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U.S. DEPARTMENT OF
ENERGY

PBL

A Novel, Medium-field Optimum Integral Dipole

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Overview

- **Optimum Integral Design – Why?, What?**
- **PBL/BNL STTR dipole (R&D not part of EIC project):**
  - ➢ **3.8 T central field, 4.2 T peak field, 114 mm aperture**
- **Design, construction and test results to-date**
- **Next step**
- **Summary**

For reference, RHIC dipole: 3.45 T, 80 mm

STTR: Small Business Technology Transfer

Challenges with Short Dipole Magnets

Coil length to coil diameter ratio in some magnets:

- 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

RHIC Coil End

Coil id: 80 mm
Coil Ends: ~160 mm
Coil Length: ~9.46 m
L/a > 100

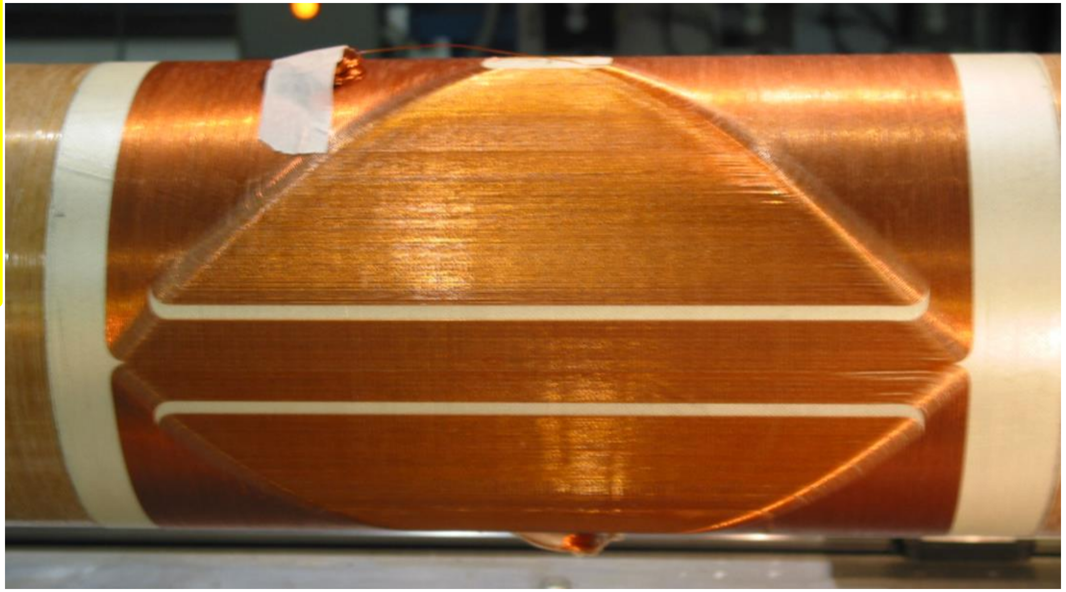
- Typical mechanical length of each coil end: ~ two coil diameter
- Loss in integral field due to ends starts becoming significant when the total coil length (*L*) < 10 X coil diameter (*a*)

First Use of the Optimum Integral Design: AGS Corrector Dipole

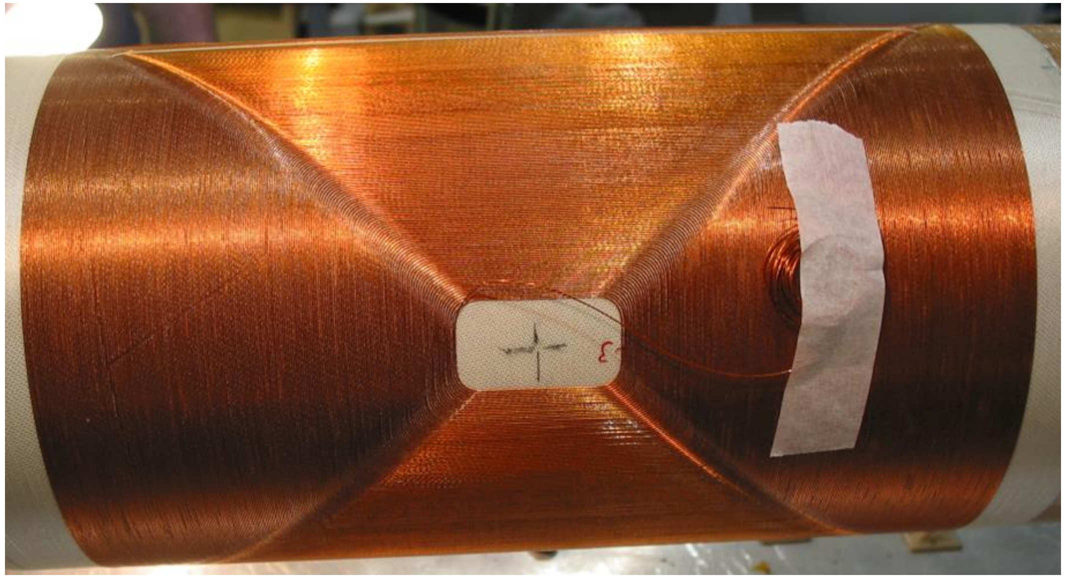
Coil Length = 182.8 mm
Coil Diameter = 300 mm

Coil length < Coil diameter

ASC/04



Note: Almost full use of the available azimuthal and axial space by the superconductor (*very 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 not measured and verified**

Conventional Design Approach

A two-step process:

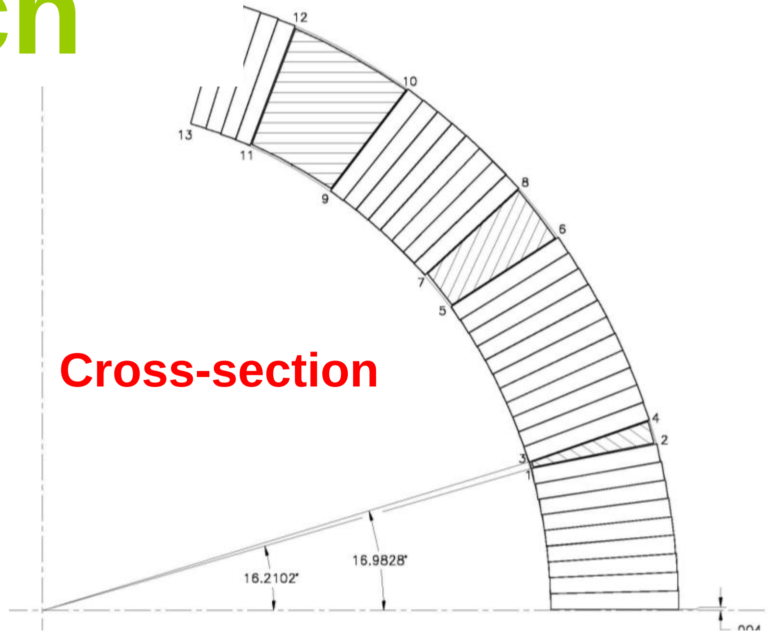
Step 1: Optimize coil cross-section to obtain cosine theta like distribution:

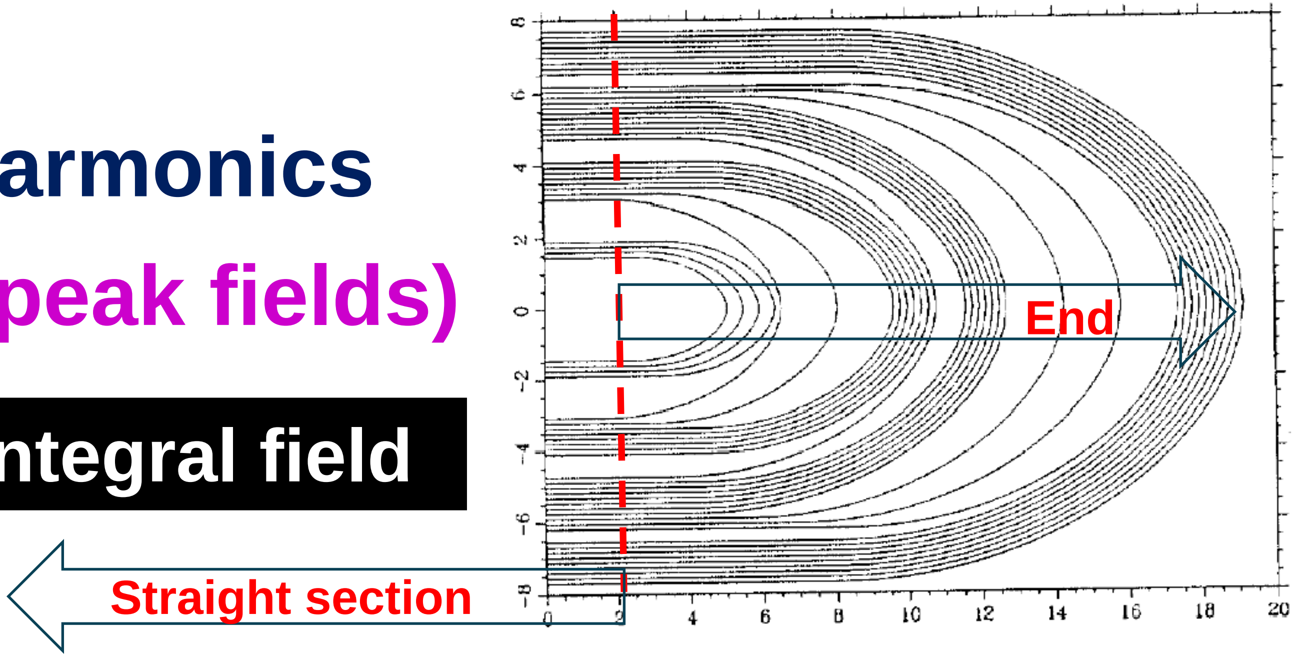
$$I(\theta)\ =\ I_o\ .\ \cos(n\theta)$$

Step 2: Optimized ends for harmonics

(also, optimize both for low peak fields)

Each step limits the maximum integral field





Optimum Integral Design Approach

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

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

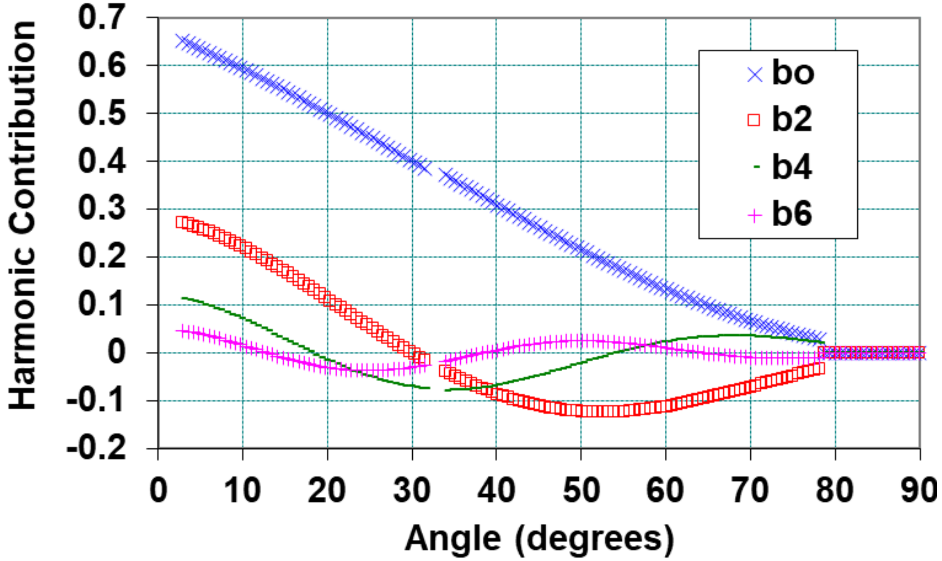
For no wedges or end spacer, function varies linearly ==> Modulate it to cos theta

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

Essentially no loss due to magnet ends.

Integral harmonics:

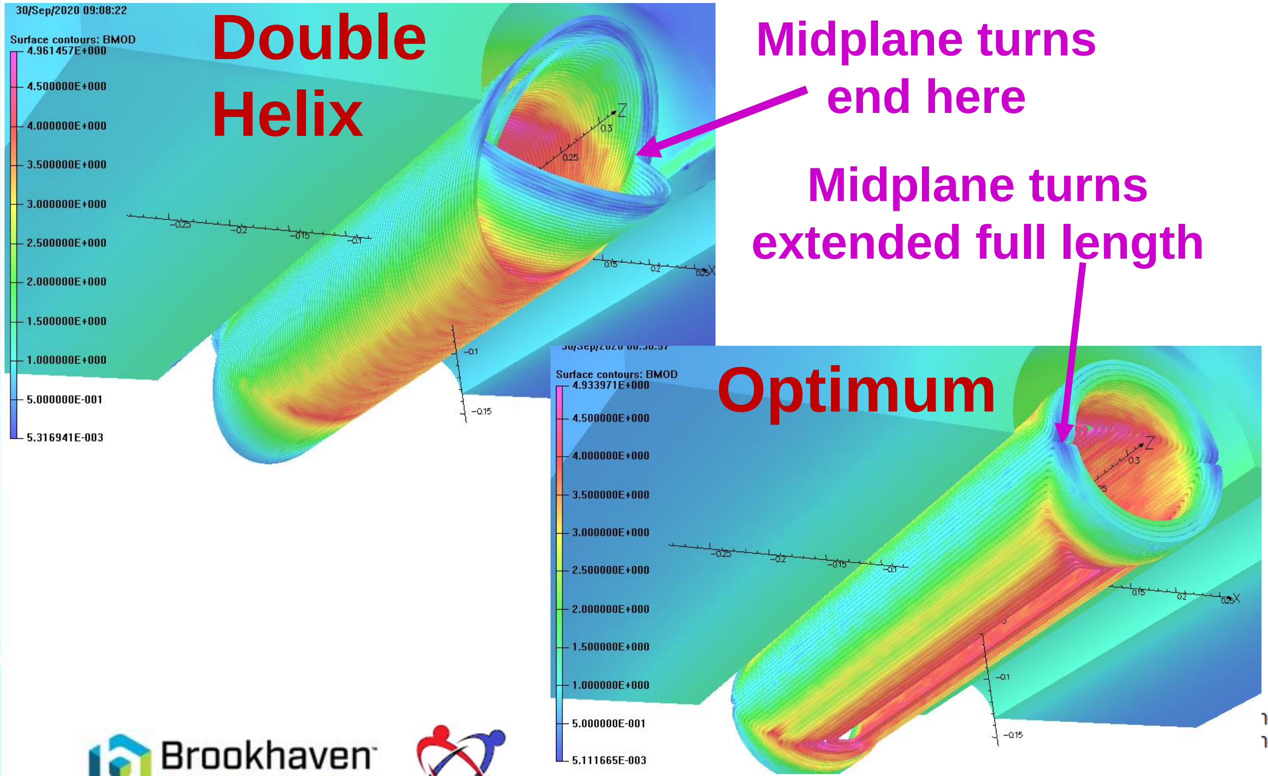
$$B_n = 10^4\left(\frac{R_0}{a}\right)^n .\,L\,.cos\left[(n+1)\,\phi\right]$$



(b_2 is sextupole)

Optimum Integral Design STTR

- **B0Apf dipole for EIC needs a coil ID of 110-120 mm and a length of 600 mm. The design field is ~3.3 T. This is ideally suited for a high impact SBIR/STTR.**
- **The optimum integral design is not part of the EIC program. It is part of STTR innovative R&D, to be operated independently of the EIC magnet work.**



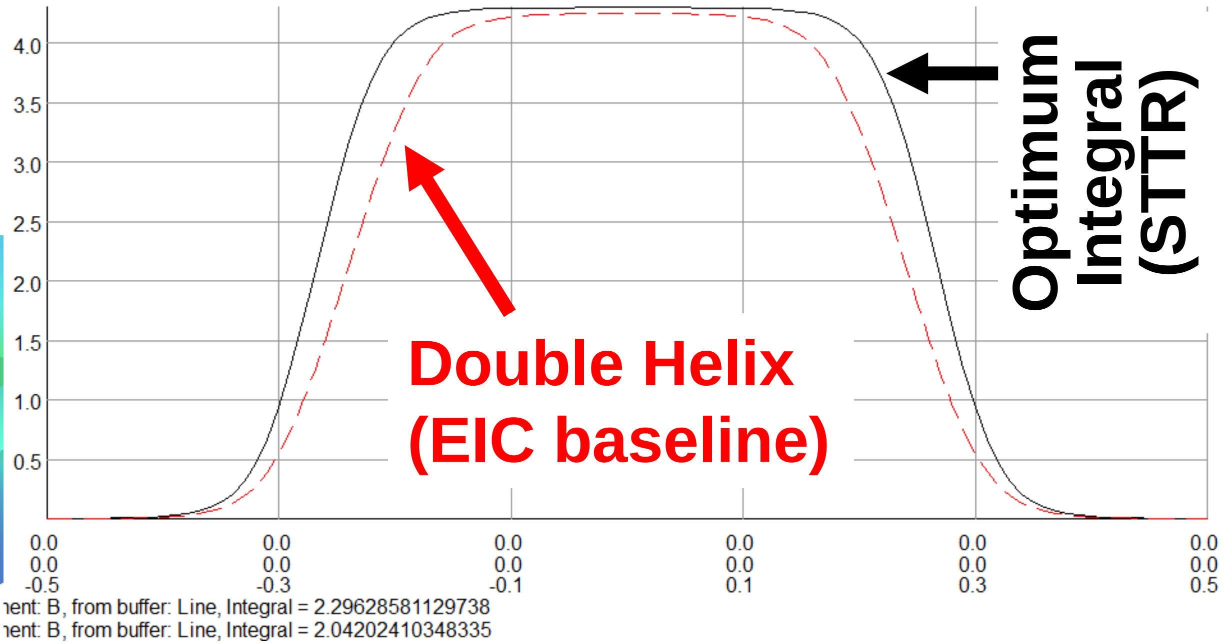
Double Helix

Midplane turns end here

Midplane turns extended full length

Optimum

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

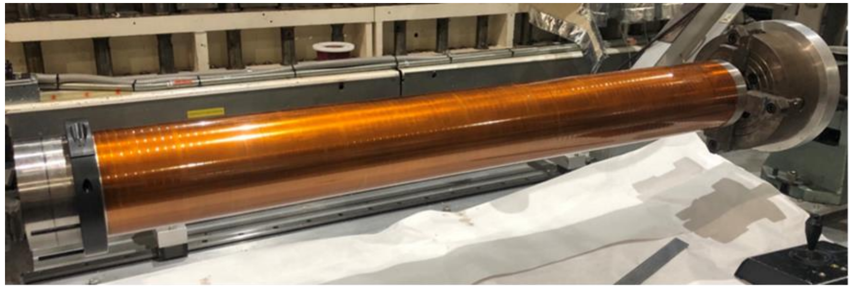


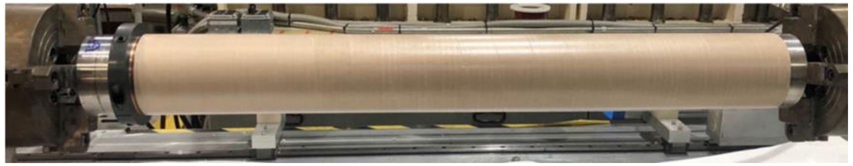
Optimum Integral (STTR)

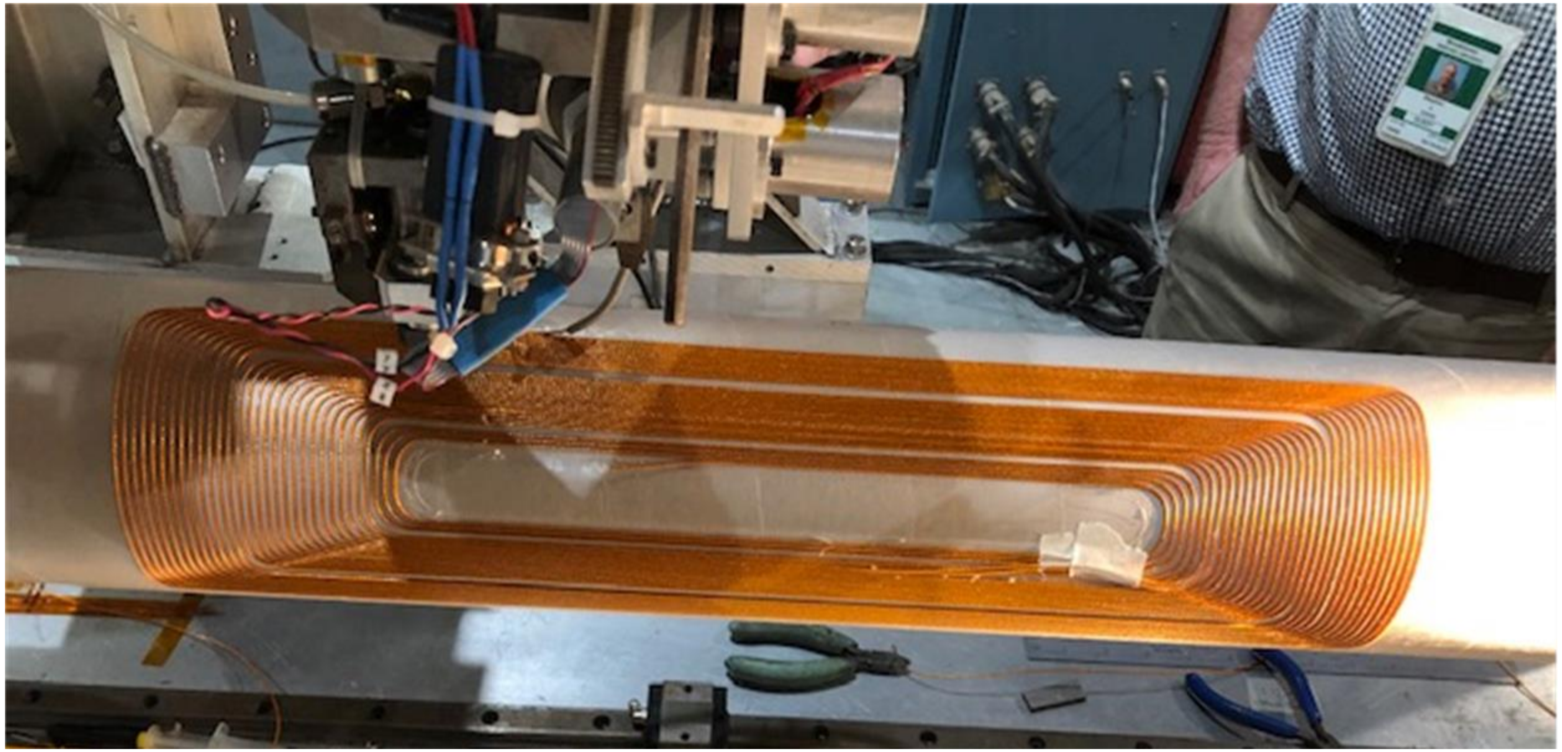
Double Helix (EIC baseline)

Key for making the ambitious magnet in the budget of a STTR program – Direct Wind Technology @BNL

- **Wire is laid directly on the tube and bonded with ultrasound onto a substrate (followed by a few other important 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**



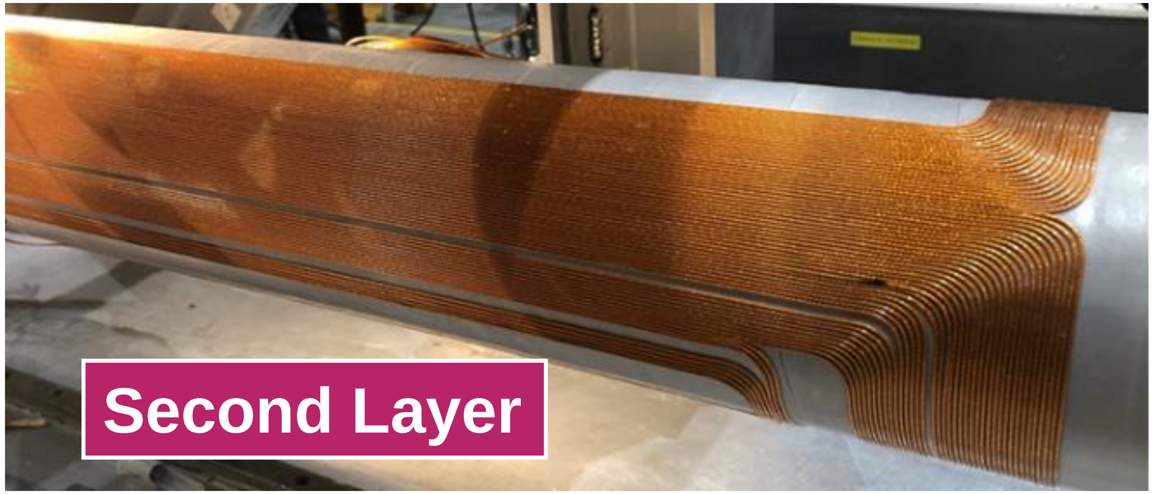


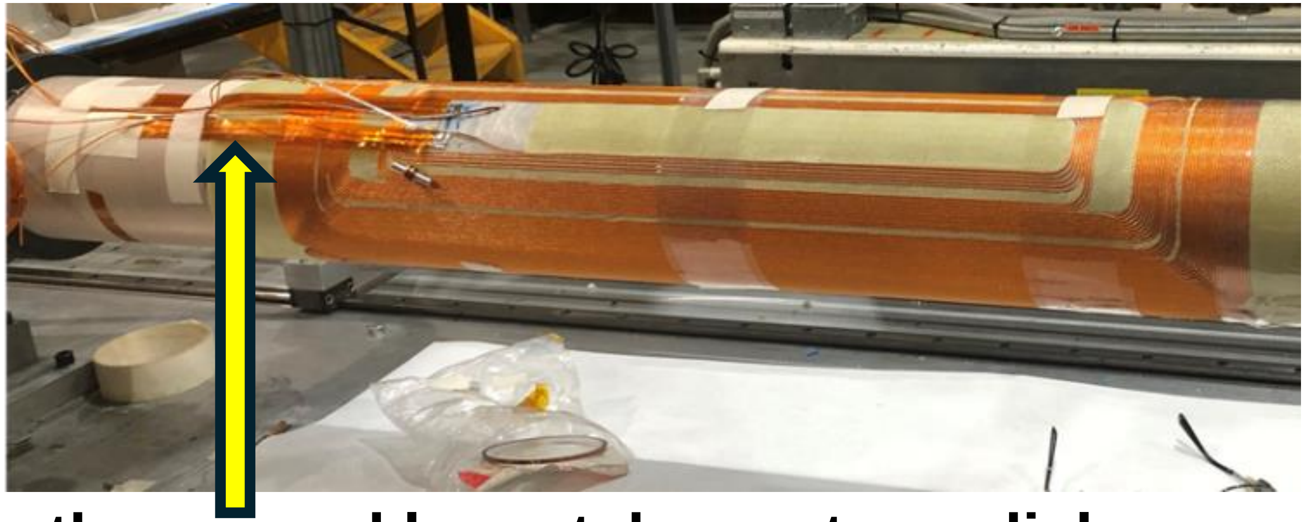


Optimum Integral Dipole - Phase I Coil (double layer)

Midplane turns extended full length

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



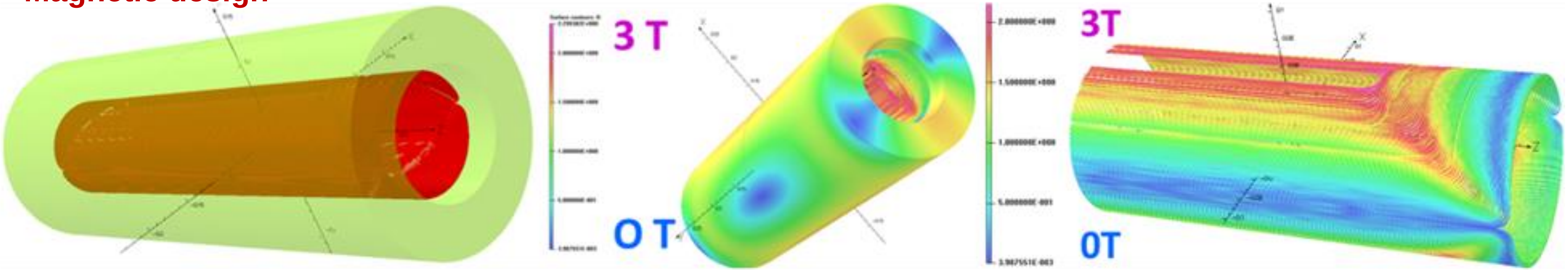


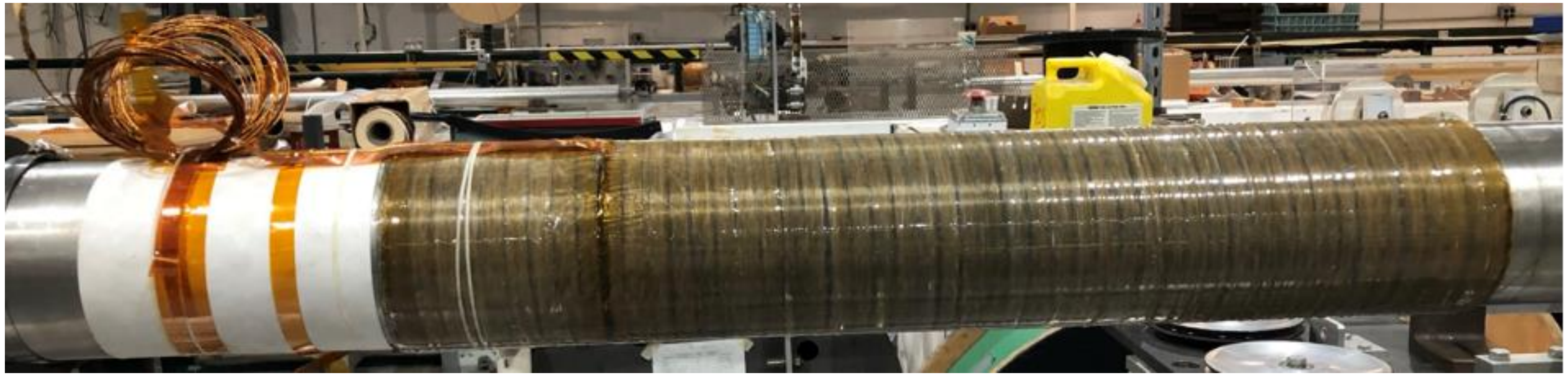
External leads out over the second layer takes extra radial space

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



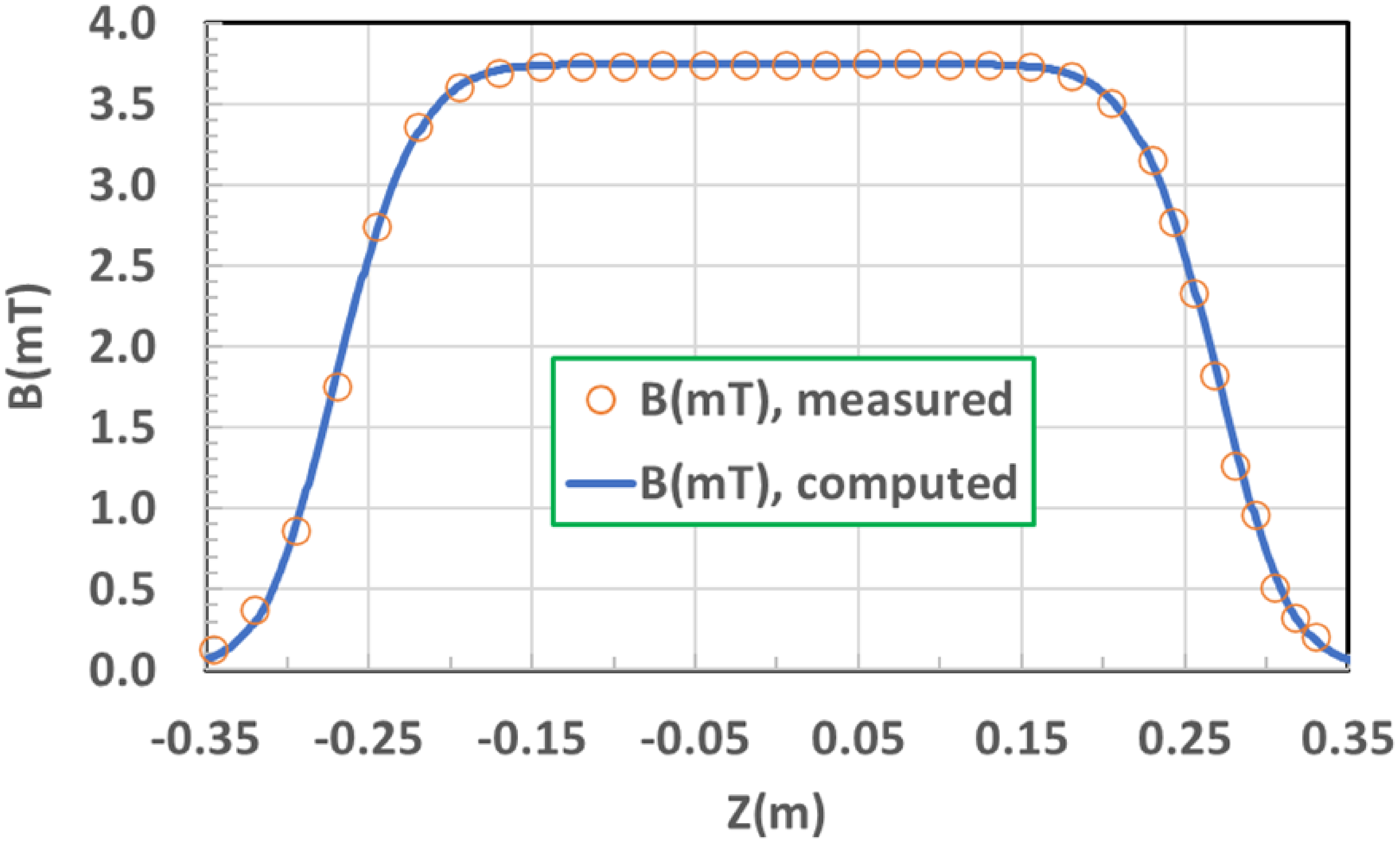


Double-layer tension wrapped and cured

Coil in yoke, ready for test

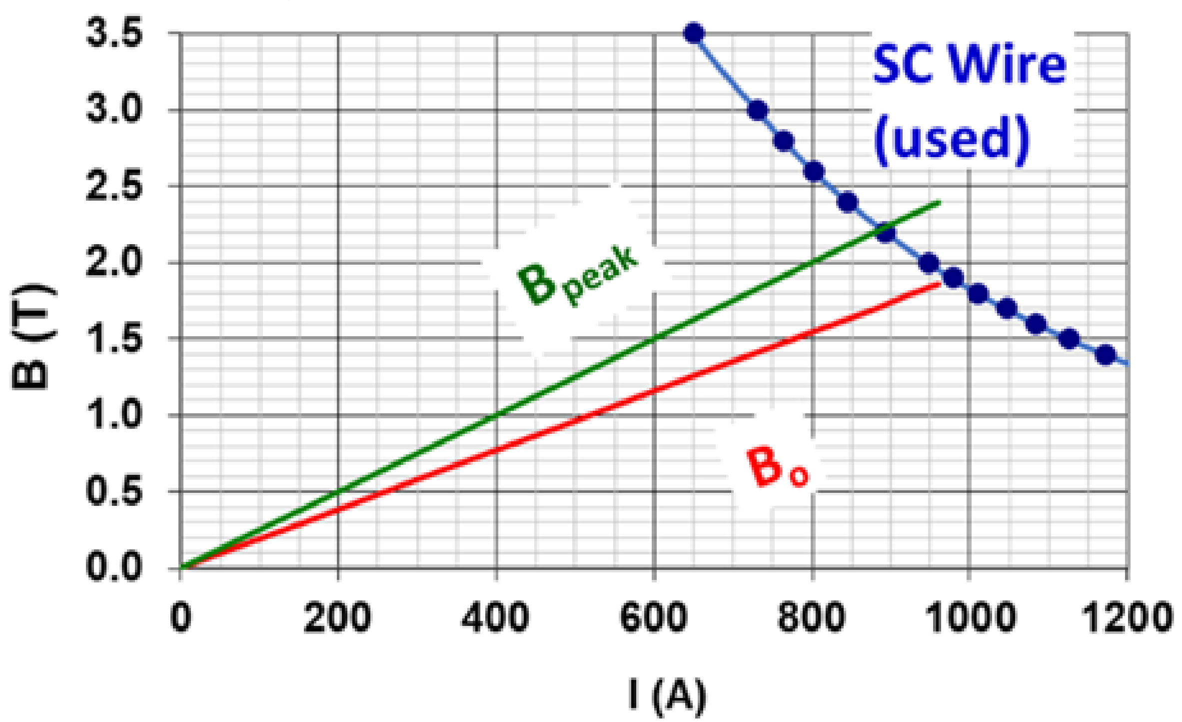
Question: Will optimum integral design extend the magnetic length?

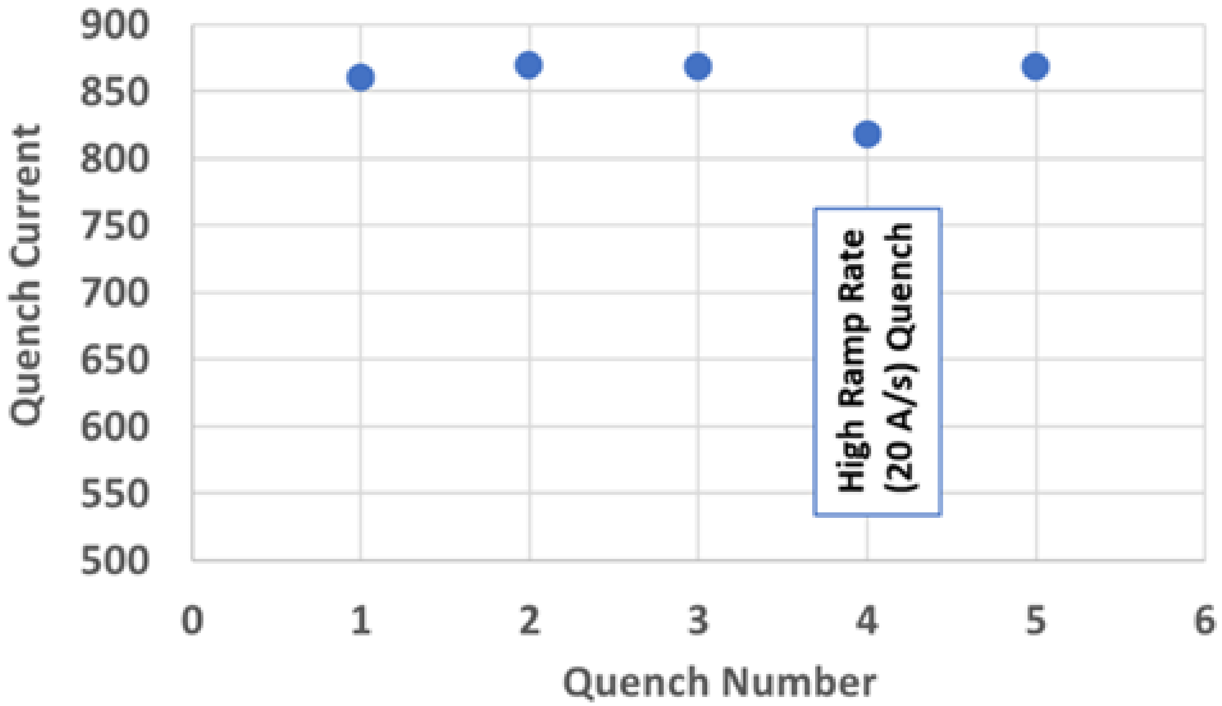
Major motivation of the optimum integral design demonstrated



Answer: Yes. Good agreement between calculations & measurements

Question: 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 (meets computed SS with no quench)

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

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

Final Goal:

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

For reference, RHIC dipole: 3.45 T, 80 mm

Intermediate Goal (~1 year):

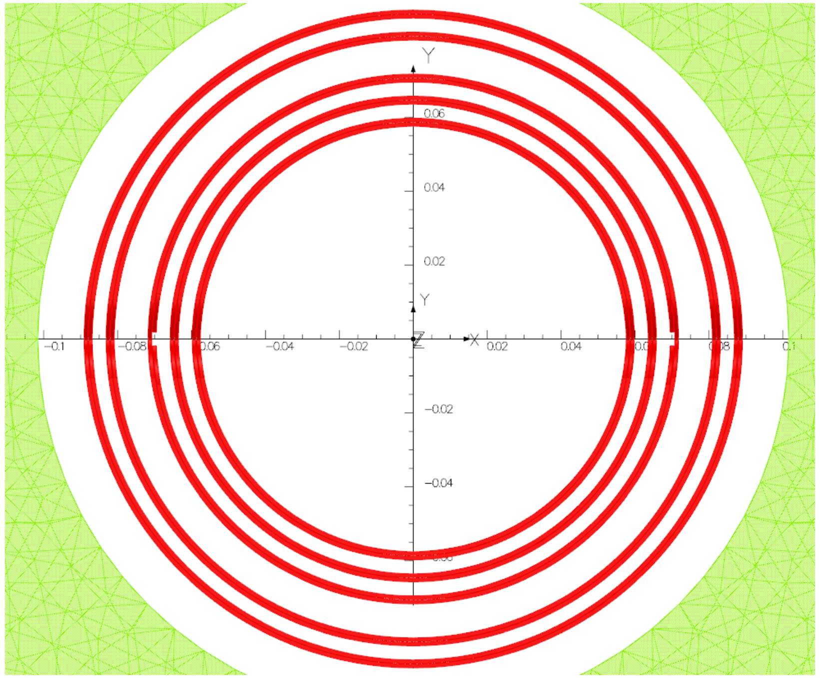
- **6 layers, ~2.9 T, ~3.5 T peak field, 114 mm**

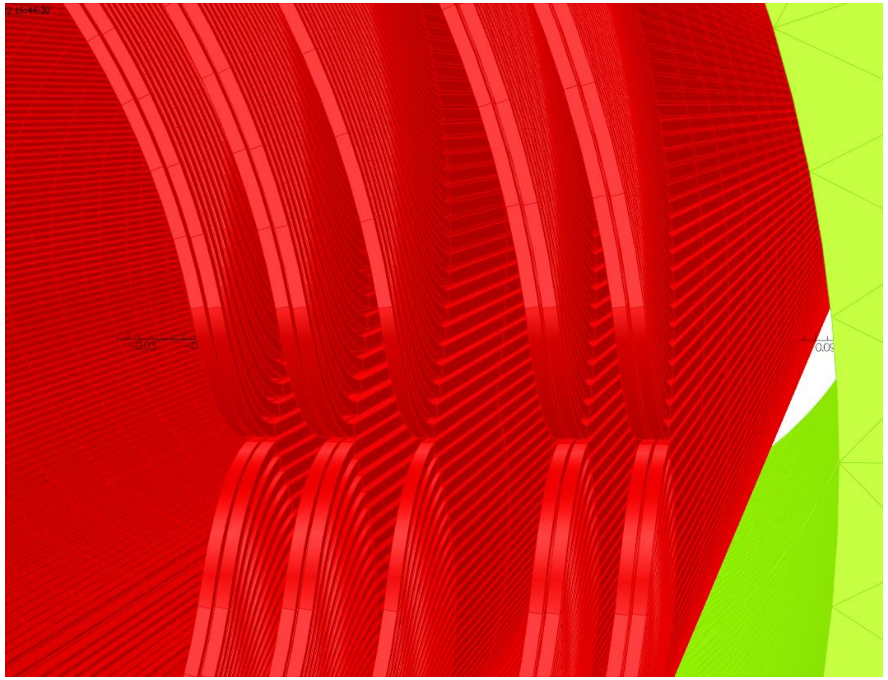
Demonstration of good field quality (warm):

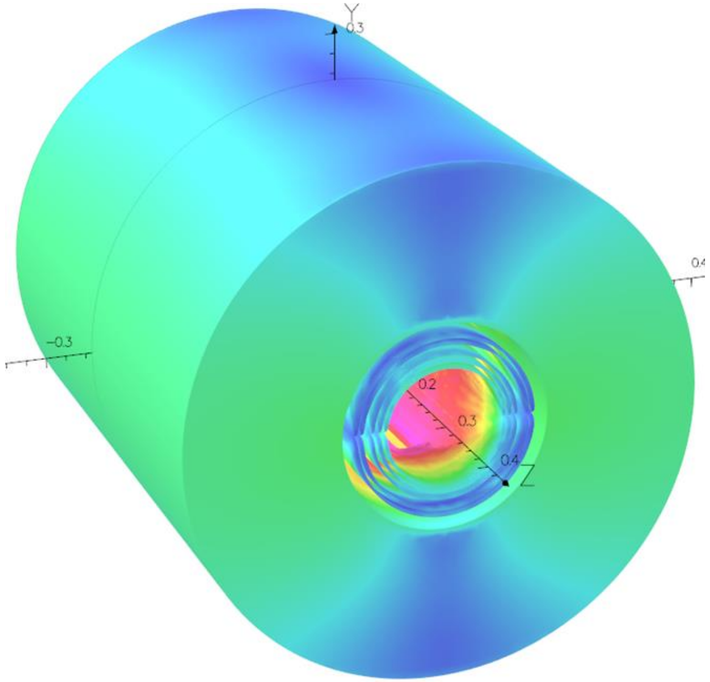
- **Validation of the optimum design and of the 3-D design software**

OPERA3d Models of the Phase II Dipole

The design is optimized for low field harmonics with the original ***OptIntegral*** *code which also creates a file for OPERA*



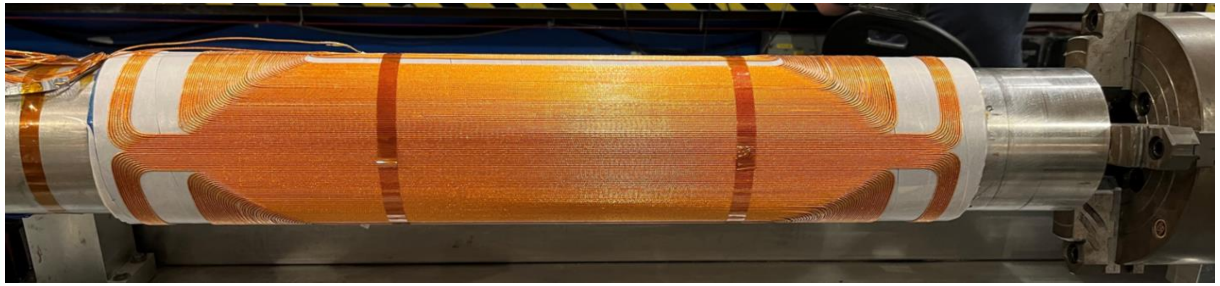


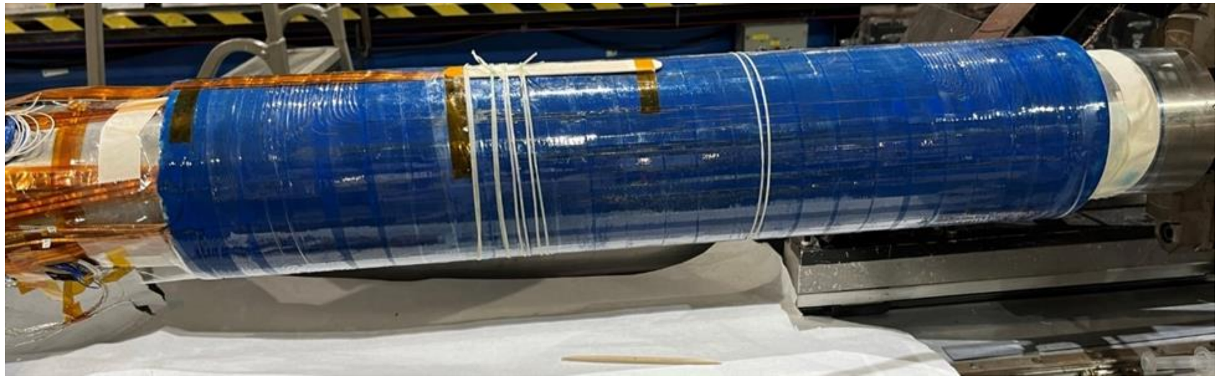


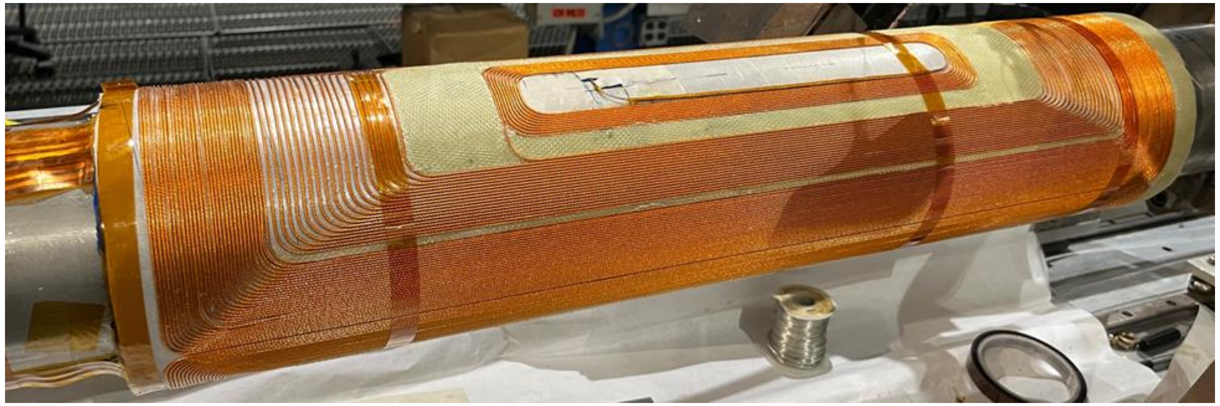
Intermediate Task: Build and test inner three double layer in a structure

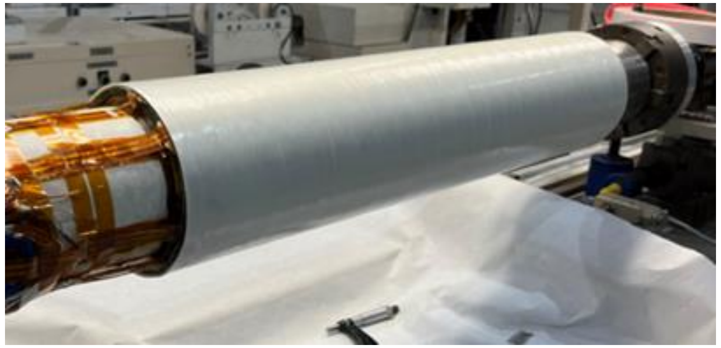
- **Final Task: Build and test five double layers (10 single layer)**

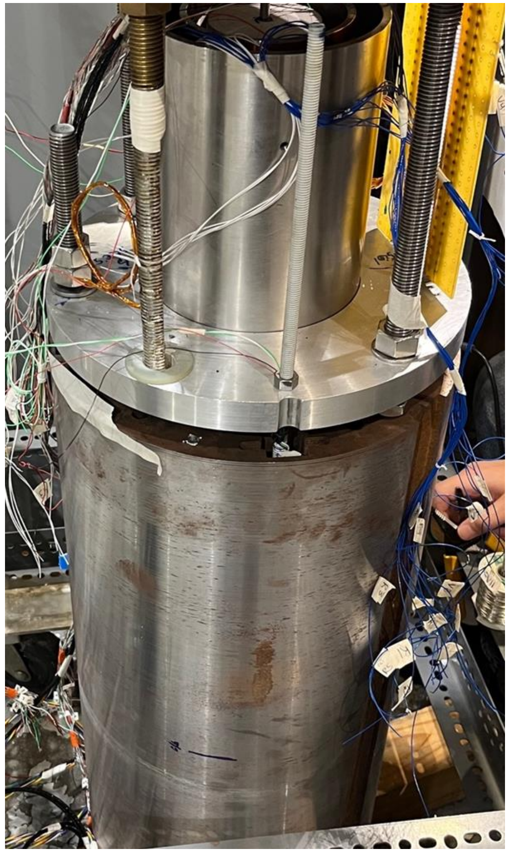
Coil Winding and Magnet Design and Construction

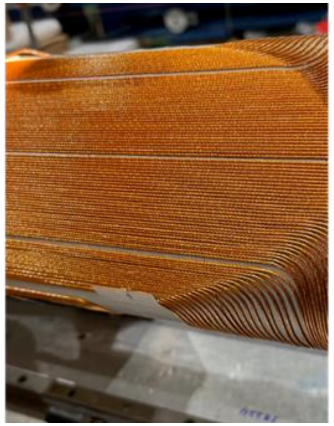


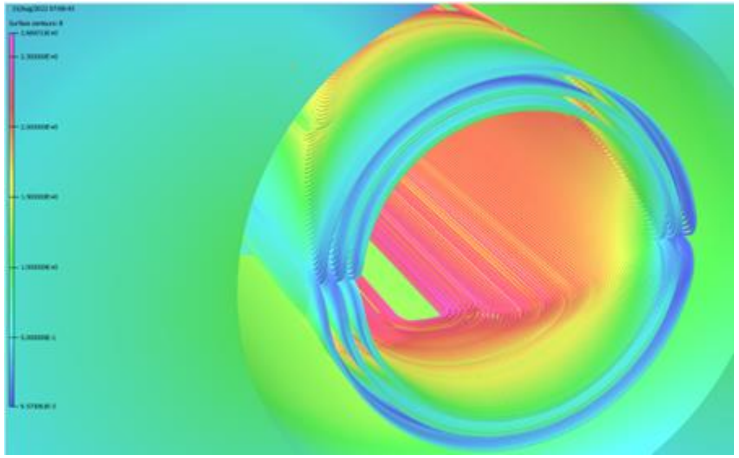












Field Quality Demonstration of the Design and of the Code

Warm testing of 6-layer design

Optimum Integral Dipole 6-layer Design		
ITF (NO Fe)	1.860	mT.meter/A

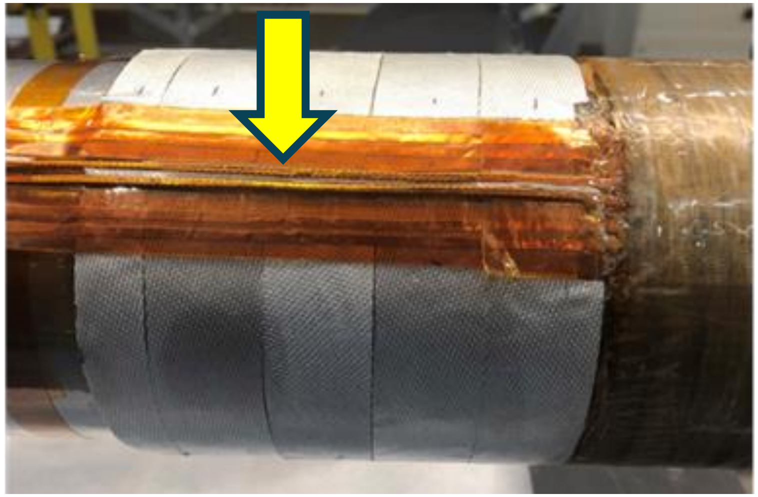
Measured Integral Harmonics@31mm

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

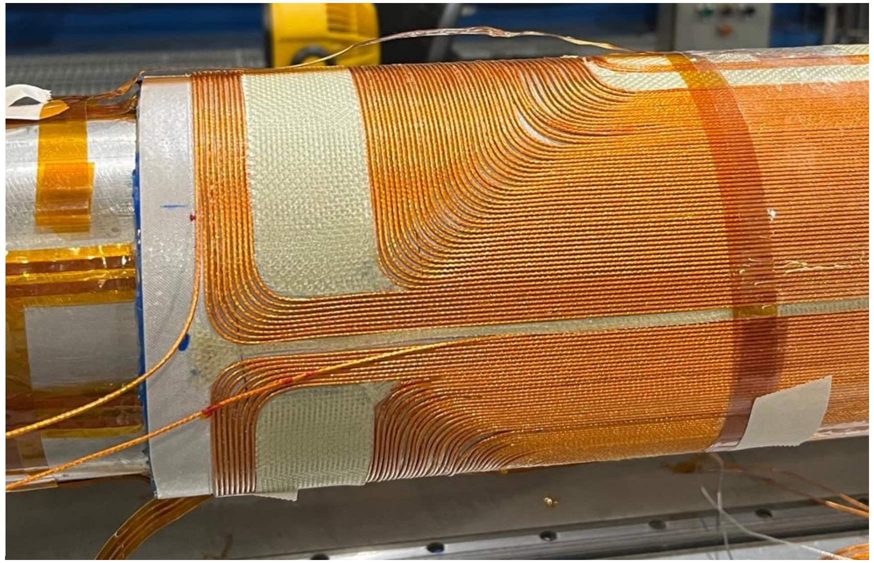
A Change in Design to Eliminate Radial Space Used by Leads

- **Phase I “Optimum Integral Design” used extra radial space for bringing leads out “over the coil” at the pole.**
- **This extra radial space is not required in the baseline “Serpentine Design” of EIC.**



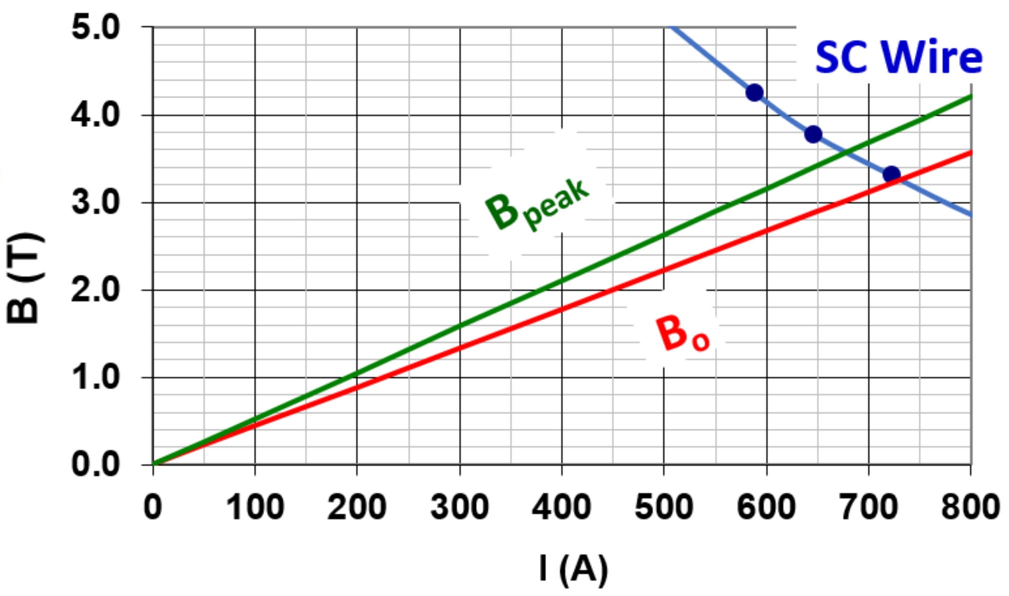
Phase I configuration

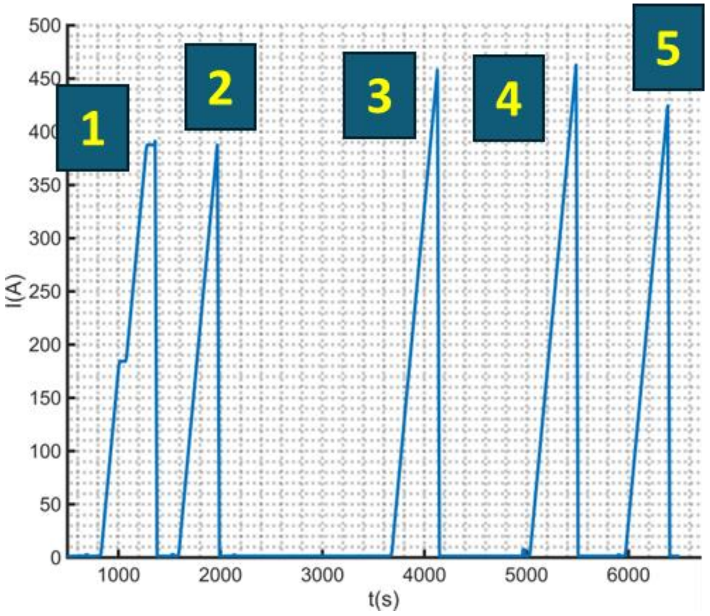
- **A solution was found to eliminate this. Bring the leads out at the midplane.**
- **However, for the present construction and tooling, this meant splice at pole (a high field region).**
- **Moreover, such a splice was never made before with the 6-around-1 cable in direct wind magnets.**

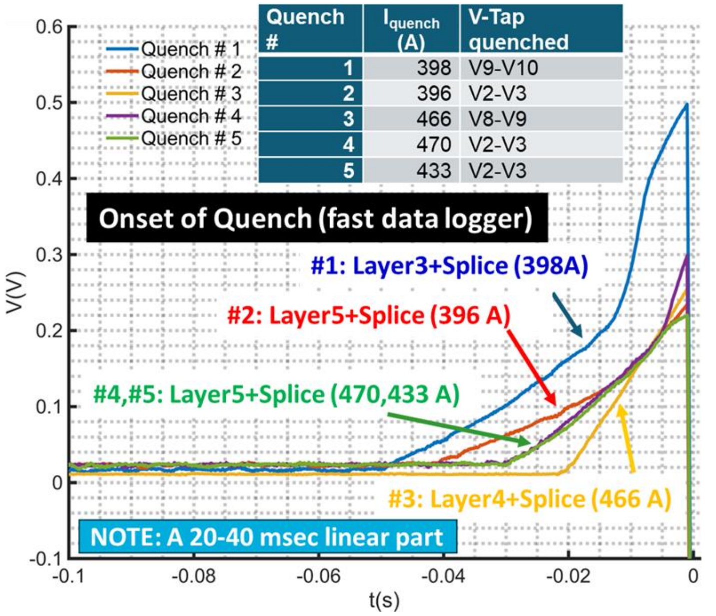


Phase II configuration

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

Onset of Quench (fast data logger)

#1: Layer3+Splice (398A)

#2: Layer5+Splice (396 A)

#4,#5: Layer5+Splice (470,433 A)

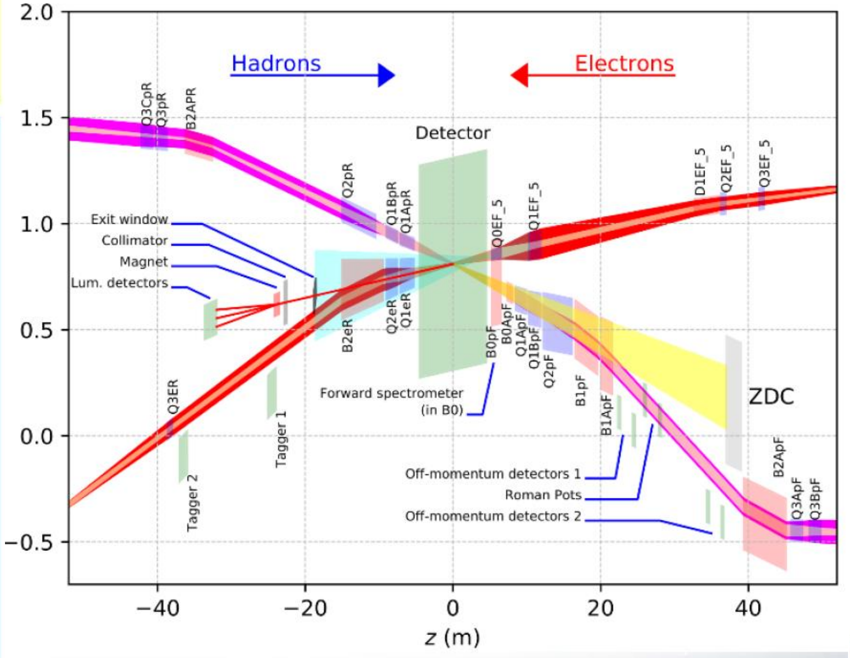
#3: Layer4+Splice (466 A)

NOTE: A 20-40 msec linear part

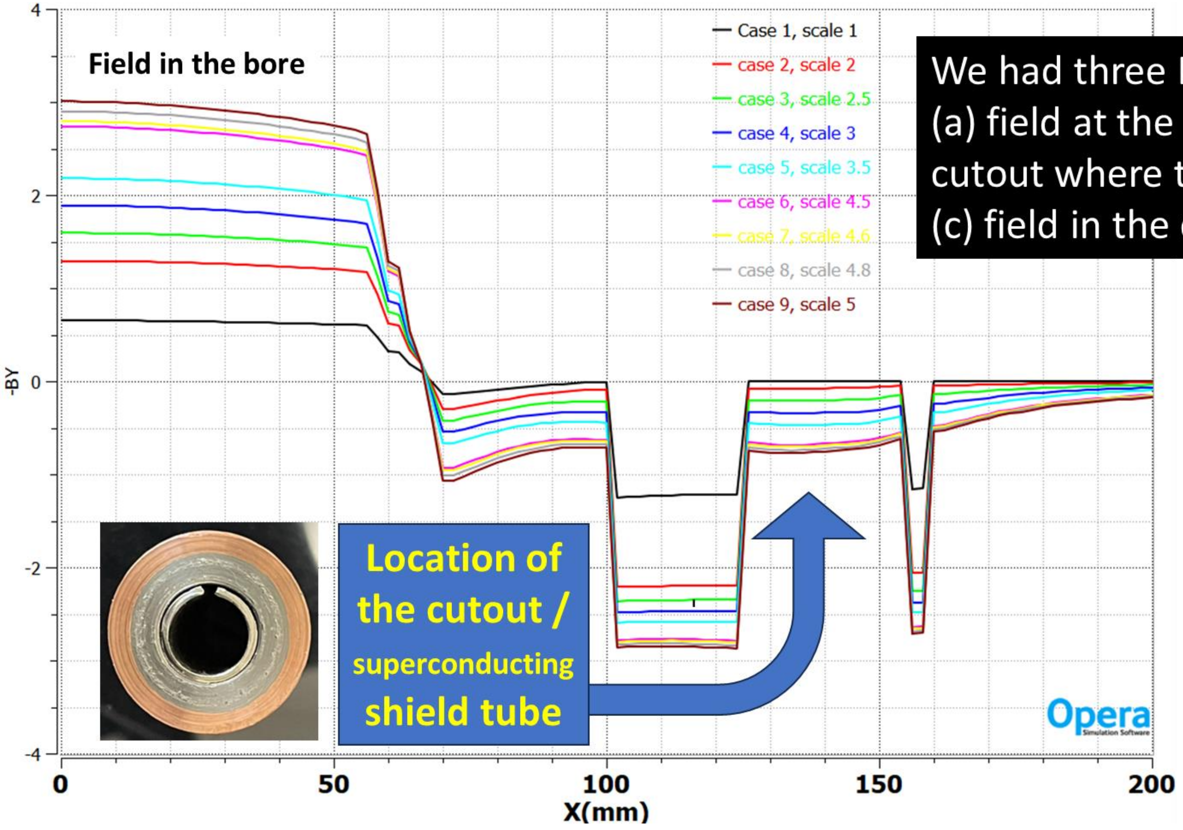
- Magnet reached only ~70% of the short sample.
- Quenches were not one place but were distributed in the outer four layers where the new splice was used to save radial space.
- Limited cooling (1st test run in <2 hours, and subsequent runs with ~20 minutes or less wait) didn’t help.
  - ➢ Note: This splice is not present in the EIC baseline design.

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



Location of the cutout / superconducting shield tube

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

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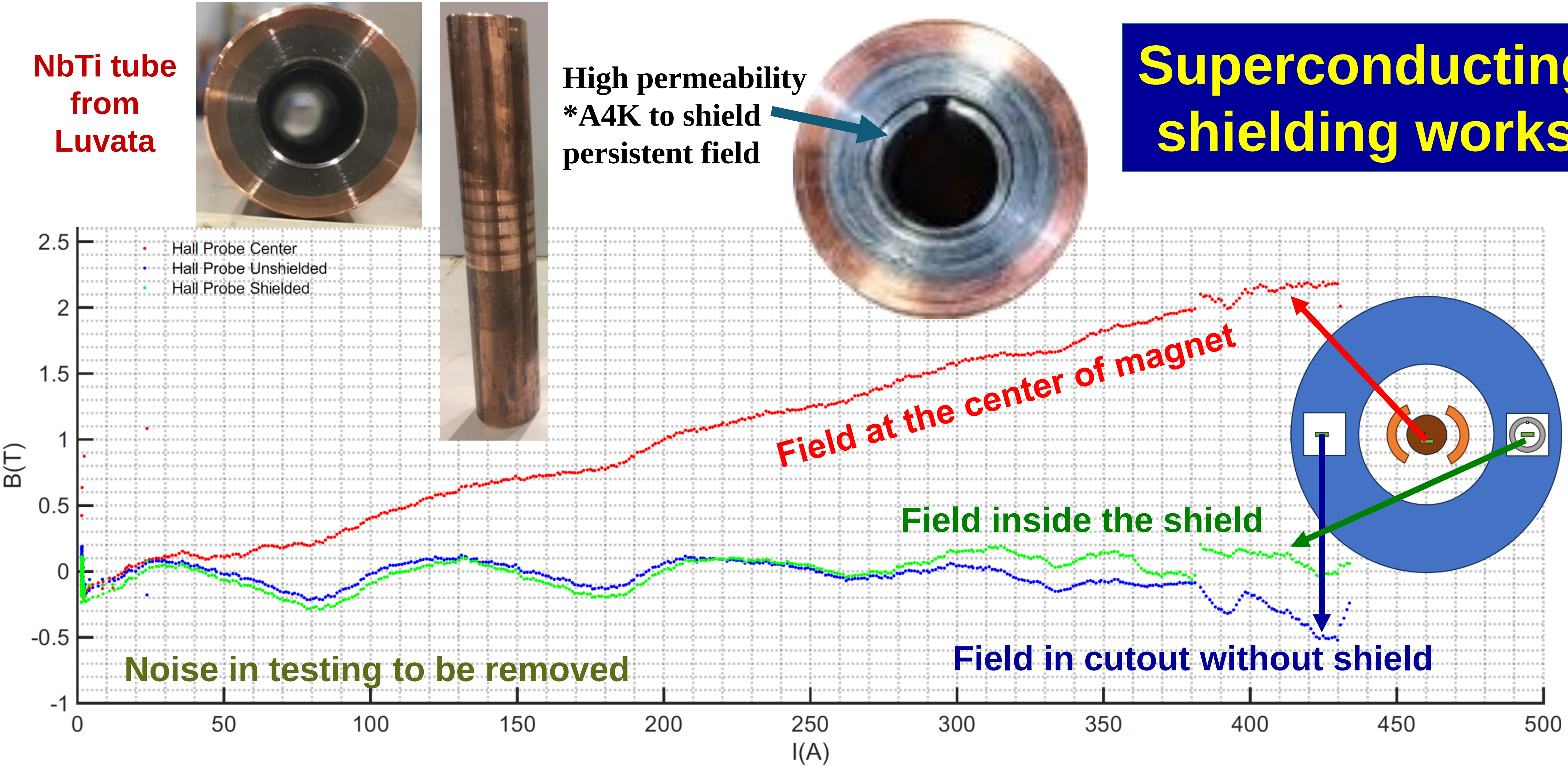
Demonstration of Superconducting Shielding (with Additional A4K)

Superconducting shielding works



NbTi tube from Luvata

High permeability *A4K to shield persistent field

Field at the center of magnet

Field inside the shield

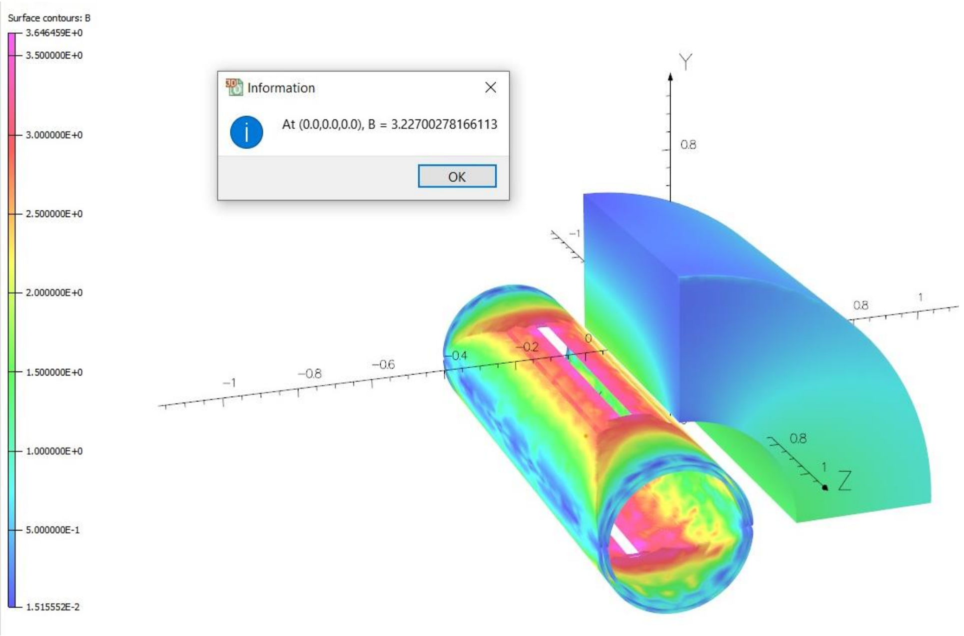
Field in cutout without shield

Noise in testing to be removed

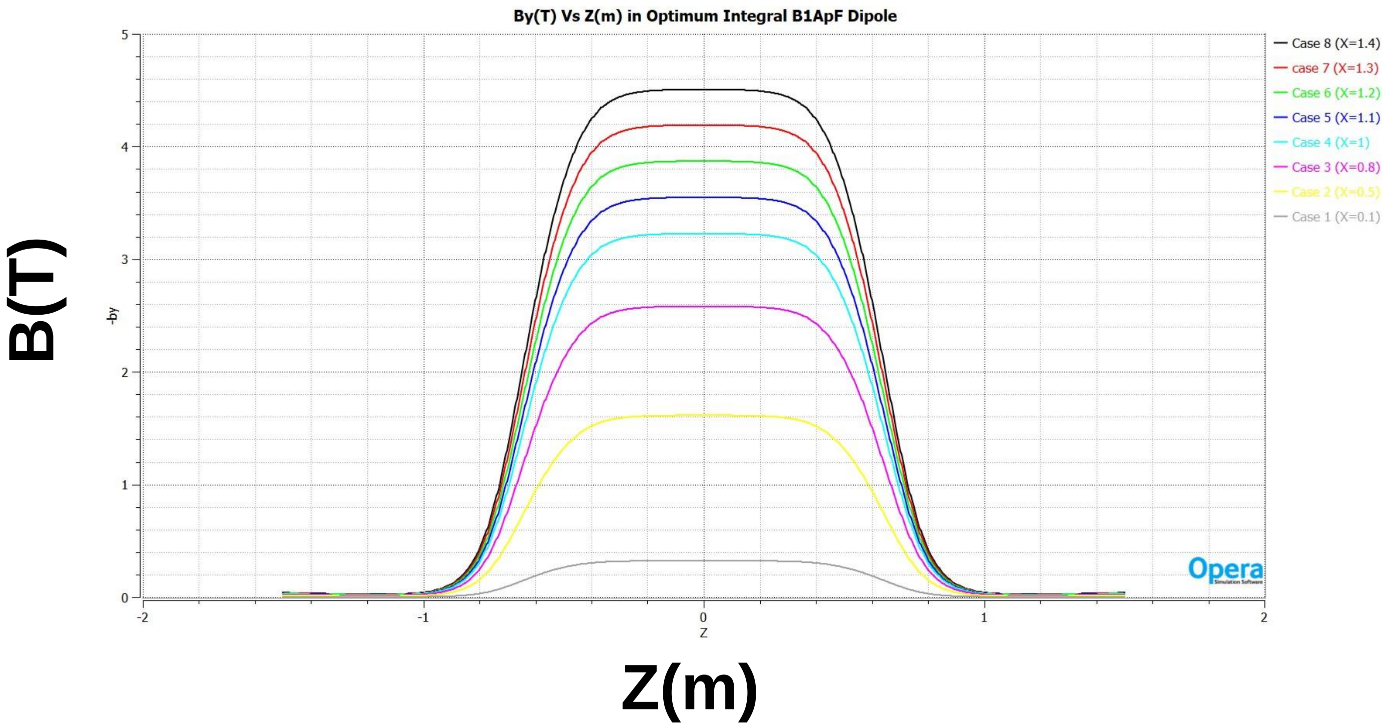
*A4K: High permeability Amumetal 4K (A4K) from Amuneal Manufacturing Corporation

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



At (0.0,0.0,0.0), B = 3.22700278166113



Summary

- Optimum integral design minimizes the loss in magnetic length due to the ends. Benefits are significant in short magnets.
- PBL/BNL, as a part of DoE funded STTR, has made a good progress in the demonstrated its essential principle in dipole B1ApF.
- Results of Phase I and Phase II results have been mostly positive so far.
- A setback occurred, likely due to a change in the splice design. It is not part of the EIC baseline design and is also not essential to the optimum integral design. It will be eliminated in the remainder of the program.
- Promising results with the superconducting shielding experiment.