PBL

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Design, Construction, and Test of a Direct Wind Dipole B0ApF based on the Optimum Integral Design

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Overview

- **Optimum Integral Design – Why?, What?**
- **PBL/BNL Direct Wind Dipole B0ApF for EIC*:**
    - ❑ **B_o = 3.9 T and coil i.d. = 114 mm – a significant magnet**
    - ➢ **Higher "field & aperture" than RHIC arc dipole (3.45 T & 80 mm)**
- **Design, construction and test results**
    - ➢ **Three phases, each with significant results**
- **Summary**

*Work supported by a DoE STTR (Small Business Technology Transfer) award

Why? Significant Loss in Integral Field Due to Ends in Short Magnets

- Typical mechanical length of <u>each</u> dipole end: ~ two coil diameter
- Loss in integral field due to ends starts becoming significant when the total coil length (*L*) < ~8 X coil diameter (*a*) in dipoles

RHIC Dipole Coil End

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

<u>Coil length to coil diameter ratio in some magnets:</u>

- AGS Corrector (*L* = 182.8 mm, *a* = 300 mm): ~0.6
- EIC B0ApF (*L* = 600 mm, *a* = 114 mm): ~5.3
- EIC B1ApF (*L* = 1600 mm, *a* = 370 mm): ~4.3

✓ There is a motivation for a design that reduce the loss in integral field due to ends in such magnets

Conventional Design Approach

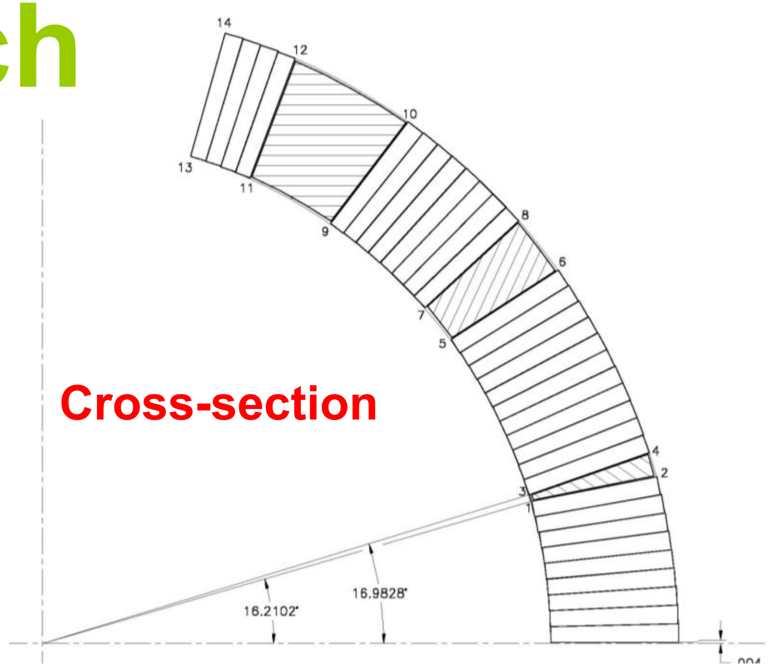
A two-step process:

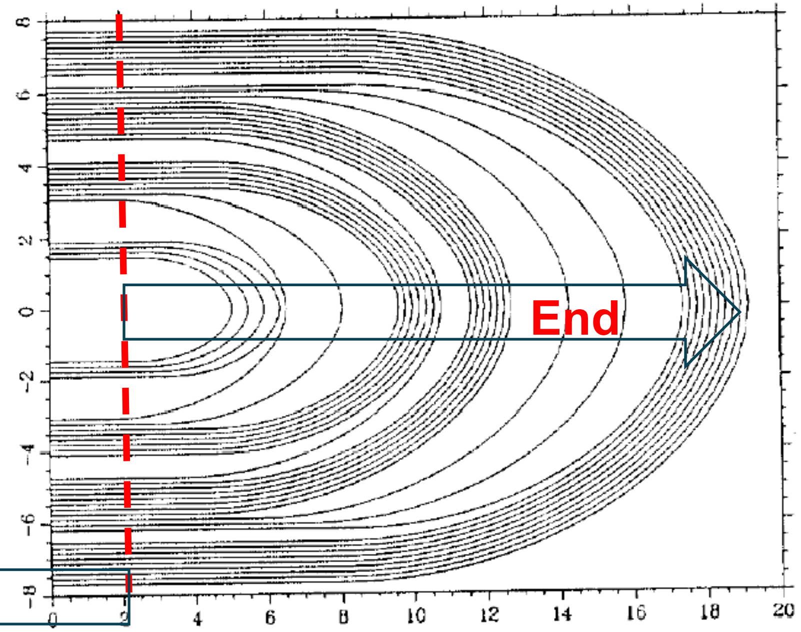
Step 1: Optimize coil cross-section to obtain cosine theta like distribution:

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

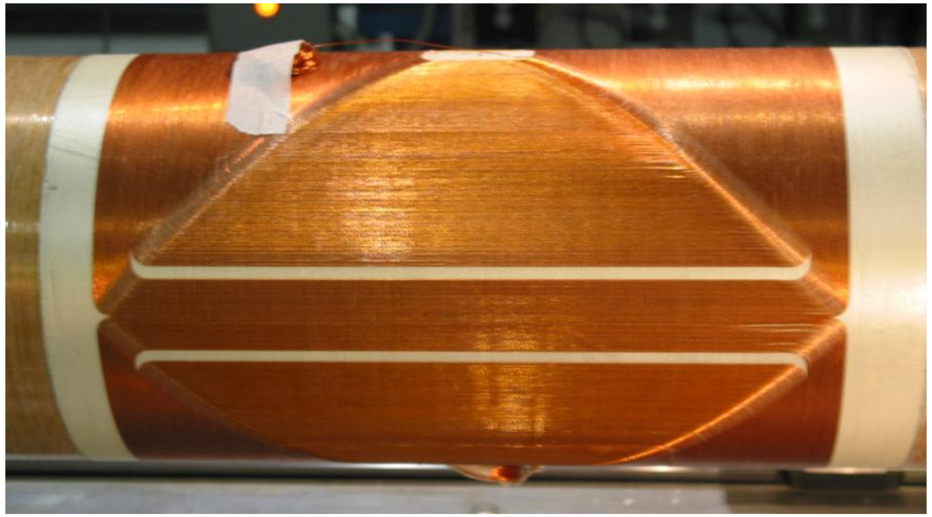
Step 2: Optimize ends for reducing harmonics and peak fields

- magnetic length: ~ ½ mechanical length
- typical loss in magnetic length due to ends
  - Dipole: one coil diameter
  - Quadrupole: one coil radii





What? Optimum Integral Design Approach



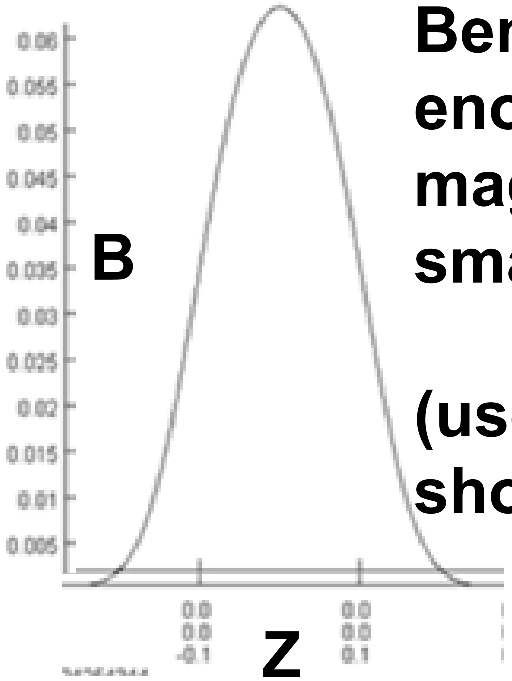
Optimize cross-section and ends together in <u>a single step</u> to obtain cosine theta distribution in an integral sense:

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

Extend midplane turns end-to-end

Length of coil ends which determines the loss in magnetic length, made nearly zero

✓ **Loss due to ends essentially eliminated**



Benefits are enormous in any magnet with small flat-top

(useful in any short magnet)

Key to this Program
Direct Wind Magnet Technology @BNL

(allowed this magnet to be built in the cost and schedule of an STTR)

Demonstrated earlier in lower field or lower aperture magnets.
But not in such a high field and large aperture magnet.

- **For more on info the direct wind technology, please visit oral session (Fri-Mo-Or4) and poster session (Fr-Mo-Po.05)**

Three Phases of the Program

- **Phase I:** **Two layers**
- **Phase II (year 1):** **Six layers**
- **Phase II (final):** **Twelve layers**

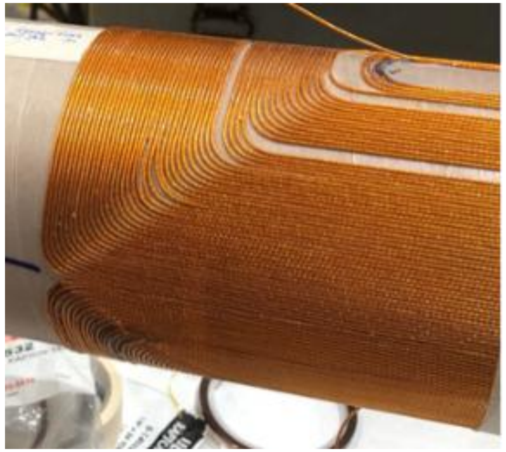
~10% margin at 4 K test temperature (EIC operates@1.92K).

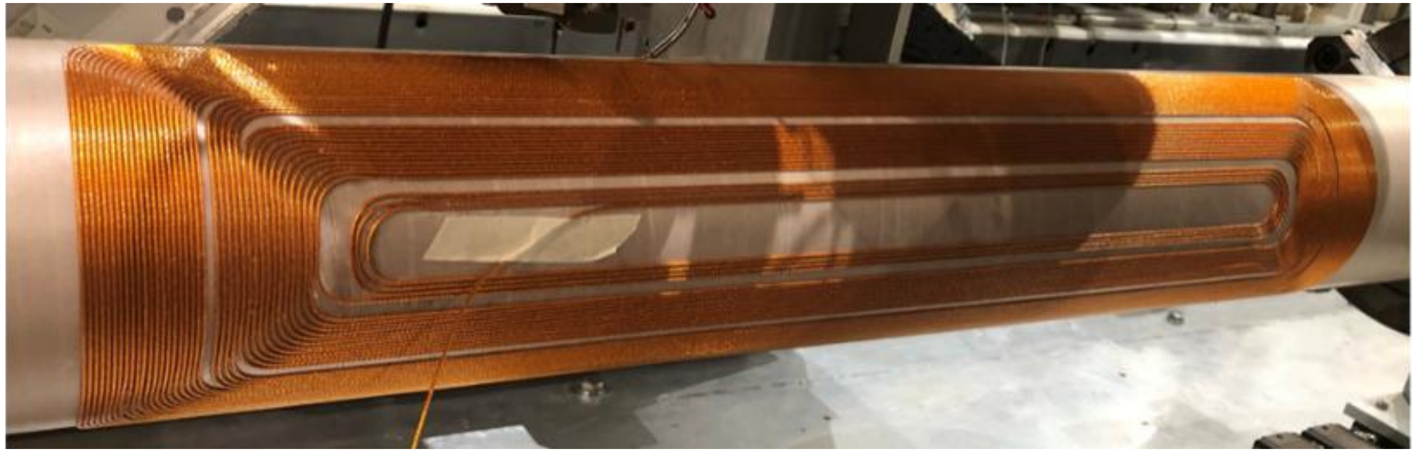
➢ **Key outcomes of each phase to be discussed briefly.**

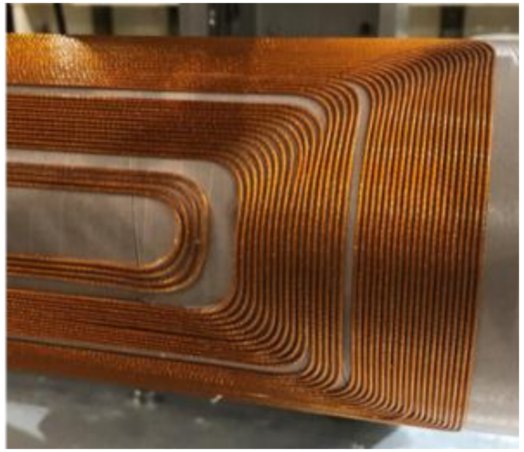
Optimum Integral Dipole - Phase I Coil (two layers)

Note: Midplane turns extends full length

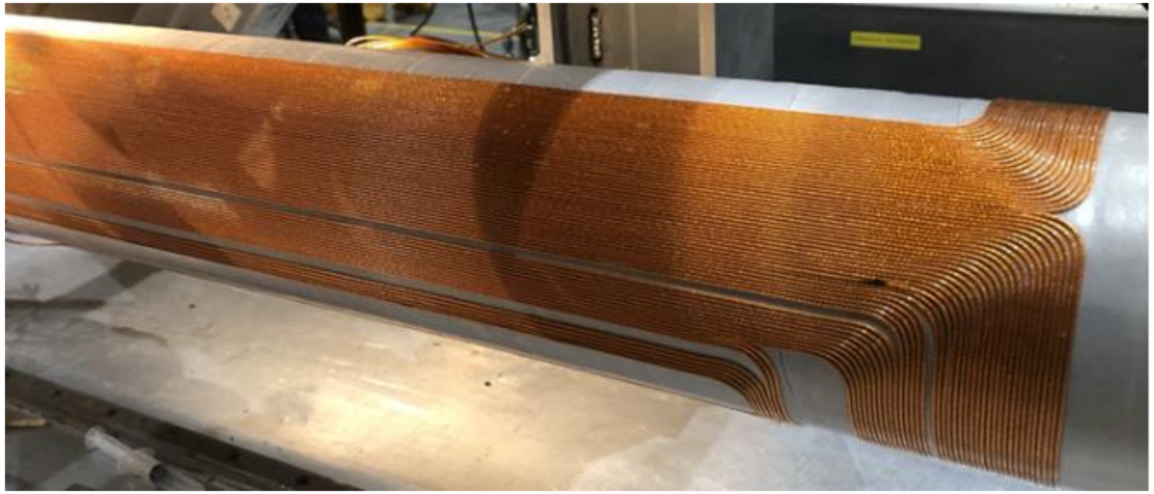
First Layer

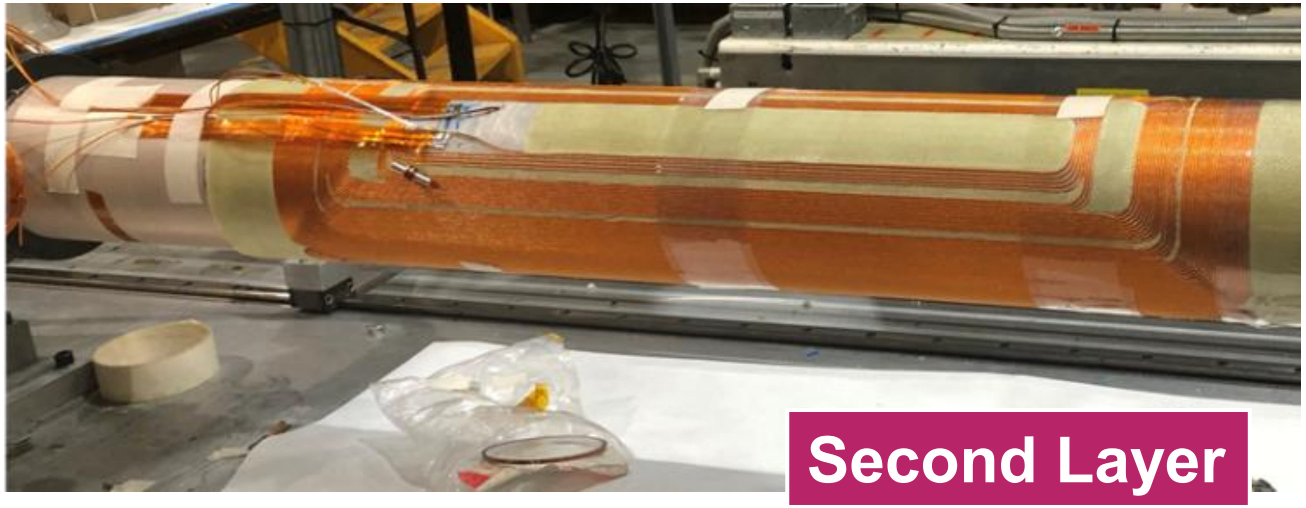






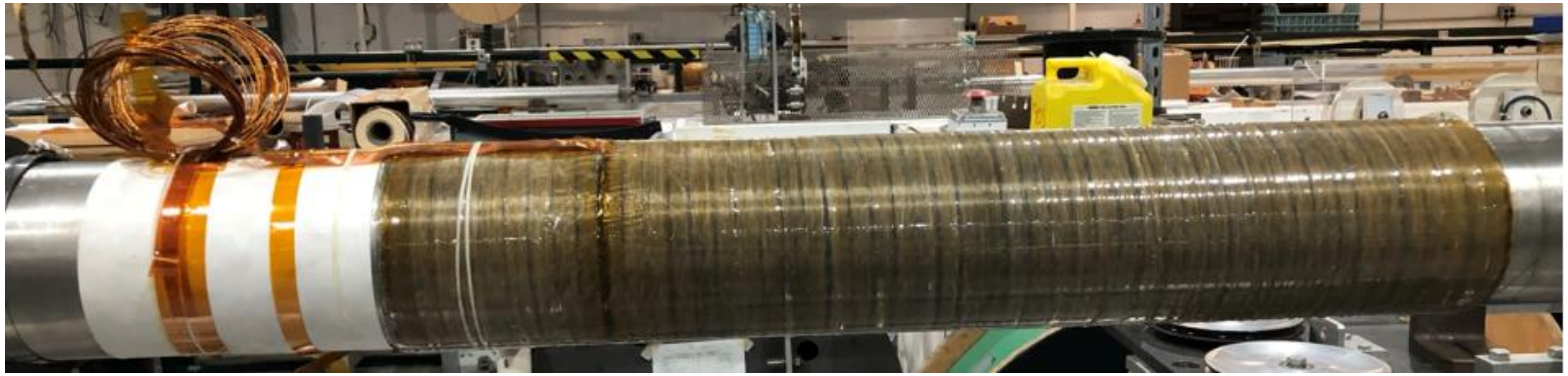
Spaces filled, epoxied, cured and the surface is prepared for the second layer





Second Layer

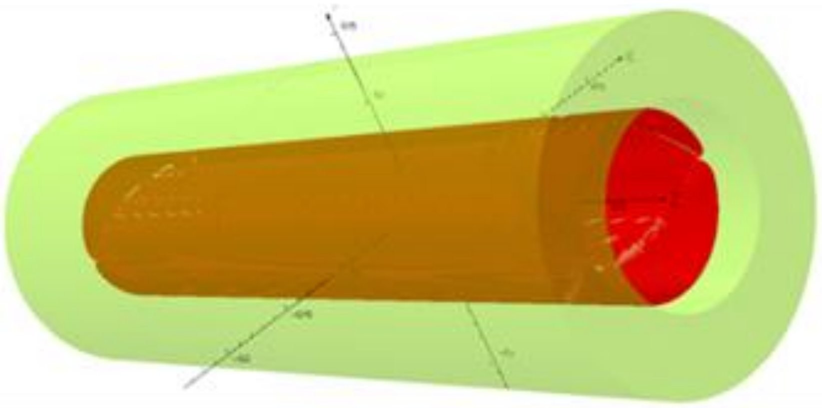
Optimum Integral Dipole in Phase I (two layers in a yoke)

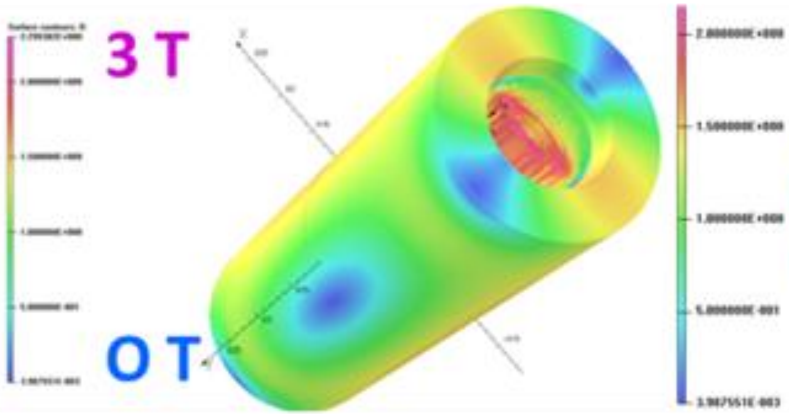


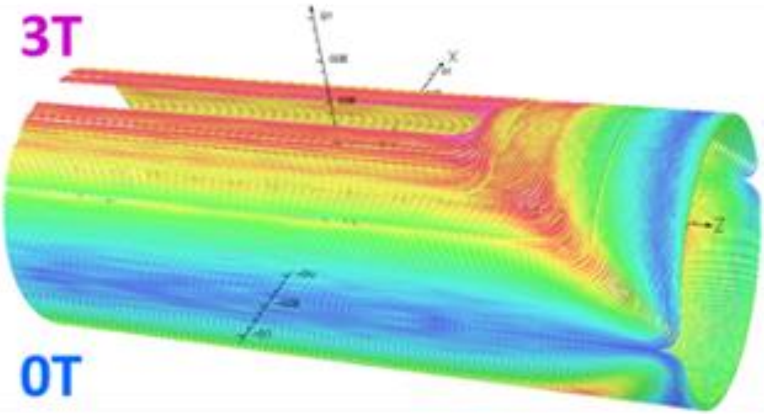
Tension rowing over two layers to contain forces

Coil in yoke, ready for test

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

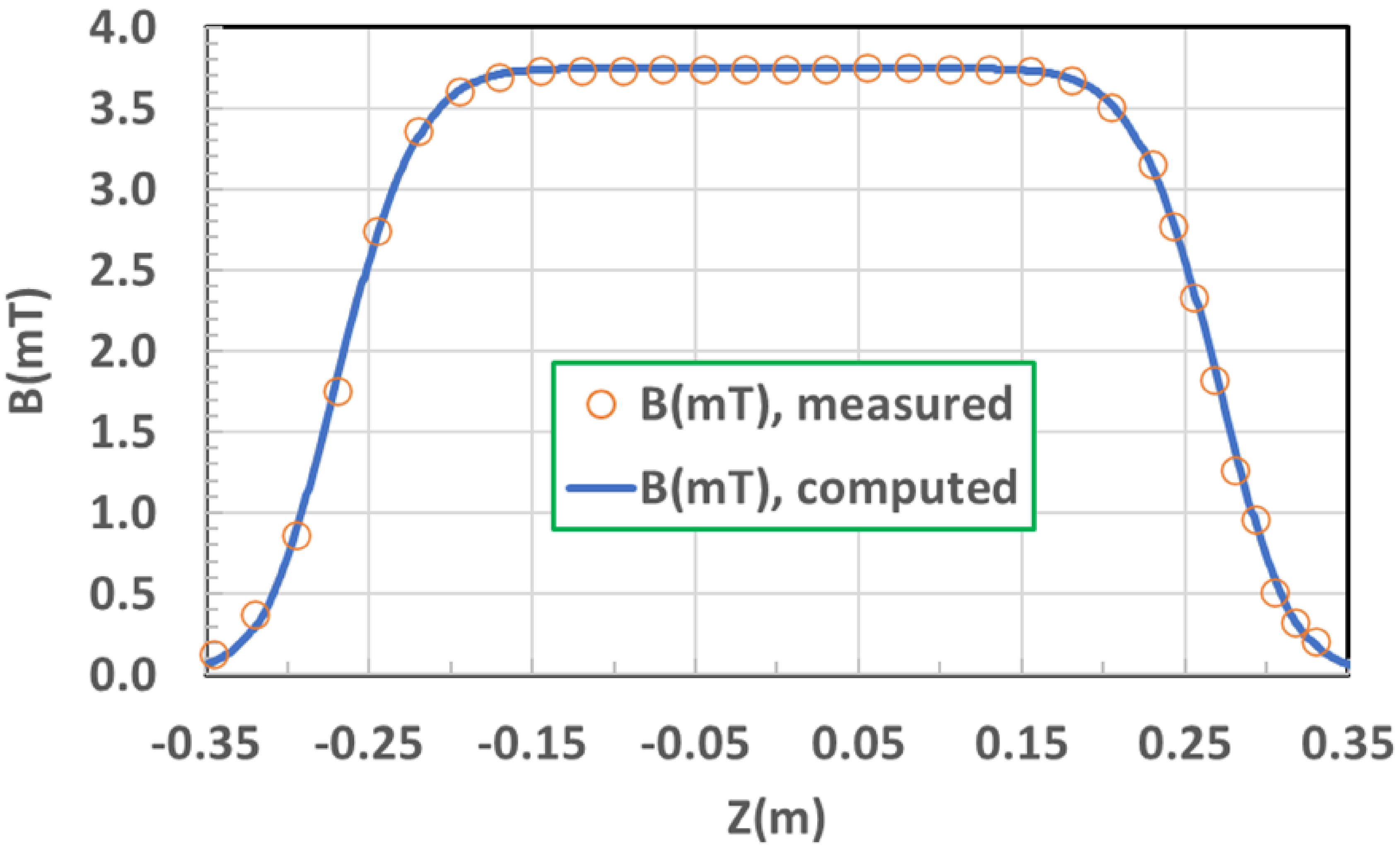






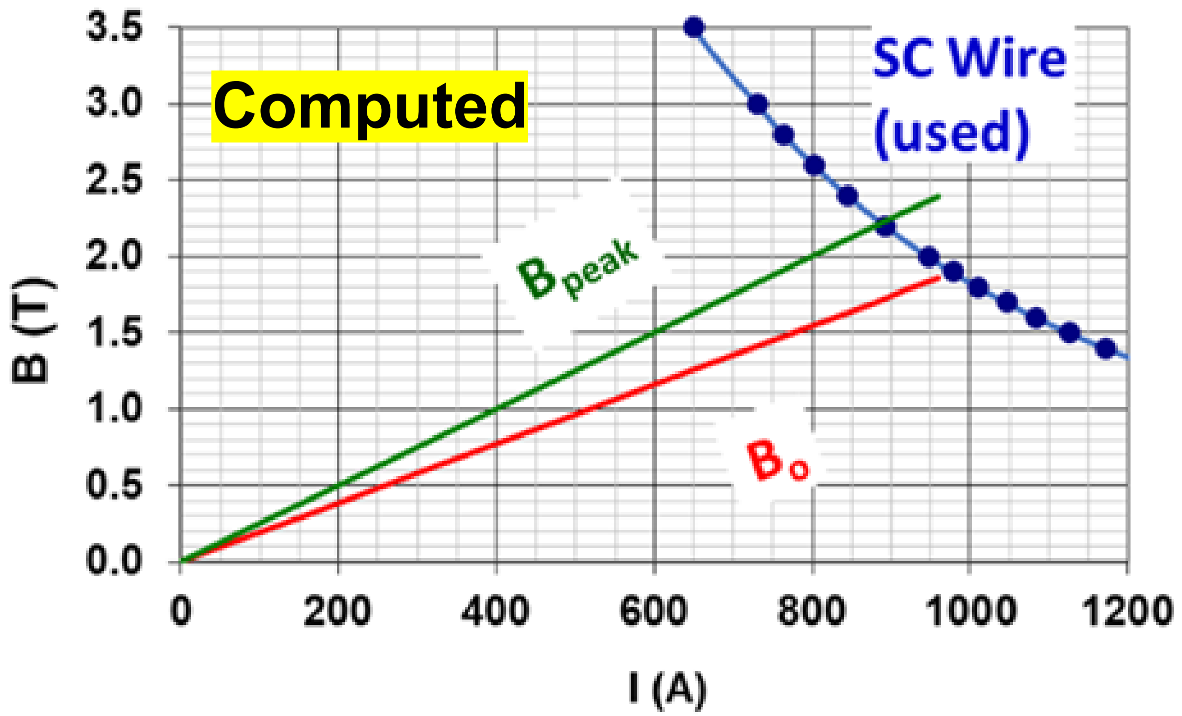
Question #1: Will optimum integral design extend the magnetic length?

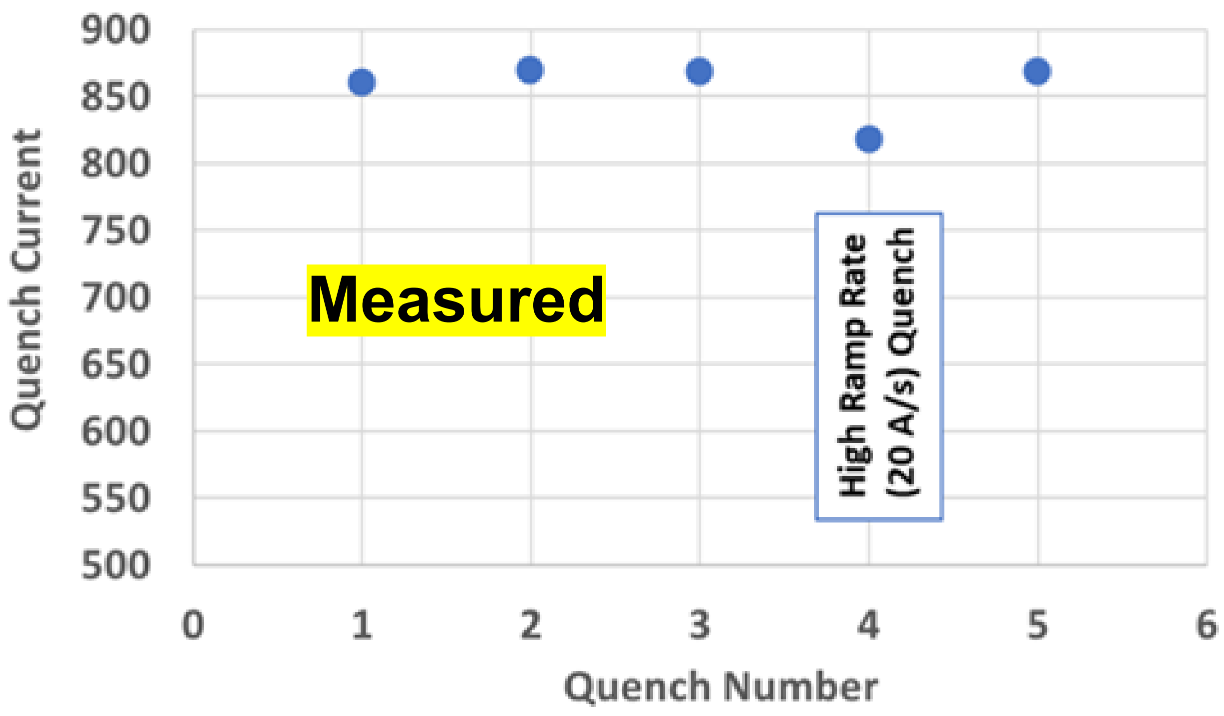
Major motivation of the optimum integral design demonstrated



✓ **Answer: Yes! 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 training)

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

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

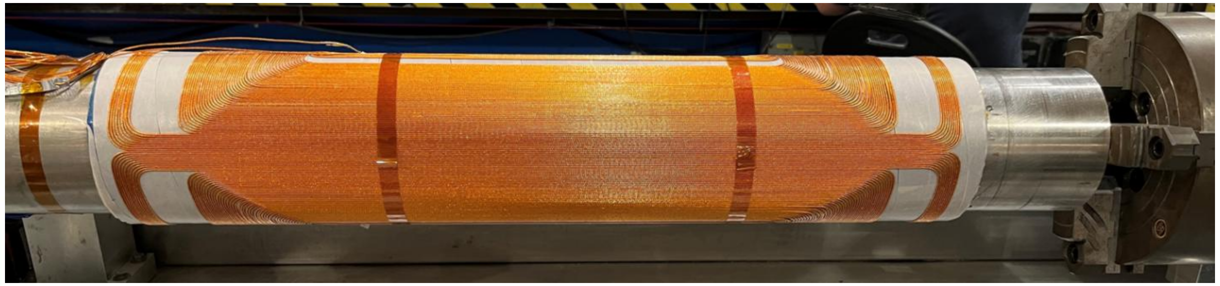
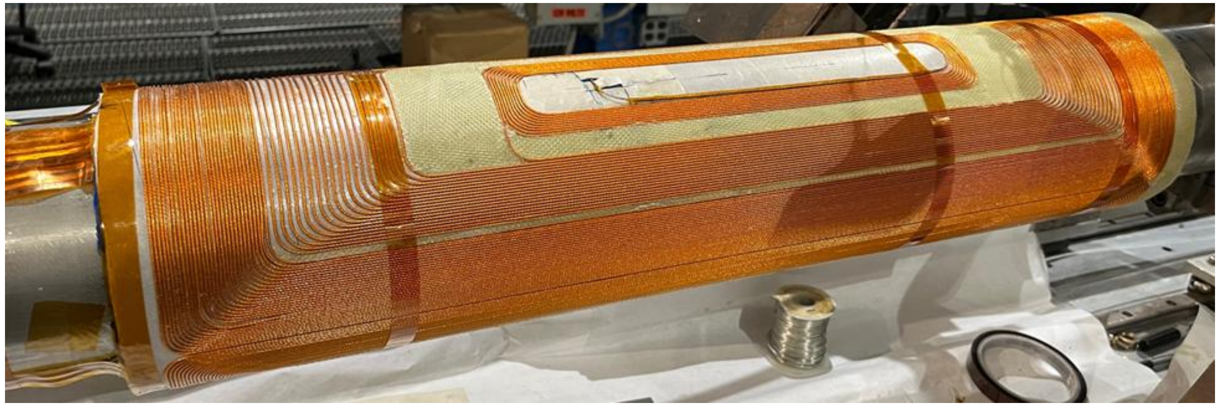
a) Demonstration of a good field quality (warm measurements):

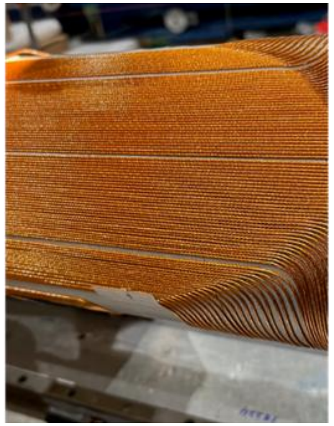
- Validation of the optimum integral design and the software

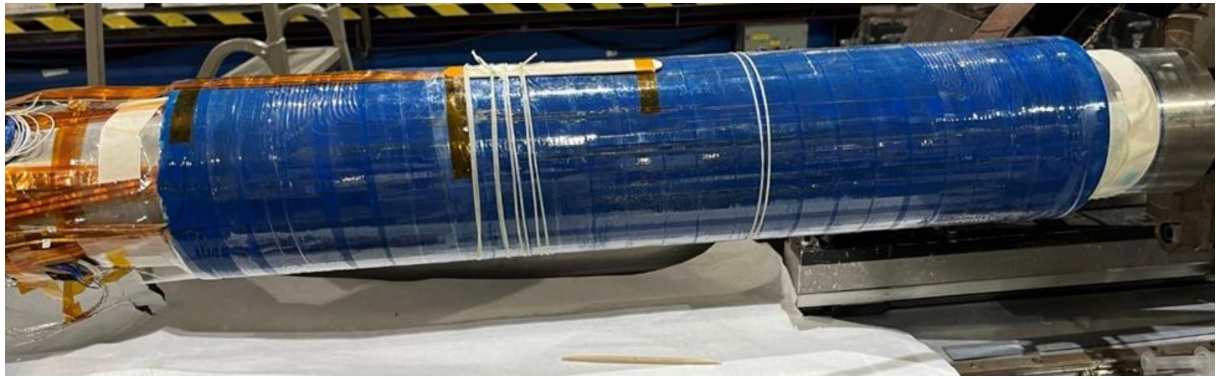
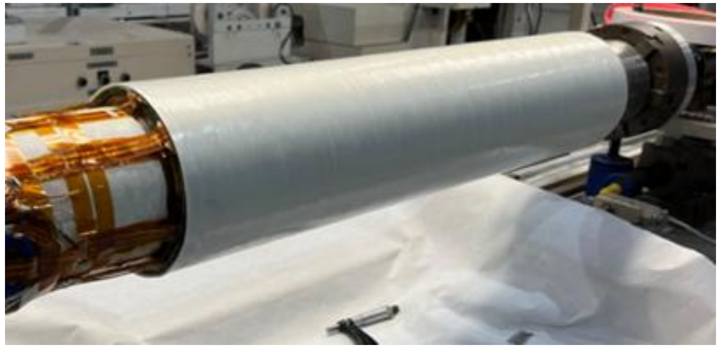
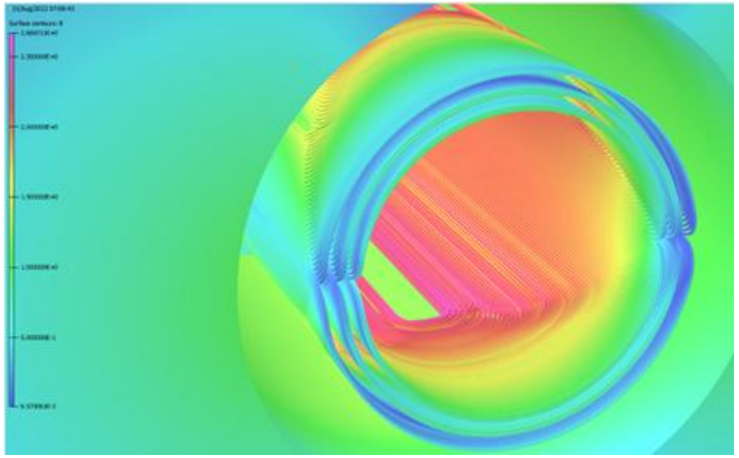
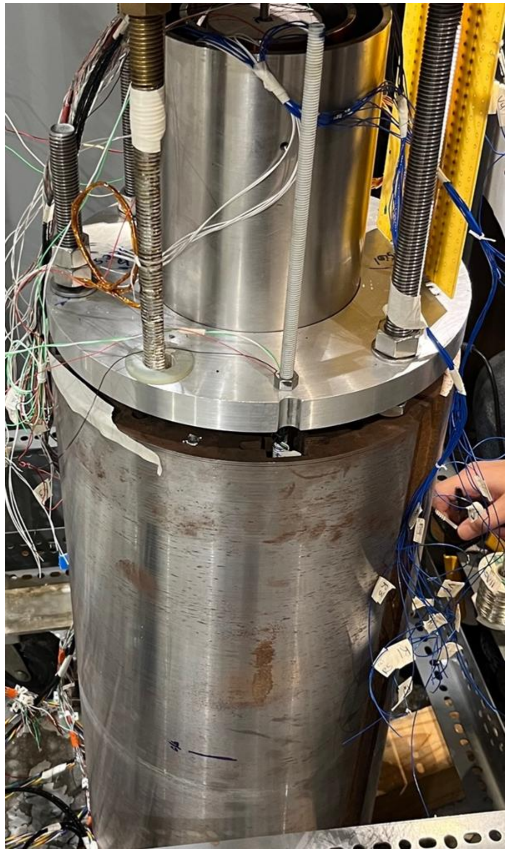
b) Demonstration of the magnet performance:

- B_o: ~2.9 T, B_{pk} ~3.5 T (coil aperture 114 mm)

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

Reference radius 31 mm, instead of 25 mm

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

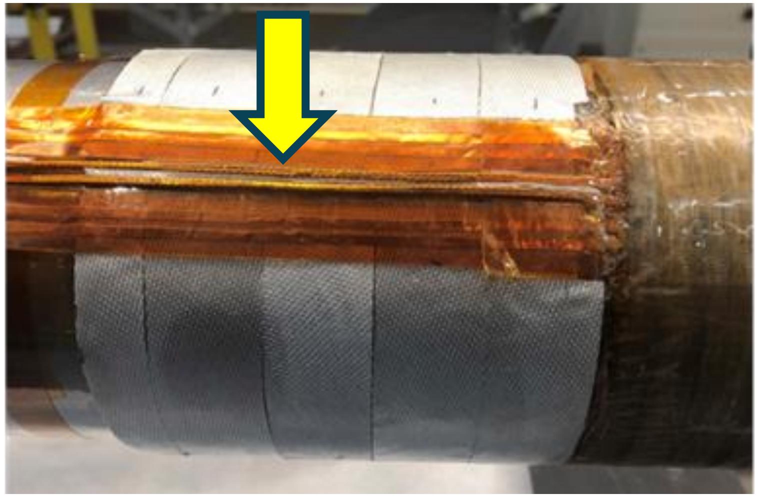
Lower order from external leads.

All other harmonics <2 units (meets the spec)

- **A good field quality despite several changes on the fly (as in any R&D project)**
- **Remaining small harmonics are compensated in the next layers.**

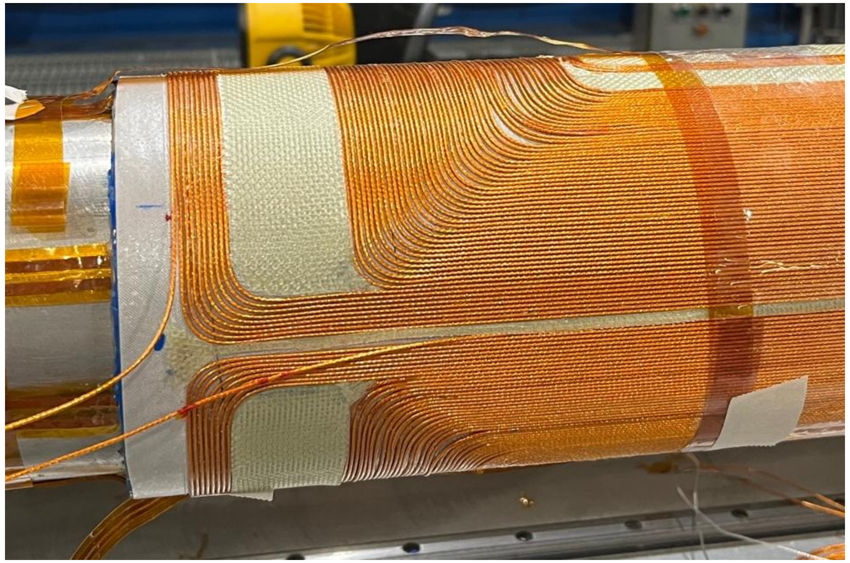
A Change in Design to Eliminate Radial Space Used by Leads

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



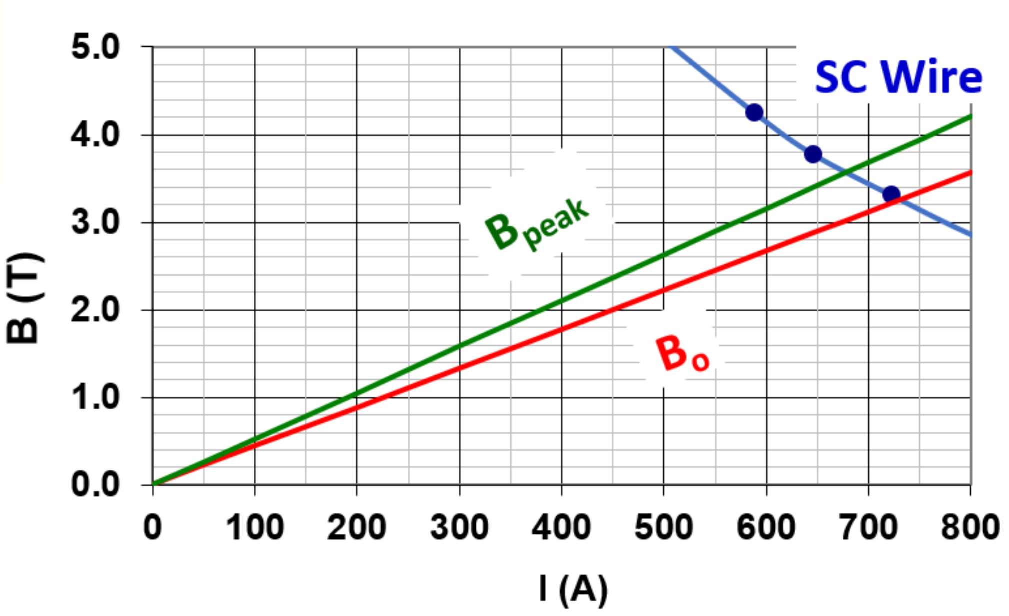
Phase I configuration

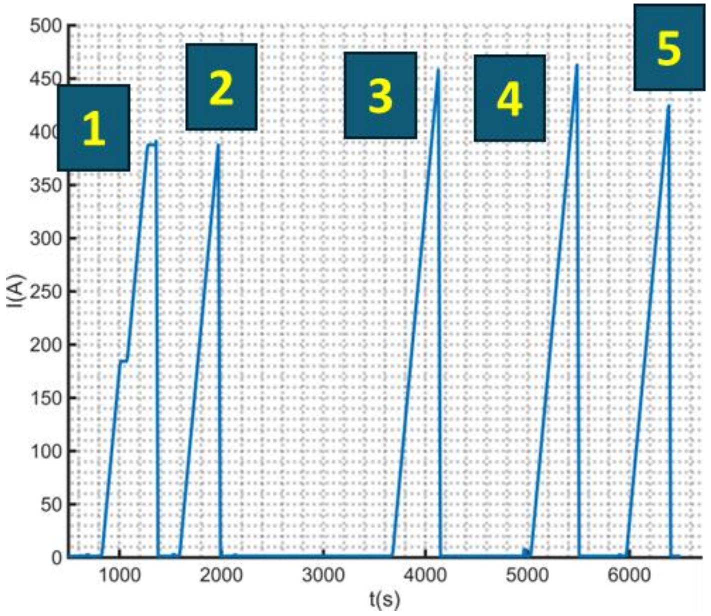
- **An innovation was implemented to remove extra radial space. Leads out at midplane.**
- **This solution required a splice at the pole in high field region and additional routing of leads outside the end of coil.**

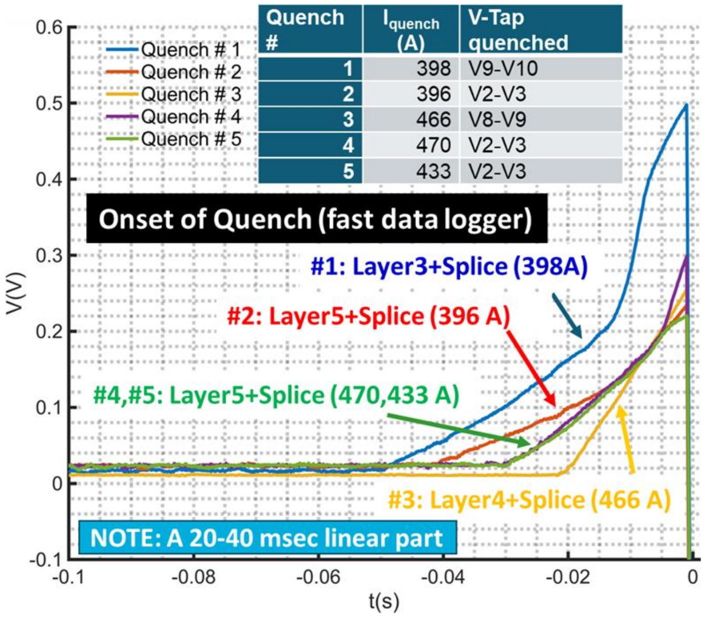


Phase II configuration

Testing of the Intermediate 6-layer Optimum Integral Dipole







- **Magnet reached 470 A (~70% of the short sample).**
- **Quenches were in the coil sets where the lead routing was changed to eliminate the need to use the extra radial space.**
- **Limited cooling (1st test run in <2 hours, and subsequent runs with ~20 minutes or less wait) didn't help.**

This issue has now been resolved

Final Goals/Targets of the Phase II

R&D Dipole B0ApF for EIC (full-length, design field integral)

B_o~3.9 T, B_{peak} ~4.3 T peak, i.d. 114 mm, L=0.6 m (1.98 T.m)

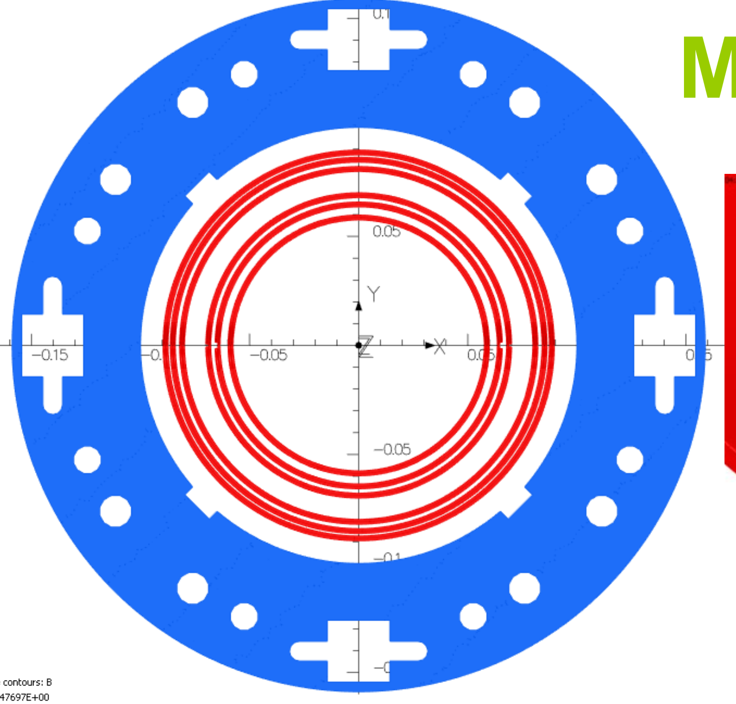
12 layers provided some additional margin for the 4.2 K test

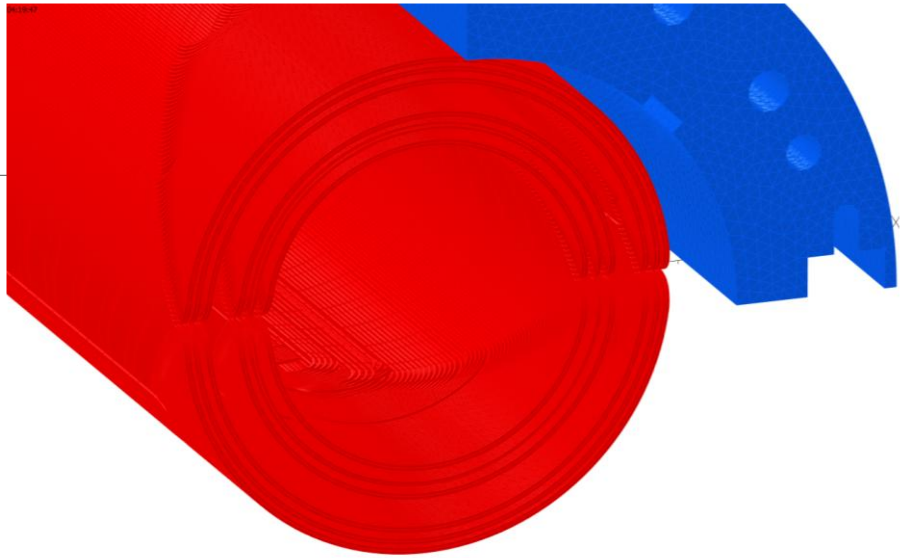
- **More margin in EIC as B0ApF will operate at ~1.9 K**

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

- **Weakness discovered in routing of the leads outside the magnet. Made robust.**

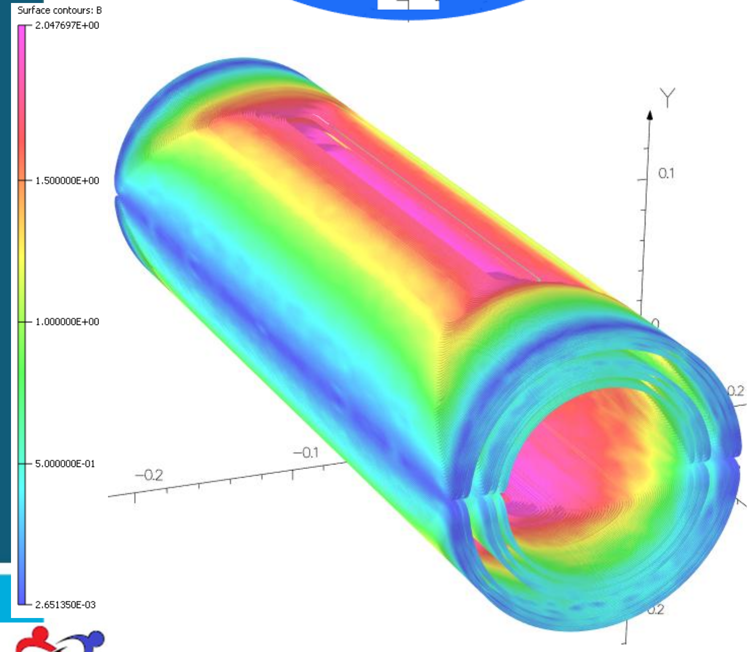
Magnetic Design of the 12 Layer OID B0ApF

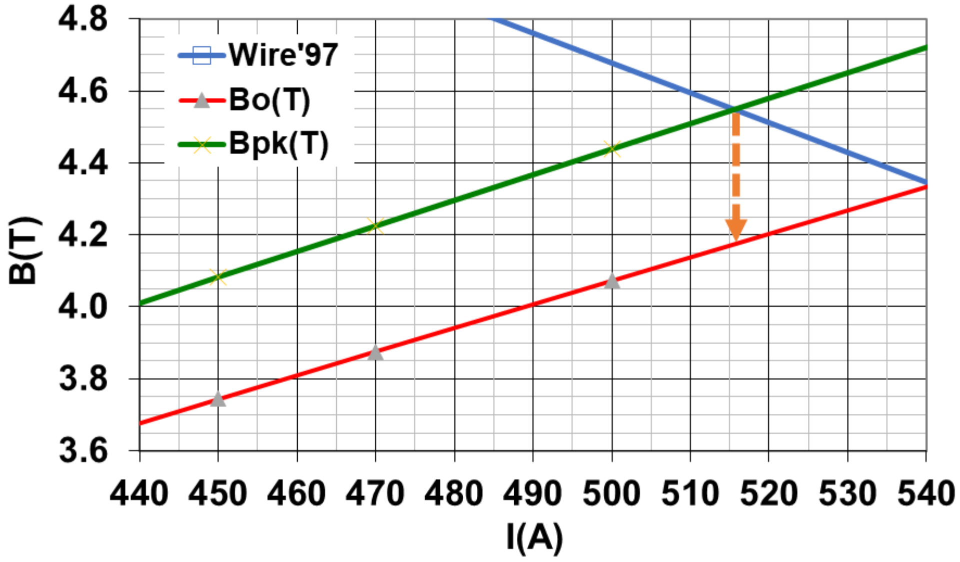




Key Parameters:

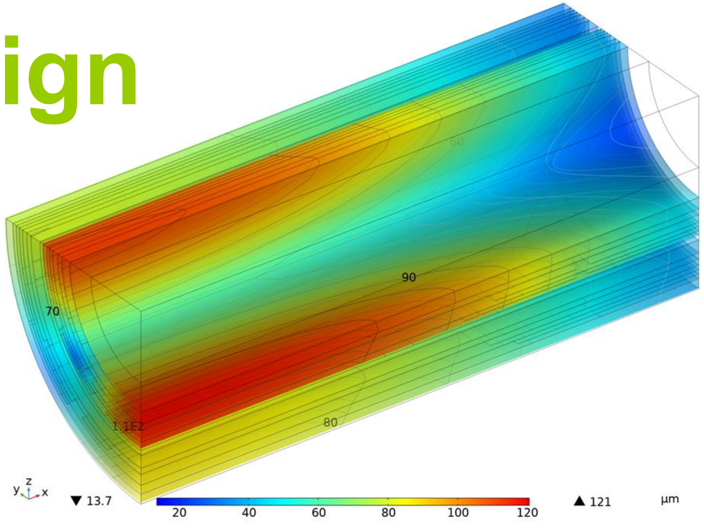
- **Coil id, od: 114, 183 mm**
- **Coil length: 600 mm**
- **B_o, B_{pk}: 3.9T, 4.3T @470A**
- **Integral field: 1.98 T.m**
- **Inductance: ~700 mH**
- **12 Layers (6 + 6)**
- **Intermediate SS tube**





- 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

Mechanical Design of the 12-layer Design



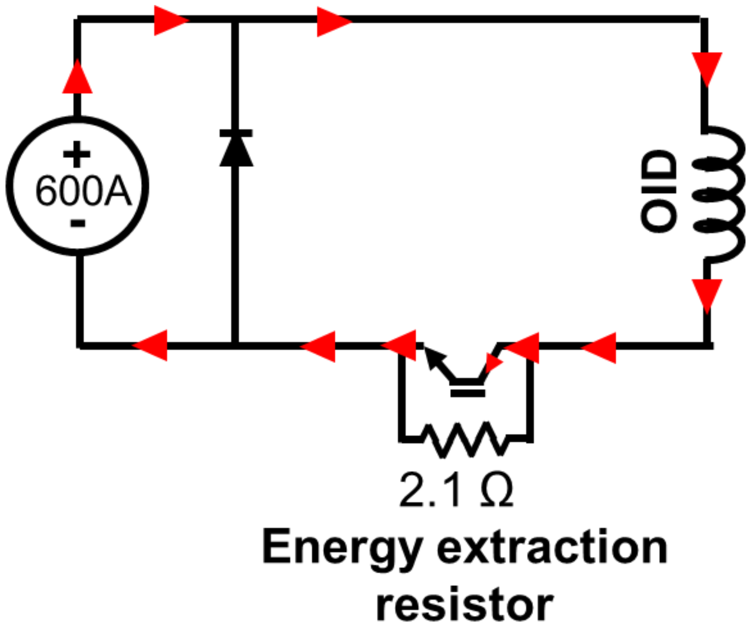
Analysis with COMSOL

Primary components of mechanical design:

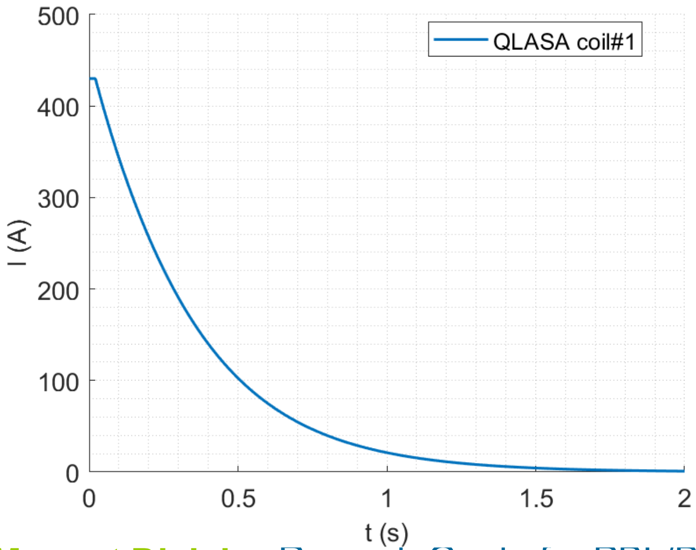
- Tension roving after every two layers
- Two stainless steel tubes
  - ➢ 2 instead of 1 to reduce stress/strain buildup

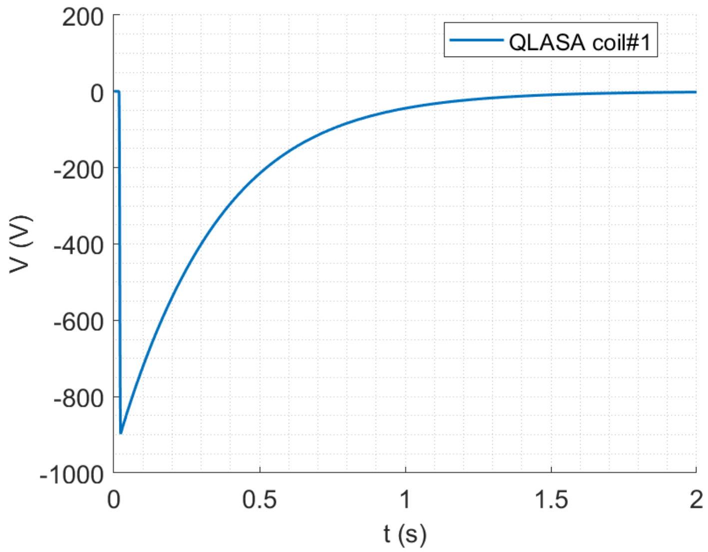
Quench Protection

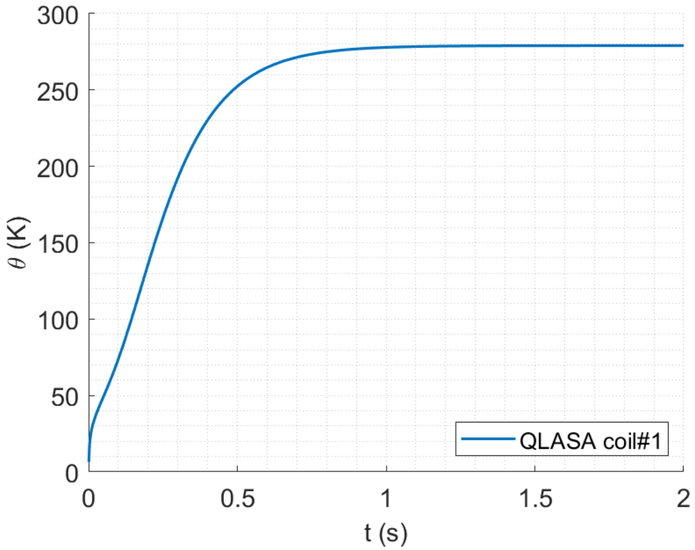
QLASA simulation
@ I = 430 A
L = ~0.7 H
R_{dump}=2.1 Ω



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



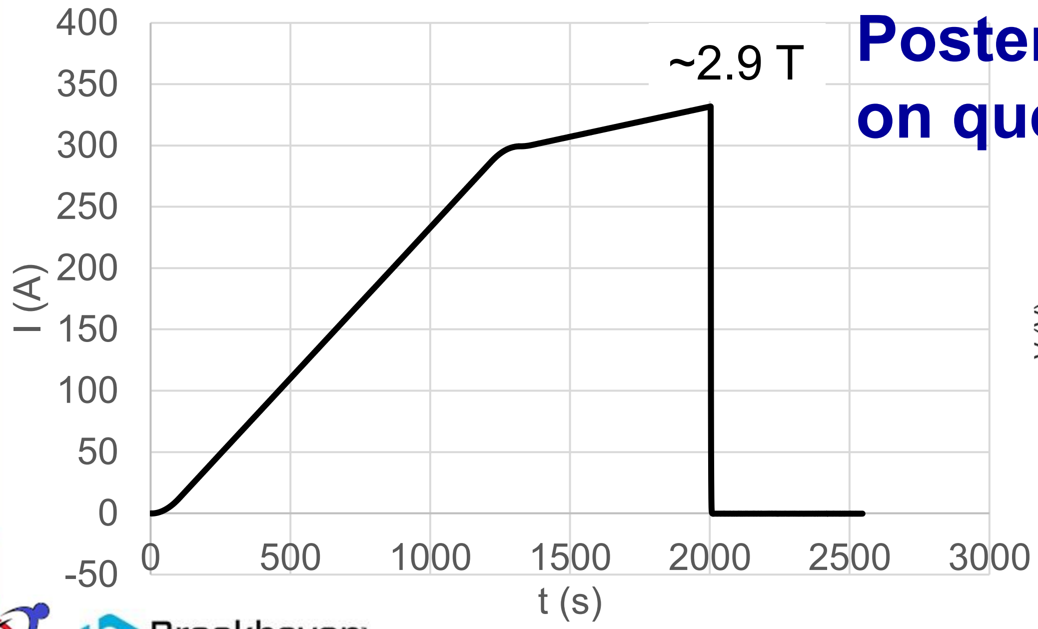




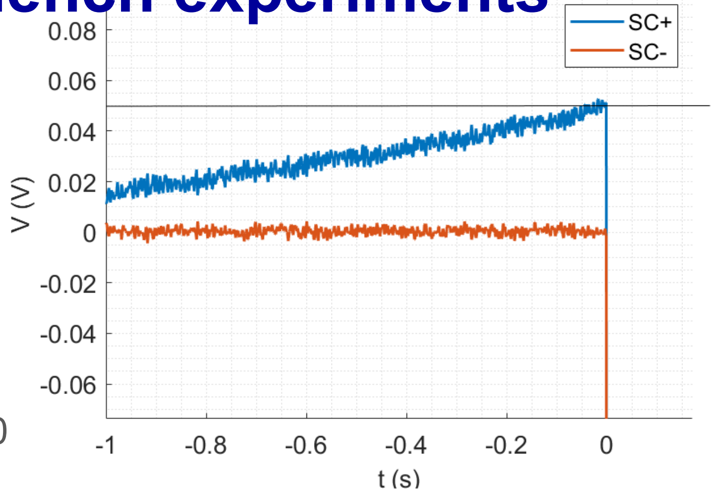
Test Results of the 12-layer Direct Wind Optimum Integral Dipole B0ApF

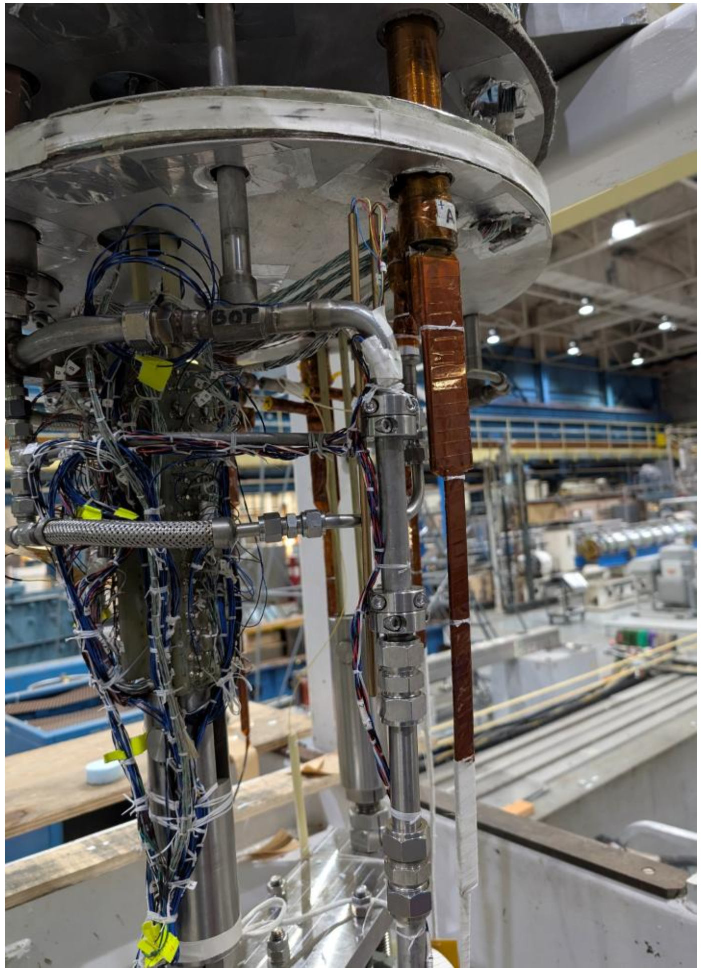
- **Magnet energized (with NO spontaneous quench) to ~2.9 T (~74% of the required field integral for B0ApF)**
- **A significant and promising test result for direct wind**
- **Innovation to reduce radial buildup worked, as planned (issue that limited performance last year, now resolved)**
- **Test seems to be limited by a superconducting lead from magnet to top hat (should be fixed in next run)**

~84% of the design field of RHIC 80mm dipole, in 114mm aperture



Poster Fri-Af-Po.01-03 on quench experiments





Quenched @331 A at the superconducting lead extension connecting magnet to the top hat helium cooled leads

Acknowledgments

- We acknowledge the contributions of our technicians who worked hard and long hours. The outcome of R&D like this, carried out with a limited engineering, depends on their skills, experience and practical solutions.
- We wish to thank support and encouragement of the EIC management.
- The work performed was possible from the Phase I and Phase II STTR funding and continued support and understanding from the project manager. Additional quench studies were performed with the LDRD funding.

Summary

- Optimum integral design minimizes the loss in magnetic length due to the ends. Benefits are significant in short magnets, as in just tested EIC IR dipole B0ApF.
  - Poster Fri-Mo-Po.05-03 for the optimum design of EIC IR dipole magnets B1pF & B1ApF.
- Extension of magnetic length and good field quality have been demonstrated.
- The 12-layer magnet, built with the direct wind technology, was energized to ~2.9 T. This produces ~74% of the required field integral at ~4.2 K (extra margin at ~1.92 K) and ~84% of the RHIC arc dipole design field with no quench in the magnet.
- Above are significant demonstrations of the direct wind technology (Bo = 3.9 T, coil i.d. = 114 mm, L = 600 mm) and of the optimum integral design for B0ApF (1.98T.m).
- We expect to continue the magnet performance test and quench studies after repairing the superconducting leads, external to magnet, to reach the design goals.

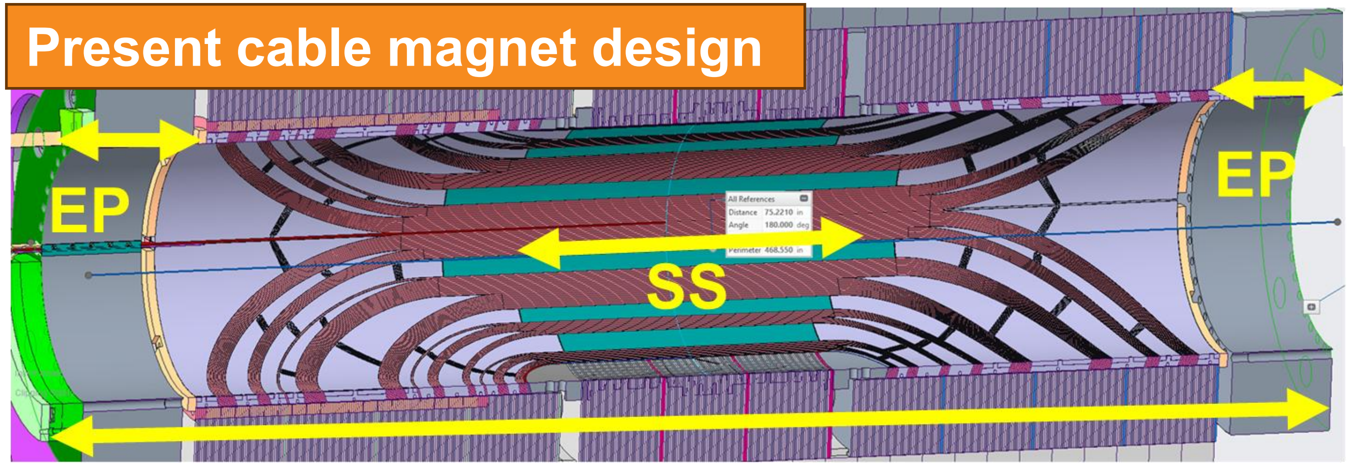
Extra Slides

Optimum Integral design as examined for B1ApF

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

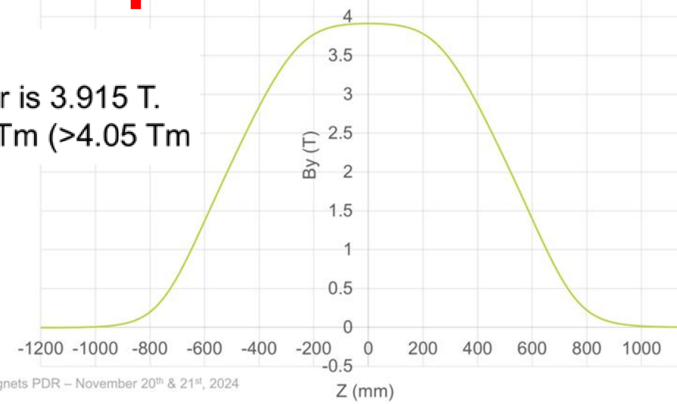
- **Important for short magnets, like B0ApF and B1ApF in EIC**

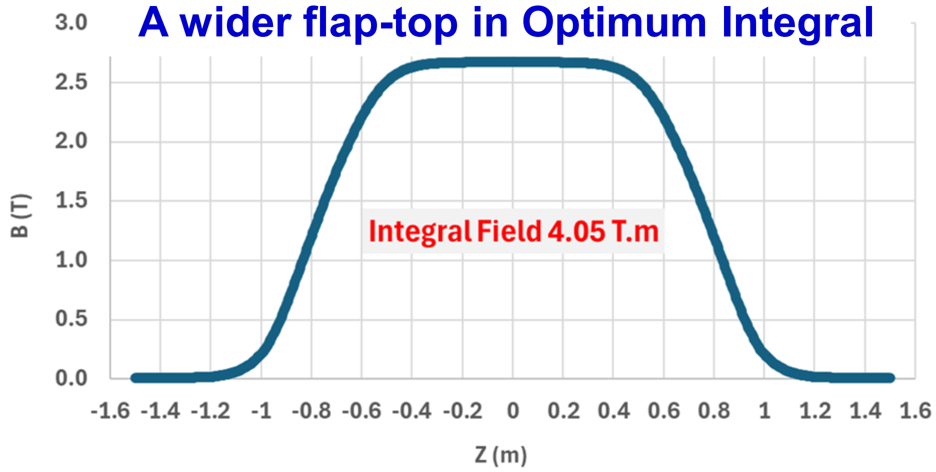
Present cable magnet design



Direct wind optimum integral design

- Short straight section
- Maximum dipole field at center is 3.915 T.
- Integrated dipole field is 4.08 Tm (>4.05 Tm

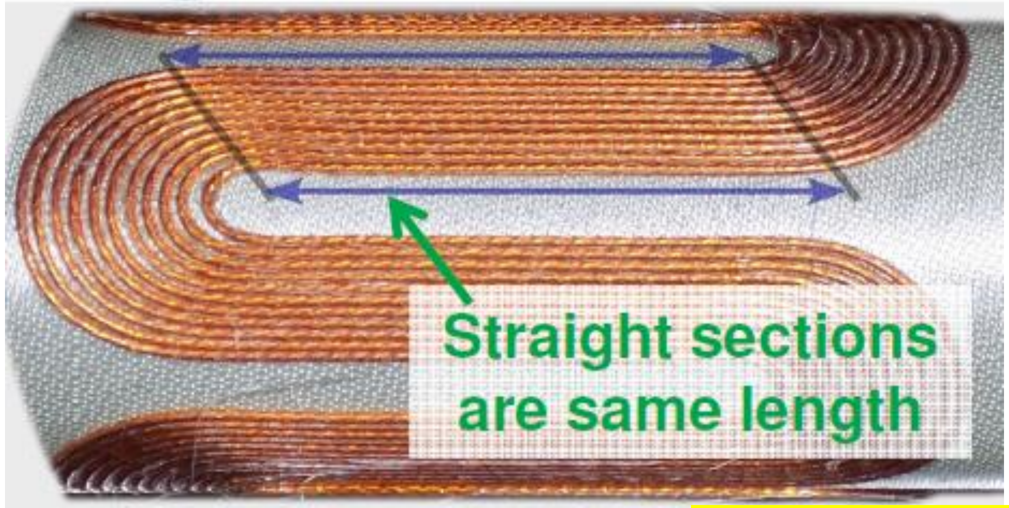




Technical benefit: B_o goes down from ~4 T to ~2.6 T; forces/stresses go down as B^2

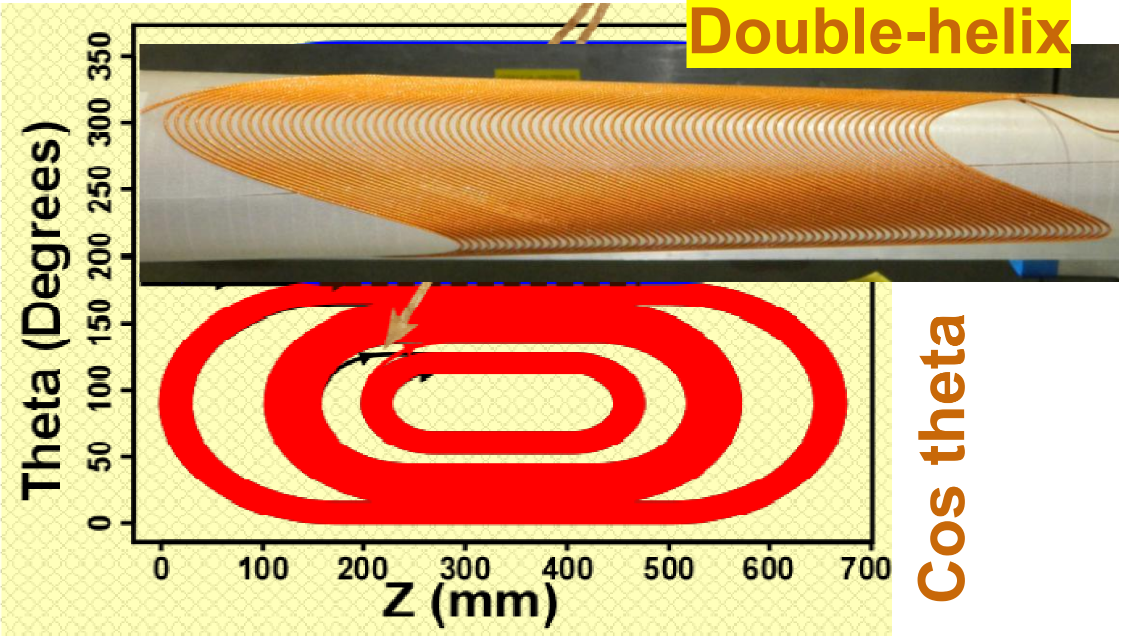
Length of the Straight Sections (SS) in Various Designs
(length of SS determines the integral field in short magnets)

- ***Space for turns in the Ends must be at least as much as that used in the arc of the straight section (usually more).***
- ***Thus, straight section will have ~1/3 of the length in a cos theta dipole or in a serpentine. It's worse in double-helix.***
- ***In the optimum integral design, straight section length is the full coil length.***

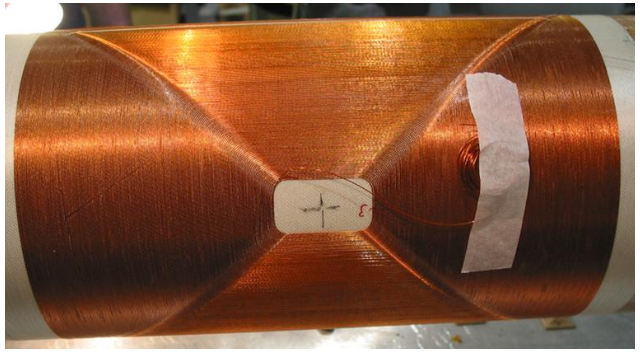


serpentine

Double-helix



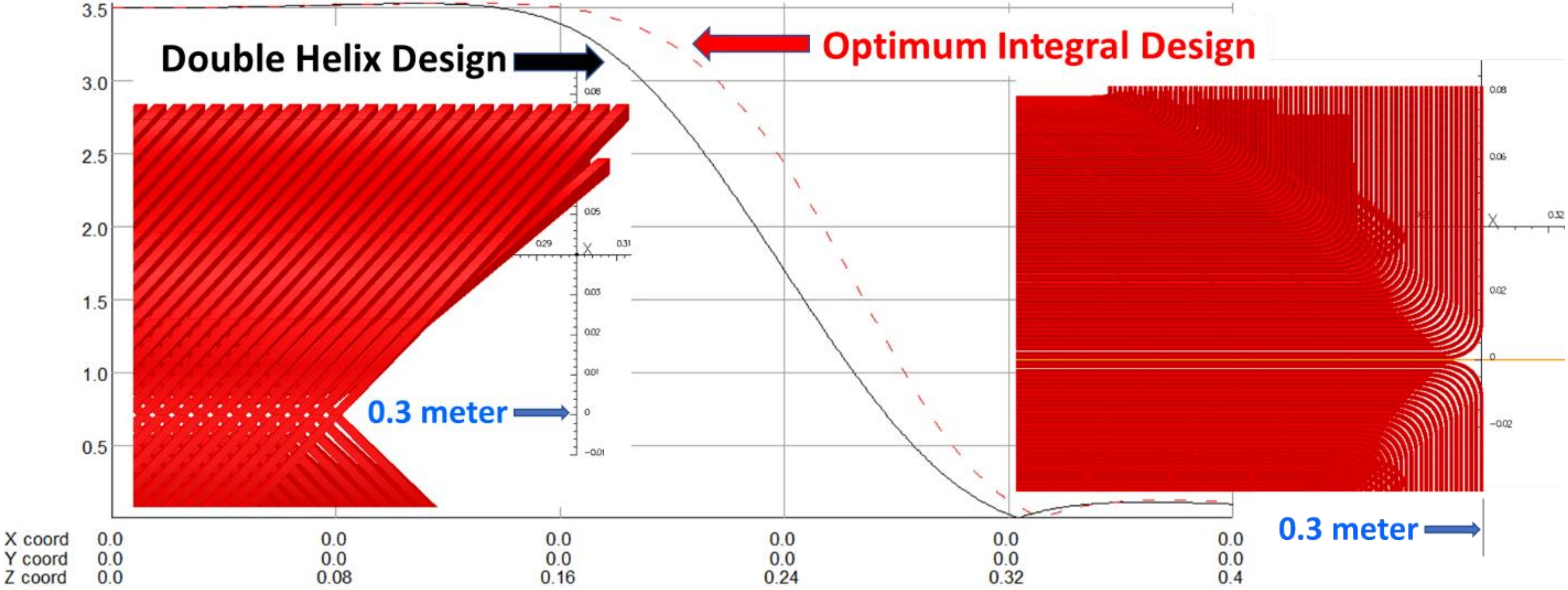
Cos theta



Optimum Integral

A Comparison between the Alternate Double Helix Design and the Optimum Integral Design as in the STTR Proposal

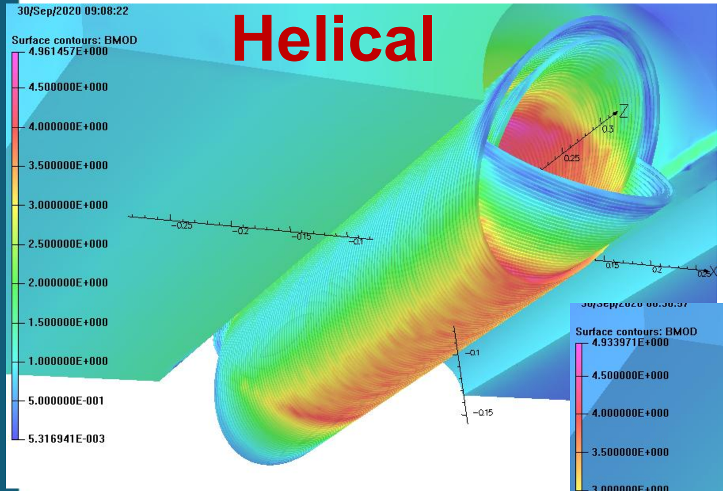
Optimum integral design extends the magnetic length for the same coil length



Phase I & Phase II funded for the demonstration of B0aPF

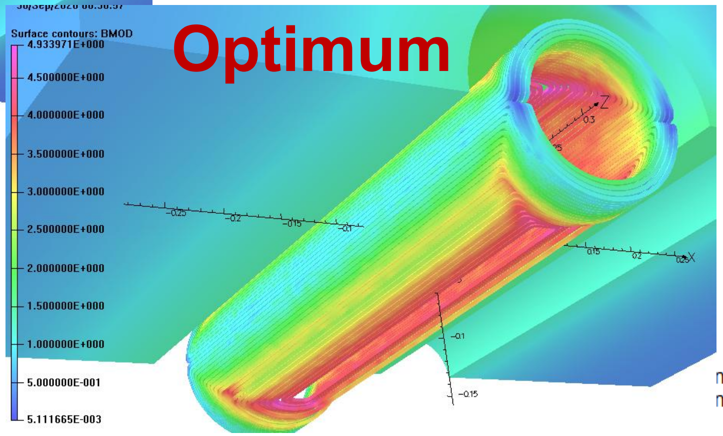
Argument Made for Optimum Integral Design B0apF STTR

- **Optimum integral design reduces the maximum field by 10-20%. Lorentz forces, stored energy and stresses goes as square of the field. The design is not part of the baseline design of EIC and therefore it can be for SBIR/STTR. Once proven, can be used in EIC.**
- **B0Apf dipole for EIC has an aperture of 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.**

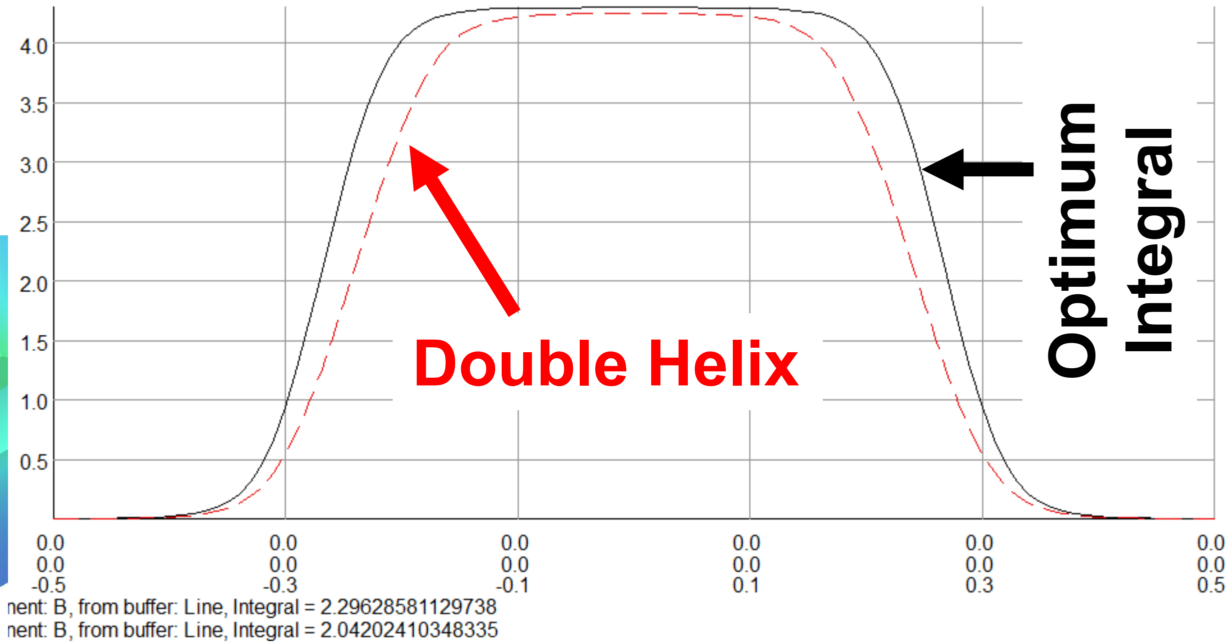


Peak Field 4.96 T for integral field of 2.042 T.m

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



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



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

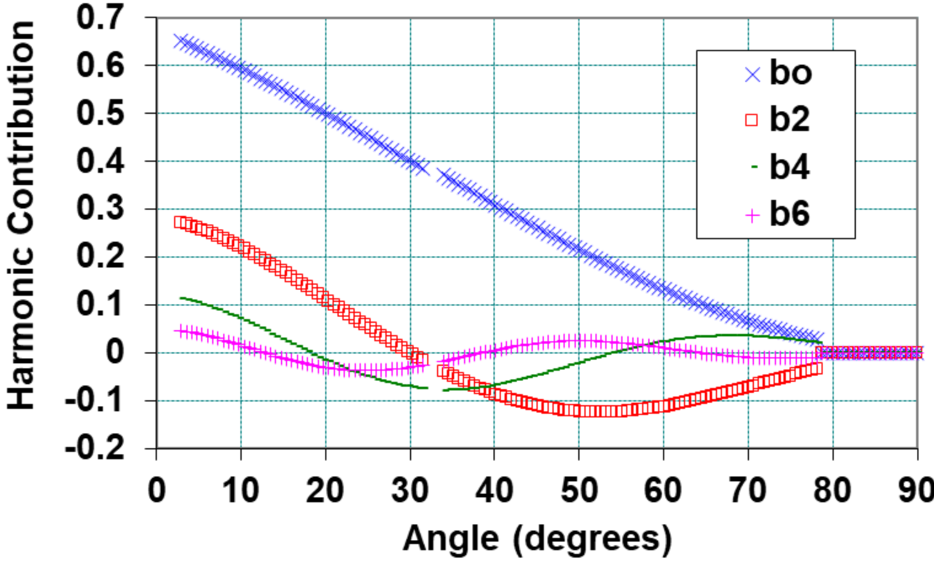
- **Full-length midplane turn defines the length of the magnet**

Essentially no loss due to magnet ends

Integral harmonics:

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

The length “L” is different for different turns



(Note: b_2 is sextupole)

Integral harmonics can be optimized with EXCEL

How Optimum Integral Design code differs from most other 3-d codes in optimizing integral harmonics

- Most codes first compute field (or vector potential) along the length at several places and then compute and integrate field harmonics and then optimize them.
- Optimum integral code directly computes integral harmonics from each conductor

Integral harmonics:

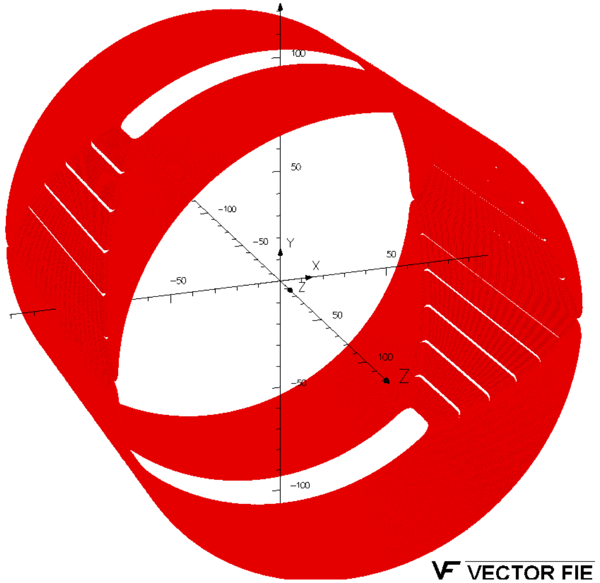
$$B_n = 10^4 \left(\frac{R_0}{a}\right)^n . L . cos\left[(n+1)\,\phi\right]$$

➢ This is an order of magnitude faster. The formulae are valid when the field is 2-d or when it is integrated over the entire length. Iron is included as the image current.

➢ The downside is that it doesn't do anything else – like peak field, field in the aperture, etc., etc., etc.. To overcome that limitation, we create output files which are input for OPERA (or RAT) and those calculations are performed there.

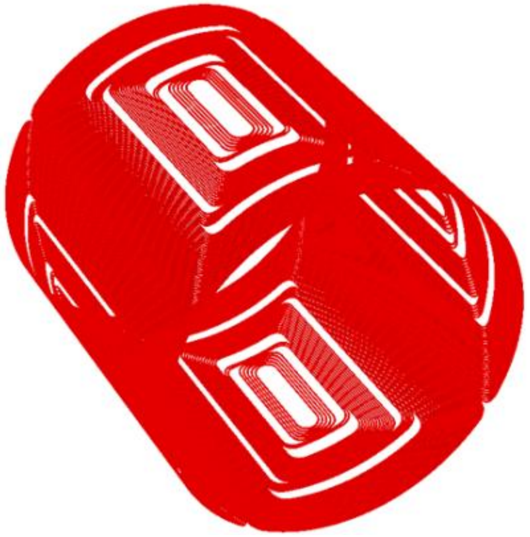
Opening A New Parameter Space with the Optimum Integral Design
(not considered practical for superconducting magnets before)

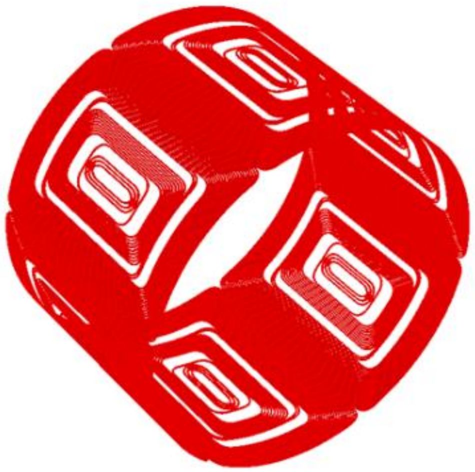
- **High field quality dipoles with coil length less than the coil diameter**
- **Quadrupole magnets with coil length less than the coil radius**
- **Sextupole magnets with coil length less than 2/3 of the coil radius**



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

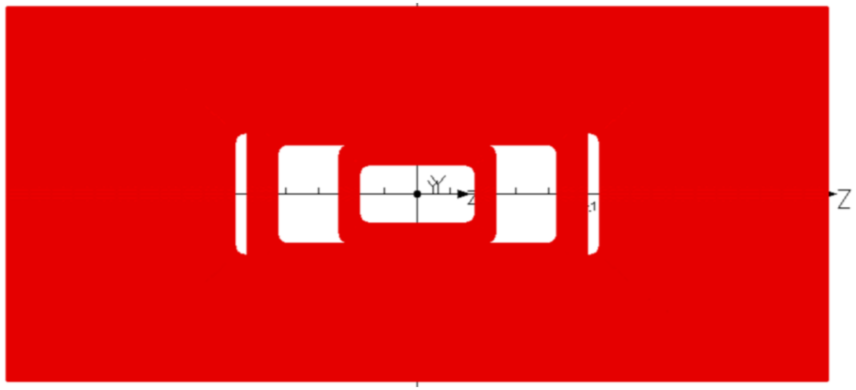
Coil length 175 mm; coil diameter 200 mm.





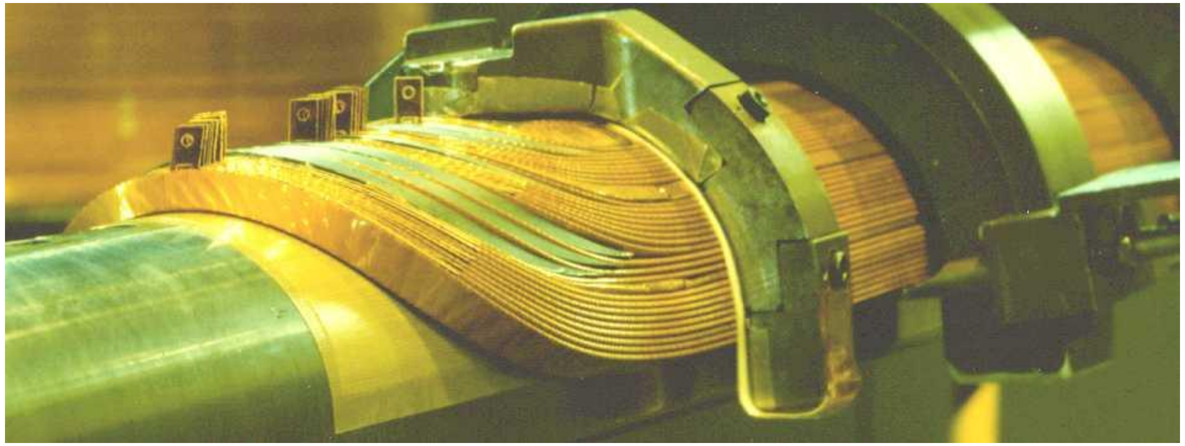
COMPUTED INTEGRAL FIELD HARMONICS FOR A SHORT DIPOLE (COIL LENGTH < DIAMETER) AT A RADIUS OF 66.6 MM. THE COIL RADIUS IS 100 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

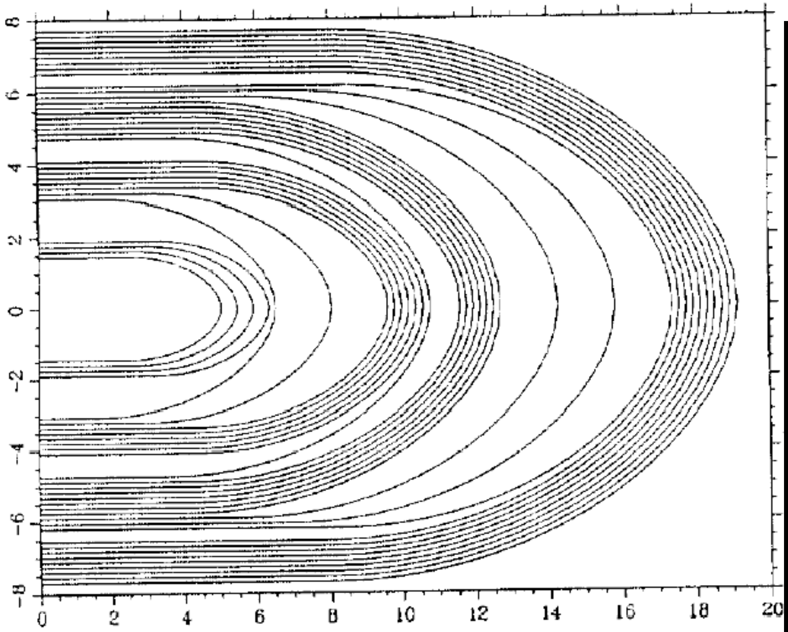
Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.00273 @ 25 A	0.0	0.0	0.0	0.0	0.0	0.0

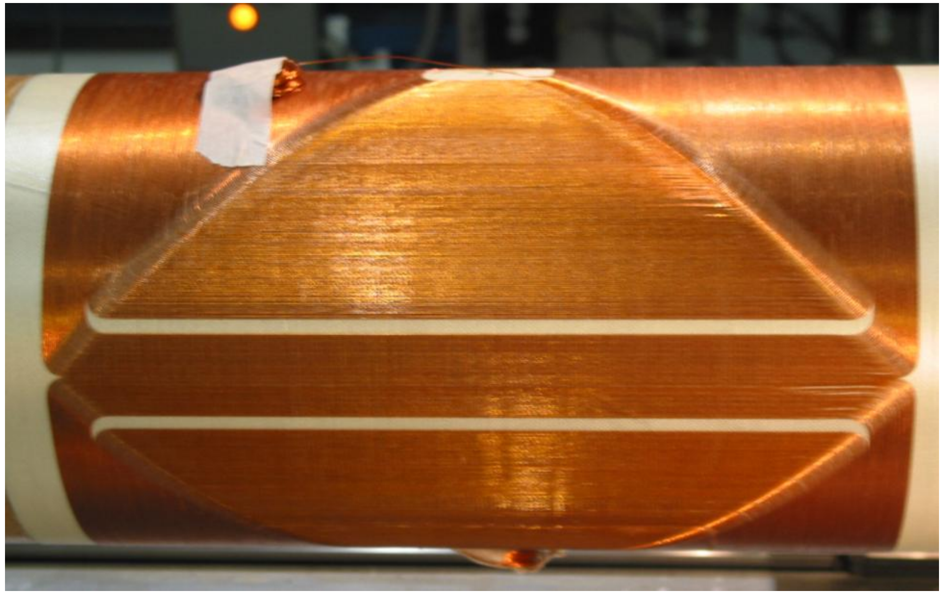


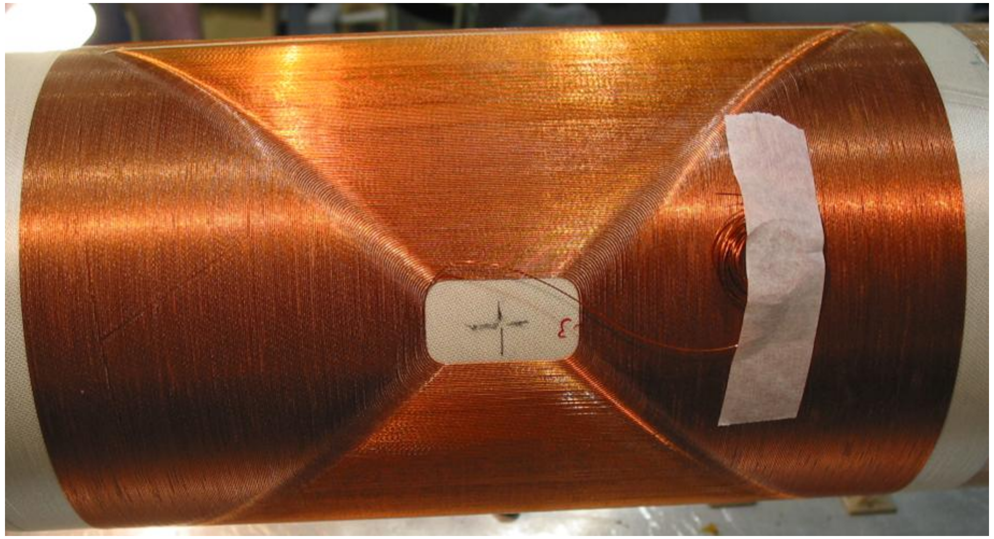
A Dipole Optimized with End Spacers Only

Comparison between the Convention and the Optimum Integral Design









Compare the length of midplane turns between the conventional and in the optimum integral design. Difference matters more in short magnets.

Three Phases of the Overall Program

(original as was in the proposal => enhanced as in built)

- Phase I: Two layers, short length => Two layers, Full length
- Phase II (year 1): Four layers => Six layers
- Phase II (final): Ten layers => Twelve layers

Twelve layers, instead of ten gave ~10% margin at 4 K.

➢ **Test results of each phase will be discussed briefly.**