0ApF

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

Larger integral field

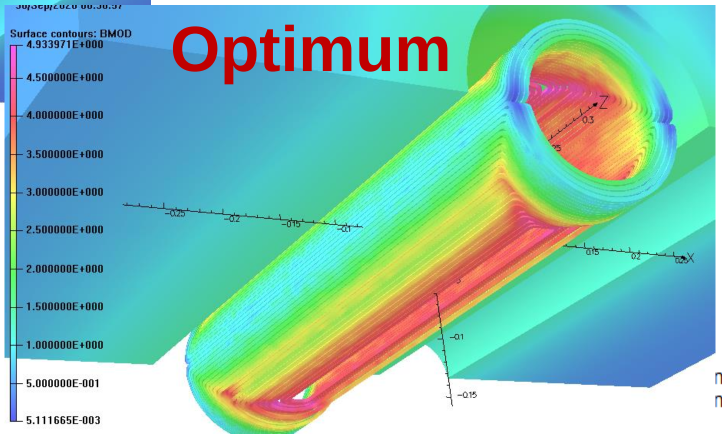
Rationale for Optimum Integral Design B0apF STTR

- For a given length, the optimum integral design reduces the required maximum field (and hence stored energy & stresses) by 10-20%. **The design is not being investigated for EIC and can be a candidate for SBIR/STTR. Once proven, it can be used in various EIC magnets.**
- B0Apf dipole for EIC needs a coil ID of 110-120 mm and a total length of 600 mm. The design field is ~3.3 T. **This is ideally suited for a potential high impact SBIR/STTR proposal.**

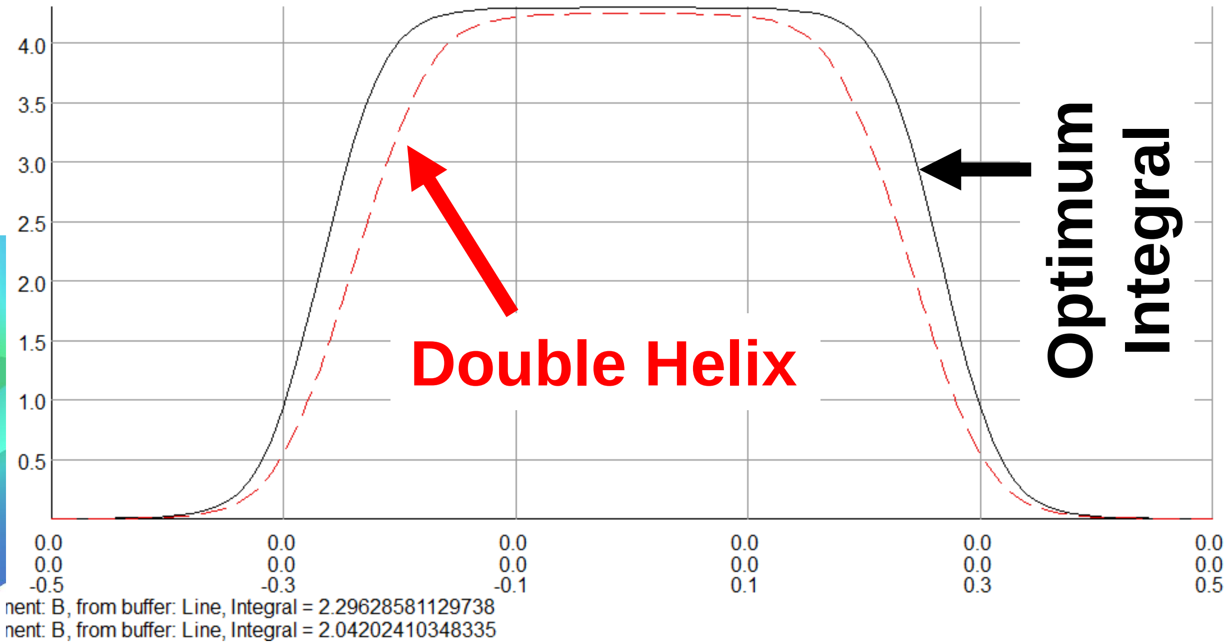


Peak Field 4.96 T for integral field of 2.042 T.m

Peak Field 4.93 T for integral field of 2.296 T.m



~12% gain in integral field for the same peak field



Brookhaven National Laboratory
Magnet Division
PBL

Question: Can this be done in the limited budget of STTR?

For Reference:

- RHIC arc dipole: 80 mm aperture, ~3.5 T central field
- RHIC insertion dipole: 100 mm aperture: ~3.5 T central field

➢ Proposed EIC B0ApF STTR: 114 mm aperture, ~3.8 T central field

Demonstration of RHIC machine magnets was a major R&D program and took significant resources (both in terms of budget and time)

➢ In STTR we are proposing a more challenging R&D magnet based on a new design with a smaller budget and in a shorter time frame

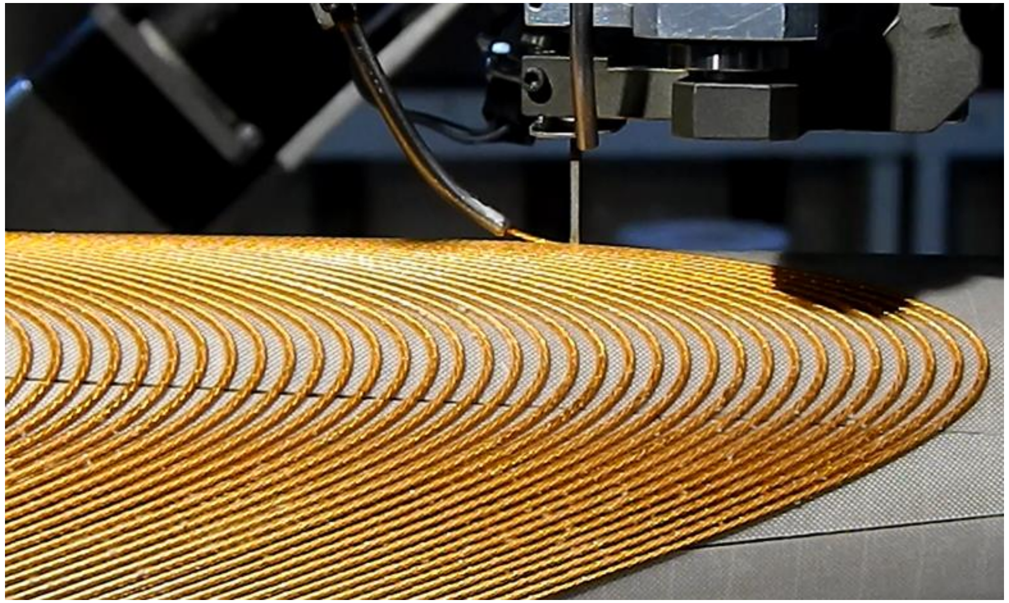
First reality check of the ambitious plan will come from the construction and test results of the Phase I R&D magnet:

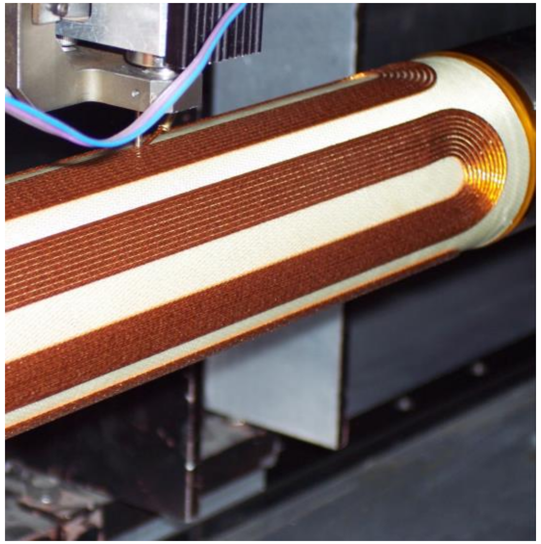
➢ **1.7 T superconducting dipole with 114 mm aperture**

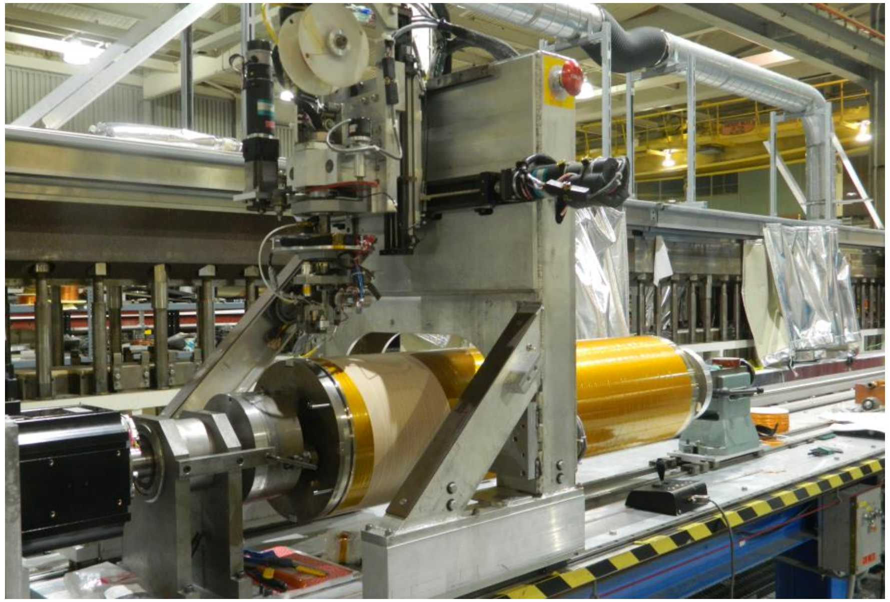
We will use a different design and construction method (next slide)

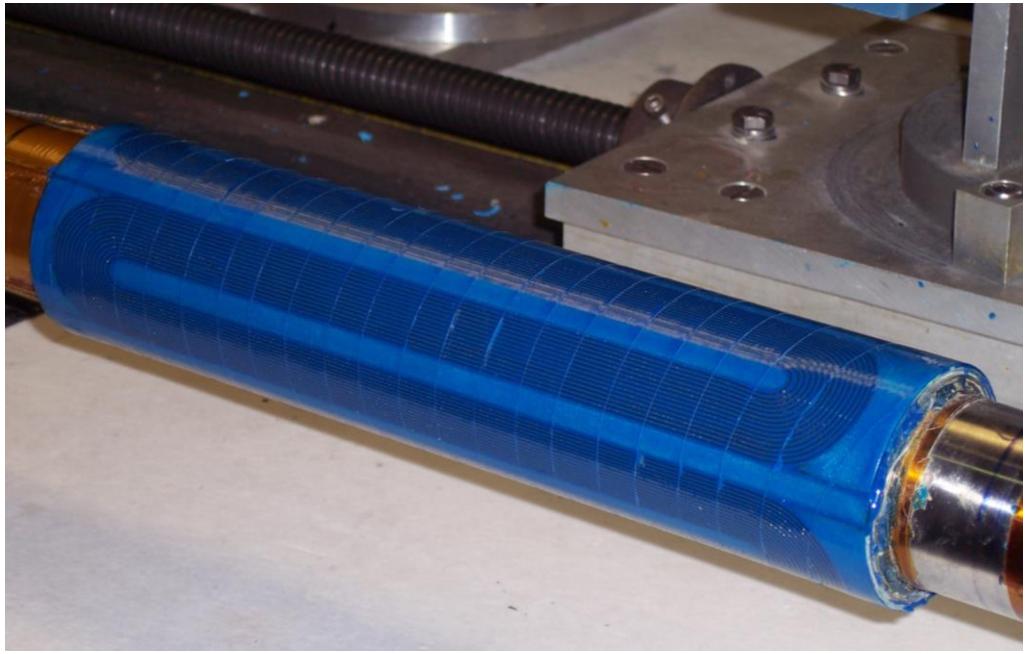
A Key Component of this STTR – the Direct Wind Technology

- **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**







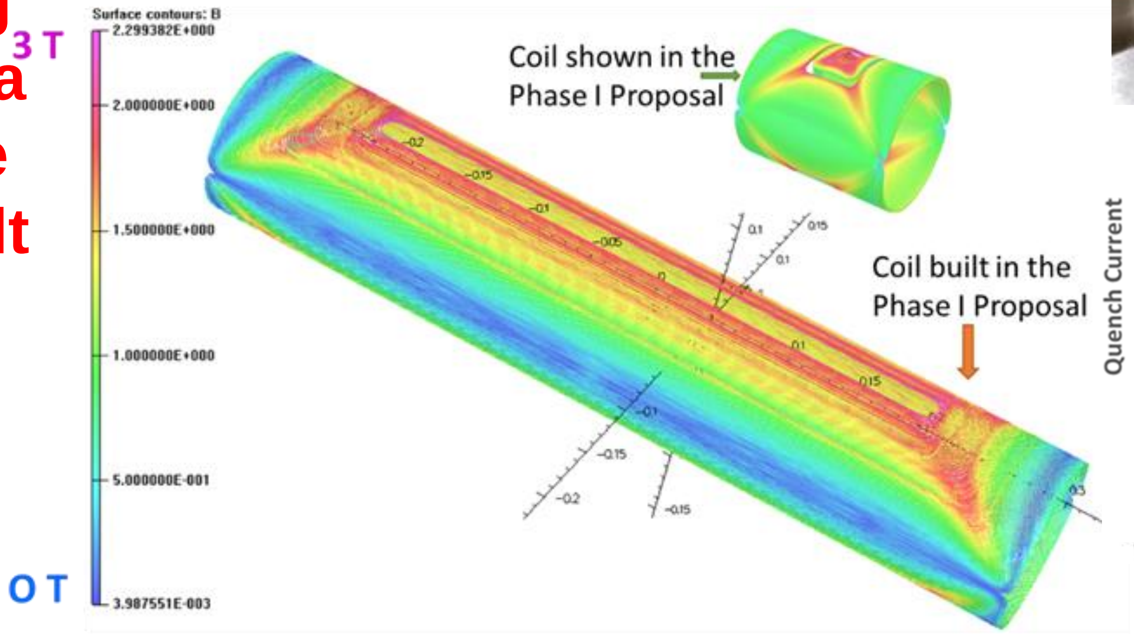


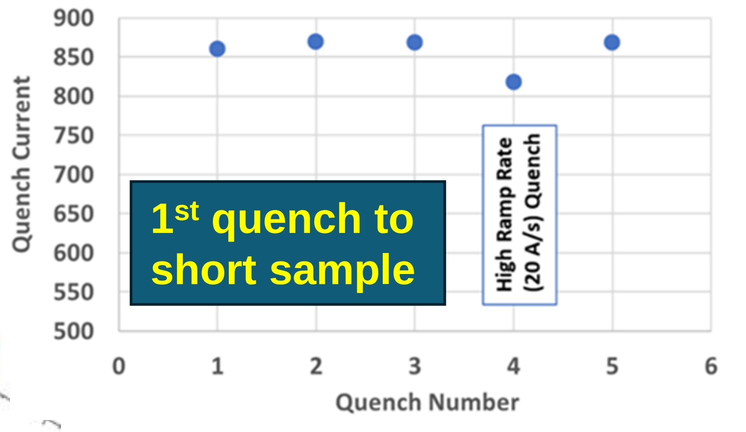
Summary of Phase I Goals and Performance

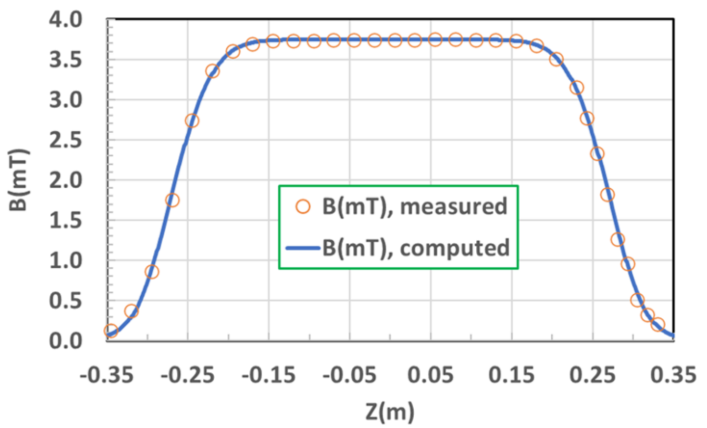
2 layers, ~1.7T field, ~2.2T peak, 114mm bore, new design => a significant superconducting dipole for a Phase I

Initial analysis during Phase I showed that a 10-layer coil in Phase II will be more difficult

Increased the length of two Phase I coils, so that they can be used in Phase II







- ✓ **Succeeded in demonstrating ~1.7 T dipole in Phase I**
- ✓ **Demonstrated: Larger integral field of optimum design**
- ✓ **Bonus: Two full-length coils good for use in Phase II**

First demo of the optimum integral dipole concept

Status and Progress in Phase II

Phase II Breakdown, Status and Goals

Phase II (intermediate): 6 layers, ~2.9 T, ~3.5 T peak field, 114 mm

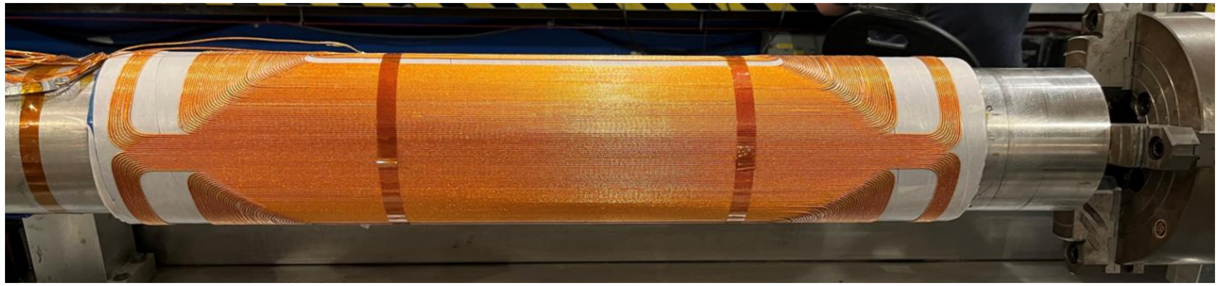
- **Demonstration of a good field quality (next slide): A major validation of the optimum design and of the 3-D design software**
- **Current status: The magnet on the test stand for quench tests**

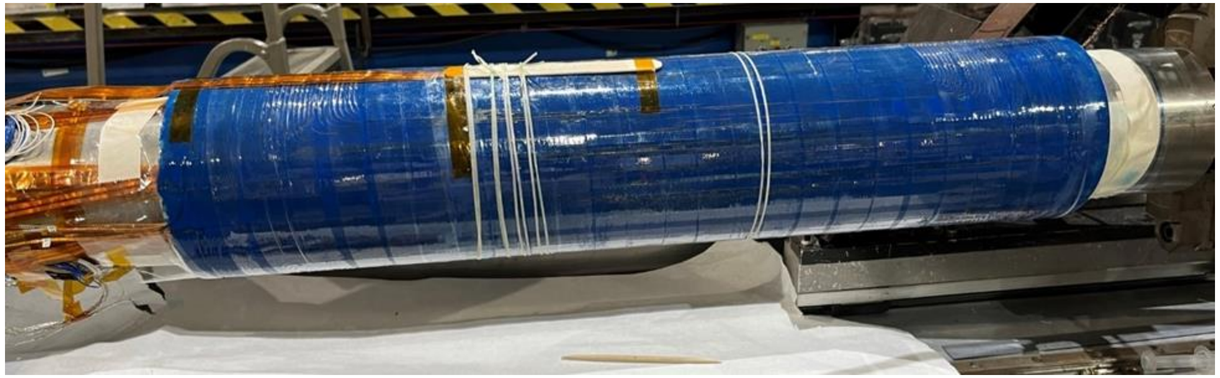
Phase II (stated goal):

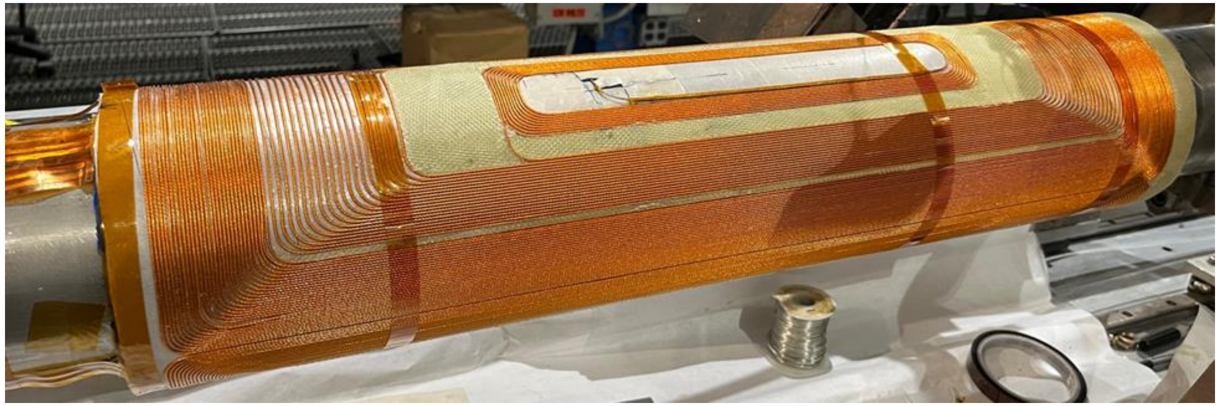
10 layers, 3.8 T central field, 4.2 T peak, 114 mm aperture

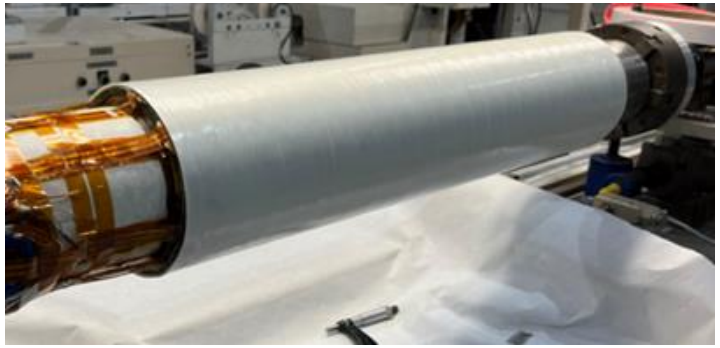
Intermediate test should provide a timely input to the remaining Phase II, and future planning for possible Phase IIA and to EIC

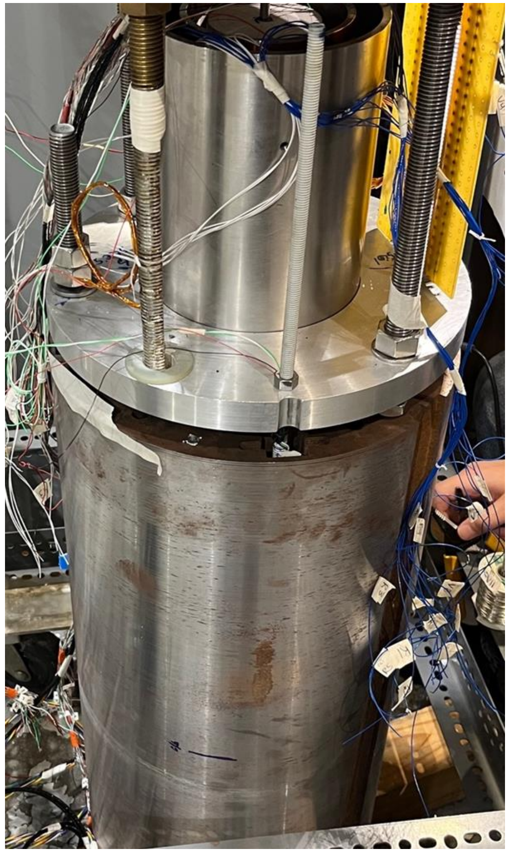
Coil Winding and Magnet Design and Construction

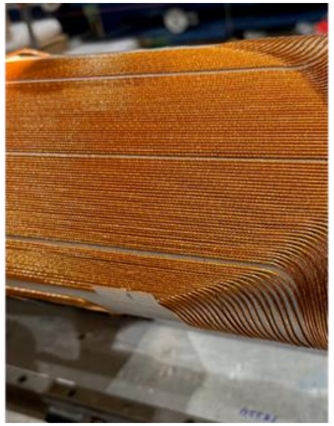


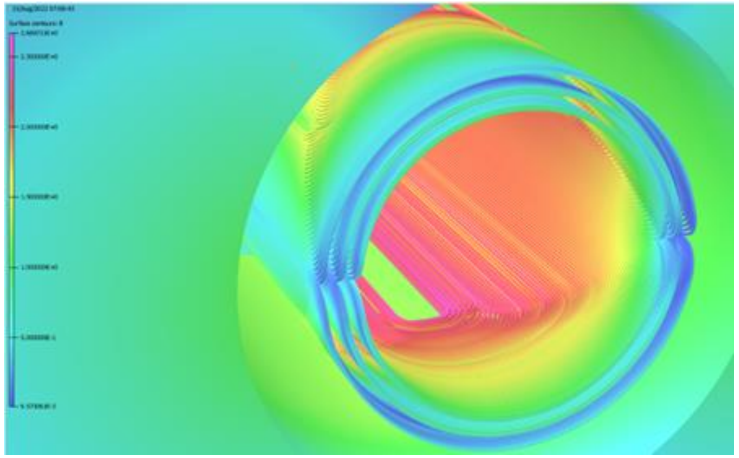












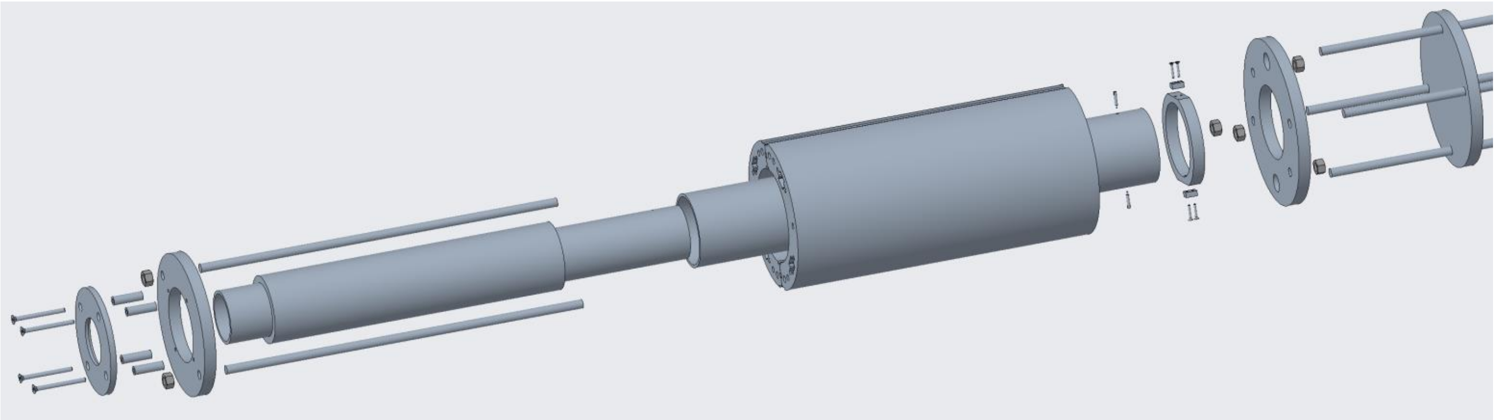
Field Quality Demonstration of the Design and of the Code

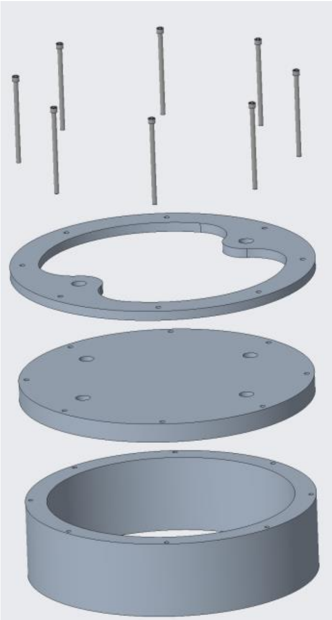
Warm testing of 6-layer design

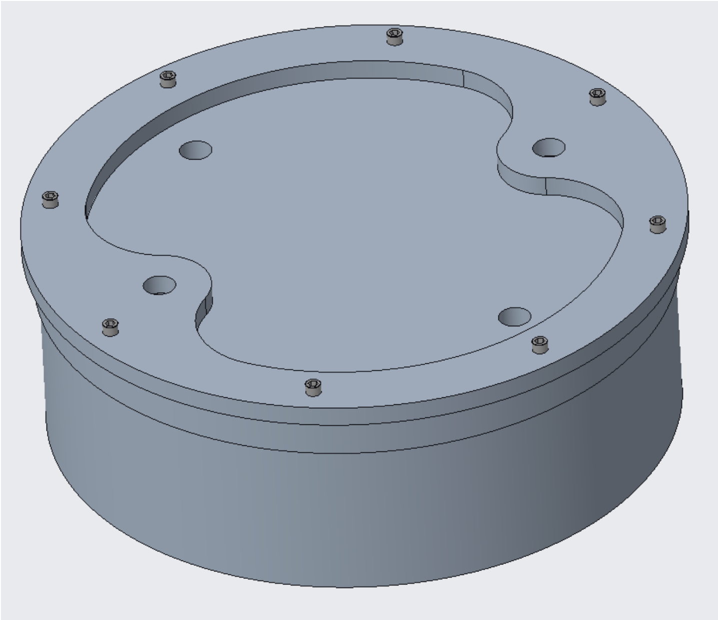
Optimum Integral Dipole 6-layer Design		
ITF (NO Fe)	1.860	mT.meter/A
Measured Integral Harmonics@31mm		
No.	bn	an
2	0.77	3.51
3	6.12	4.32
4	0.43	-0.98
5	0.93	0.50
6	0.20	-0.61
7	1.85	0.58
8	-0.02	0.22
9	-0.66	-0.19
10	0.02	-0.08
11	0.18	0.05
12	0.00	0.02

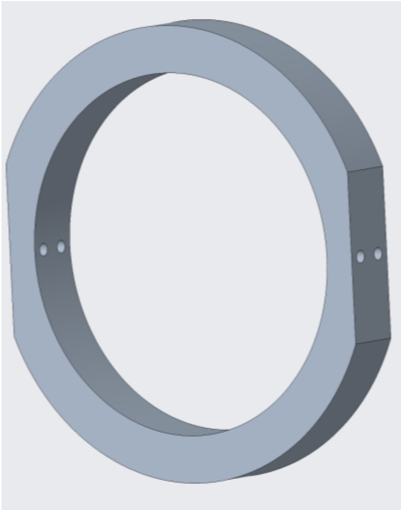
- A good field quality despite several changes on the fly (as in any R&D project)
- Next 4 layer to be used in compensating small harmonics

Test Stand Modifications Designed by the Summer Student*







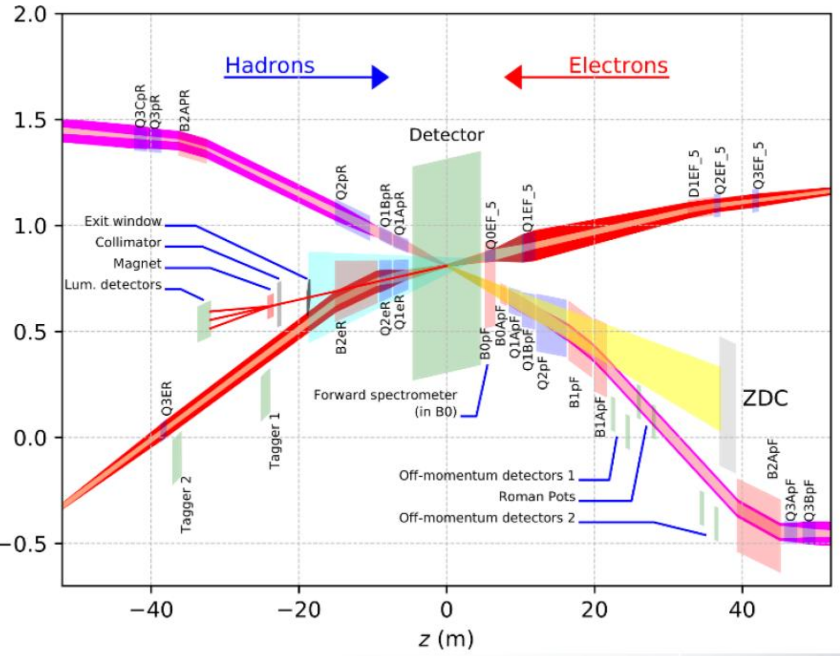


*Courtesy Jared Nicholson (summer student)
Construction and assembly during the internship

An Opportunity to do a Key Validation Test that was Part of Another Phase II Proposal

<u>A major challenge in EIC IR:</u>

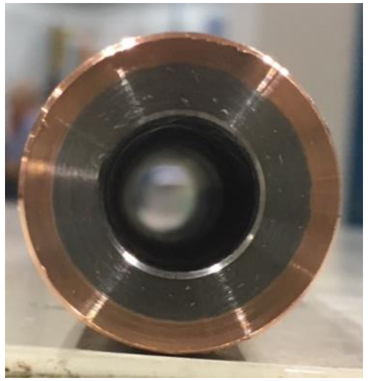
e-beam traverse very close to Ion beam in EIC IR region



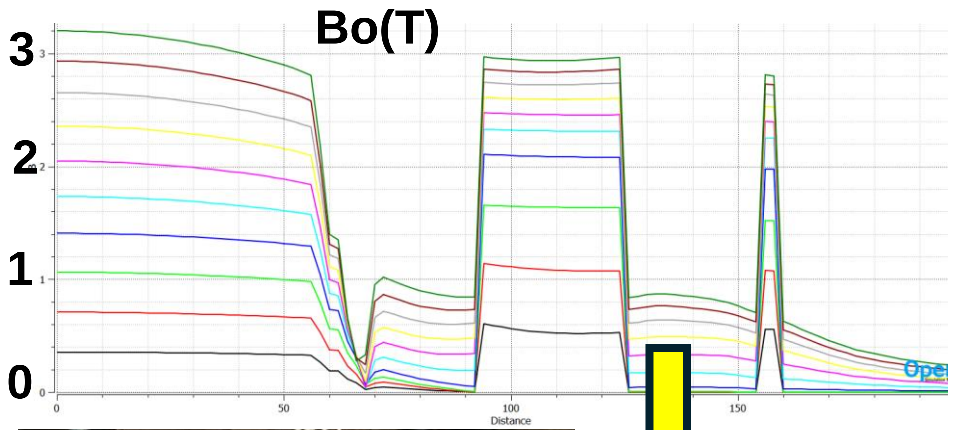
Field from the high field magnets for ion beams must be shielded on the path of e-beam

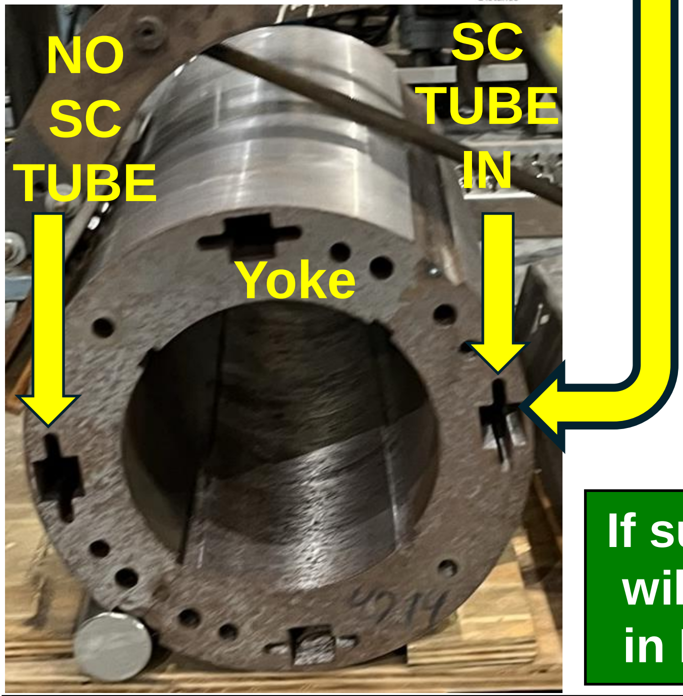
<u>Another Phase I SBIR</u>:

Superconducting Shielding



- **NbTi superconducting tubes were obtained in Phase I from two vendors**
- **Testing was part of Phase II proposal (not funded)**
- **Choice of yoke and some planning is allowing the idea to be tested in this Phase II (was not part of the original proposal)**





If SC shield works, field in this cutout should become zero!

If successful, will be used in Phase IIA

Compare the fields in two cutouts: one without SC shield, another with shield

Status of various Tasks and Future Plans

- Several other tasks completed (or almost completed)
  - ❑Magnetic design, mechanical design and quench analysis
  - ❑Software development
- Perform the intermediate test of the magnet – a major milestone
  - ❑Magnet on test stand, results expected within a week (to be reported at MT)
- Iterate design, build and test the final 10-layer EIC B0ApF R&D dipole
- Potential of taking this promising design and program to the next Phase
  - ❑Turn B0ApF R&D magnet to a prototype (all accelerator requirements must be satisfied, e.g., real yoke, low field in the hole for electron beam, etc.)
  - ❑ Examine potential of the Optimum Integral dipole for other EIC magnets, and other applications beyond EIC
  - ❑Current partner General Atomics (GA); open to other partners as well

Summary

- Optimum integral design is well suited for short magnets, as it essentially makes full use of the length of the coil in creating field by avoiding/minimizing the loss in magnetic length due to the ends
- PBL/BNL team has made a good progress on the ambitious goal of building and testing a relatively large aperture and medium (high) field dipole in Phase II (3.8 T, 114 mm Vs 3.45 T, 80 mm RHIC arc dipole)
- Demonstration of the "Optimum Integral Design" in a specific EIC dipole (B0ApF) should have a wider impact on the other EIC IR magnets also; and in applications beyond DOE/NP, as well