



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*:
 - $B_0 = 3.9$ 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 each dipole end: \sim two coil diameter
- Loss in integral field due to ends starts becoming significant when the total coil length (L) $< \sim 8 \times$ coil diameter (a) in dipoles

RHIC Dipole Coil End



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

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, $a = 114$ 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

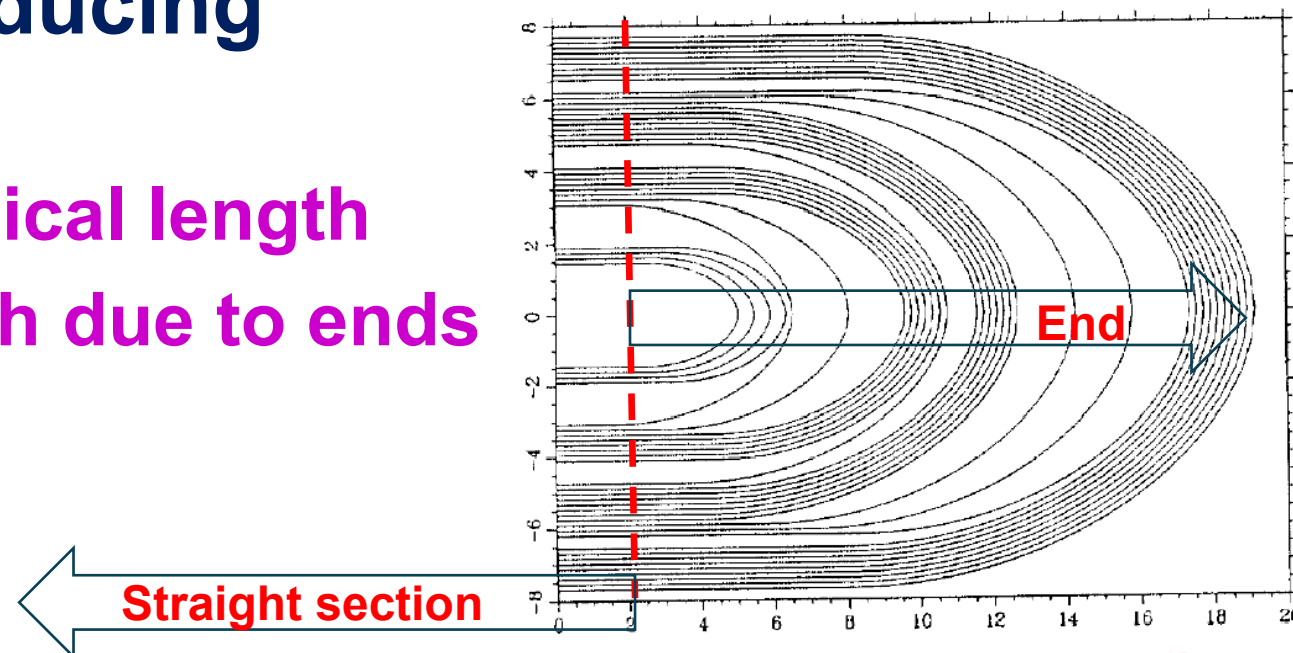
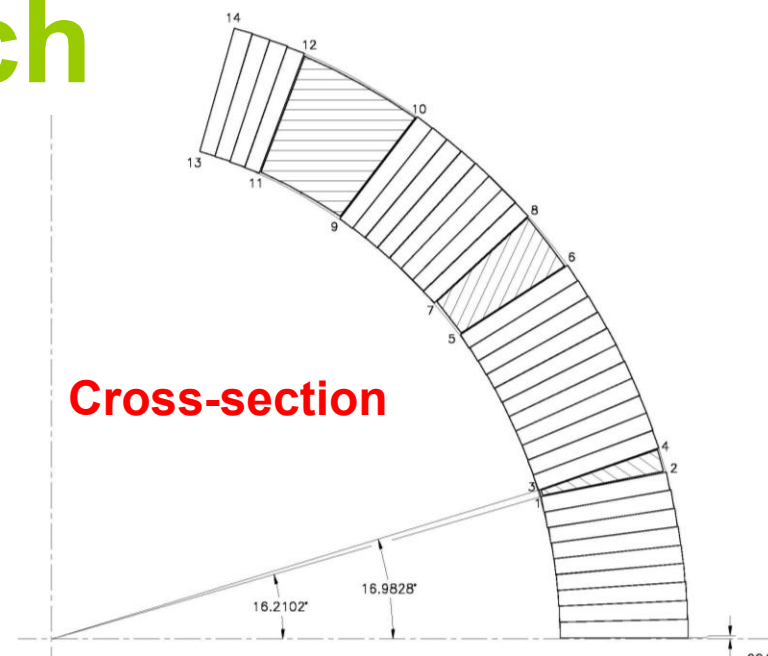
A two-step process:

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

$$I(\theta) = I_0 \cdot \cos(n\theta)$$

Step 2: Optimize ends for reducing harmonics and peak fields

- ❑ magnetic length: $\sim \frac{1}{2}$ mechanical length
- ❑ typical loss in magnetic length due to ends
 - Dipole: one coil diameter
 - Quadrupole: one coil radii



What? Optimum Integral Design Approach

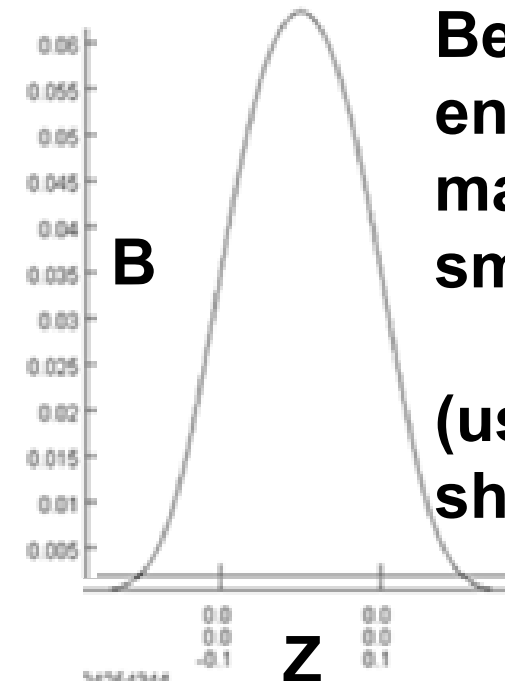
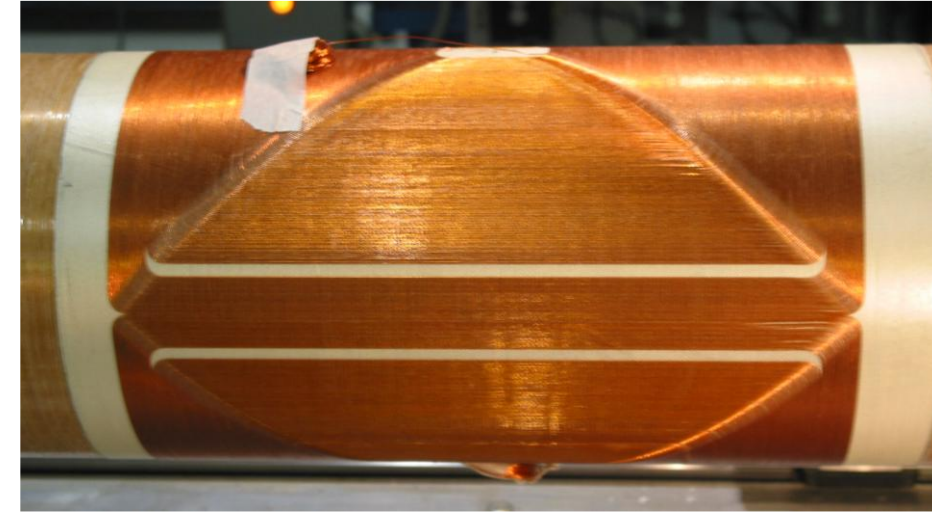
Optimize cross-section and ends together in a single step to obtain cosine theta distribution in an integral sense:

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

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.

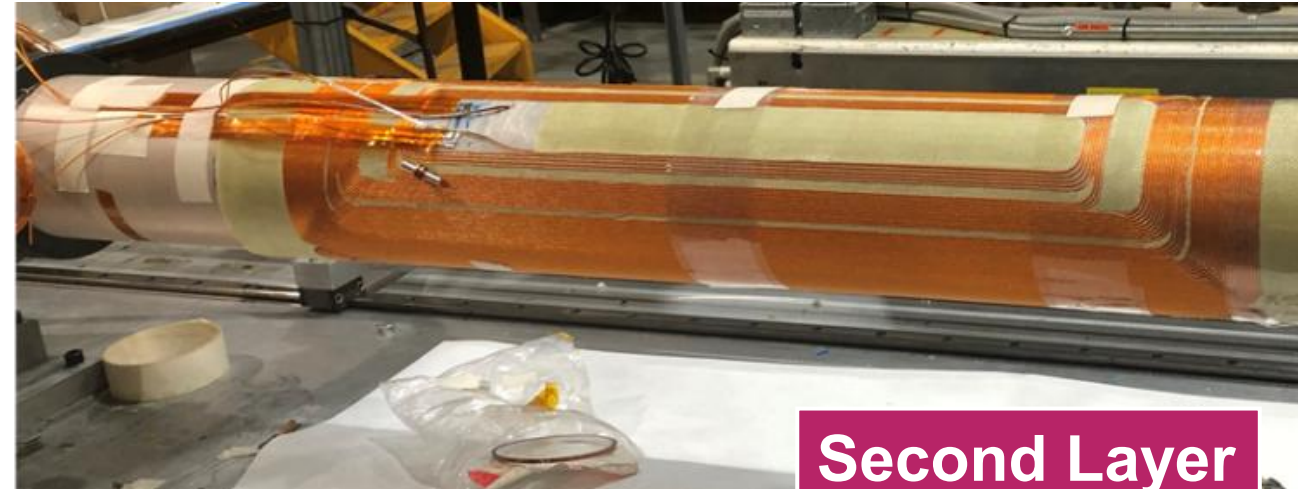
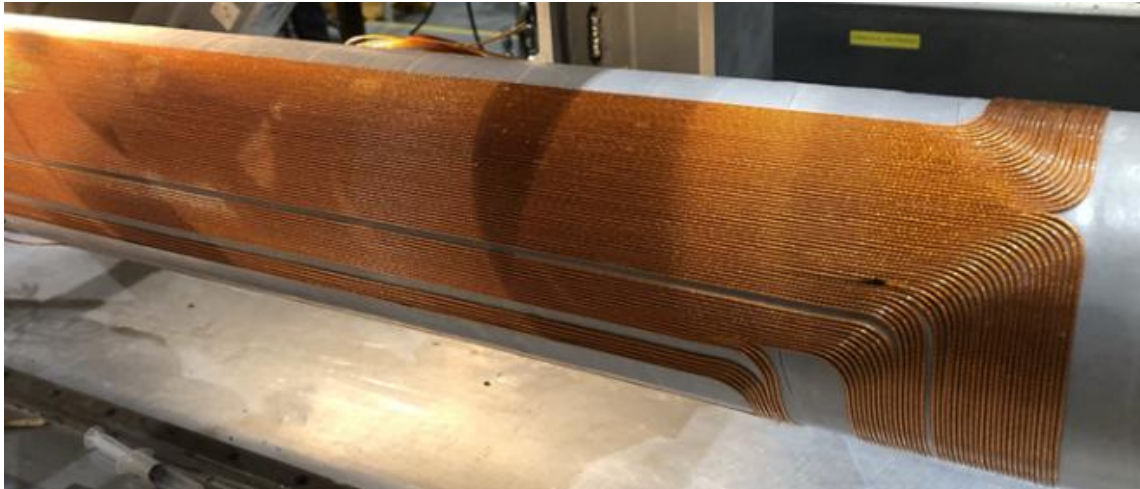
Optimum Integral Dipole - Phase I Coil (two layers)

Note: Midplane turns extends full length

First Layer



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

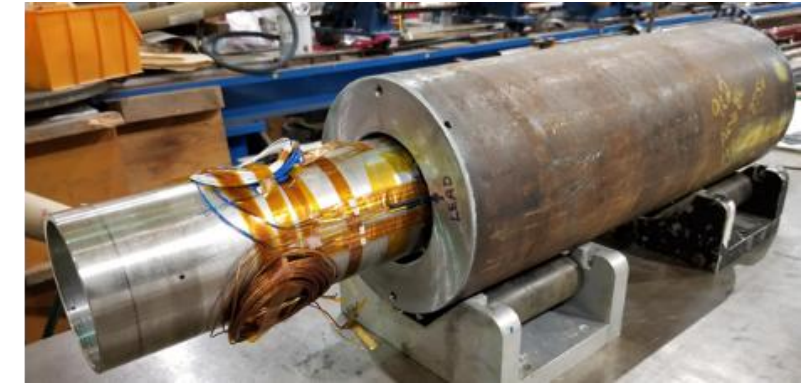


Second Layer

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

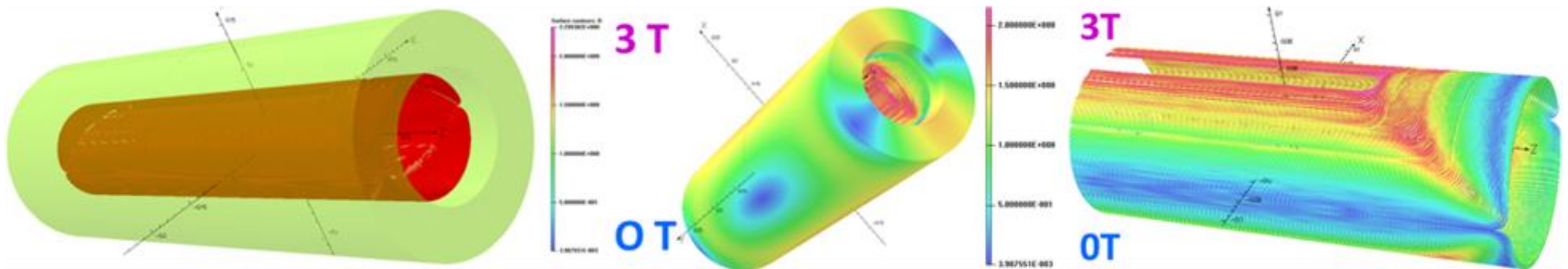


Tension rowing over two layers to contain forces



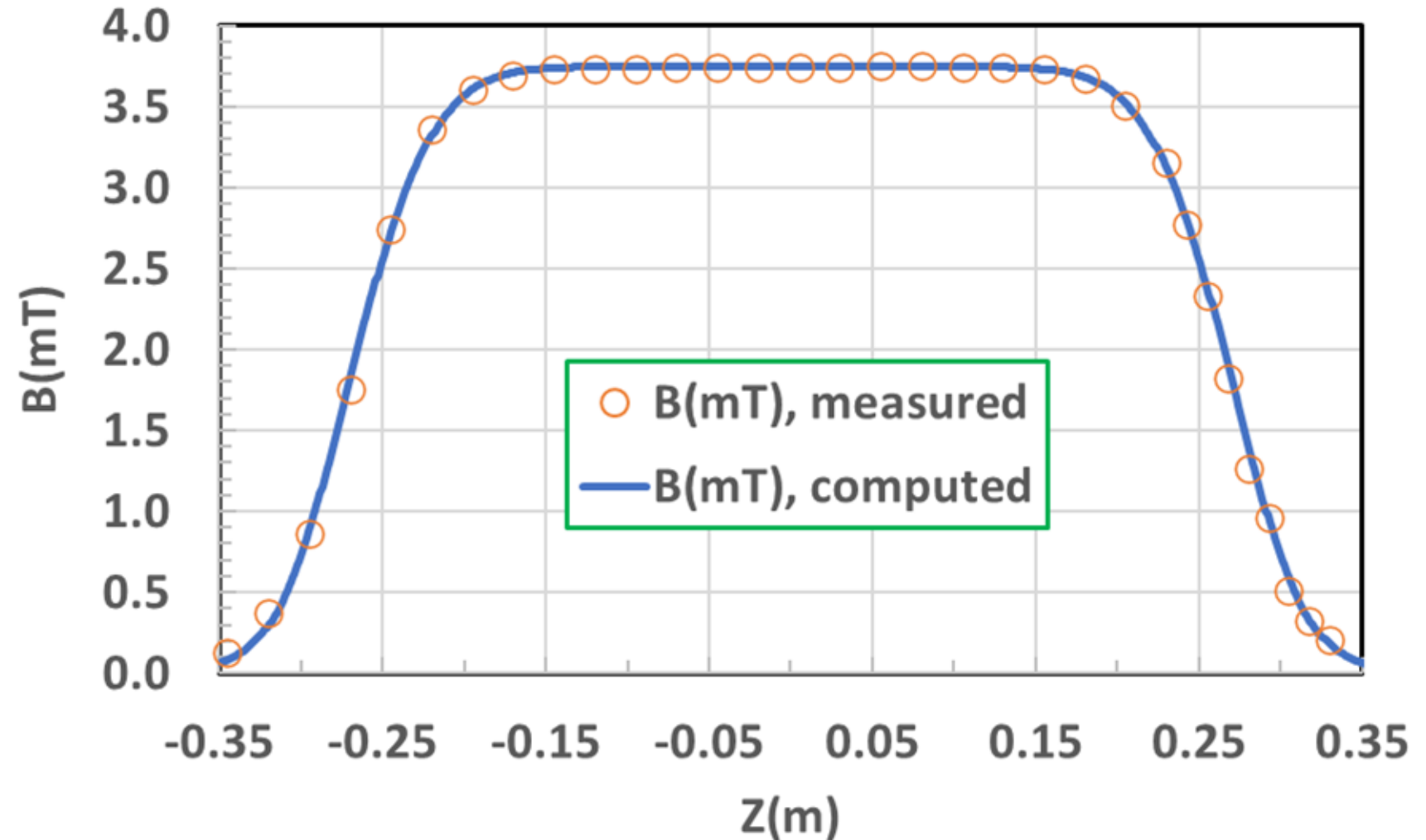
Coil in yoke, ready for test

Expected Performance: $B_o = \sim 1.7 \text{ T}$, $B_{pk} = \sim 2.2 \text{ T}$, Coil i.d. = 114 mm



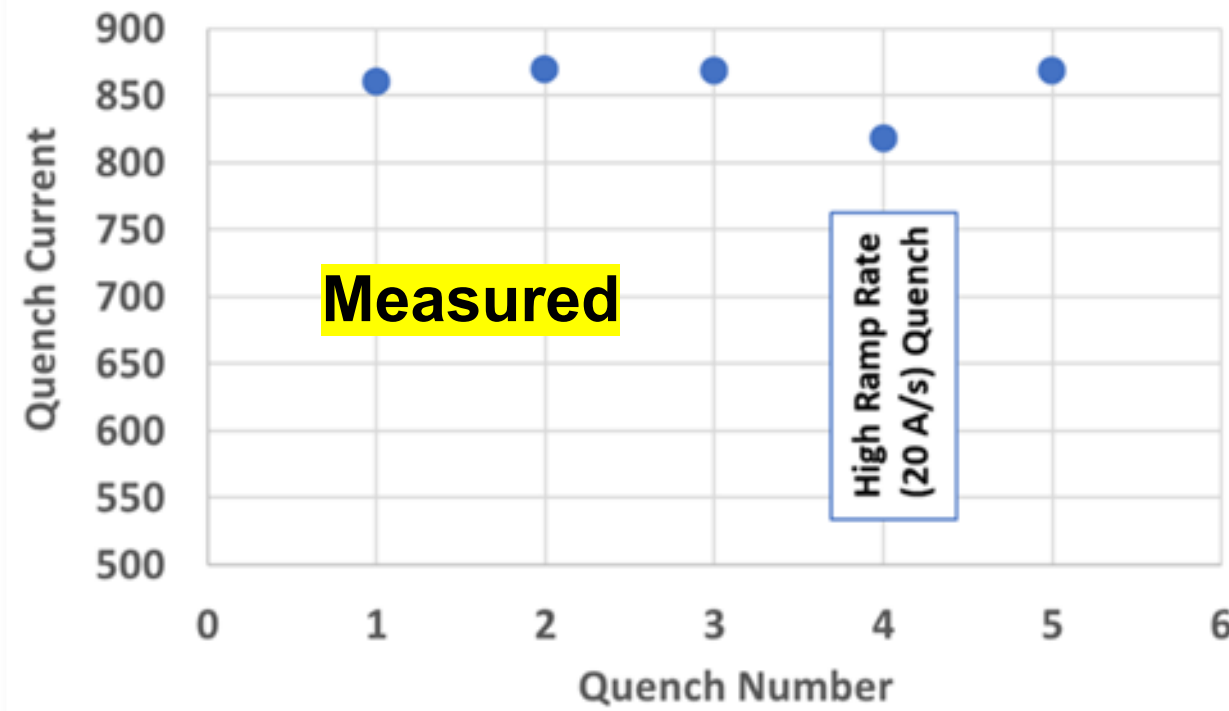
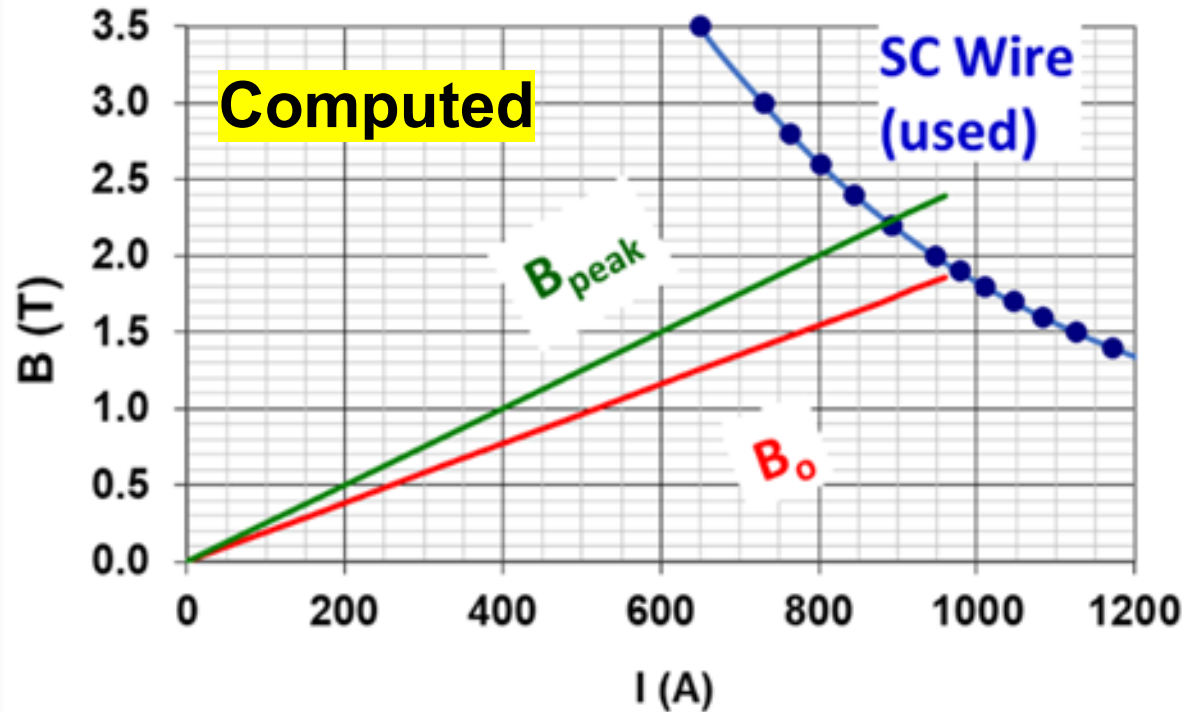
Question #1: Will optimum integral design extend the magnetic length?

**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?



$B_o = \sim 1.7$ T, $B_{pk} = \sim 2.2$ 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)

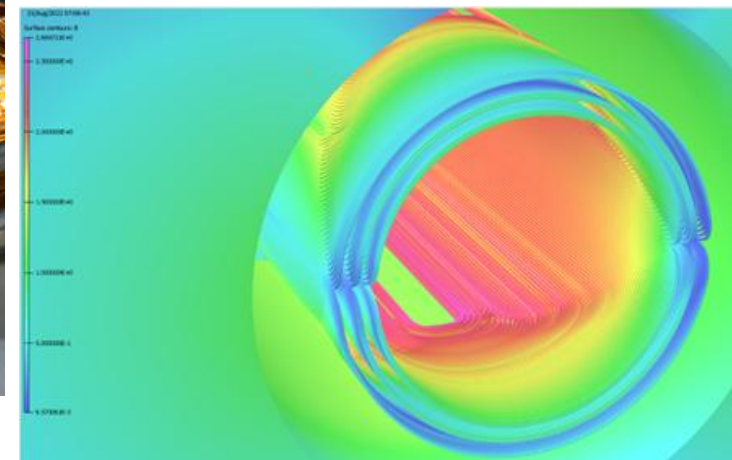
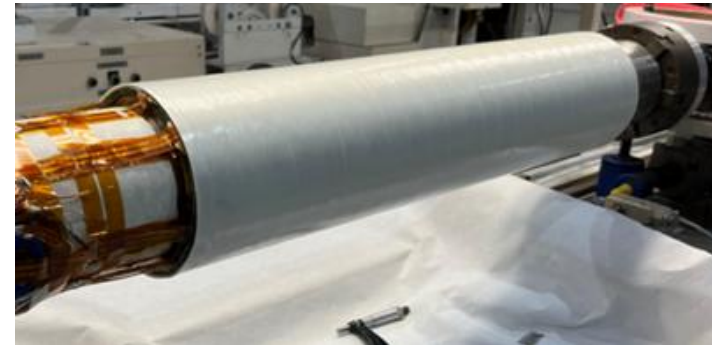
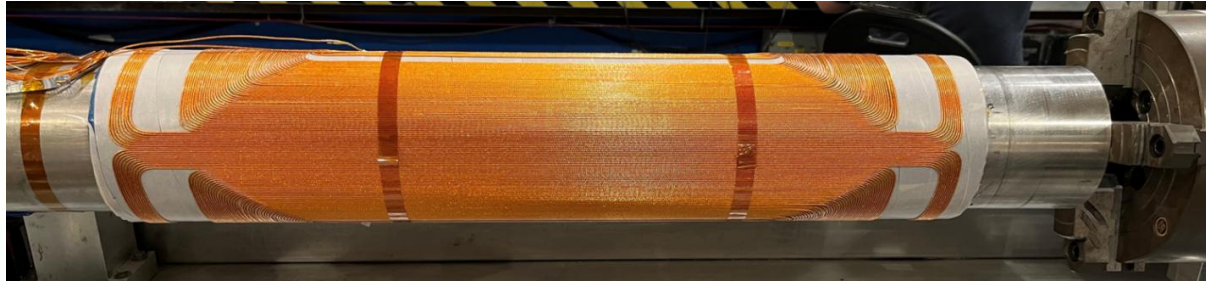
a) Demonstration of a good field quality (warm measurements):

- 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)



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.

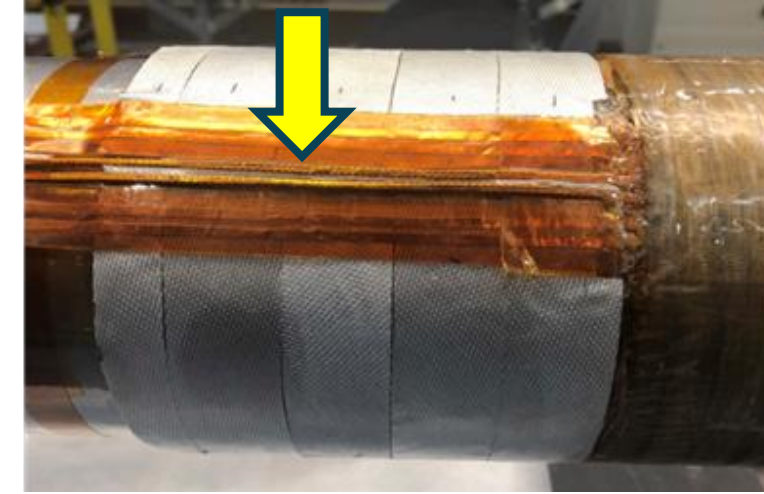
All other harmonics <2 units (meets the spec)

➤ A good field quality despite several changes on the fly (as in any R&D project)

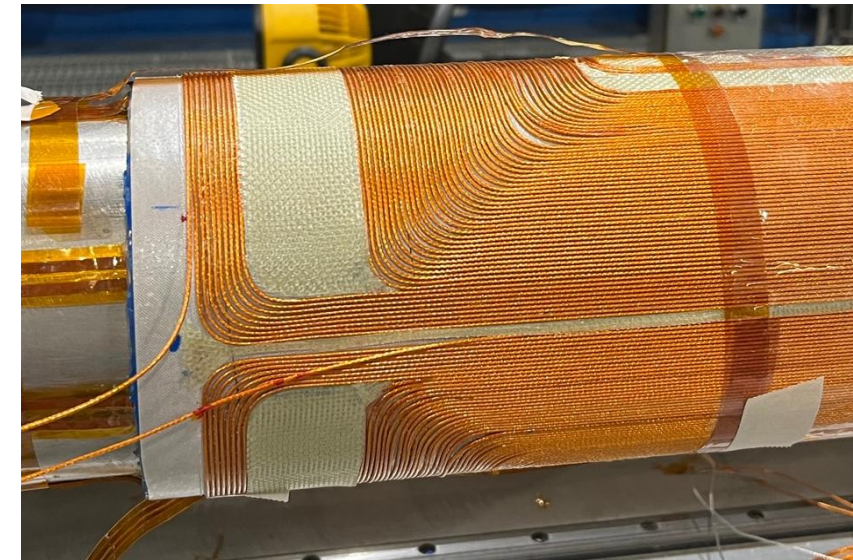
➤ Remaining small harmonics are compensated in the next layers.

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.
- 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.

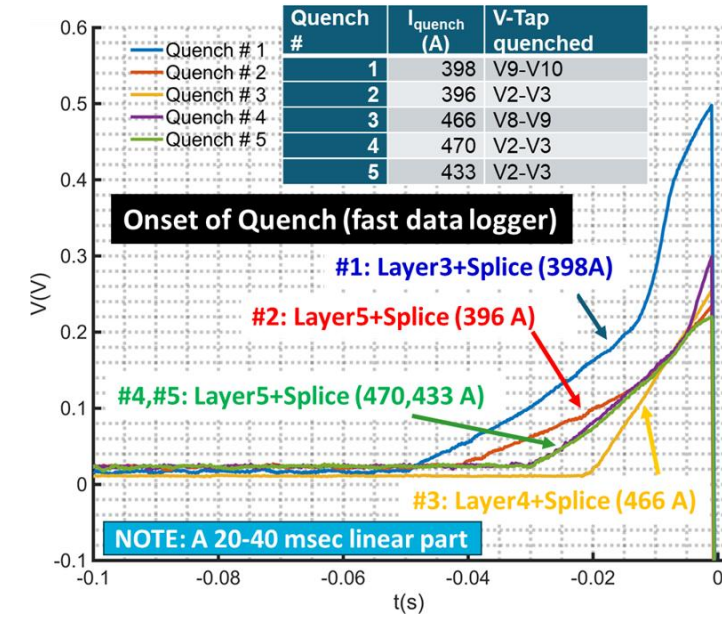
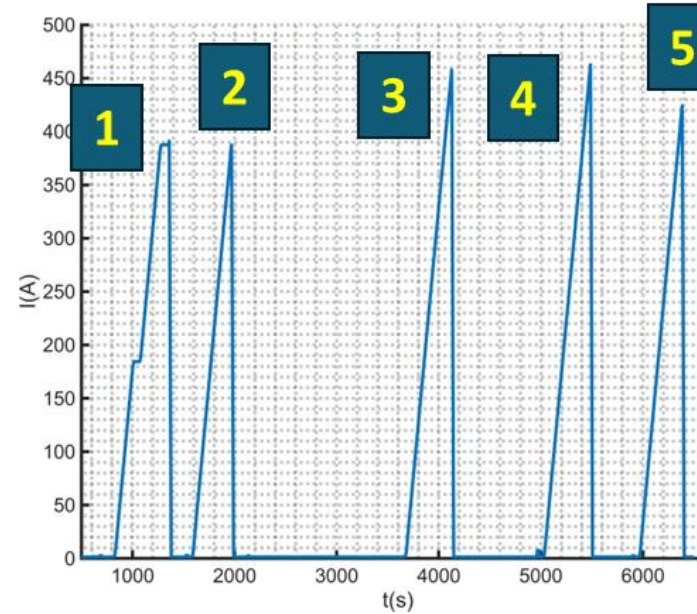
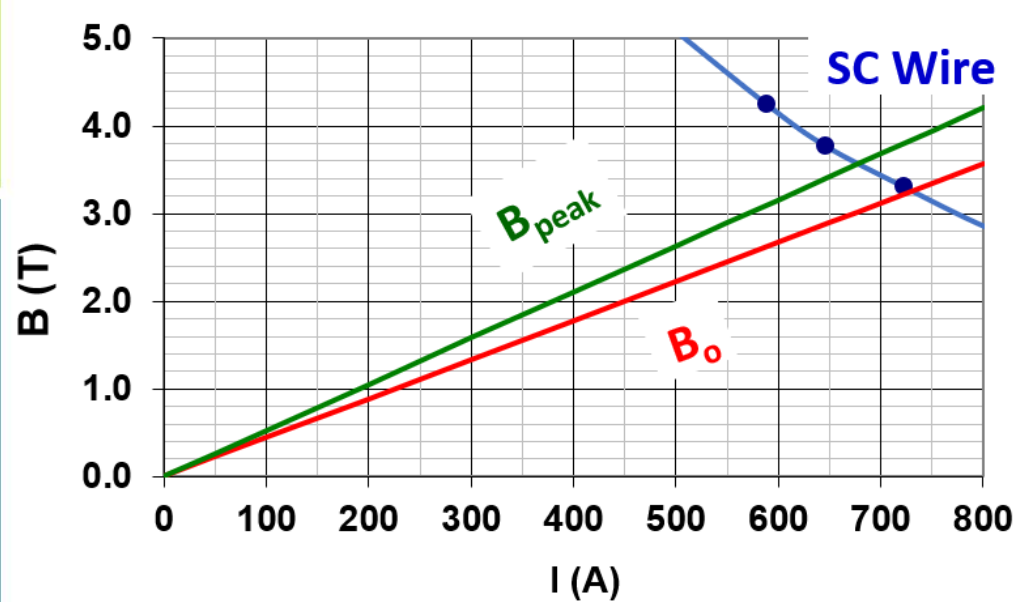


Phase I configuration



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.

Final Goals/Targets of the Phase II

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

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

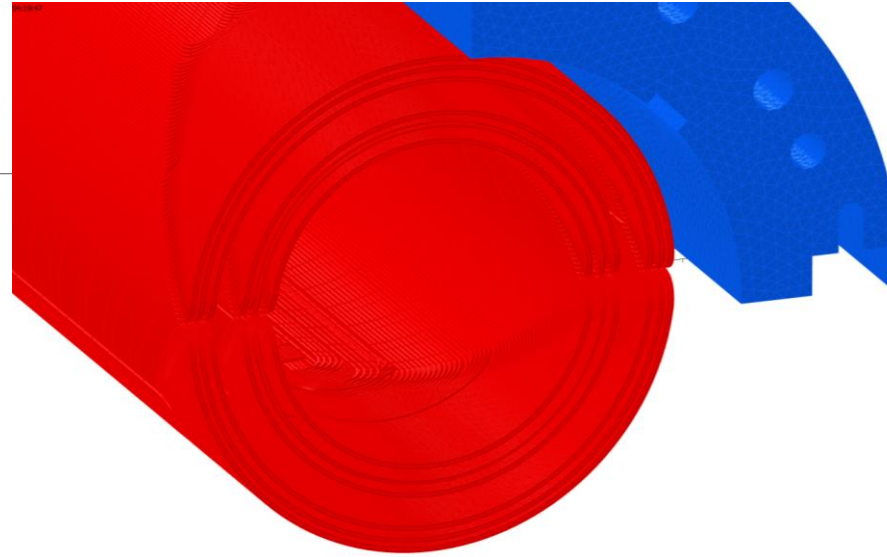
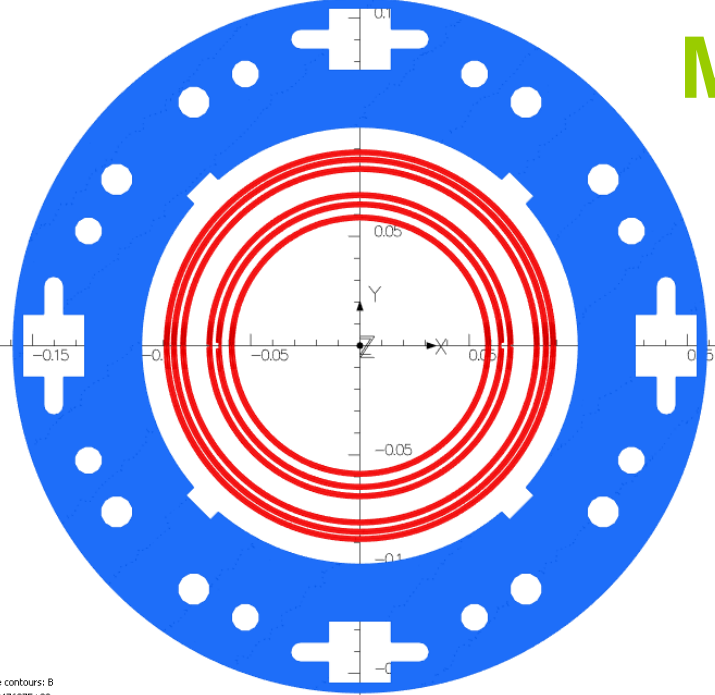
12 layers provided some additional margin for the 4.2 K test

➤ 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 OI D 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**

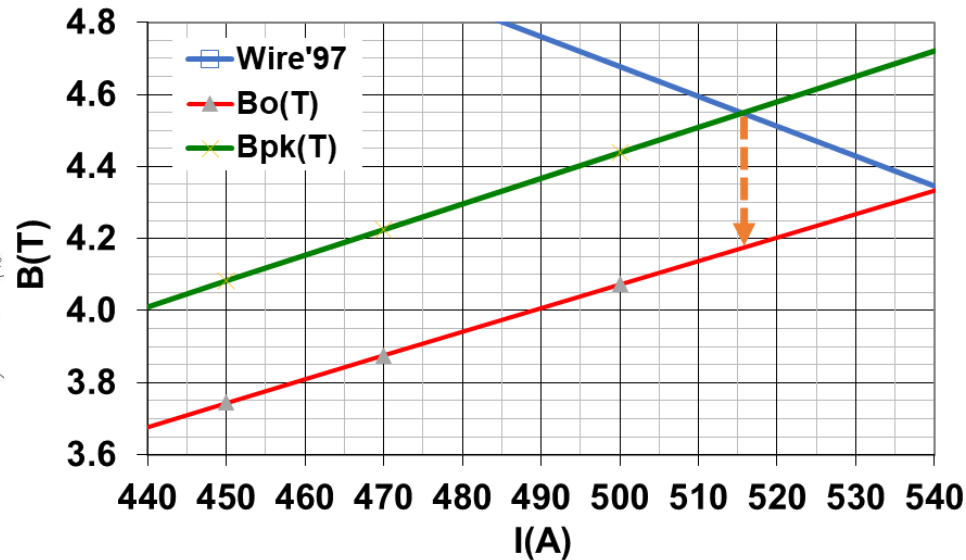
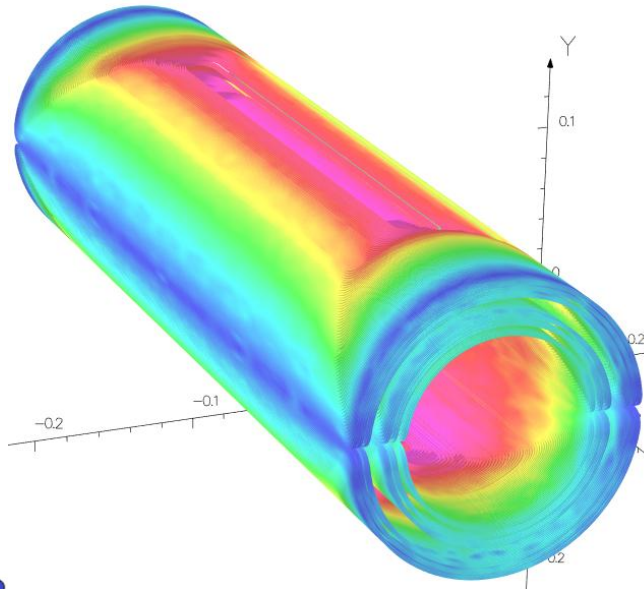
Surface contours: B
2.047697E+00

1.500000E+00

1.000000E+00

5.000000E-01

2.651350E-03

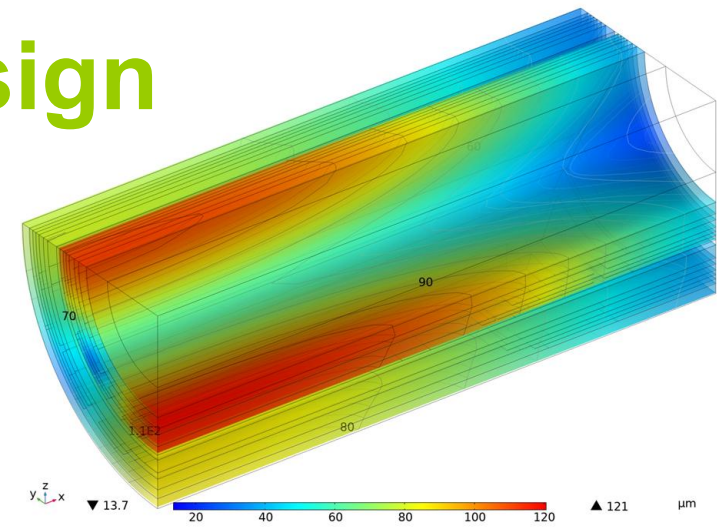


- Superconducting wire diameter: 0.33 mm
- Filament diameter: 10 μ m
- Cable type: 6-around-1
- Cable diameter (bare): 1 mm
- Cable diameter (Kapton insulated): 1.1 mm
- Critical current (4.2K, 5T): > 421 A
- Copper to superconductor ratio: 2.25
- Cable used in the magnet: 1.7 km
- Computed quench current at 4.2 K: ~500 A

Mechanical Design of the 12-layer Design

Primary components of mechanical design:

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

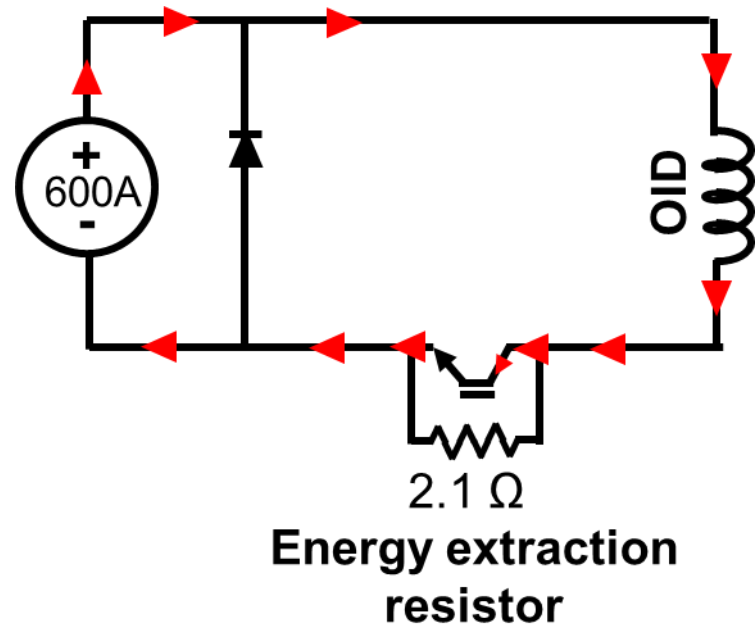


Analysis with COMSOL

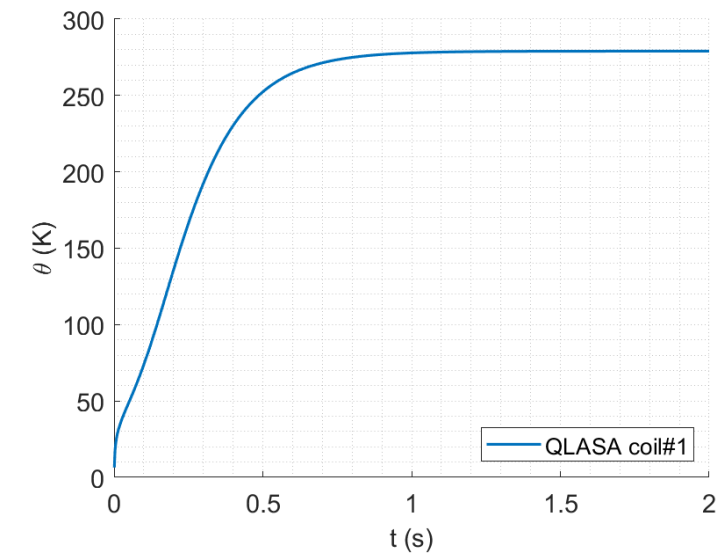
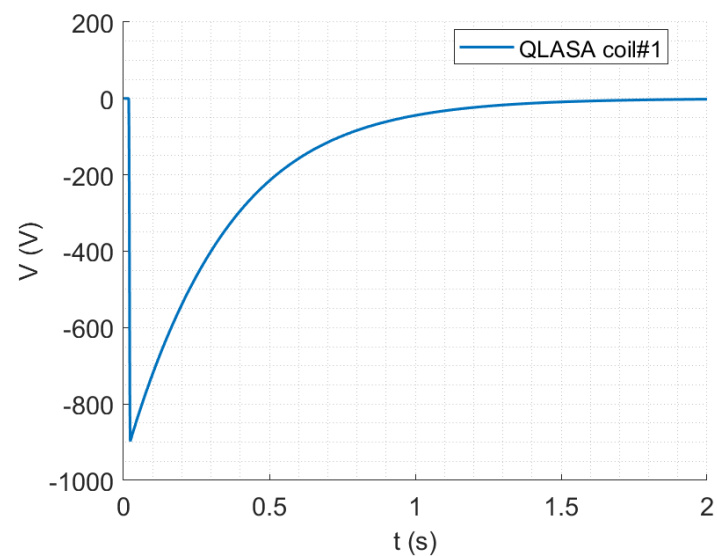
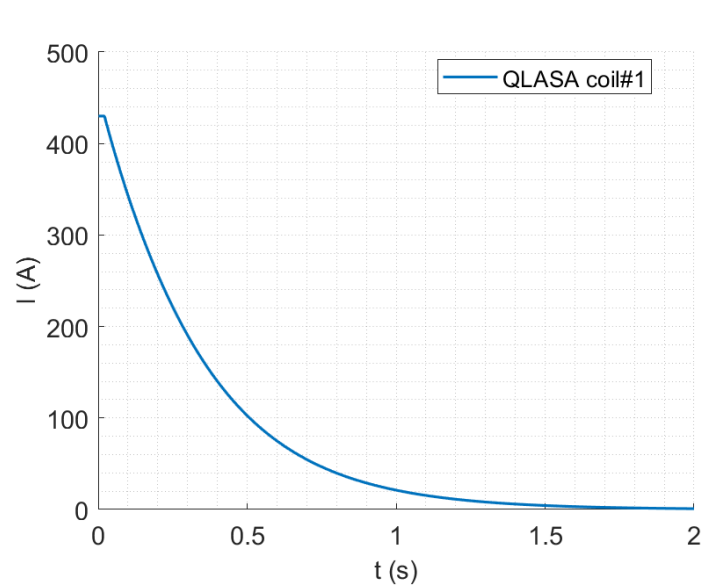


Quench Protection

QLASA simulation
@ $I = 430\text{ A}$
 $L = \sim 0.7\text{ H}$
 $R_{\text{dump}} = 2.1\text{ }\Omega$



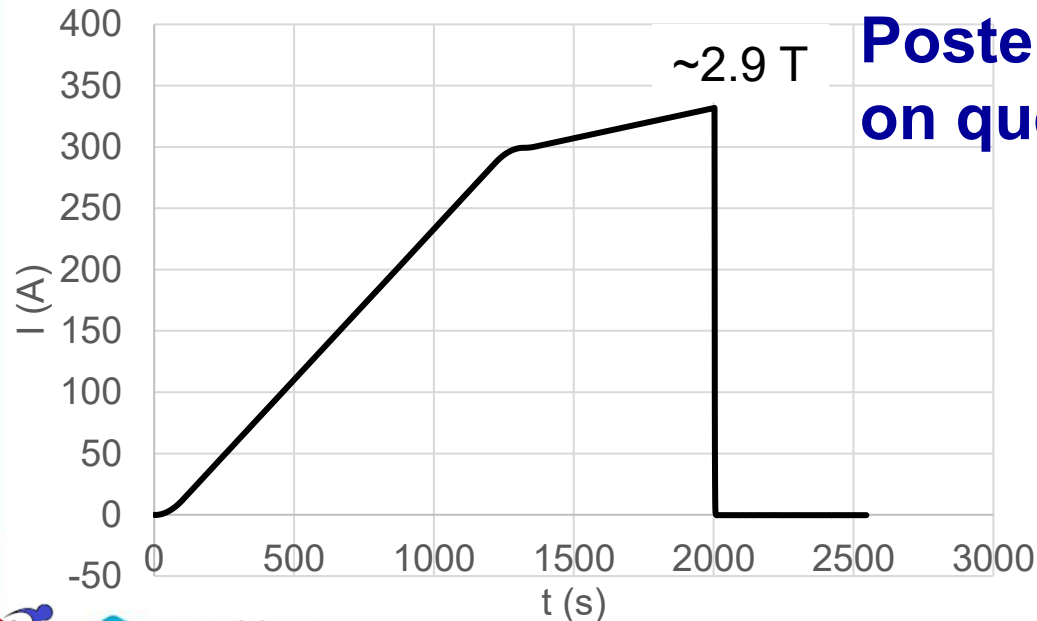
Parameter	Value
MITs	0.0353
Hotspot temperature	279 K
Voltage total	898 V
Voltage to GND	449 V
Decay time constant	337 ms



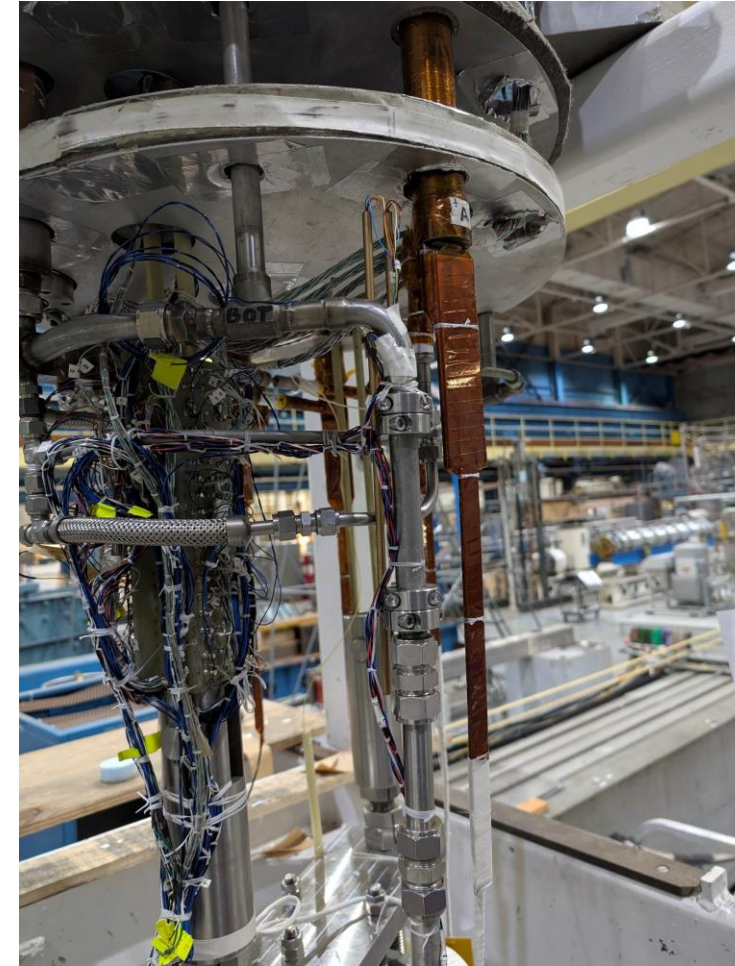
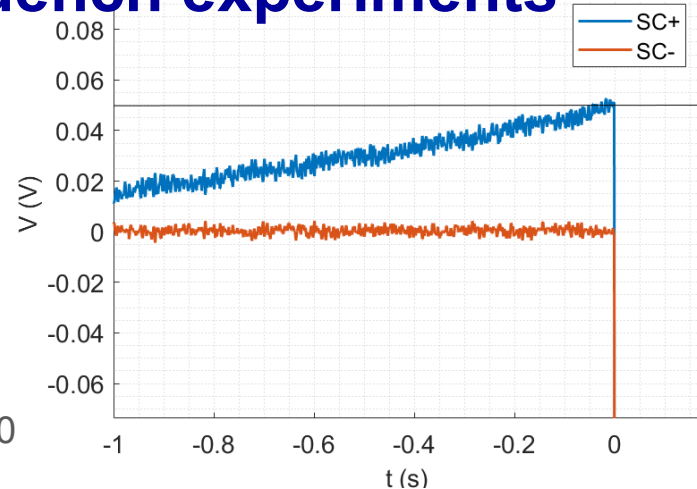
Test Results of the 12-layer Direct Wind Optimum Integral Dipole B0ApF

- 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
- 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



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

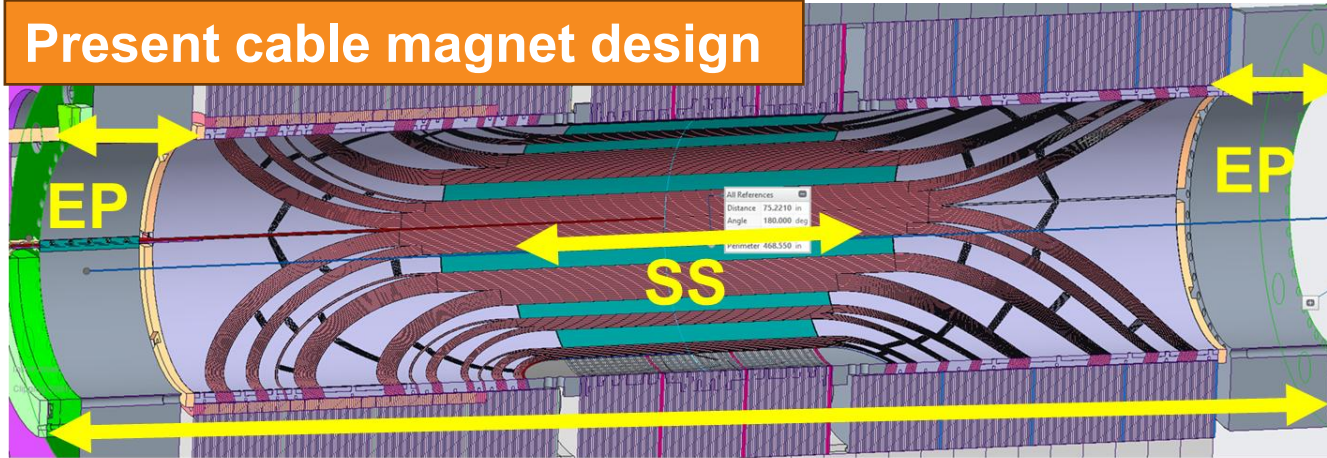
- Optimum integral design minimizes the loss in magnetic length due to the ends. Benefits are significant in short magnets, as in just tested EIC IR dipole B0ApF.
 - Poster Fri-Mo-Po.05-03 for the optimum design of EIC IR dipole magnets B1pF & B1ApF.
- Extension of magnetic length and good field quality have been demonstrated.
- The 12-layer magnet, built with the direct wind technology, was energized to ~ 2.9 T. This produces $\sim 74\%$ of the required field integral at ~ 4.2 K (extra margin at ~ 1.92 K) and $\sim 84\%$ of the RHIC arc dipole design field with no quench in the magnet.
- Above are significant demonstrations of the direct wind technology ($B_0 = 3.9$ T, coil i.d. = 114 mm, $L = 600$ mm) and of the optimum integral design for B0ApF (1.98 T.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

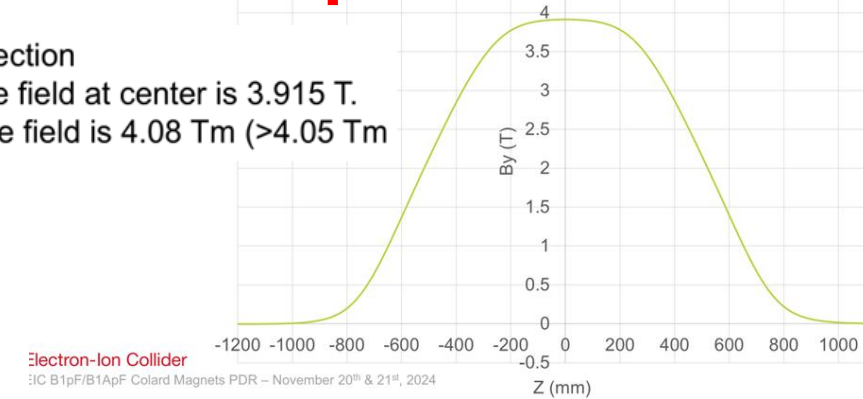
Optimum Integral design as examined for B1ApF (midplane turn extends full length to minimize the loss due to ends)

➤ Important for short magnets, like B0ApF and B1ApF in EIC

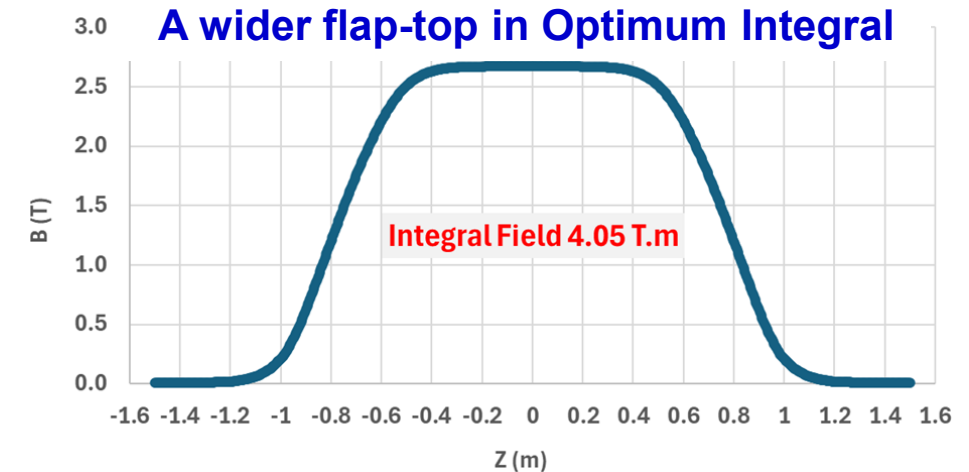
Present cable magnet design



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



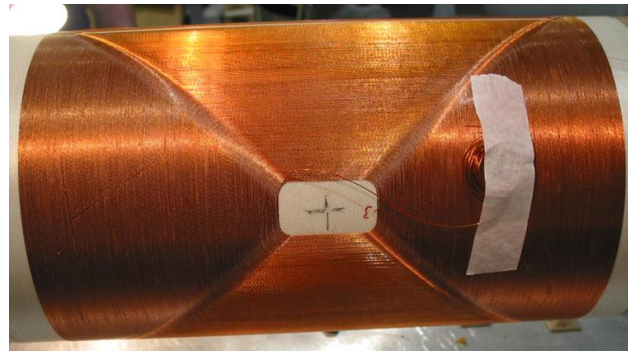
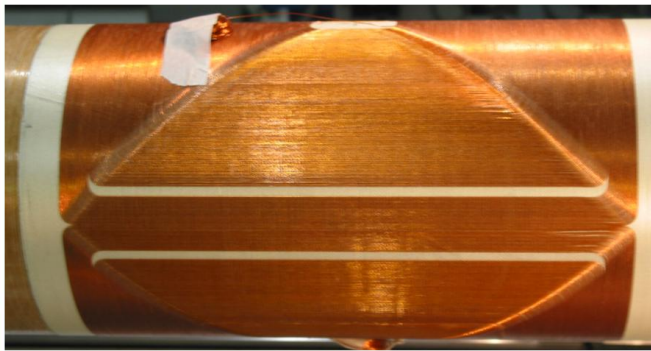
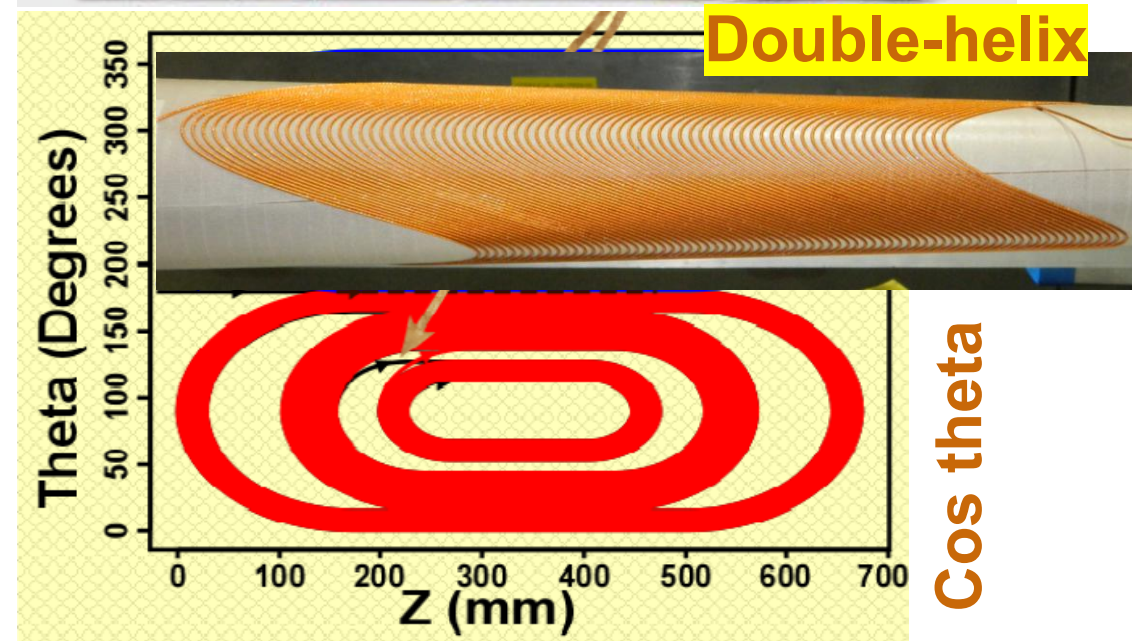
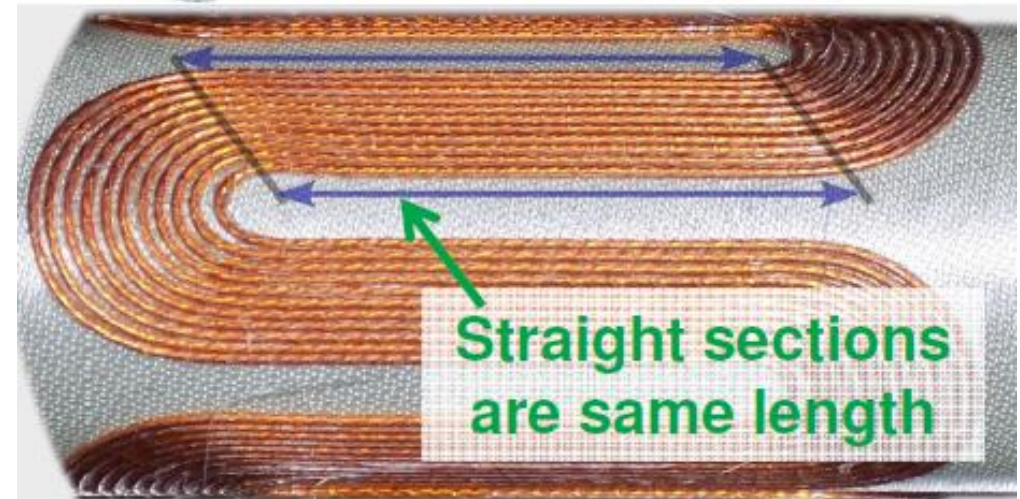
Direct wind optimum integral design



Technical benefit: B_0 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)

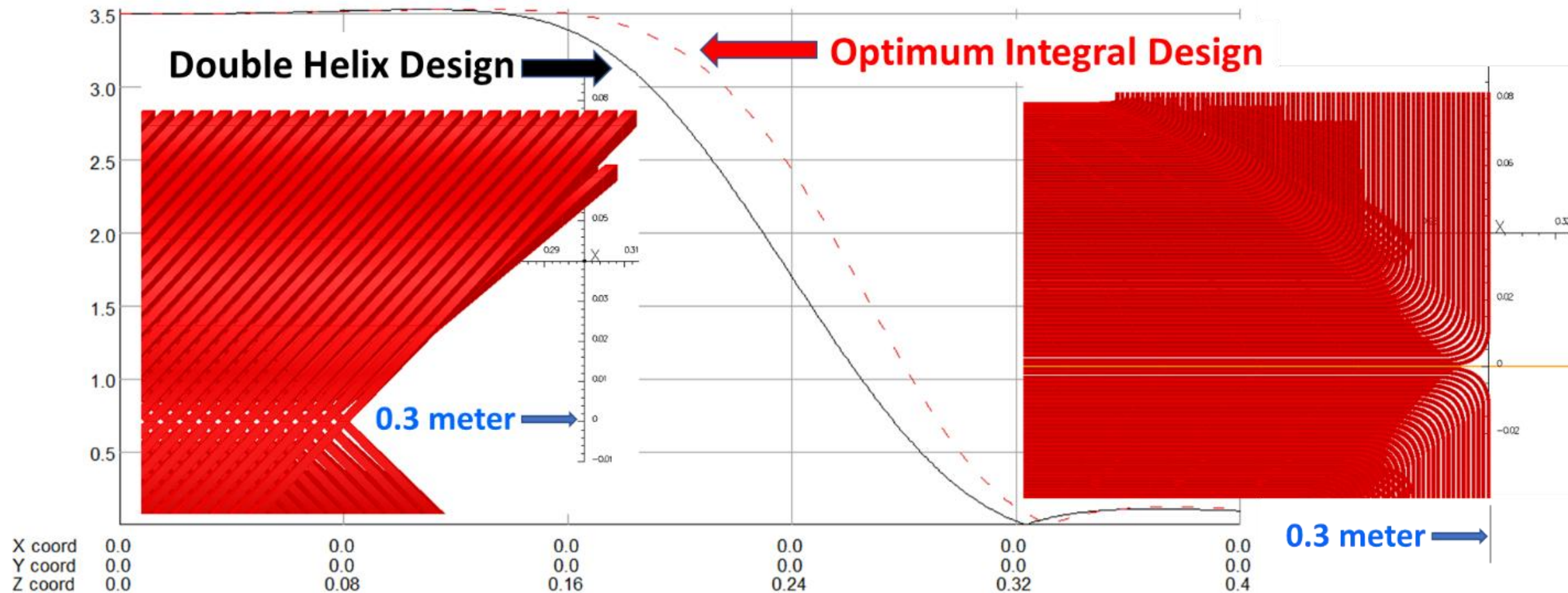
- Space for turns in the Ends must be at least as much as that used in the arc of the straight section (usually more).
- Thus, straight section will have $\sim 1/3$ of the length in a cos theta dipole or in a serpentine.
- In the optimum integral design, straight section length is the full coil length.



Optimum Integral

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

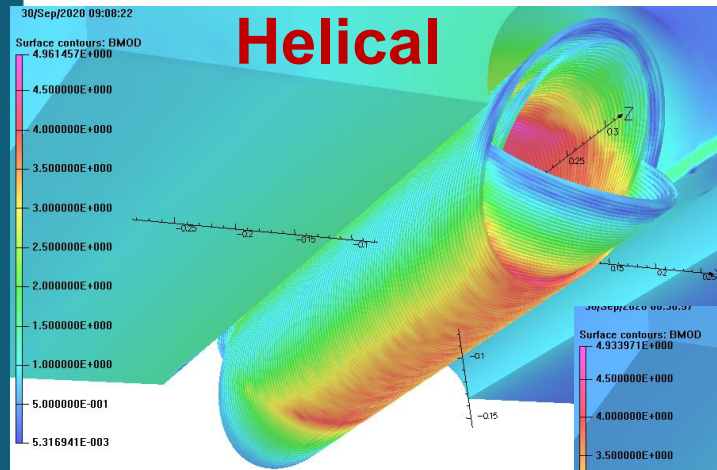
Optimum integral design extends the magnetic length for the same coil length



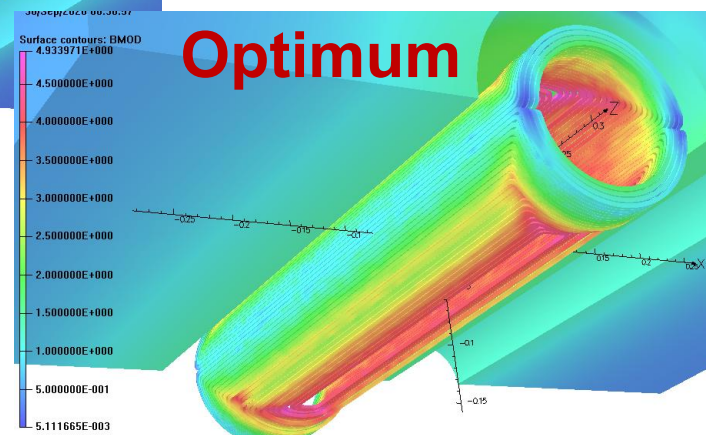
Phase I & Phase II funded for the demonstration of B0aPF

Argument Made for Optimum Integral Design B0apF STTR

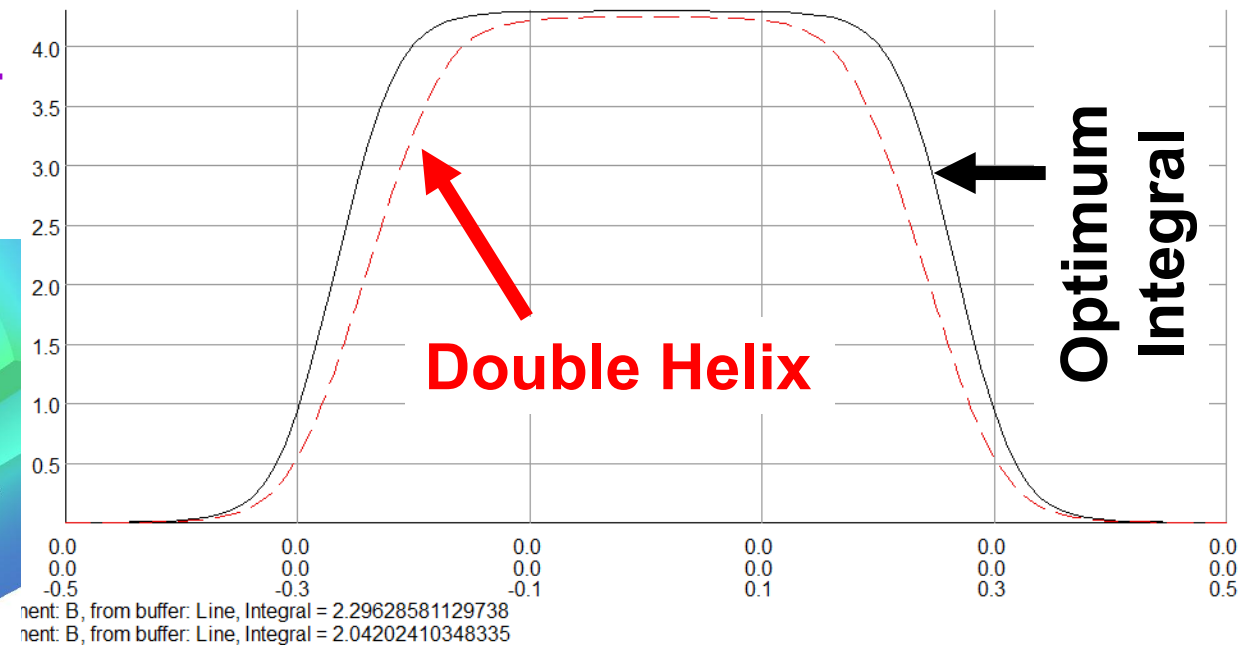
- Optimum integral design reduces the maximum field by 10-20%. Lorentz forces, stored energy and stresses goes as square of the field. The design is not part of the baseline design of EIC and therefore it can be for SBIR/STTR. Once proven, can be used in EIC.
- B0Apf dipole for EIC has an aperture of 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 4.93 T
for integral field
of 2.296 T.m



$\sim 12\%$ 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

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

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

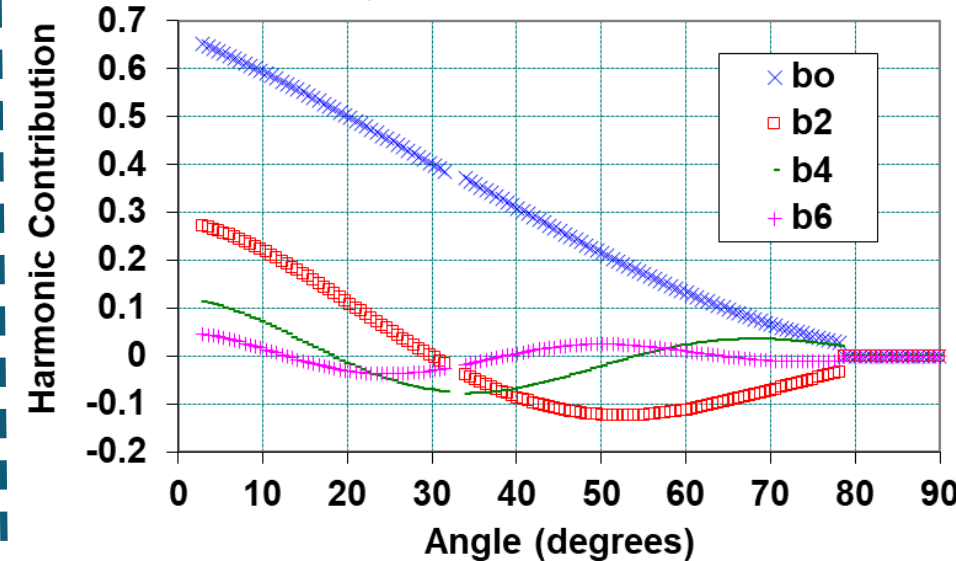
➤ Full-length midplane turn defines the length of the magnet

Essentially no loss due to magnet ends

Integral harmonics:

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

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

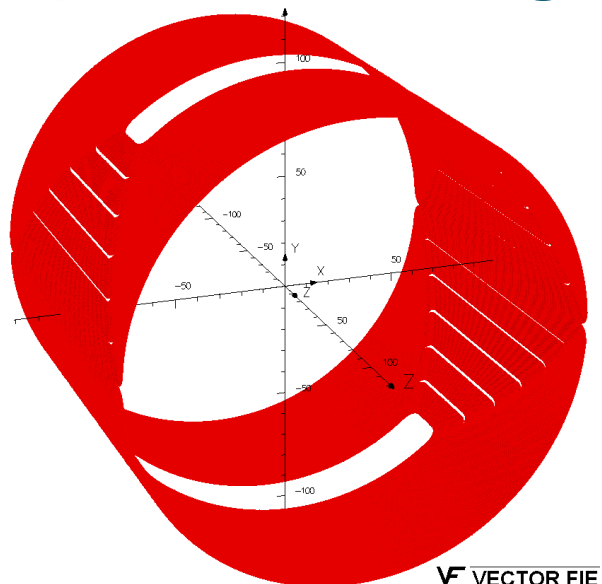
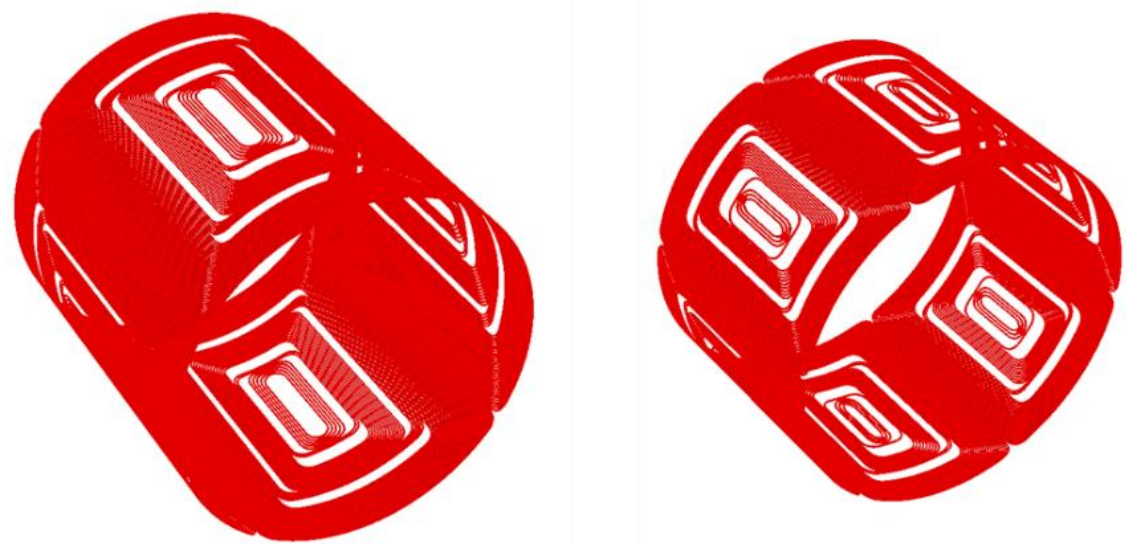
Integral harmonics:
$$B_n = 10^4 \left(\frac{R_0}{a} \right)^n L \cos [(n + 1) \phi]$$

- 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

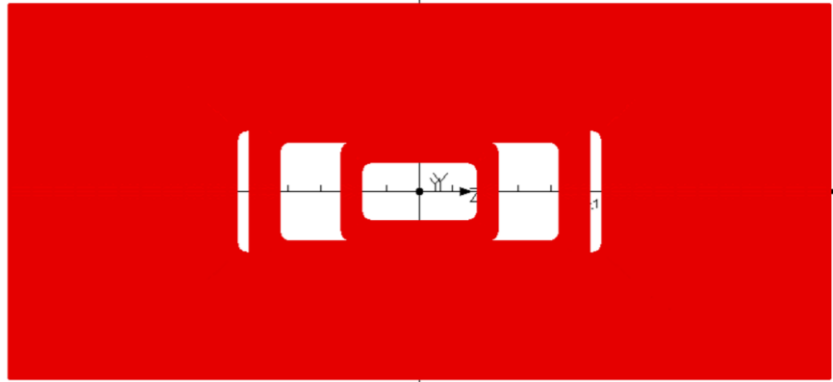


Model of a short length dipole based on the Optimum Integral Design.

Coil length 175 mm; coil diameter 200 mm.

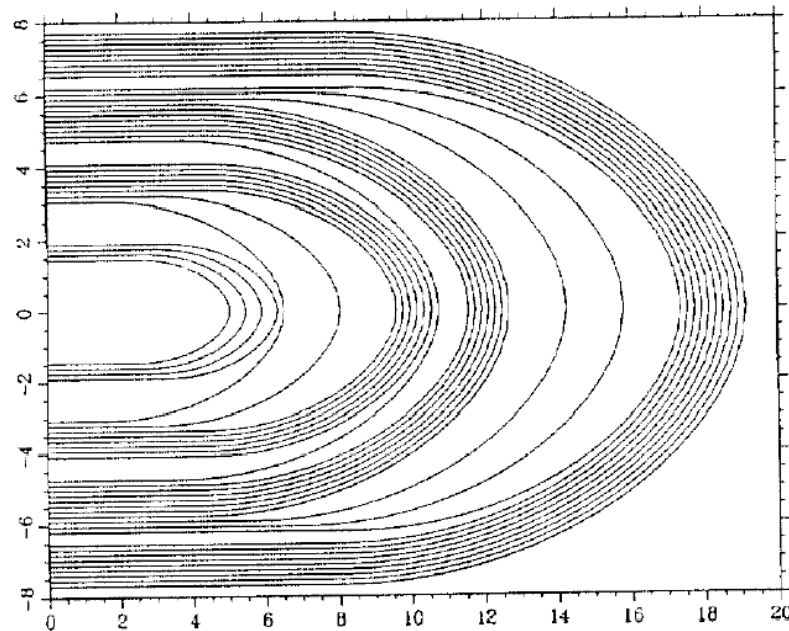
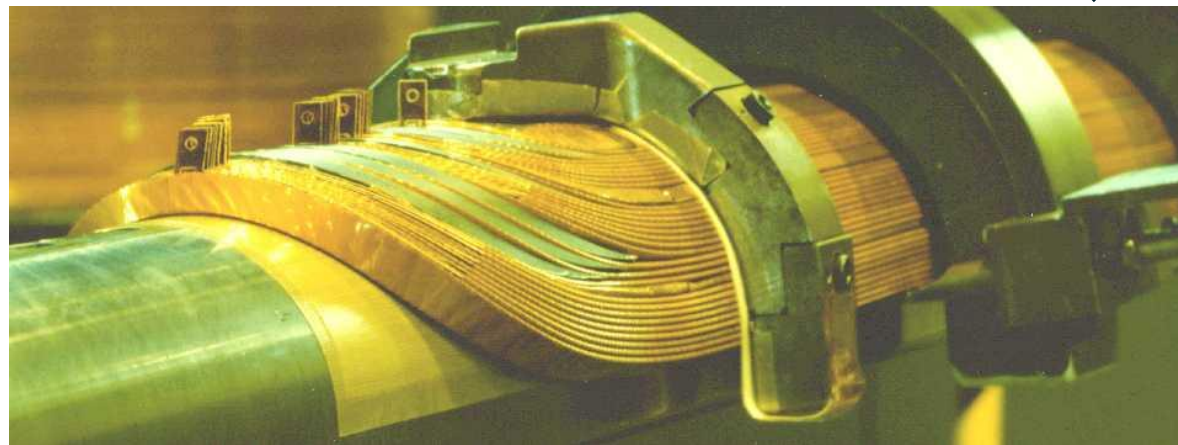
COMPUTED INTEGRAL FIELD HARMONICS FOR A SHORT DIPOLE (COIL LENGTH < DIAMETER) AT A RADIUS OF 66.6 MM. THE COIL RADIUS IS 100 MM. NOTE b_2 IS SEXTUPOLE MULTIPLIED BY 10^4 (US CONVENTIONS).

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

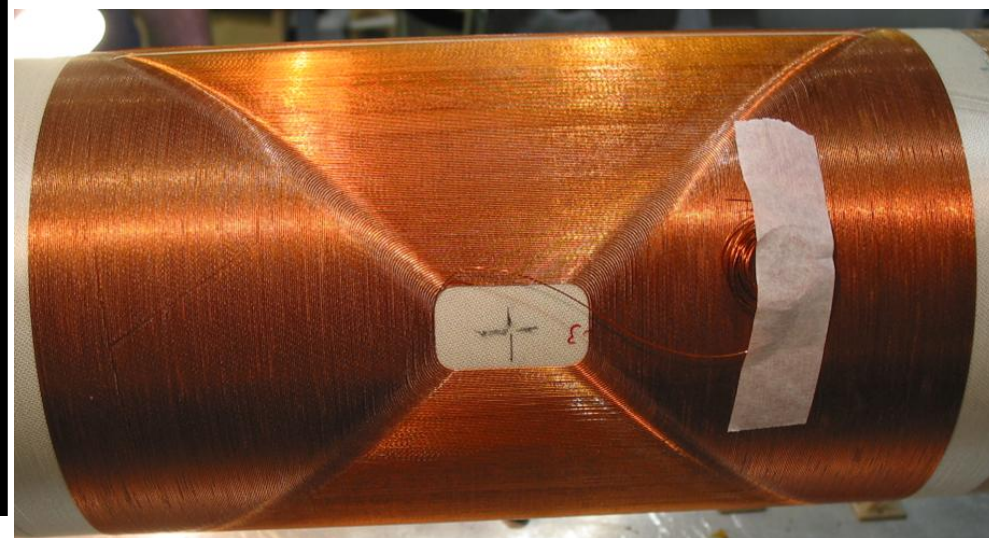


A Dipole Optimized with End Spacers Only

Comparison between the Conventional 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.**