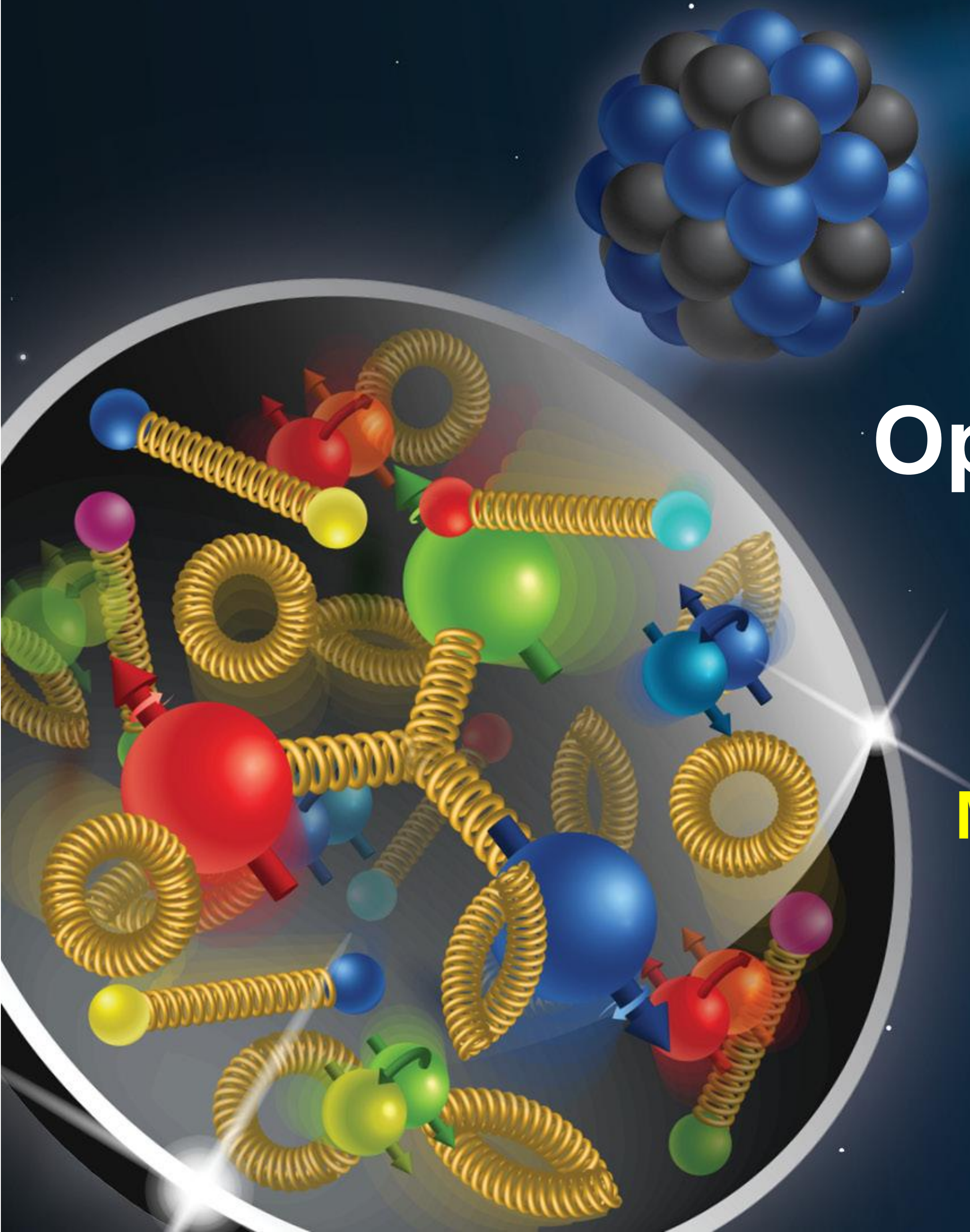

Optimum Integral Dipole B0ApF

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Magnet Steering Group Meeting

June 6, 2025

Electron-Ion Collider

PBL | BROOKHAVEN NATIONAL LABORATORY | Jefferson Lab | U.S. DEPARTMENT OF ENERGY Office of Science

Introduction

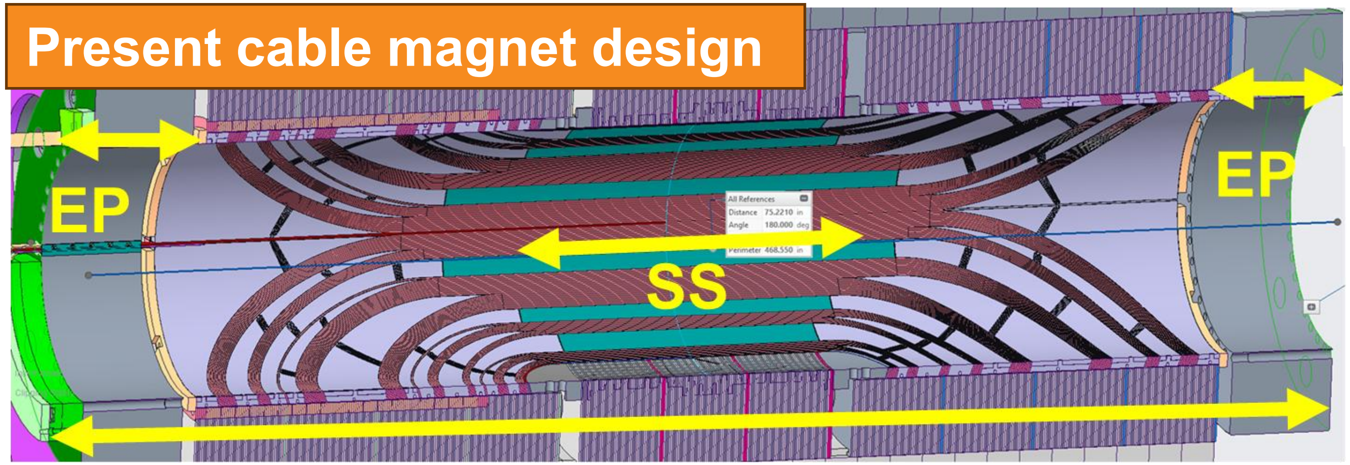
- We would like to share some exciting test results of the optimum integral dipole B0ApF. The design, construction and test results should be relevant to addressing quench and other technical issues in the challenging direct wind magnets for EIC.
- The program was originally funded by DOE STTR office to Particle Beam Lasers, (PBL) and BNL for demonstrating (a) benefits of the optimum integral design in short magnets and (b) direct-wind technology in a high field, large aperture, full-length EIC magnet. B0ApF needs higher field and larger aperture than that in a RHIC arc dipole.
- Since limited opportunity to do desired R&D become available in a real magnet, we extended the above goal by merging it with other programs for (a) quench studies by varying key parameters, (b) demo of superconducting shield, and (c) evaluating tiny Fiber optics wire for measuring local temperature/strain in small gaps between turns.
- Keeping this activity off-project offered the technical flexibility **and** connecting it to EIC kept the focus on the project needs (not just on academic studies). Having a PI from BNL, and well-known and well-intentioned magnet experts in PBL team helped.

Optimum Integral design as examined for B1ApF

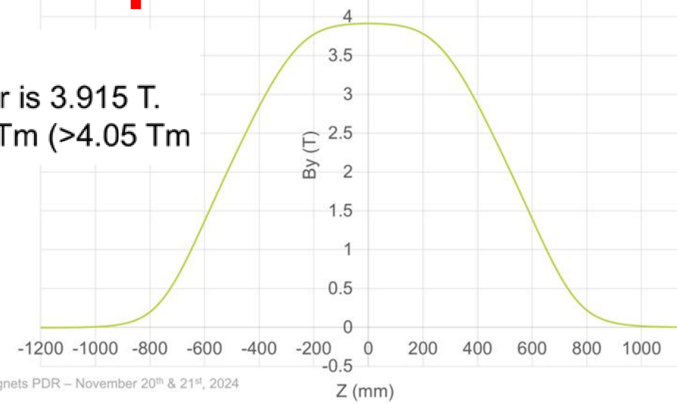
(midplane turn extends full length to minimize the loss due to ends)

- **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



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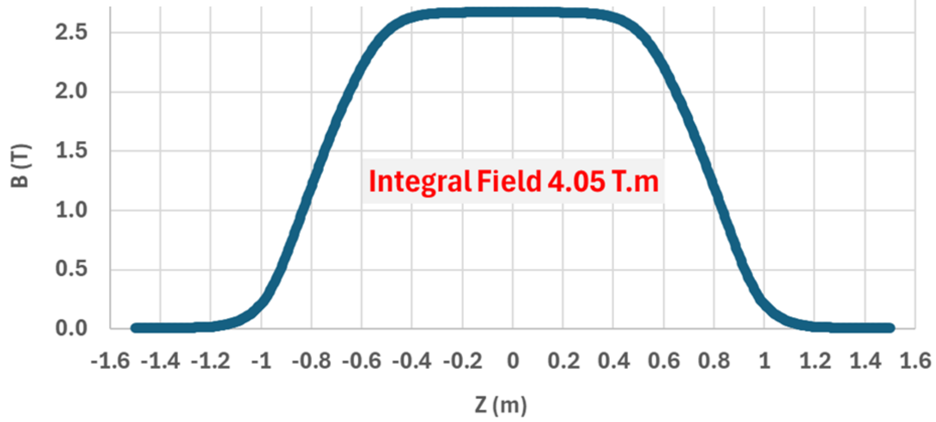
Direct wind optimum integral design

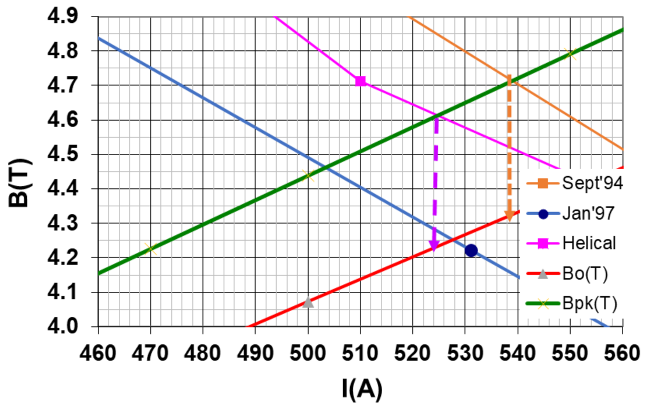
A wider flap-top in Optimum Integral

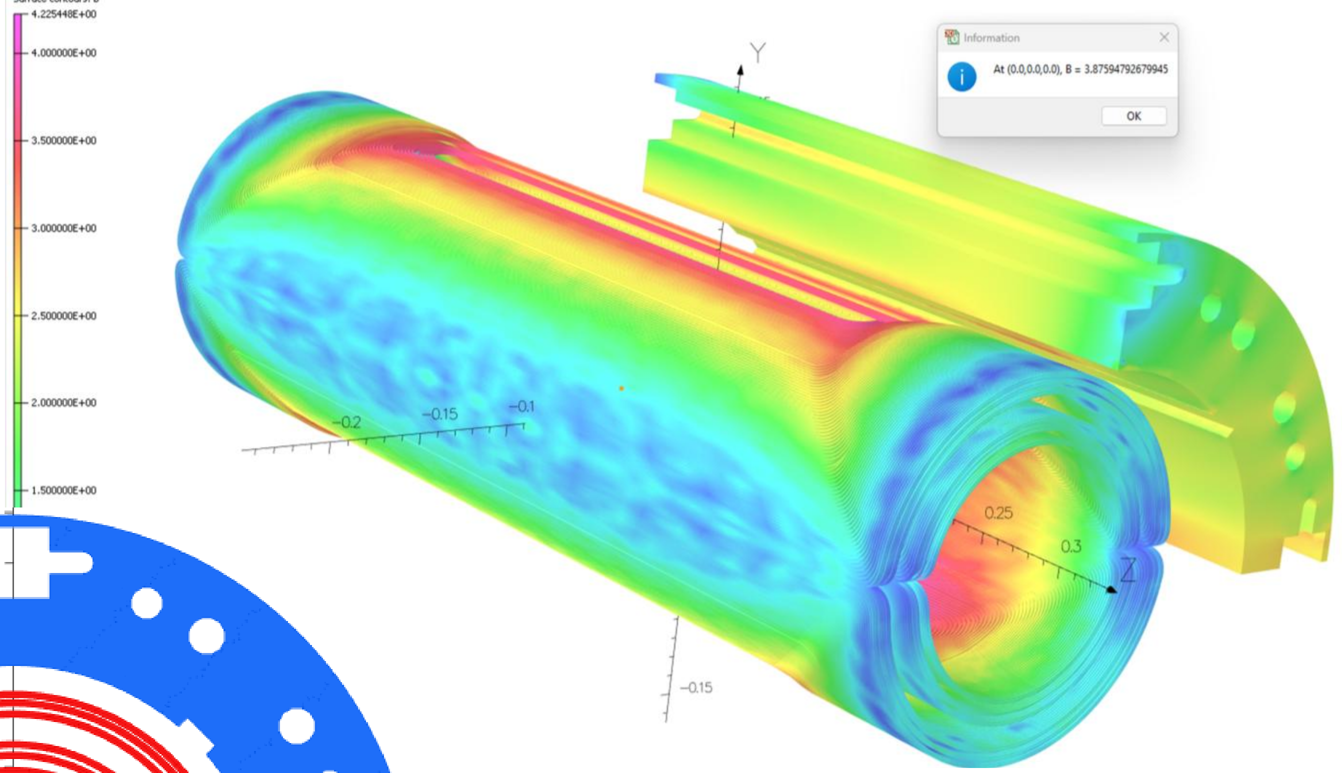


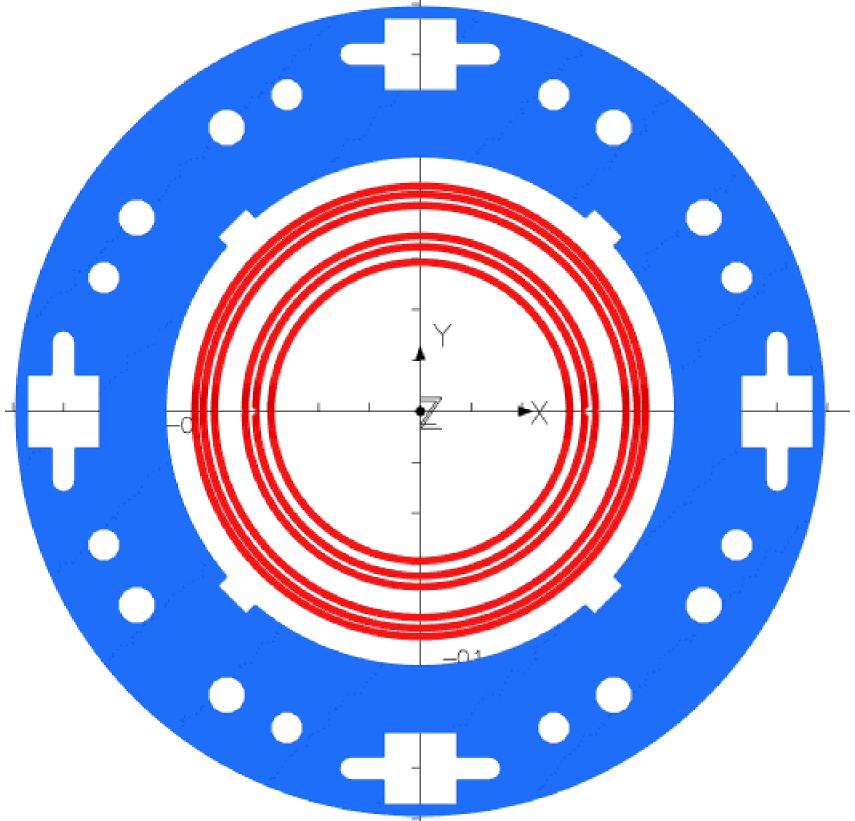
Technical benefit: B_o goes down from ~4 T to ~2.6 T; forces/stresses go down as B^2

Key parameters of the PBL/BNL Phase II *optimum integral design* for EIC dipole B0ApF:

- Coil inner diameter: 114 mm
- Design integral field: 1.98 T.m
- Design current: 470 A
- Field at center at design: 3.87 T
- Peak field at design: 4.26 T
- Coil length: 0.6 m
- Magnetic length: 0.51 m
- Stored energy (at design): 70 kJ
- Inductance: 0.7 Henry
- Number of layers: 12
- Number of turns per quadrant: 76
- Inner tube inner diameter: 102.3 mm
- Inner tube outer diameter: 113.5 mm
- Intermediate support tube inner diameter: 145.1 mm
- Intermediate support tube outer diameter: 158.0 mm
- Coil outer diameter: 182.7 mm
- Yoke inner diameter: 200 mm
- Yoke outer diameter: 317.6 mm
- Yoke length: 667 mm
- 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
- Computed quench field at 4.2 K: ~4.2 T
- Computed quench current at 1.92 K: ~610 A
- Computed quench field at 5.0 K: ~5.0 T
- External dump resistor for design field: 2.1 Ohms







Yoke for shielding experiment

Key Parameters/Features:

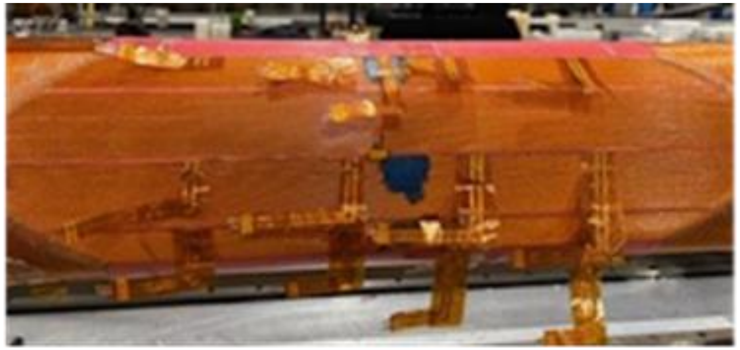
- **Coil id, od: 114, 183 mm**
- **Coil length: 600 mm**
- **B_o, B_{pk}: 3.9T, 4.3T @470A**
- **Integral field: 1.98 T.m**
- **Inductance: ~700 mH**
- **12 Layers (6 + 6)**
- **Intermediate SS tube**

Summary of Test Results

- We carried out several quench experiments by initialing several heater induced quenches at different currents and with different dump resistors. We got a lot of useful data but not a complete set of data in a limited time and instrumentation.
- Preliminary test results show that the superconducting shield worked well in suppressing field for e-beam more than what would be present anywhere in EIC IR.
- Fiber optics wire picked up signal (even though the wire was not designed and procured for this experiment), implying that this tiny wire could be a good fit for the direct wind coils with small gaps between the turns.
- Only two attempts were made to energize the magnet to quench. The maximum current was limited by one of the superconducting lead developing resistive voltage. Though we need to verify this but it appears to be either a bad joint or not properly stabilized superconductor between the magnet and the current leads at the top-hat.
- The test results are still impressive, as we were able to energize a large aperture EIC IR R&D magnet without any quench to ~2.9 T, which is ~74% of ~3.9 T for 1.98 T.m.

A Heavily Instrumented Direct Wind Magnet for Quench Experiments

Coil set 6 (layers 11 and 12) was heavily instrumented, with v-taps, heaters, temp sensor and Fiber optics wire



SIGNAL DESCRIPTION	LOCATION			VOLTAGE from (+) @ 100 mA
HEATER L6H-1	TRANSITION, DOWNSTREAM 1	TRANS. POLE		
V27				0.7438 V
V28				0.7440 V
V29	NLE, DOWNSTREAM 2			0.7450 V
V30				0.7453 V
V31	NLE, UPSTREAM 2	BLOCK 2		0.8661 V
V32				0.8664 V
V33	UPSTREAM 1			0.8669 V
V34				0.8670 V
HEATER L6H-2	CENTER			
V35	DOWNSTREAM 1			0.8673 V
V36				0.8675 V
V37	LE, DOWNSTREAM 2			0.8677 V
V38				0.8679 V
TS 1 X46443	NLE, CORNER	OPEN MID-PLANE		58.236 Ω @ 26.0°C
V39	UPSTREAM 2			1.090 V
V40				1.090 V
V41	UPSTREAM 1			1.091 V
V42				1.091 V
HEATER L6H-3	CENTER			
V43	DOWNSTREAM 1			1.091 V
V44				1.092 V
V45	LE, DOWNSTREAM 2			1.092 V
V46				1.092 V
V47	UPSTREAM 1	OUTER TURN, LE		1.092 V
V48				1.092 V
TS 2 X225525	LE, CORNER			50.745 Ω @ 26.0°C
HEATER L6H-4				
V49	DOWNSTREAM 1			1.093 V
V50				1.093 V
V51	DOWNSTREAM 2			1.093 V
V52				1.094 V
V53	NLE, UPSTREAM 2	LEAD POLE		1.439 V
V54				1.439 V
V55	UPSTREAM 1			1.440 V
V56				1.440 V
TS 3	CENTER			> 100 MΩ @ 26.0°C
HEATER L6H-5				
V57	DOWNSTREAM 1			1.441 V
V58				1.441 V
V59	UPSTREAM 1			1.441 V
V60				1.442 V
HEATER L6H-6	EXIT LEAD, DOWNSTREAM 1			
V61				1.442 V
V62				1.442 V
Exit Lead (-)				1.443 V

Quench protection issue in various Direct Wind Magnets

Quench protection was a major issue in B0ApF

- large inductance, large dump resistor, high temperature rise, high voltage, etc.

Testing beyond the design current would have been based on the experimental data

- More in Mithlesh's talk

Key parameters for quench protection:

	B0ApF	Q1ABpF	Spectrometer(B0pF)
Inductance	~0.7H	~0.08H	~1.3H
No. of layers	12	12	8+2
Design current	470A	1360A	1143 A
Dump resistor(max)	2.1Ω	0.6Ω	1.6Ω

Maximum voltage is also of concern

An Opinion on Quench Modelling and Benchmarking

- Time has now past to compare the results of different codes against each other by forcing them to simulate a situation for which they were not originally developed. In particular, we shouldn't be moving away from simulating the coils, as built.
- With so much experimental data available from this and previous two-layer and six-layer coil test of this magnet (and hopefully more data becoming available in further demanding experiments in protecting this magnet with even higher stored energy), our focus should shift to benchmarking these codes against the measured data.
- We should rely on the code(s) explain experimental.
- And if no code explain the results, then check the basic assumptions. Are they satisfactorily representing the reality of the direct-wind coil with 6-around-1 cable.
- If we need to develop new code or tweak existing codes to better simulate the reality, then so be it. We must though understand that tweaking to reliably extrapolate.

Possible Next Step (1)

- Despite the often-stated cost and schedule advantage of the direct-wind technology, there remains two major technical concerns in relying on this for EIC IR magnets:
  - Will direct wind technology still work in field and aperture range needed for EIC?
  - Can direct wind magnet be protected after quench?

  On both accounts, the optimum integral dipole B0ApF came close.
- Indeed, a significant achievement in R&D carried out with limited engineering and rigor needed for building superconducting magnets.
- Above R&D was performed off-projects but focus was kept to what EIC project needed. The magnet chosen was one of the IR magnet B0ApF.

Possible Next Step (2)

- With funds exhausted and the relevance and value demonstrated, this needs to be supported by the project to continue further.
- Good news is that the magnet itself appears to be sound and there is a good chance that by fixing external issue, the team should be able to take B0ApF from 74% to the required design integral in a short time.
- This will an important demonstration both technically & administratively.
- Recall that B0ApF needs a higher field and a larger aperture than what was in RHIC arc dipoles.
- This demo will be helpful to management when presenting it to DOE.
- Many quench experiments can be done quickly, and others after some time with more additon. They will provide good experimental data to develop models for designing well protected direct wind EIC magnets.

BACKUP Slides

Latest on the Optimum Integral Design

Optimum Integral Design : https://wpw.bnl.gov/rgupta/optimum-integral/

At MT29:

Oral:

Design, construction, and test of a superconducting dipole based on the Optimum Integral Design (https://mt29-conf.org/), Thu-Mo-Or1-03, Boston (abstract).

Poster:

Optimum Integral Design for EIC Dipole B1pF/B1ApF, (https://mt29-conf.org/), Fri-Mo-Po.05-04, Boston, July 1 – 6, 2025 (poster).

Conventional Design Approach

A two-step process:

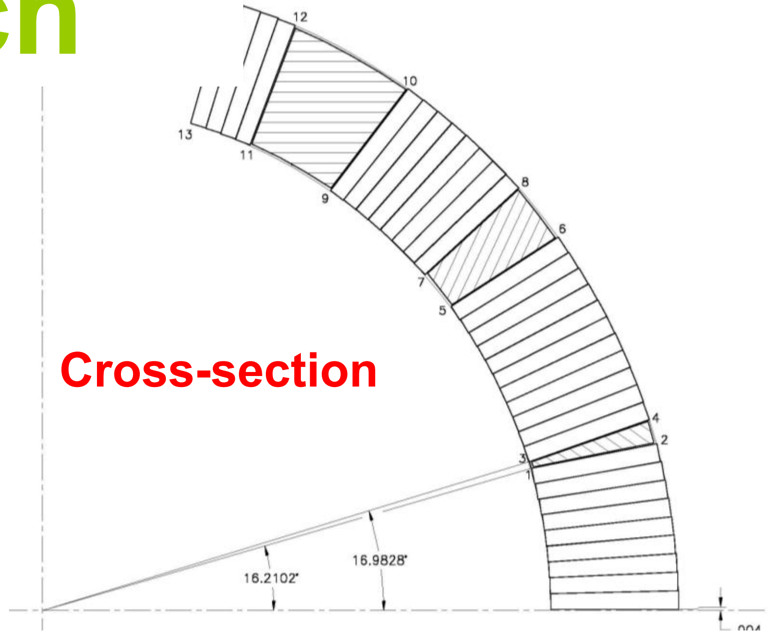
Step 1: Optimize coil cross-section to obtain cosine theta like distribution:

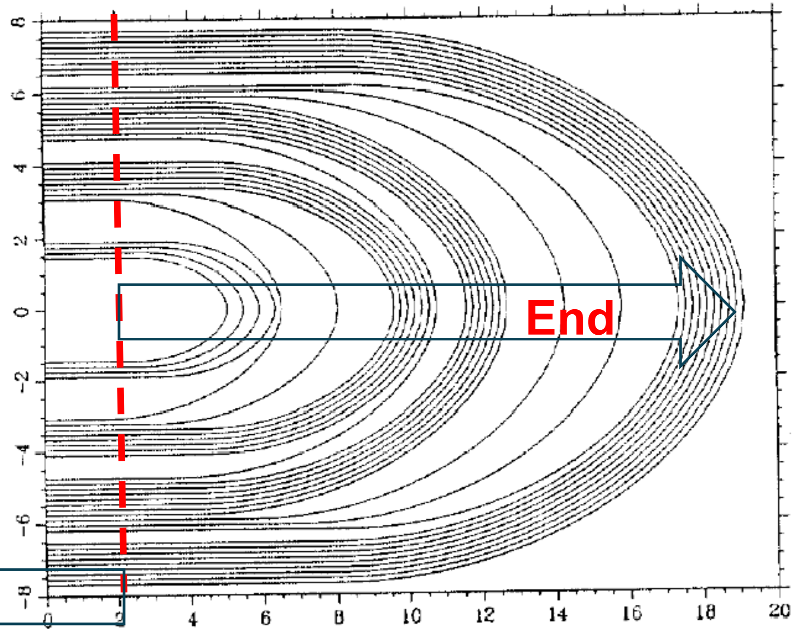
$$I(\theta) = I_o \,.\, \cos(n\theta)$$

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

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

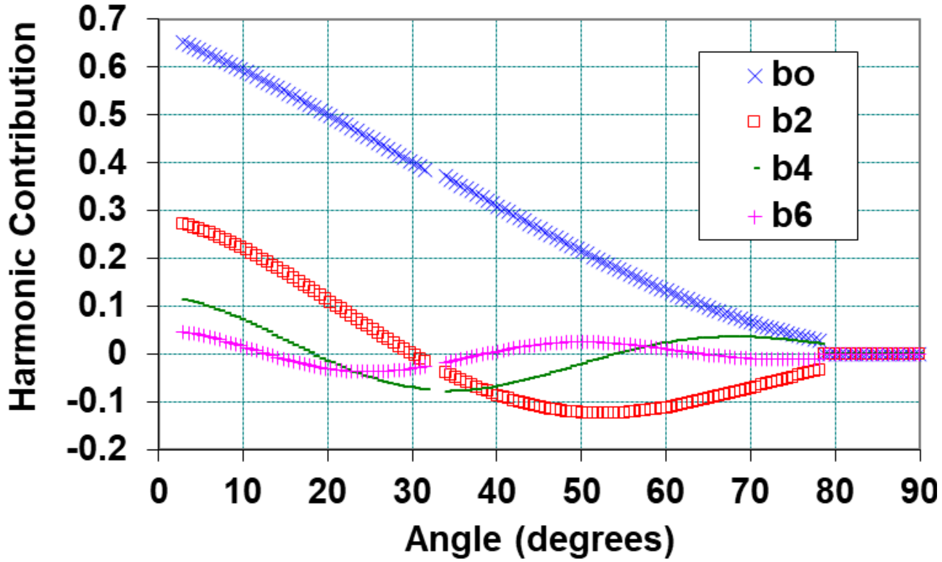
For no wedges or end spacer, function varies linearly ==> Modulate it to cos theta

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

Essentially no loss due to magnet ends.

Integral harmonics:

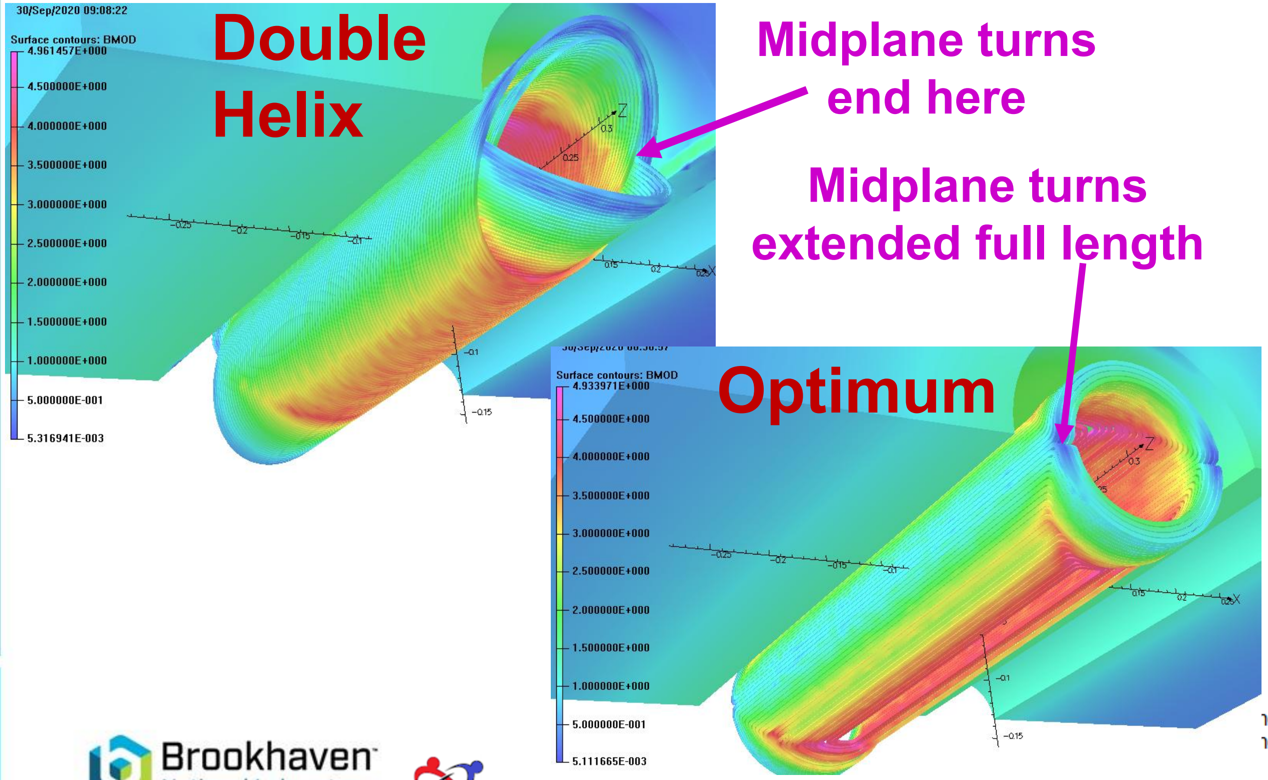
$$B_n = 10^4 \left(\frac{R_0}{a}\right)^n . L . \cos[(n+1)\phi]$$



(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.**



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