Optimum Integral Magnet Design

(includes work performed under PBL/BNL STTR)

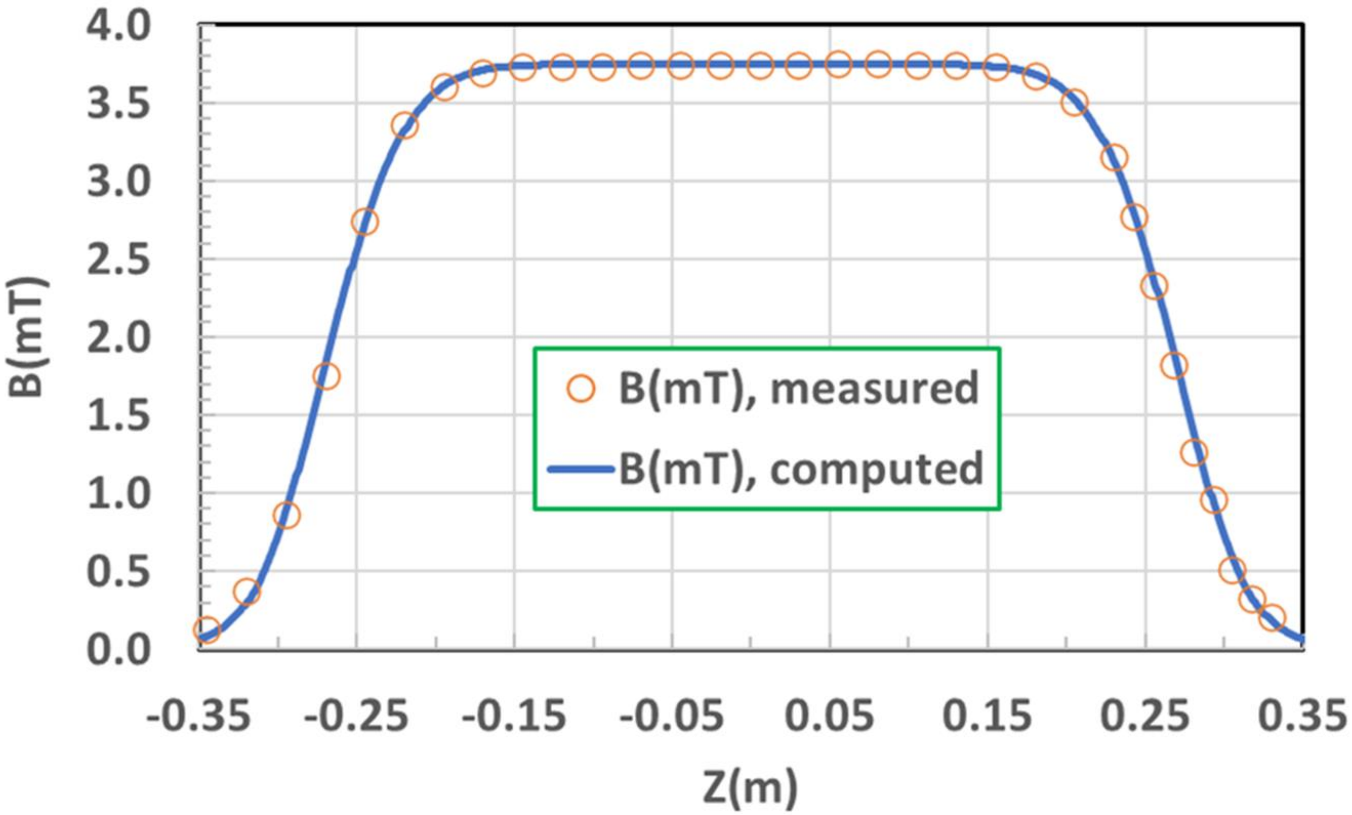
Ramesh Gupta
on behalf of PBL/BNL Team

October 25, 2023

In Memory of Bill Sampson (1934-2023)

16 T HTS Solenoid – record at that time

Passed away on October 17, 2023.
After making numerous contributions to magnet science (including to many PBL/BNL programs)



Optimum Integral dipole field profile (as measured by Bill Sampson)

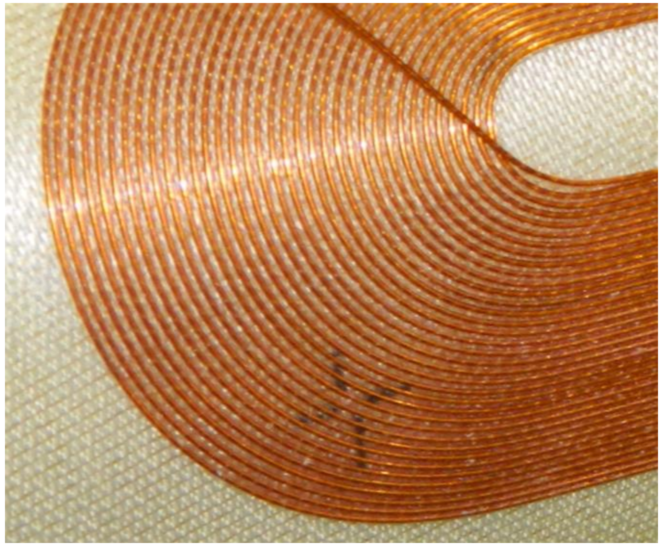
Overview

- **Optimum Integral Design**
  - **Why, What, Initial application**
- **PBL STTR Dipole B0ApF for EIC**
  - ➢ **An ambitious goal for STTR: B_o = 3.8 T, B_{pk} = 4.2 T, id = 114 mm**
  - ➢ **Progress to date: Phase I and Phase II (year 1)**
- **Other Applications and Summary**

Why? : Challenges in Short Magnets

- **Turns in the body (SS) take space in the ends as well**
- **Space taken by SS turns is most productive in creating field whereas the space taken in ends is not**
- **In short magnets, one is forced to put fewer turns than possible in body to allow space for the end turns**
- **With field quality and peak field consideration included, typical dipole end take one coil diameter on each side**
- **Typical ends contributes ~1/2 field/length of body (SS)**
- **These limitations make short s.c. magnets inefficient, and even impractical if they must be very short**

✓ **Optimum integral design overcomes these limitations and allows short magnets to become efficient and possible**



Many turns in body takes similar space in the Ends

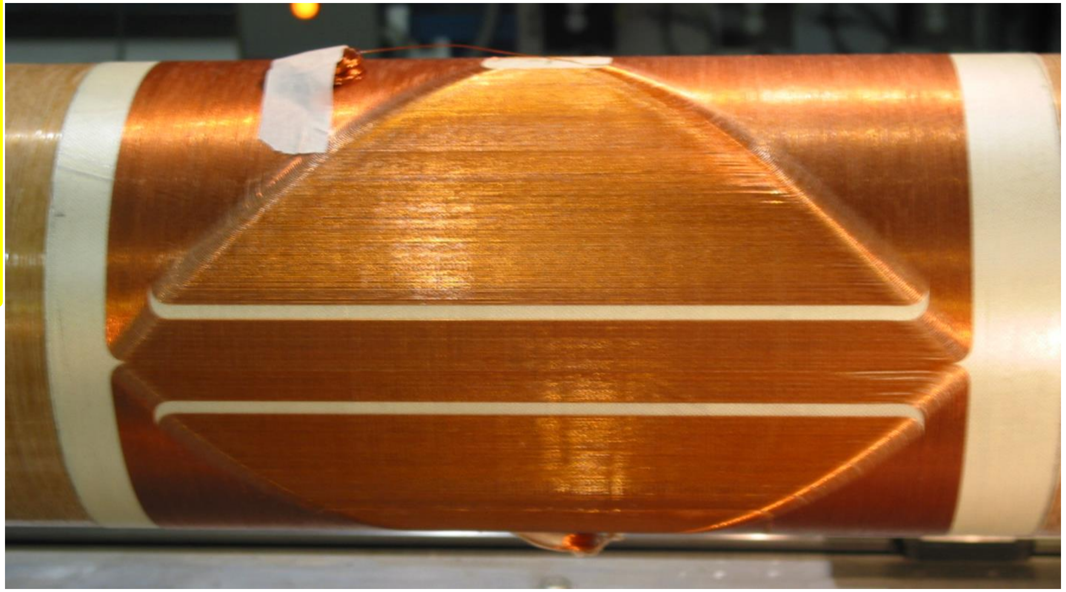
To limit space in the Ends, body also has fewer turns

First Use of the Optimum Integral Design: AGS Corrector Dipole

Coil Length = 182.8 mm
Coil Diameter = 300 mm

Coil length < Coil diameter

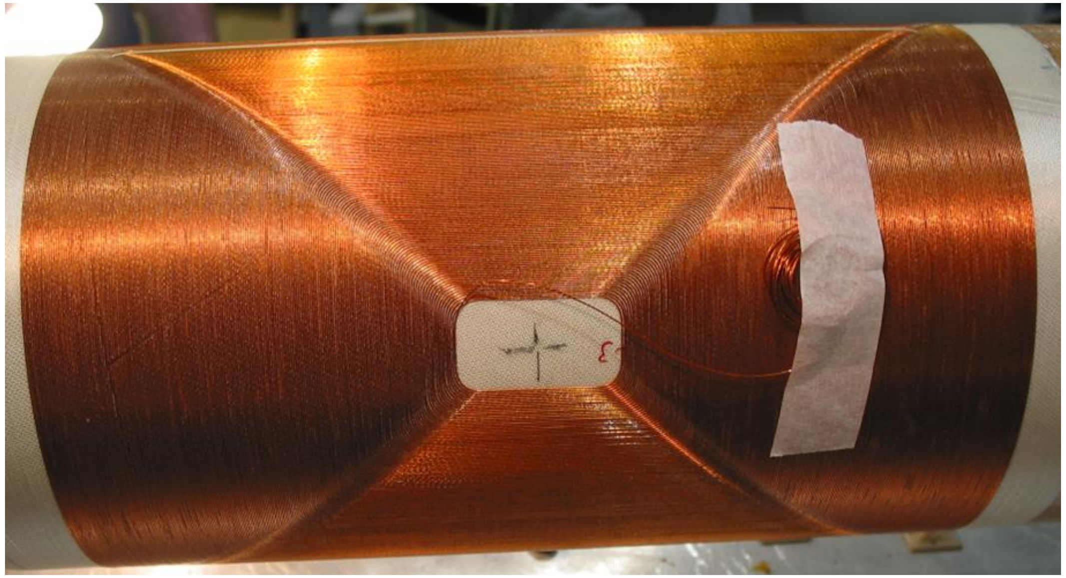
ASC'04



Note: Almost full use of the available longitudinal and azimuthal space by the superconductor (*high fill factor*)

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

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



- **Design not yet used in a significant magnet**
- **Field quality was not measured and verified**

Conventional Design Approach

A two-step process:

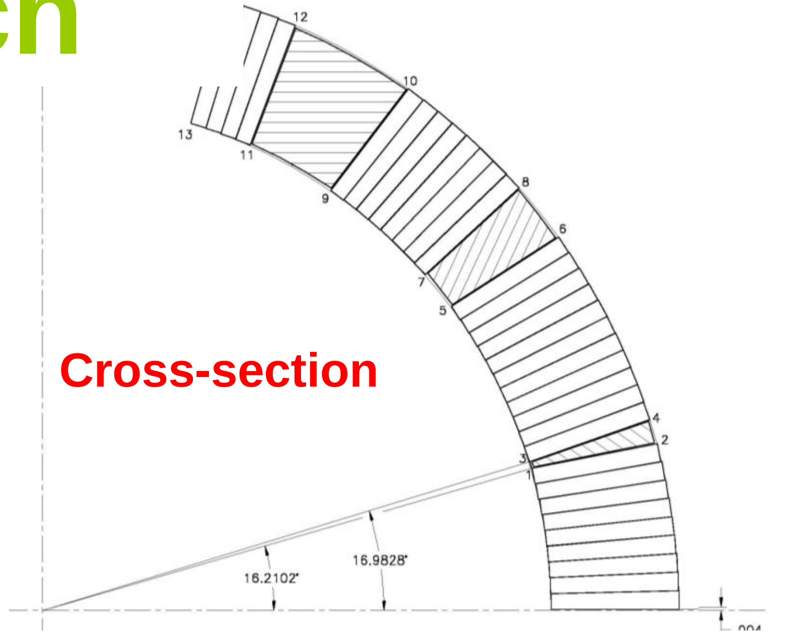
Step 1: Optimize coil cross-section to obtain cosine theta like distribution:

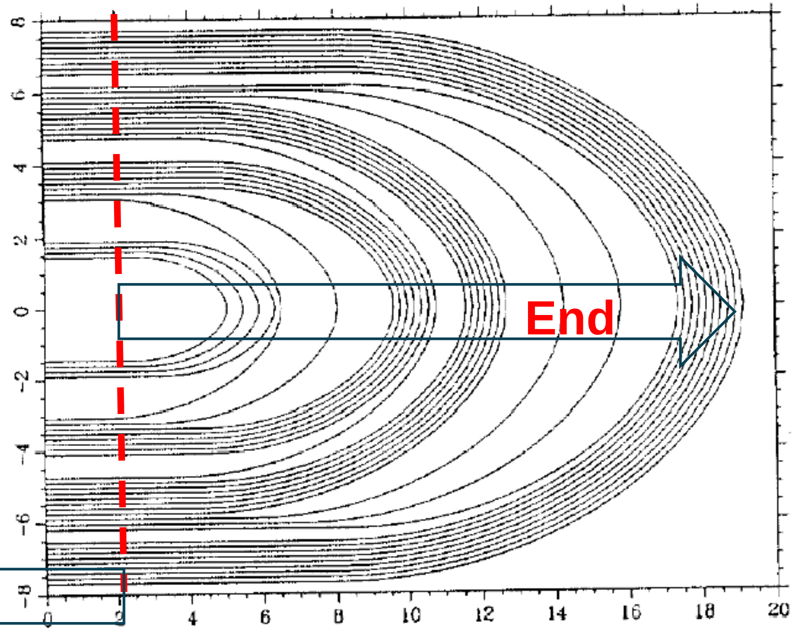
$$I(\theta) = I_o \cdot \cos(n\theta)$$

Step 2: Optimized ends for harmonics

(also, optimize both for low peak fields)

Each step limits the maximum integral field





Optimum Integral Magnet Design Approach

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

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

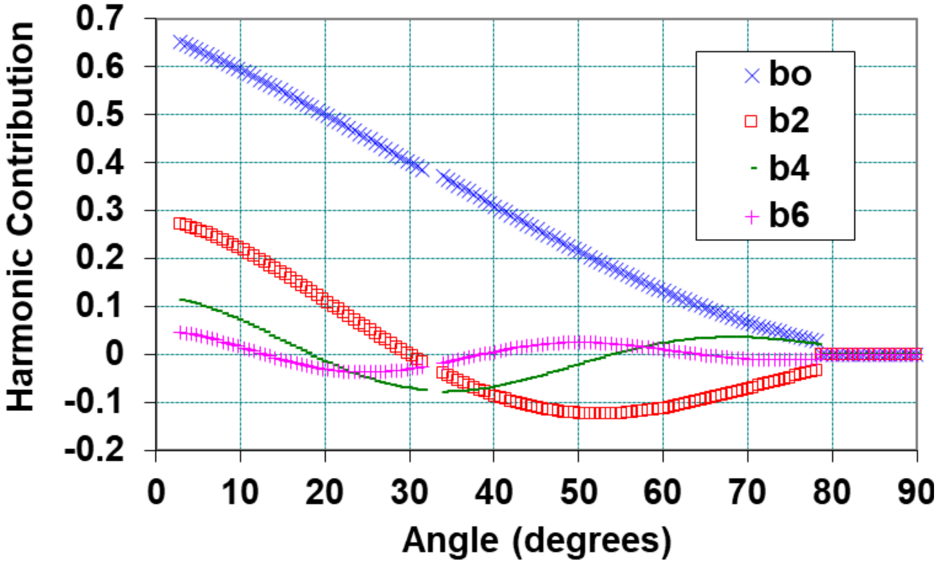
For no wedges or end spacer, function varies linearly ==> Modulate it to cos theta

- **Full-length midplane turn defines the length of the magnet**

Essentially no loss due to magnet ends

Integral harmonics:

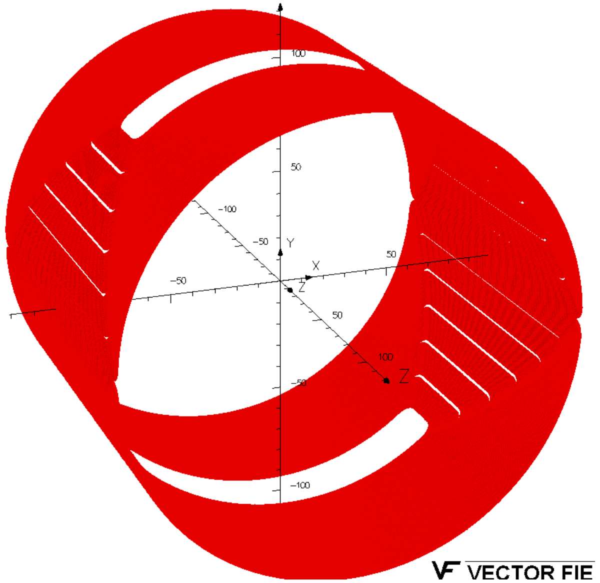
$$B_n = 10^4 \left(\frac{R_0}{a}\right)^n .\,L\,.\cos\left[(n+1)\,\phi\right]$$



(b_2 is sextupole)

Opening A New Parameter Space with the Optimum Integral Design
(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**

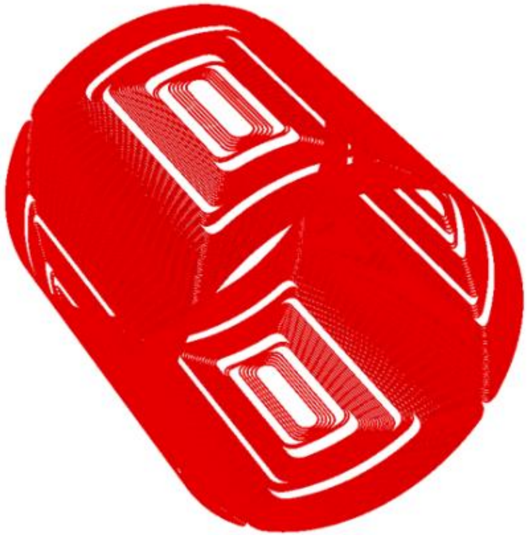


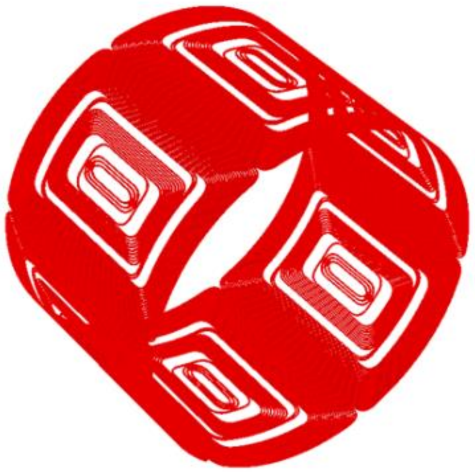
Model of a short length dipole based on the Optimum Integral Design.

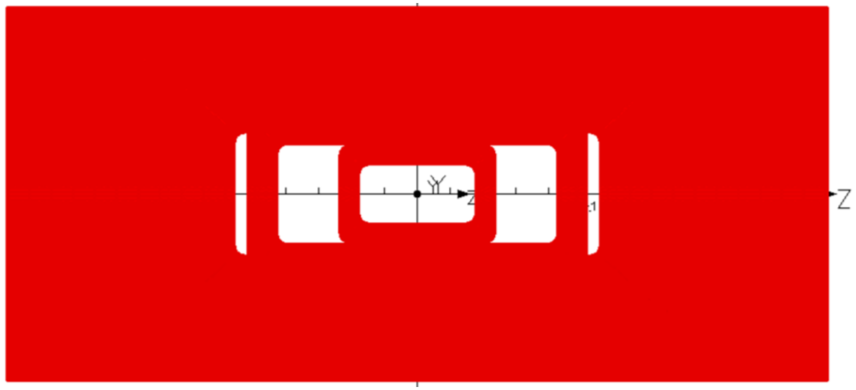
Coil length 175 mm; coil diameter 200 mm.

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







A Dipole Optimized with End Spacers Only

A Few Relatively Short Dipoles of Interest

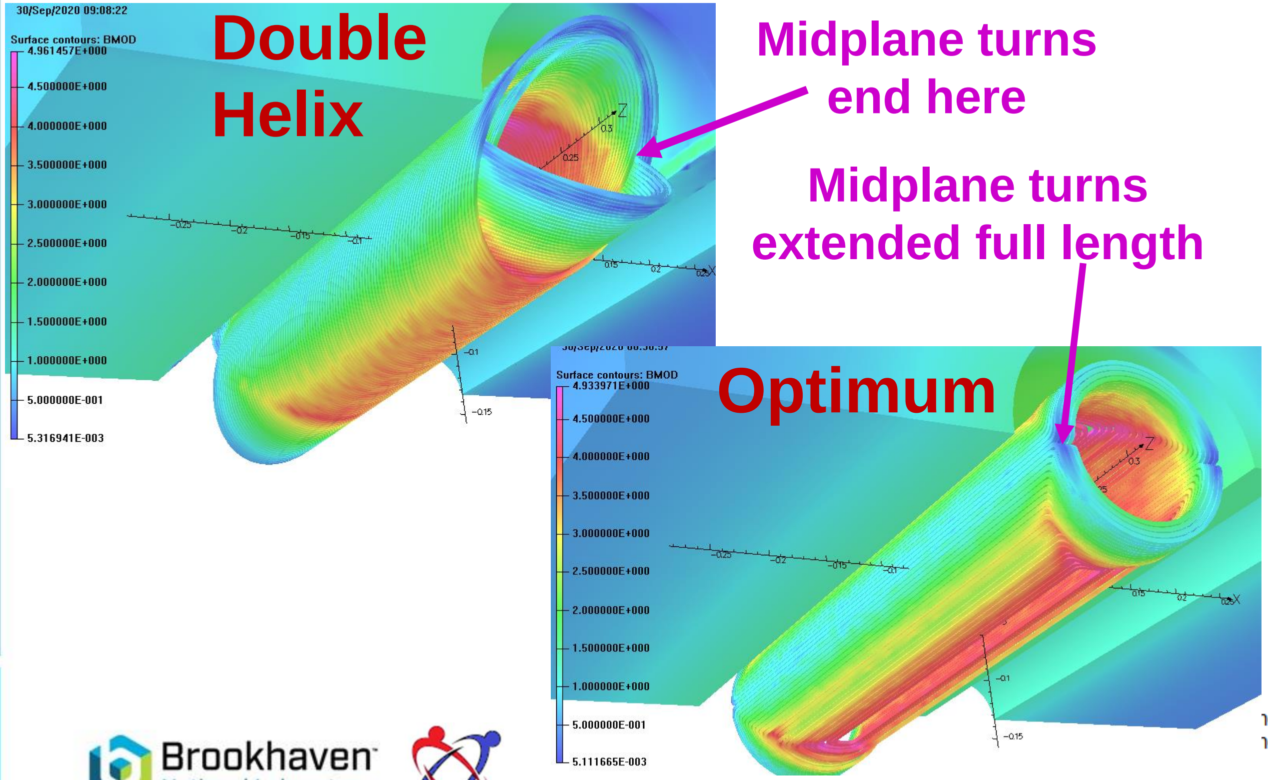
Coil length to coil diameter ratio:

- **AGS Corrector (*L* = 182.8 mm, *a* = 300 mm): ~0.6**
- **EIC B0ApF (*L* = 600 mm, *a* = ~120 mm): ~5**
- **EIC B1ApF (*L* = 1600 mm, *a* = 370 mm): ~4.3**
  - **Typical mechanical length of each coil end: ~ two coil diameter**
  - **Loss in integral field due to ends starts becoming significant when the total coil length (*L*) < 10 X coil diameter (*a*)**

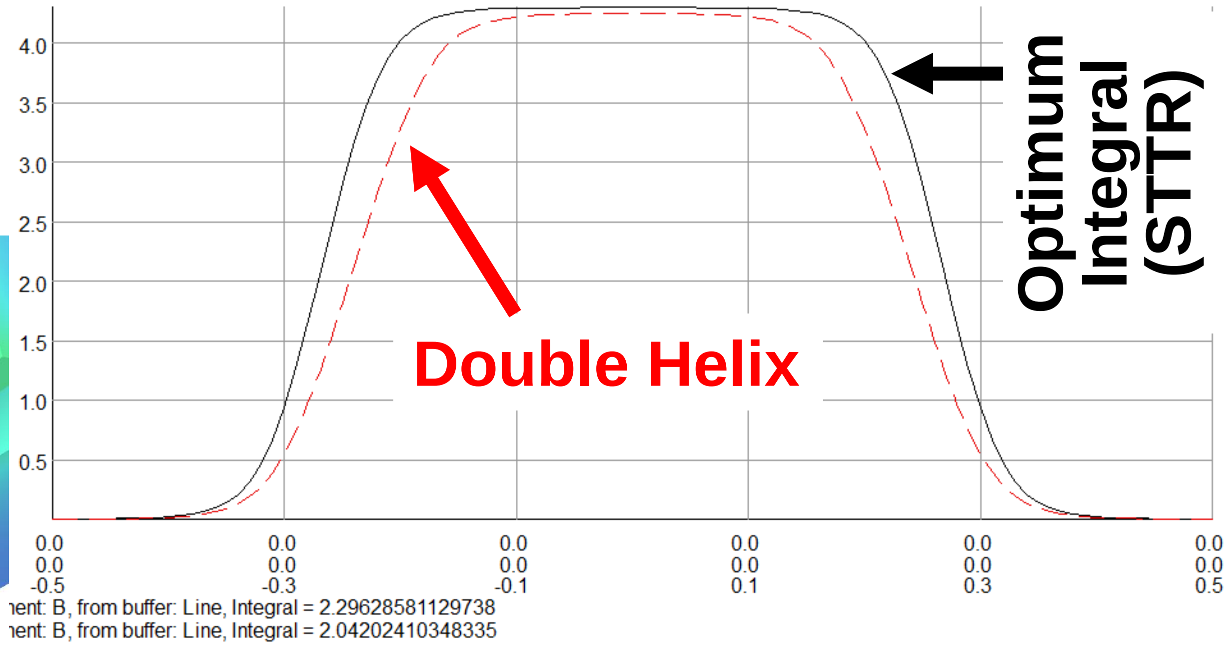
Modern collider dipoles have coil length > 100 X coil diameter

Optimum Integral Design STTR: B0ApF for EIC

- **B0Apf dipole for EIC needs a coil ID of 110-120 mm and a length of 600 mm. The design field: ~3.5 T. Good for an ambitious & a high impact SBIR/STTR.**
- **Note: The optimum integral design is not part of the EIC R&D program. It is part of PBL/BNL STTR, being operated independently of the EIC project.**



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



Overall Goals of Phase I and Phase II STTR Programs

Goal of Phase I (Year 1):

- **2 layers, B_o: ~1.7 T, B_{pk}: ~2.2 T, Bore: 114 mm**

Intermediate Goal of Phase II (Year 2):

- **6 layers, B_o: ~2.9 T, B_{pk}: ~3.5 T, Bore: 114 mm**

Final Goal of Phase II (Year 3)

- **2 layers, B_o: ~3.8 T, B_{pk}: ~4.4 T, Bore: 114 mm**

For reference
RHIC dipole: 3.45 T, 80 mm

Also: Demonstration of a good field quality:

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

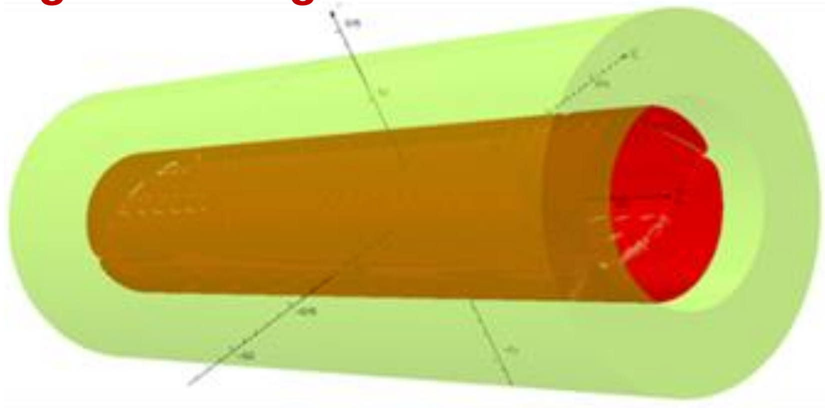
Technically ambitious, but schedule and budget wise achievable goals, if no major setbacks (high risk, high reward R&D, not possible under regular program)

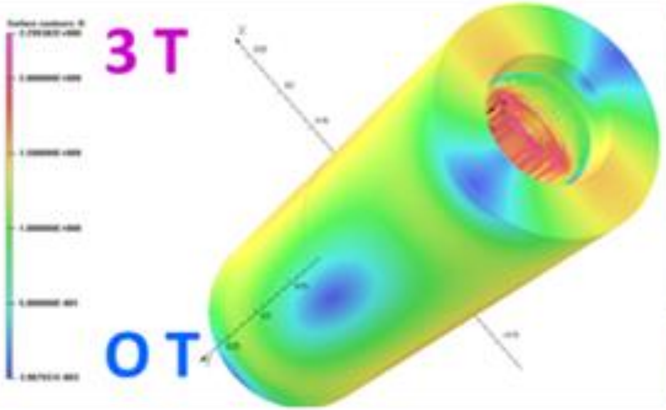
Over the years, PBL/BNL team has delivered on many ambitious goals and made high impact contributions such as: record breaking HTS solenoid, record breaking HTS/LTS dipole, revival of common coil design and overpass/underpass design,…

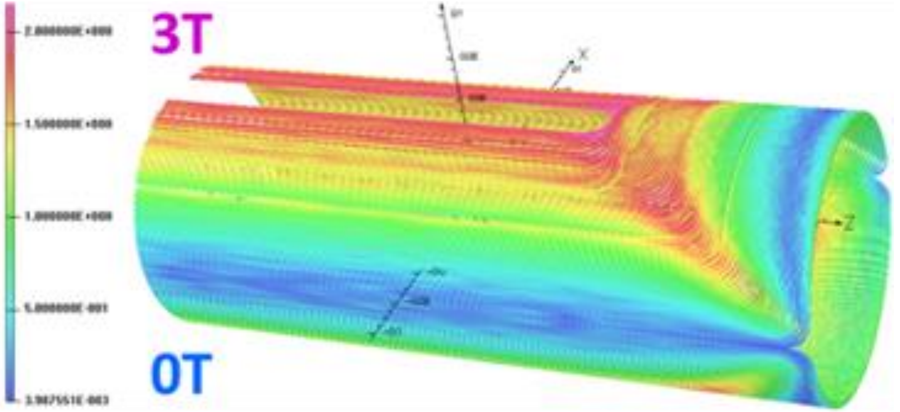
Optimum Integral Dipole (Phase I – 1 year term)

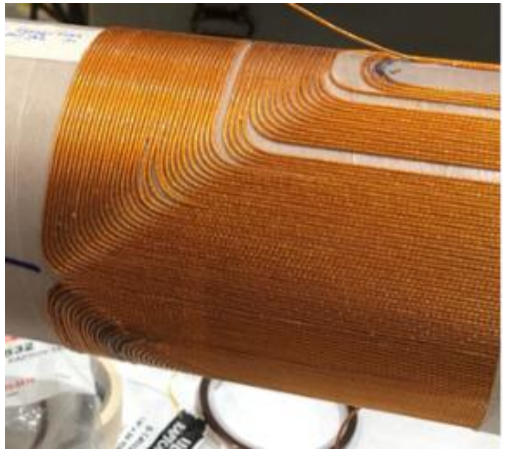
B_o = ~1.7 T, B_{pk} = ~2.2 T, Coil i.d. = 114 mm

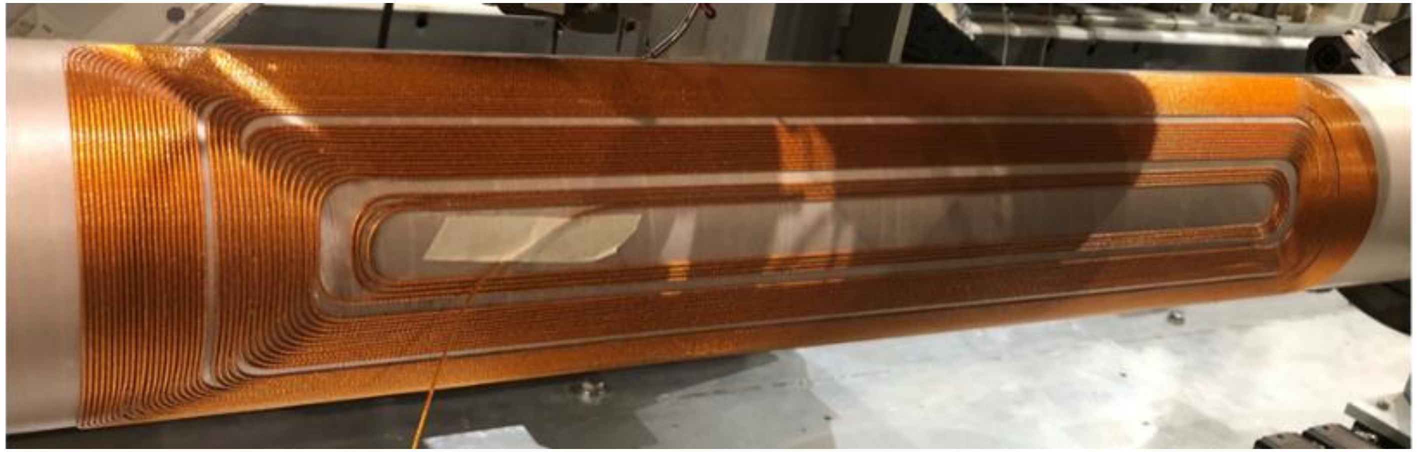
Magnetic design

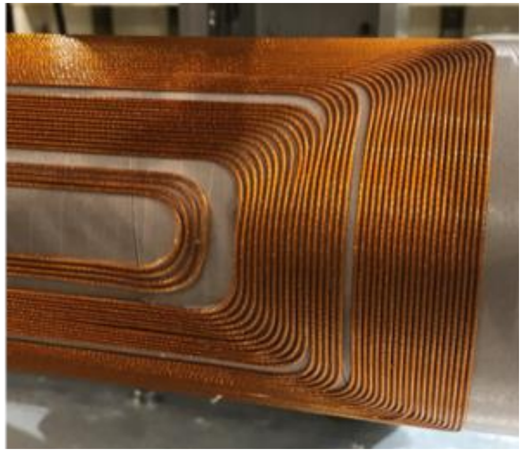










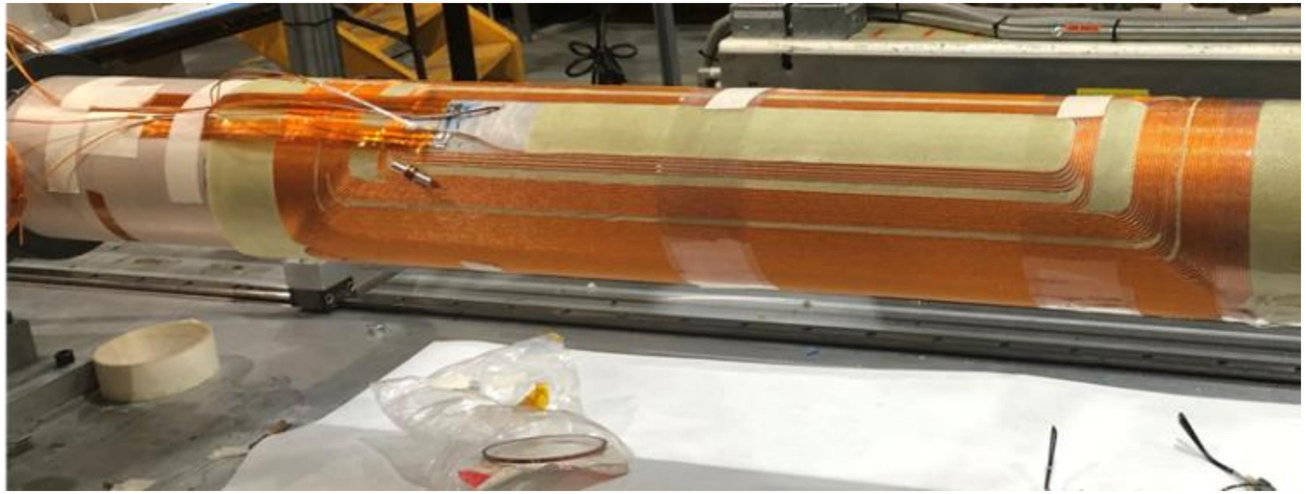


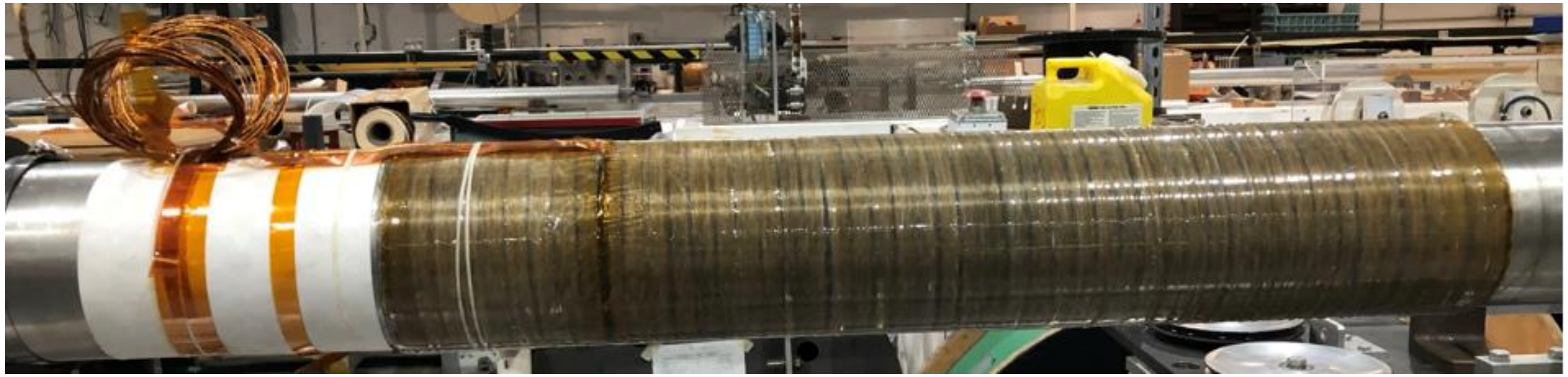
Midplane turns extended full length

First Layer

Optimum Integral Dipole - Phase I Coil and Magnet

Spaces filled, epoxied, cured and the surface is prepared for the second layer

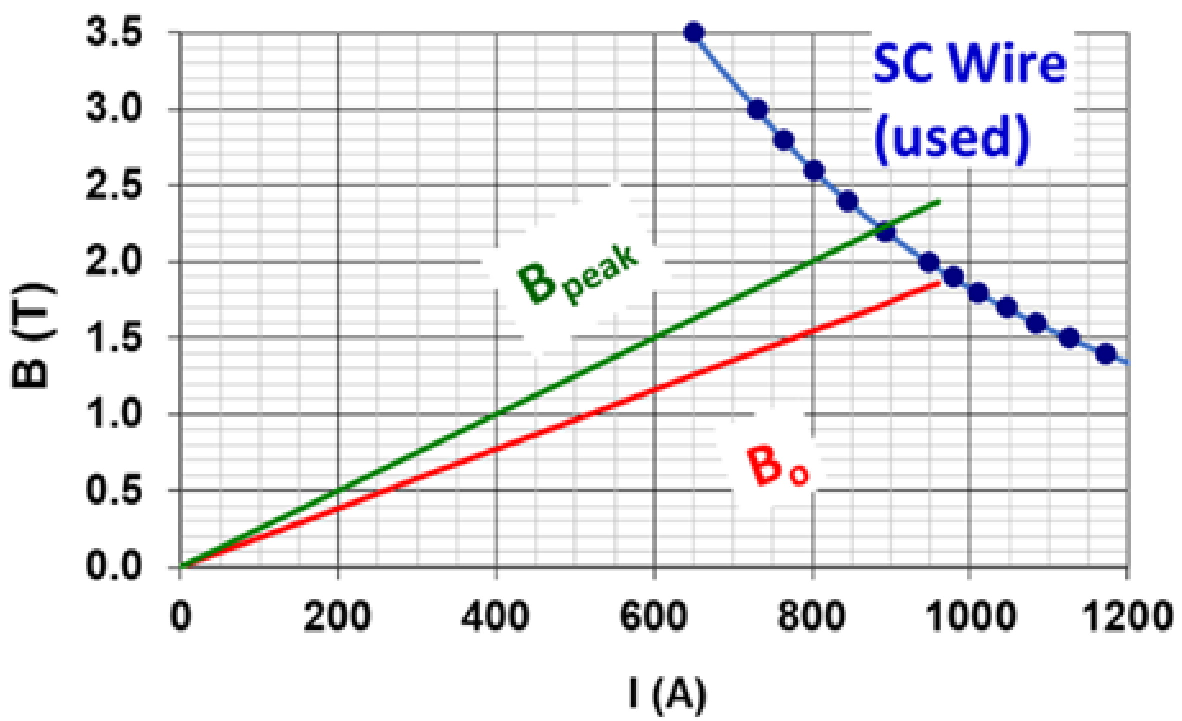


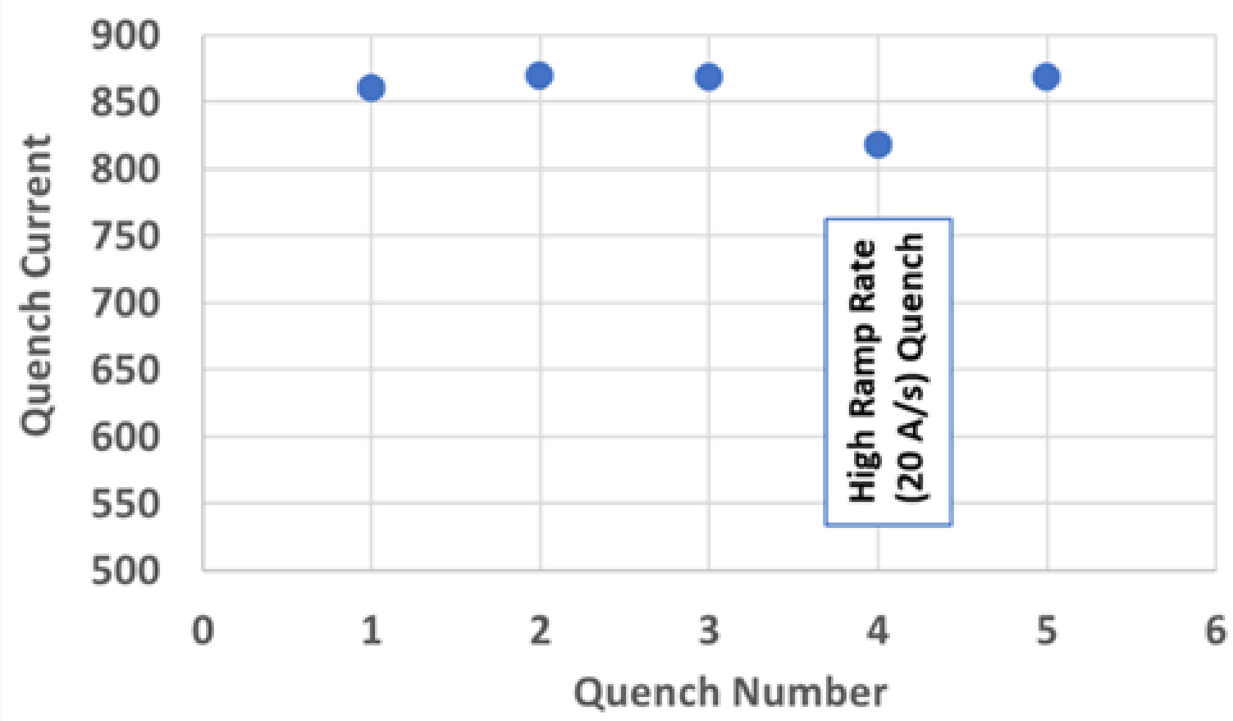


Double-layer tension wrapped and cured

Coil in yoke, ready for test

Question: Will the direct wind coil based on the optimum integral have a good quench performance to field promised in Phase I?





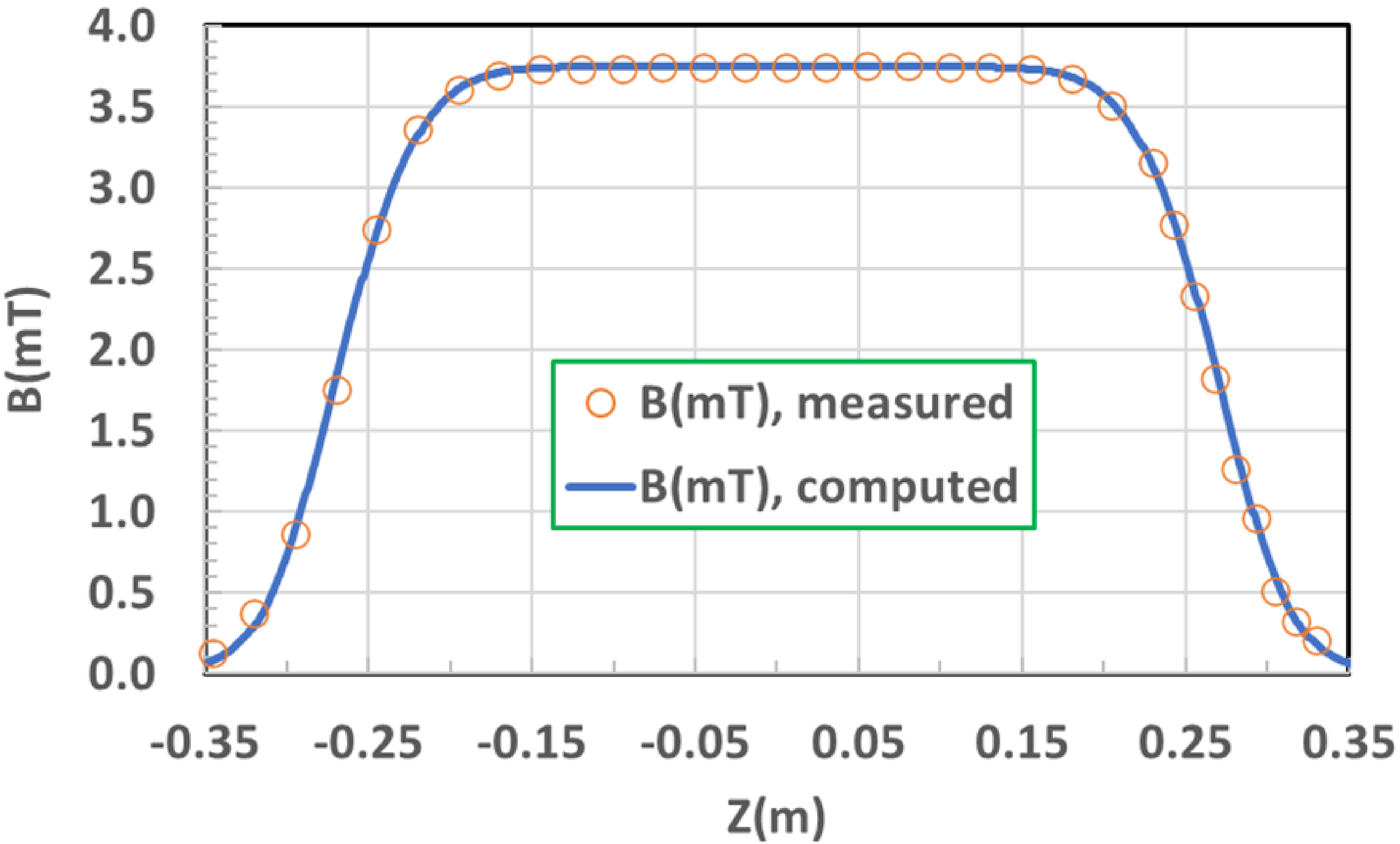
B_o = ~1.7 T, B_{pk} = ~2.2 T, Coil i.d. = 114 mm

Answer: Quench performance remains excellent (meets computed SS with no quench)

Question: Will optimum integral design extend the magnetic length?

Answer: Yes. Good agreement between calculations & measurements

Major motivation of the optimum integral design demonstrated

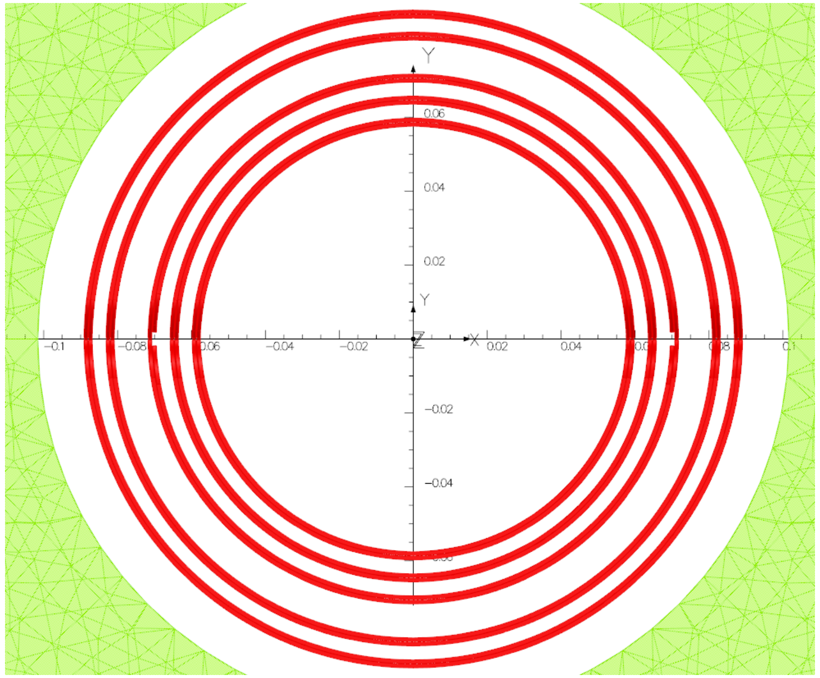


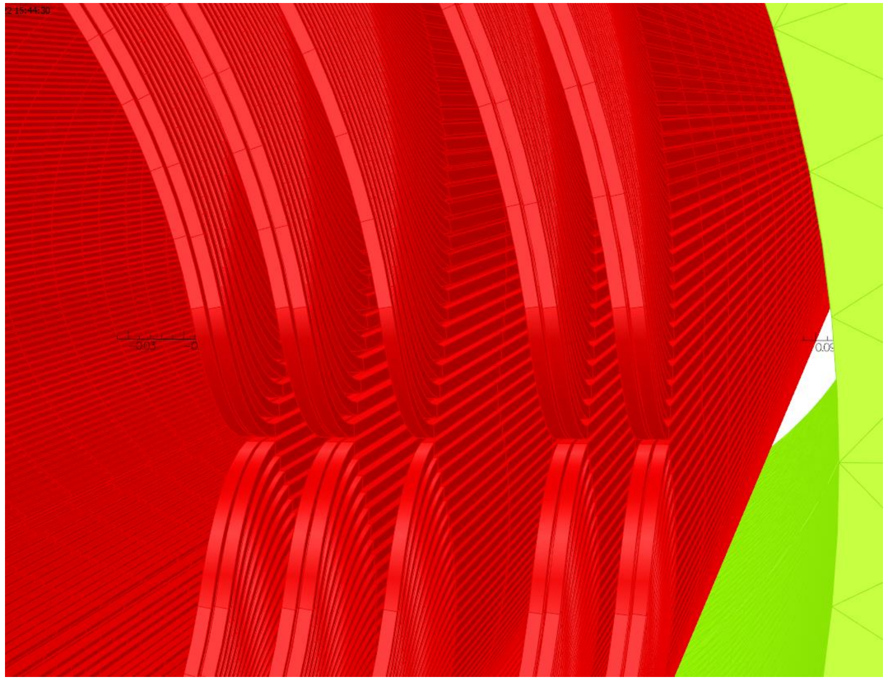
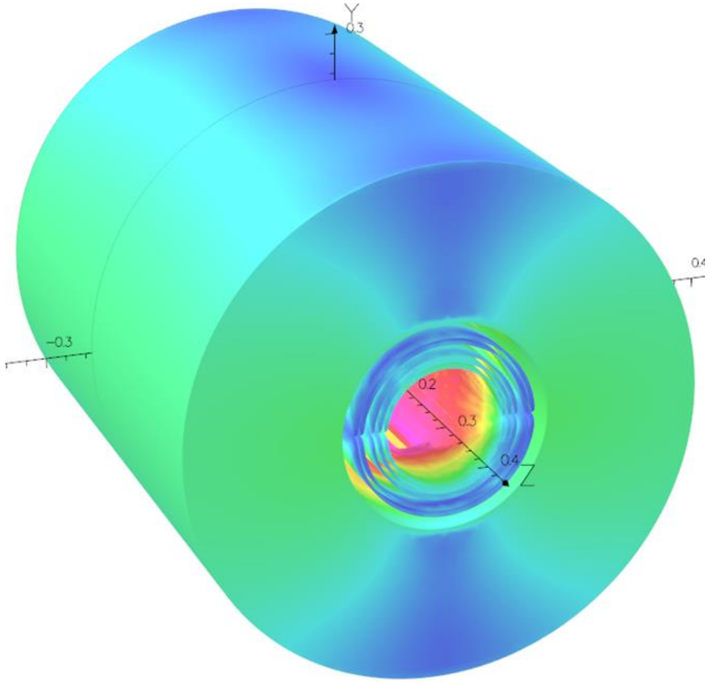
Measurements:
Courtesy Bill Sampson

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

Phase II: Build and test five double layers (10 single layer)

OPERA3d Models of the Phase II Dipole



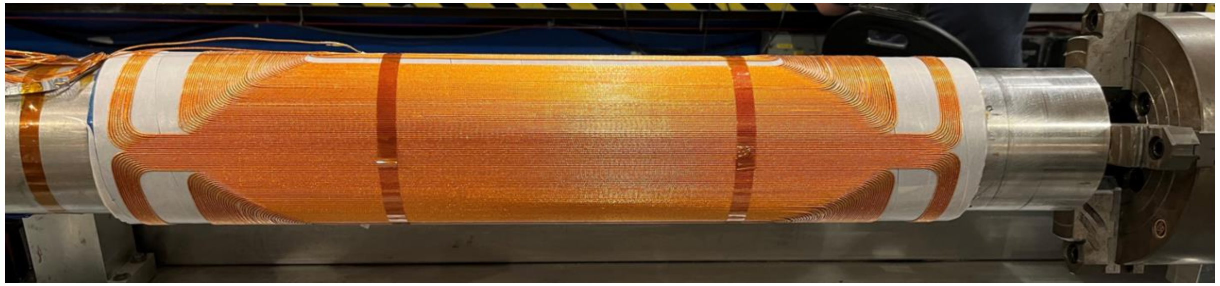
The design is optimized for low field harmonics with the ***IntegralOpt*** *code which also creates OPERA3d input file*

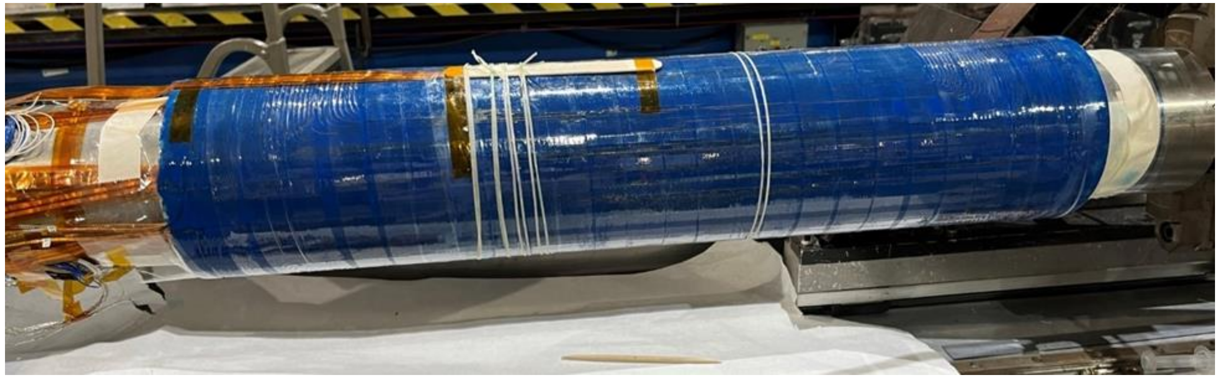
Intermediate Task: Build and test inner three double layer in a structure

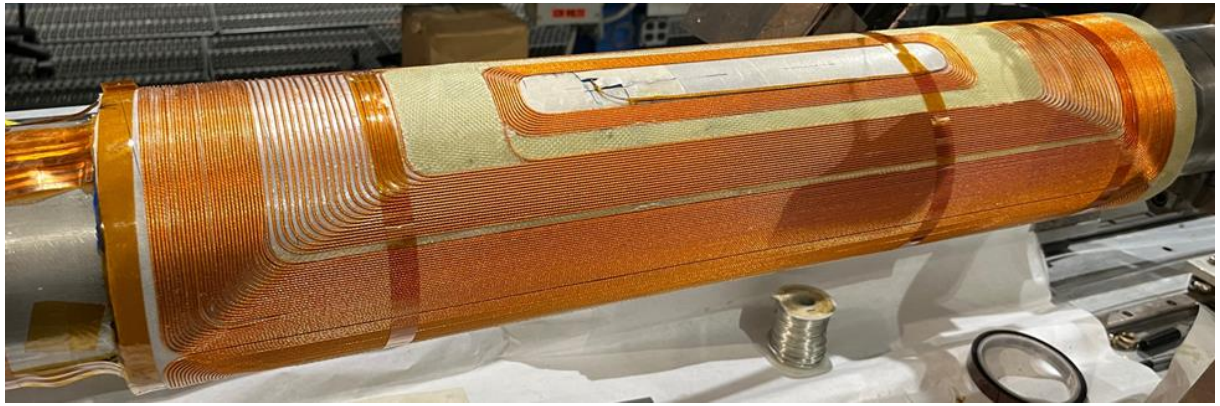
Phase II Year 1

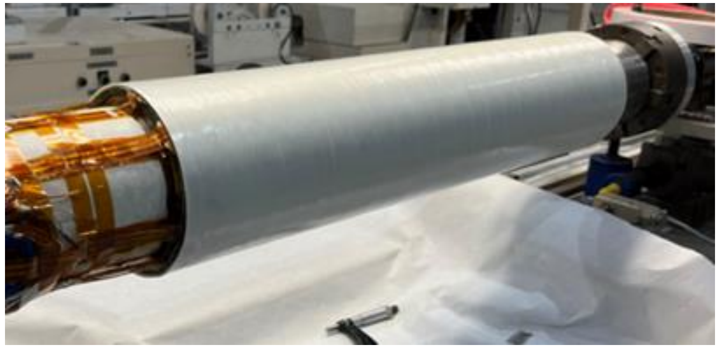
Construction and Test Results

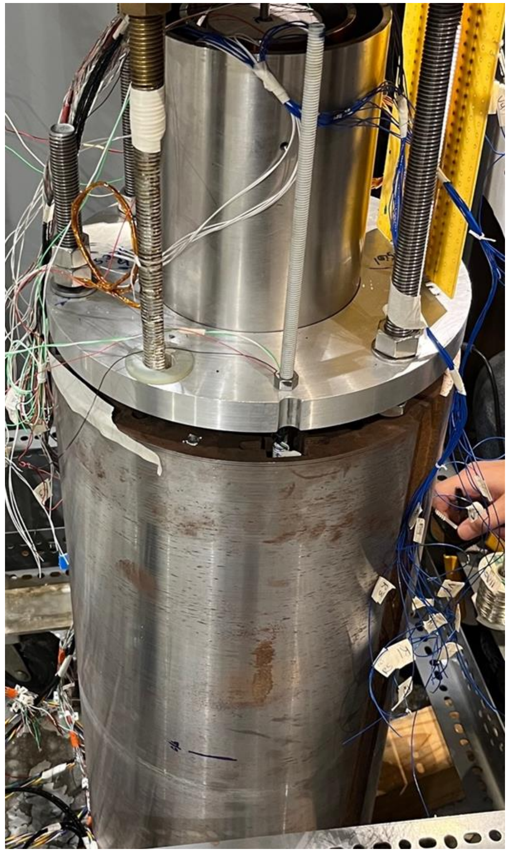
Coil Winding and Magnet Design and Construction

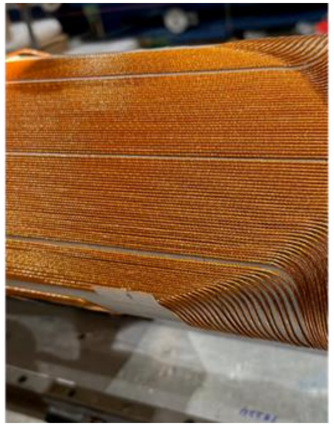


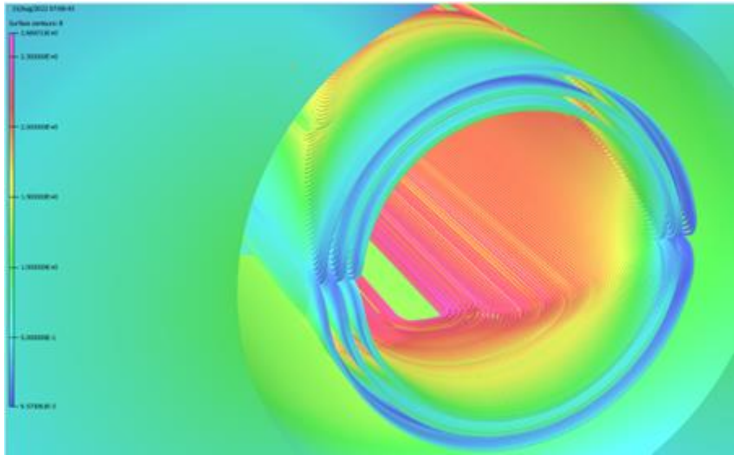












Field Quality Demonstration of the Design and of the Code

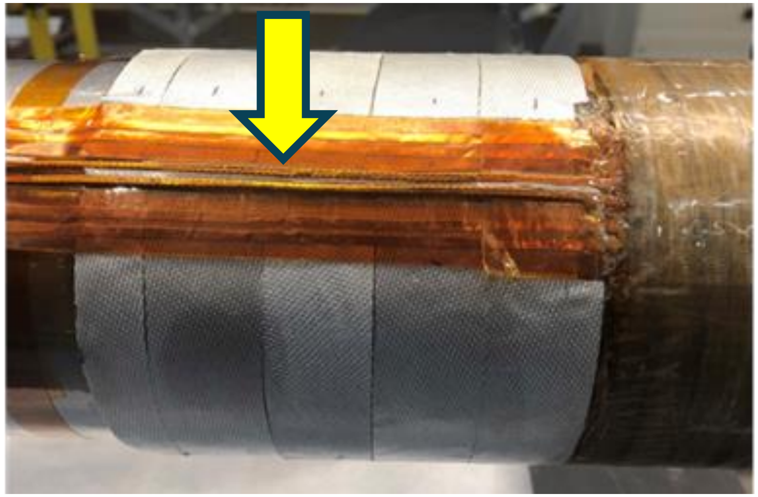
Warm testing of 6-layer design

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

- **Reasonably good field quality despite construction errors and changes on the fly**
- **Next 4 layer can be used in compensating small harmonics**

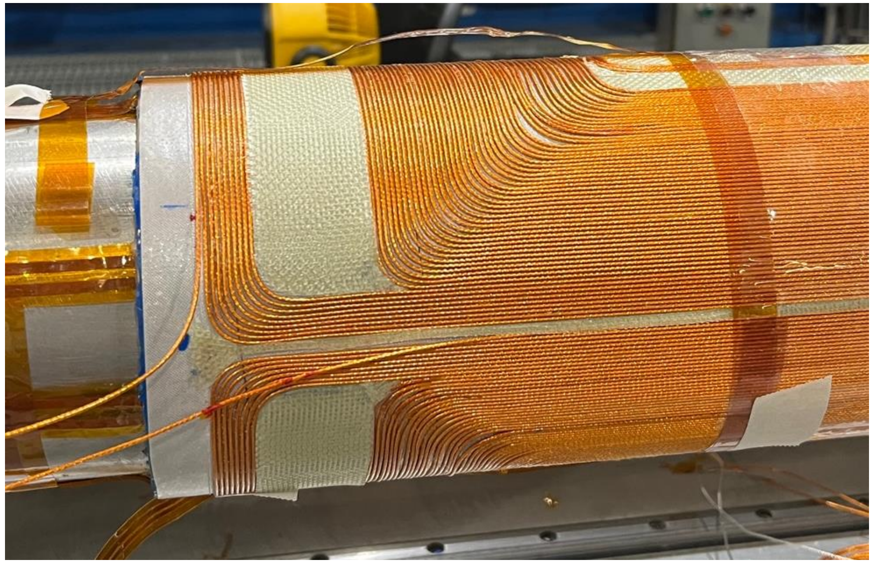
A Change in Design to Eliminate Radial Space Used by Leads

- Phase I "Optimum Integral Design" used extra radial space for bringing leads out "over the coil" at the pole



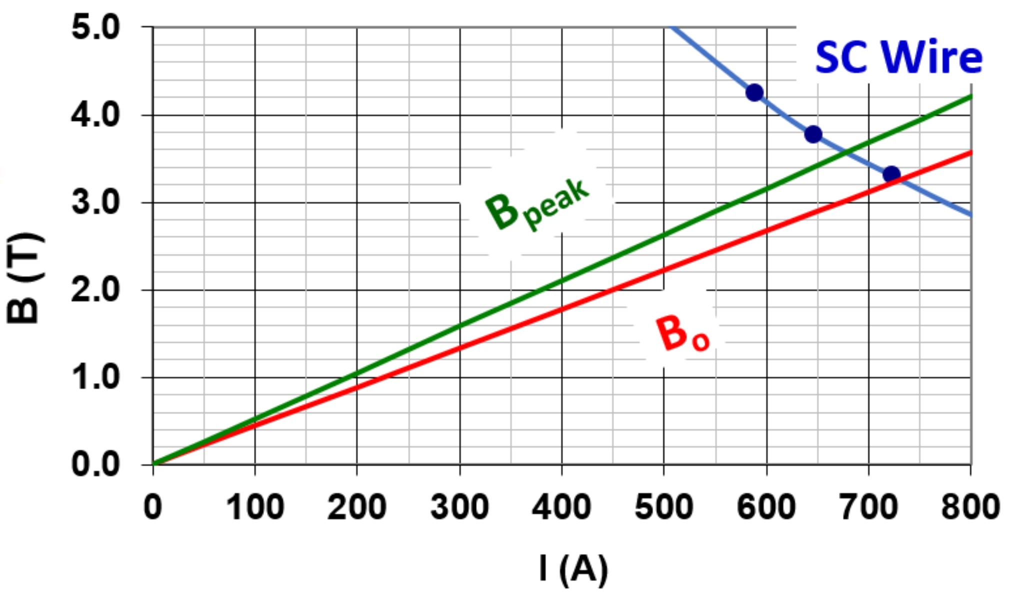
Phase I configuration

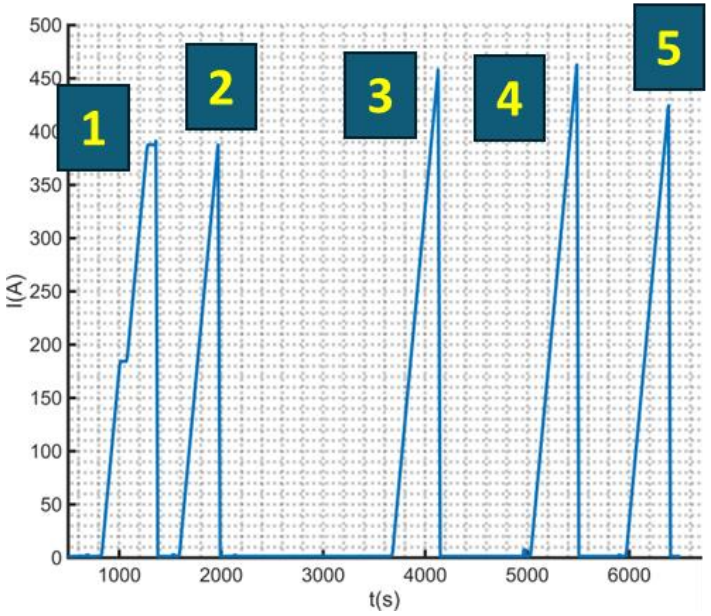
- An innovative solution was found to eliminate this
- Bring the leads out at the midplane (as shown)
- Considered clever at that time but may be the source of the problem (not all innovations work)
- This required a splice at pole (a high field region)
- Such a splice was never made before at BNL with the 6-around-1 cable in direct wind magnets

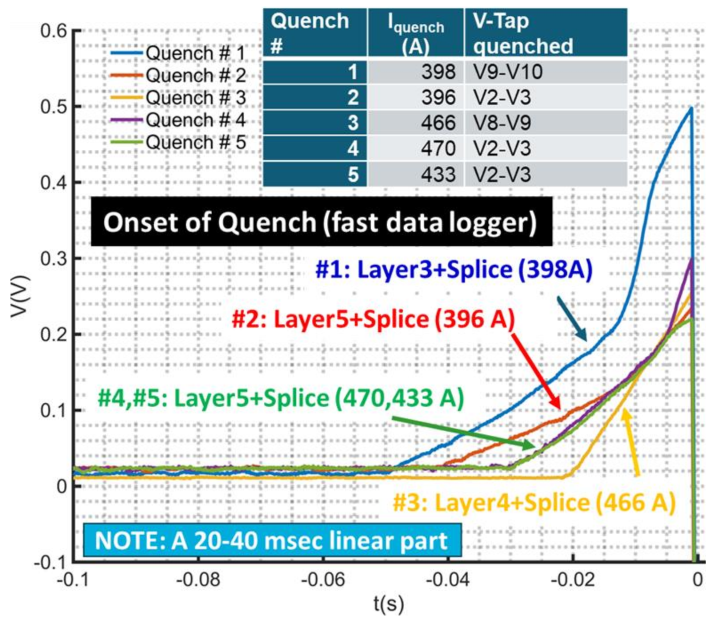


Phase II configuration

Testing of the Intermediate 6-layer Optimum Integral Dipole







- **Magnet reached only ~70% of the short sample.**
- **Quench location was distributed, with all in the outer four layers where the new splice was used to save radial space (inner two ok).**
- **Limited cooling (1st test run in <2 hours, and subsequent runs with ~20 minutes or less wait) didn't help.**

Revised Plan

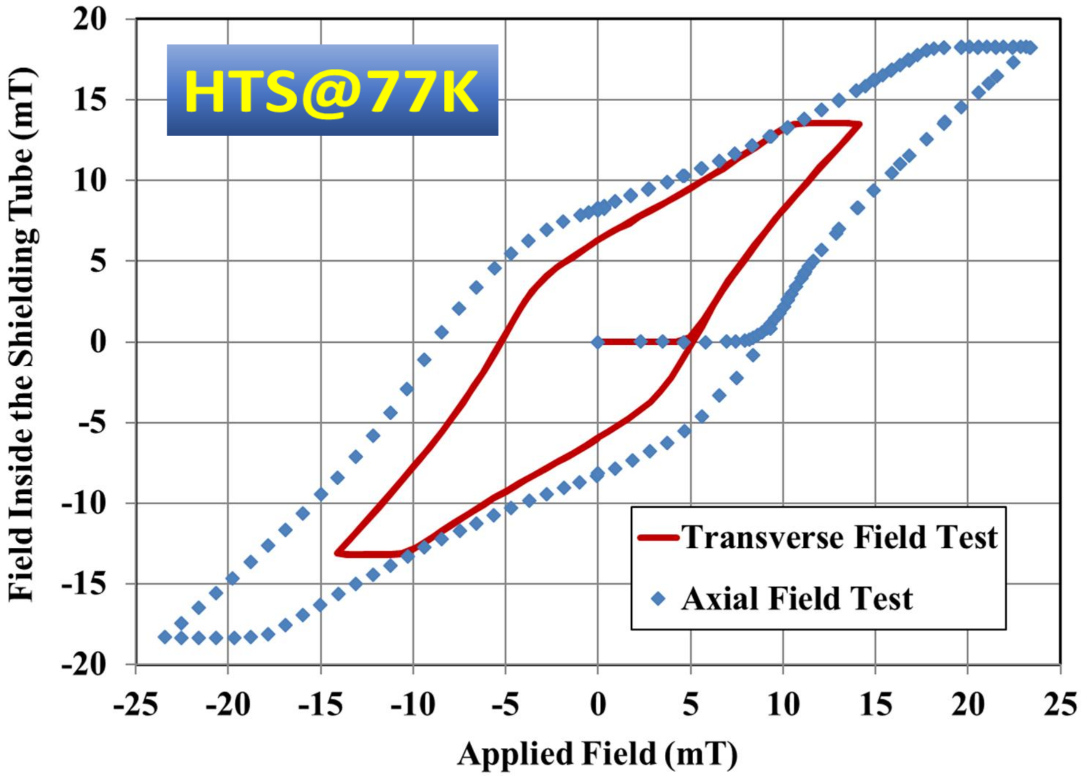
- Original proposal has two coils with 6 and 4 layers on the two separate SS tubes (intermediate tube for stress management)
- Tube to wind outer coil is already procured
- Wind six instead of four layers for the outer coil, with no splice at the pole (go back to the original Phase I configuration of B0ApF that worked well)
- Integrate two coils, as planned, and energize inner and outer with two separate power supplies
- A successful test of the outer coil with 6 layers will demonstrate the technology. This test will also indicate that the design may be suitable for B1ApF (last slide)
- Reduced current in the inner coil with more layers in outer should allow us to reach the original target

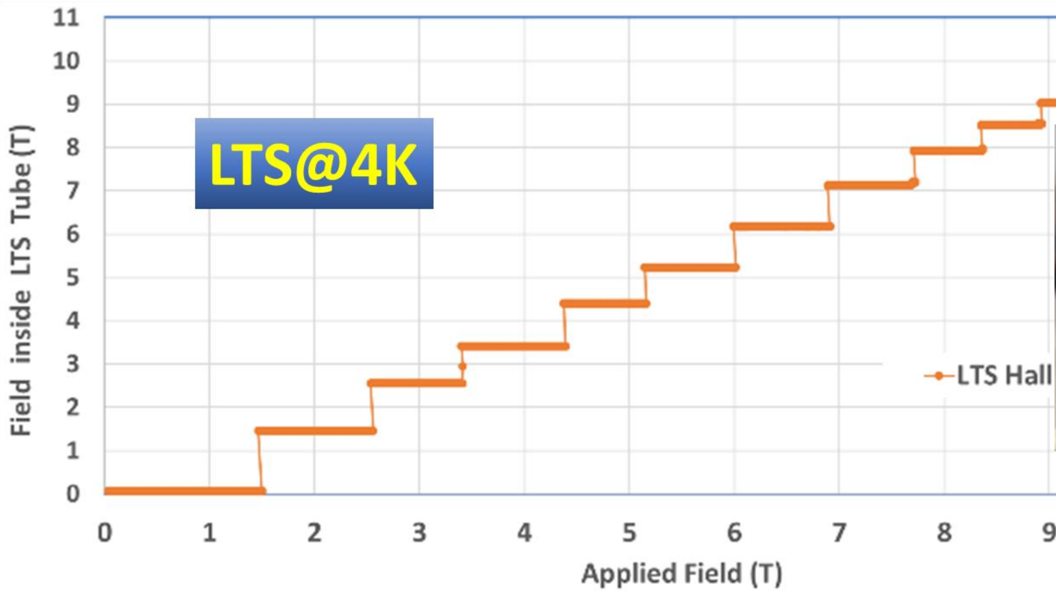
Demonstration of Superconducting Shielding

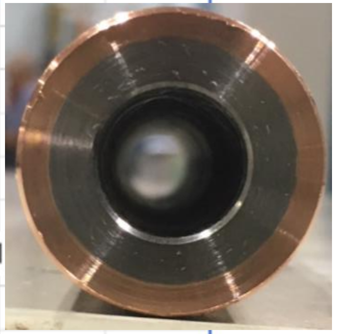
(was not part of this STTR originally. It was part of a previous Phase I SBIR for EIC. Then final test couldn't be carried as Phase II was not funded despite good review)

Superconducting Shielding for e-beam in EIC Magnets

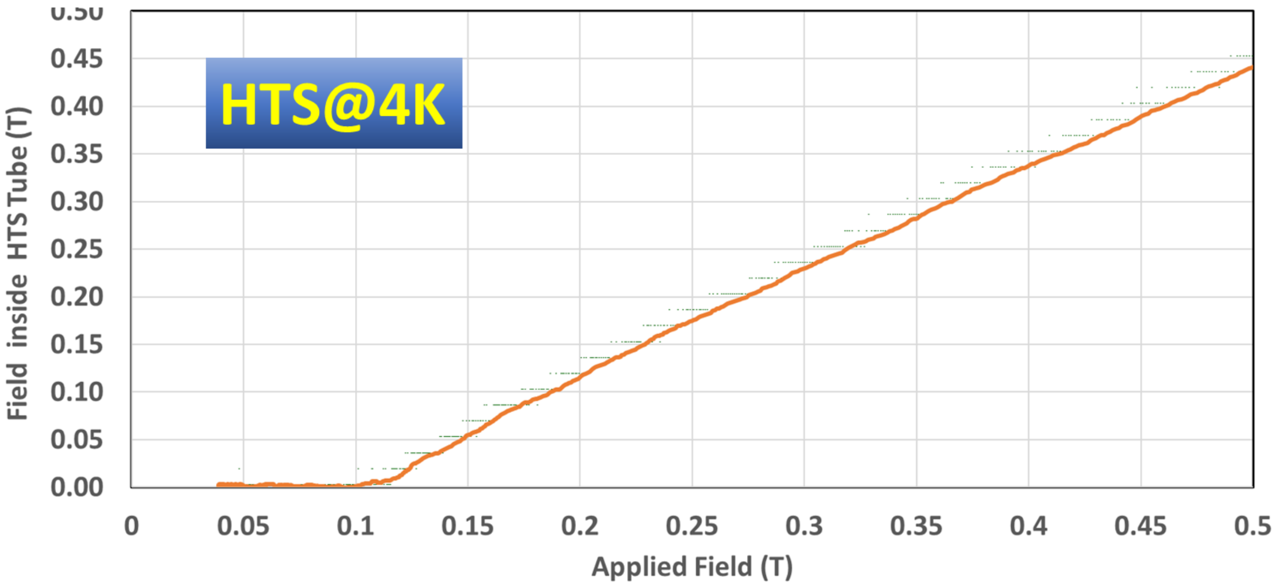
Test Results from a Previous PBL/BNL Phase I SBIR for EIC





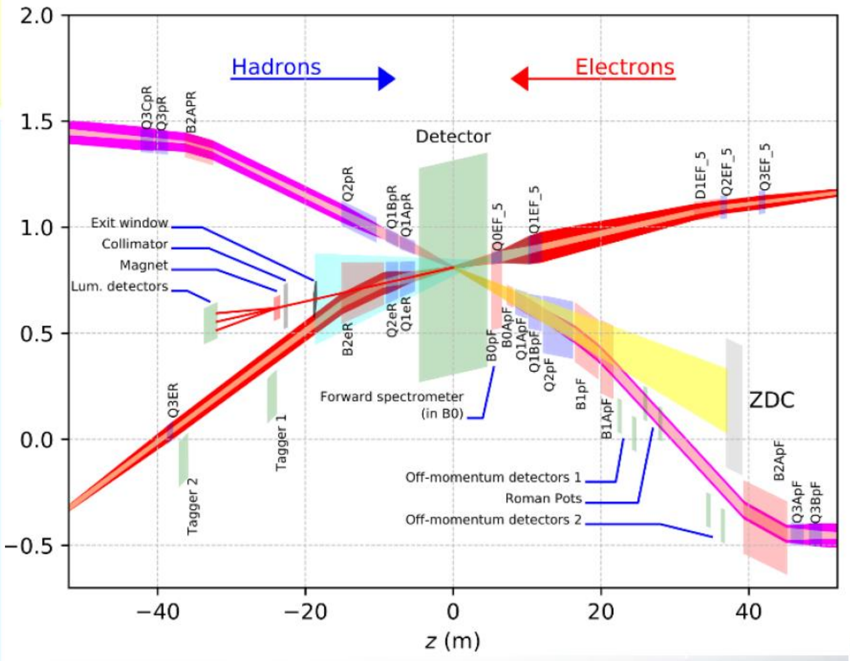


NbTi from Luvata



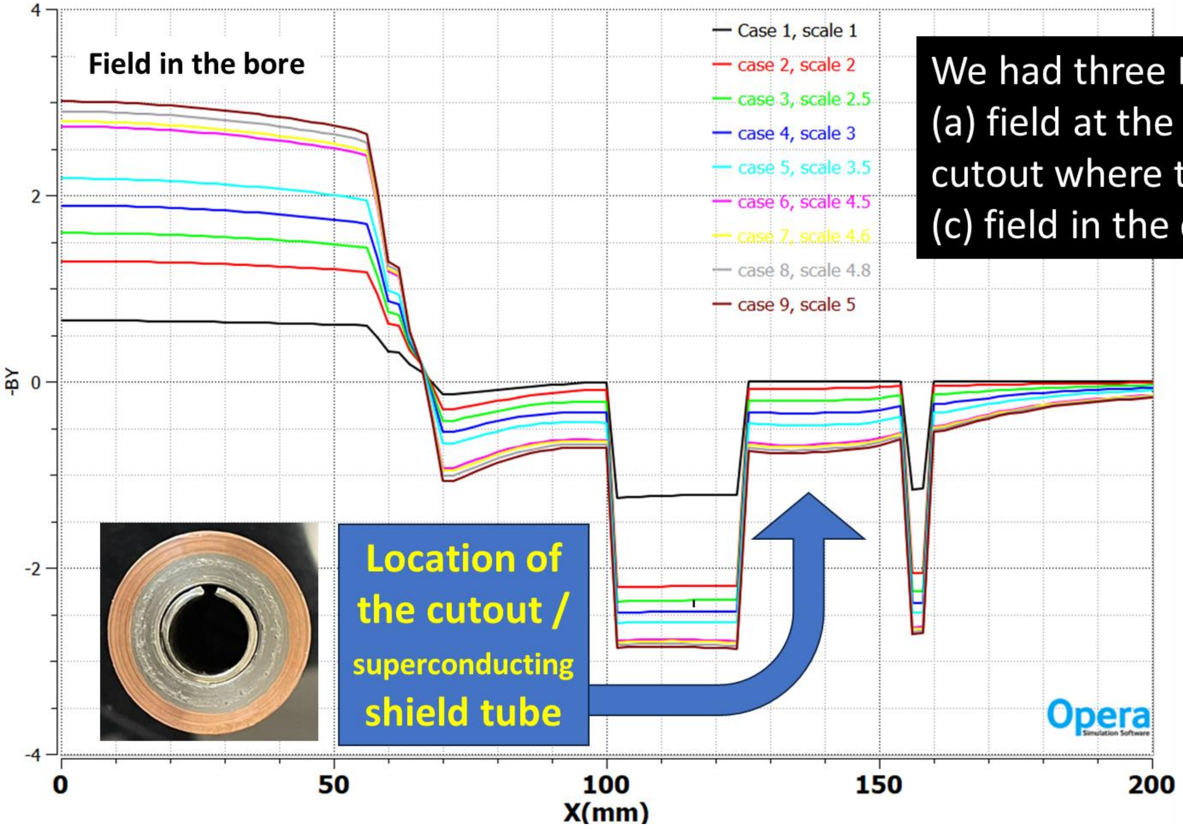
Test of Superconducting Shielding for EIC Magnets

A major challenge in EIC IR: e-beam traverse 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

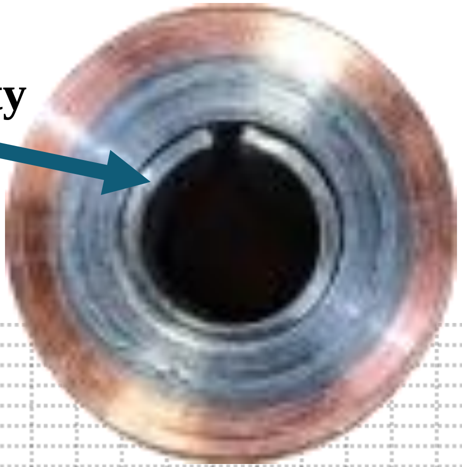
Field from the high field magnets for ion beams must be shielded on the path of e-beam



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).

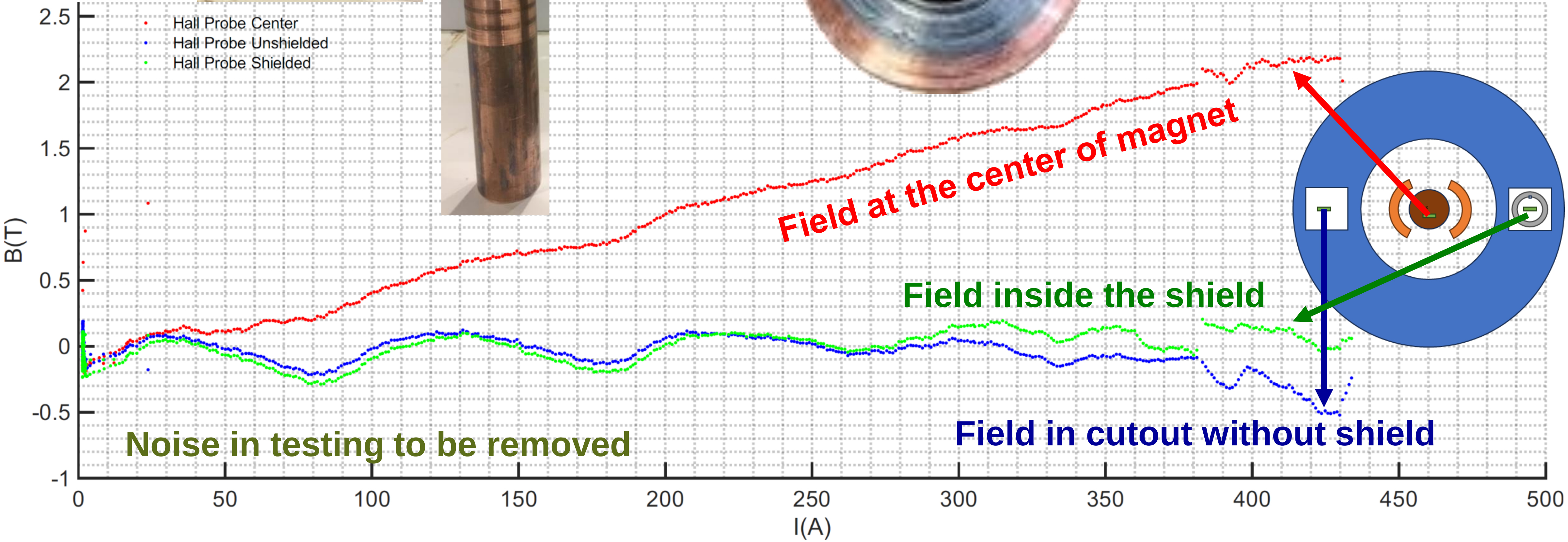
Demonstration of Superconducting Shielding (with Additional A4K)

NbTi tube from Luvata



High permeability *A4K to shield persistent field

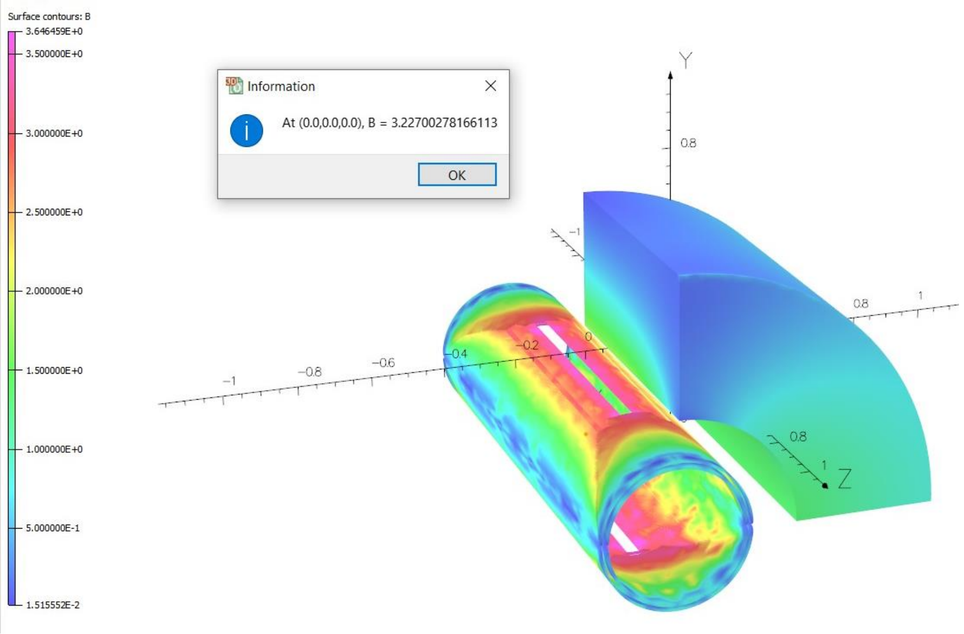
Superconducting shielding works

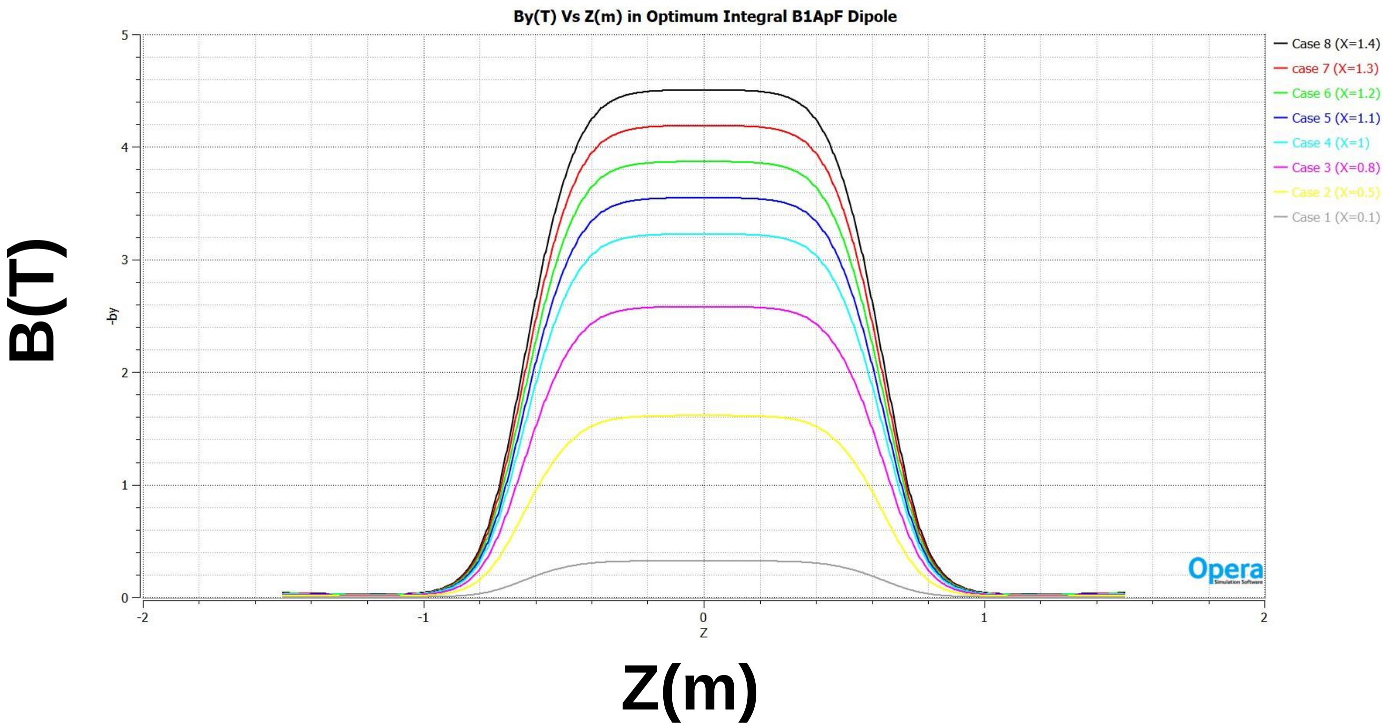


*A4K: High permeability Amumetal 4K (A4K) from Amuneal Manufacturing Corporation

Investigation of Optimum Integral Dipole in B1ApF

- One of the task of this STTR is to investigate optimum integral design in other EIC magnets where it has potential to provide benefit
- B1ApF is a relatively short dipole (1.6 m) with large aperture (370 mm)
- Current design of 3^{+} T B1ApF is based on the cable magnet
- Initial analysis shows that a 6-layer optimum integral dipole should work





Summary

- *Optimum Integral Design* minimizes the loss in magnetic length due to the ends. Benefits are significant in short magnets (some are needed in EIC).
- PBL/BNL is demonstrating this design as a part of DoE Phase I and Phase II STTR.
- Essential principles of the *Optimum Integral Design* have been demonstrated in the magnetic models and in the actual magnets built and tested so far.
- Phase I produced a 1.7 T, 114 mm dipole, with higher integral field, as predicted.
- Phase II, year 1, had 6 layers. It also had the demo of superconducting shielding.
- A setback occurred in the outer 4 layers, most likely due to a change in the splice geometry. This change is not part of the *Optimum Integral Design*, and it will be eliminated in the next layers. It should not impact the final outcome of the program.
- Superconducting shielding experiment produced promising test results for e-beam.

Extra Slides

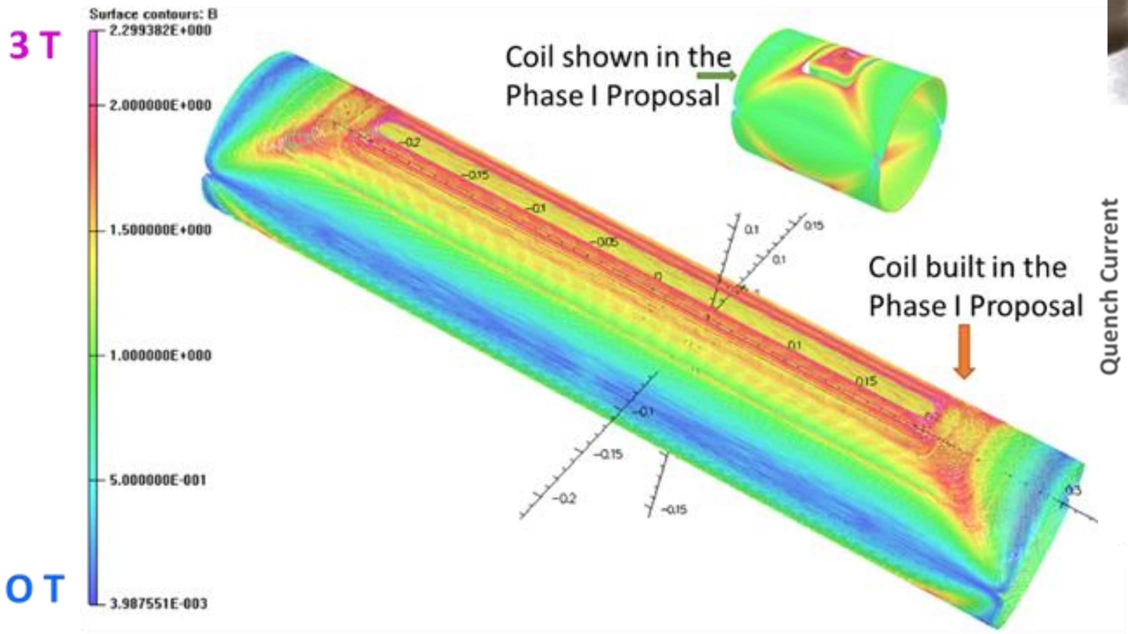
PBL SBIR/STTR Awards with BNL

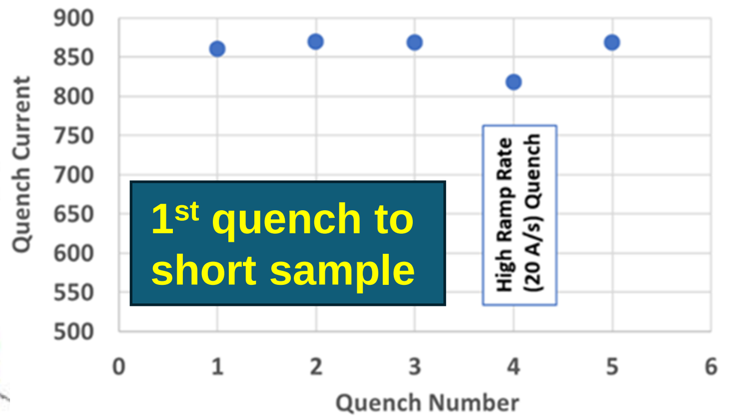
1. A 6-D Muon Cooling System Using Achromat Bends and the Design, Fabrication and Test of a Prototype High Temperature (HTS) Solenoid for the System. DE-FG02-07ER84855 August 2008 $850,000
2. Study of a Final Cooling Scheme for a Muon Collider Utilizing High Field Solenoids. DE-FG02-08ER85037 June 2008 $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. DE-SC0021578 February 2021 $200,000
18. A New Medium Field Superconducting Magnet for the EIC. DE-SC0021578 April 2022 $1,1500,000

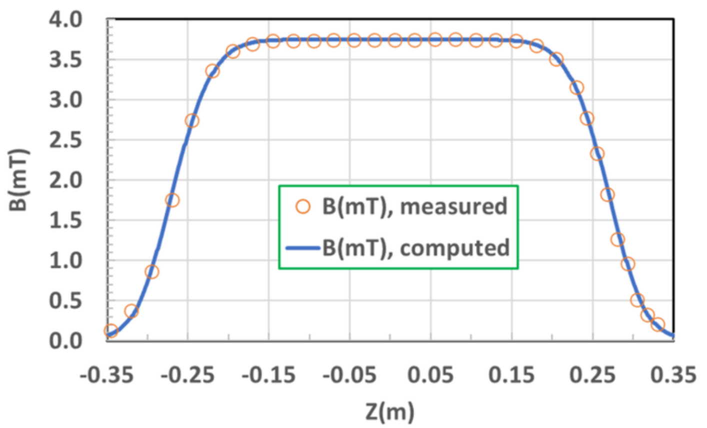
Summary of Phase I Goals and Performance

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





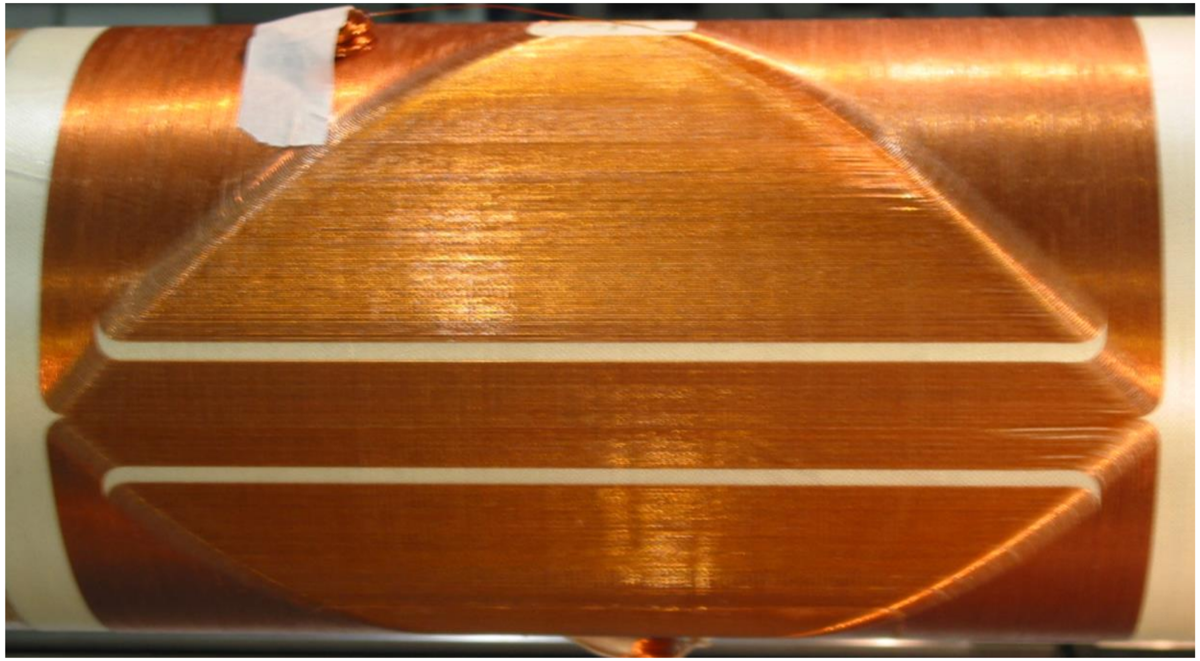


- ✓ **Succeeded in demonstrating ~1.7 T dipole in Phase I**
- ✓ **Demonstrated: Larger integral field of optimum design**
- ✓ **Bonus: Two full-length coils good for use in Phase II**

First demo of the optimum integral dipole concept

Examples of the Magnet Designs based on the Optimum Integral Approach

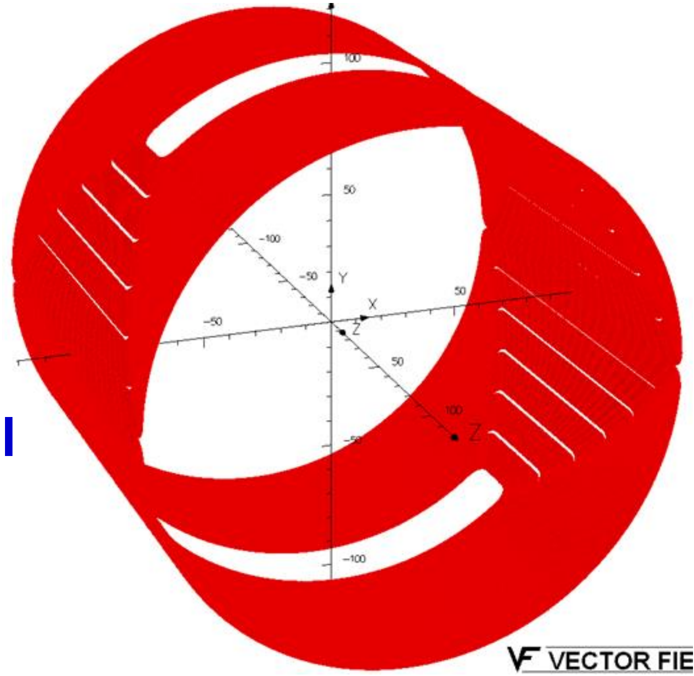
Note that the midplane turns span almost the full end-to-end length and the coil has a high fill factor



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

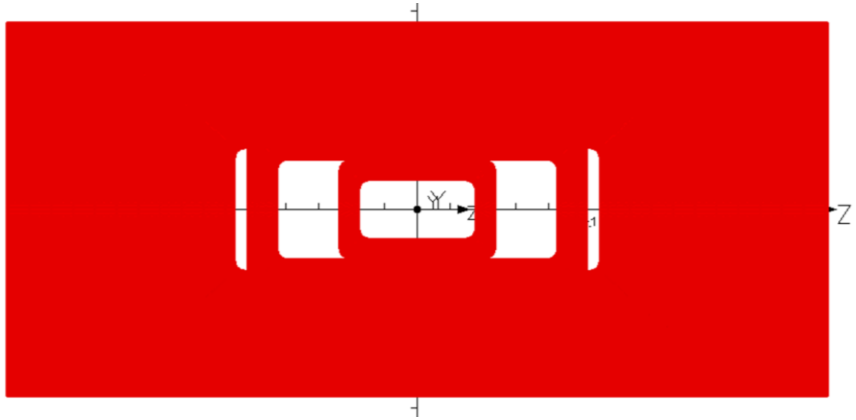
Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.0082 @ 25 A	0.4	0.8	-4.7	4.1	5.3	2.4

An Optimum Integral Dipole Design with Coil Length Less than the Coil Diameter



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



A Dipole Optimized with End Spacers Only