2LOr2B-05

Design, construction, and test of R&D dipole B0ApF for the EIC

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PLUS, many technicians…

Electron-Ion Collider

September 8, 2026

Highlight and Content

- A significant Direct Wind Dipole built under SBIR/STTR:
  - ❑ B_o = 3.9 T, coil i.d. = 114 mm (RHIC: B_o = 3.5 T, coil i.d. = 80 mm)
- Optimum Integral Design for Short Superconducting Magnets
- Design, construction and test results
- Application of Optimum Integral Design (OID) to other EIC magnets
- Summary

*DoE STTR (Small Business Technology Transfer) award # DE-SC0021578

Significant Loss in Integral Field Due to Ends in Short Magnets

- **Typical mechanical length of <u>each</u> dipole end: ~ 2 coil diameters (*a*)**
- **Loss in integral field due to ends becomes significant in short magnets: coil length (*L*) < ~8 X diameter in dipoles; ~4 X in quads**

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 RATIOS in some EIC magnets:</u>

➢ **B0ApF (this): *L* = 600 mm, *a* = 114 mm; RATIO ~5.3**
  ➢ **Length is now reduced to 500 mm => RATIO ~4.4**

➢ **B0pF: *L* = 1250 mm, *a* = 656 mm; RATIO ~1.9**

➢ **Q3pF: L = 400 mm, a = 137 mm; RATIO ~2.9**

✓ **Strong motivation for developing designs that minimize the loss in integral field due to ends**

Conventional Design Approach

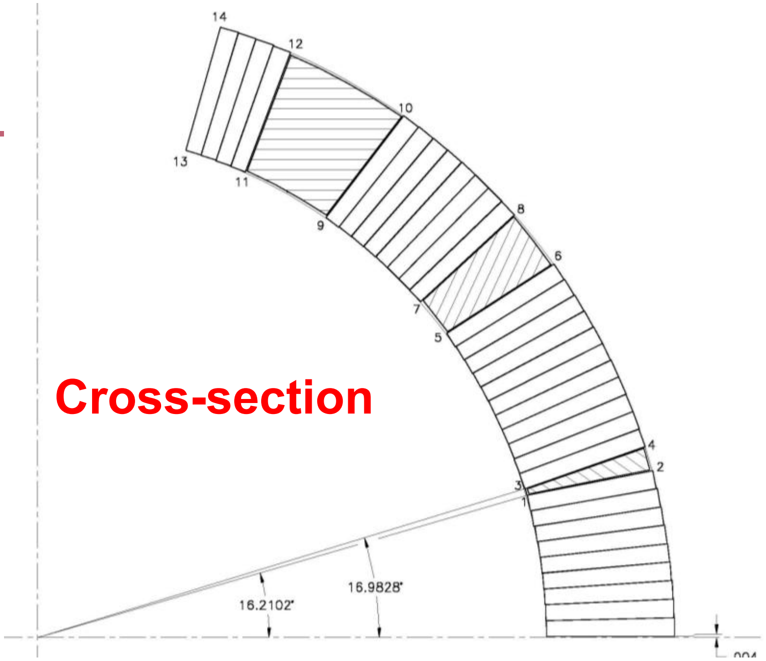
A two-step process:

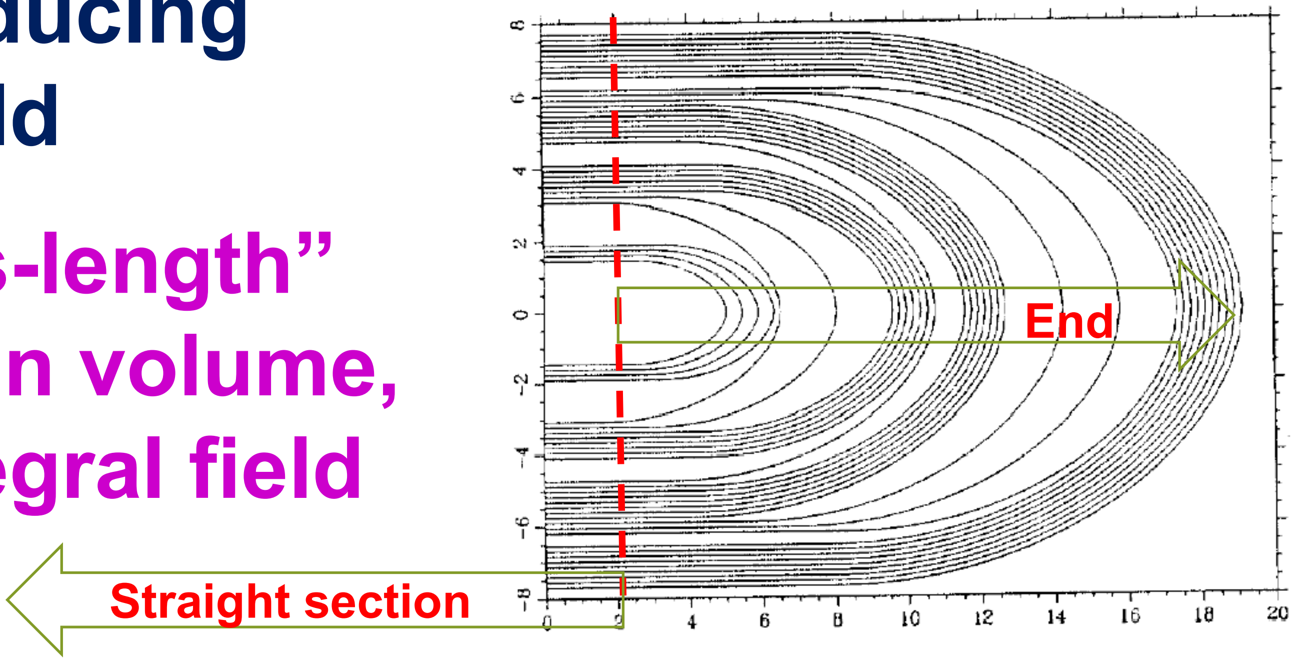
Step 1: Optimize coil cross-section to obtain cosine theta like distribution:

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

Step 2: Optimize ends for reducing harmonics and the peak field

Both limit the "Ampere-turns-length" that one can pack in the given volume, and hence the maximum integral field





Optimum Integral Design (OID) Approach

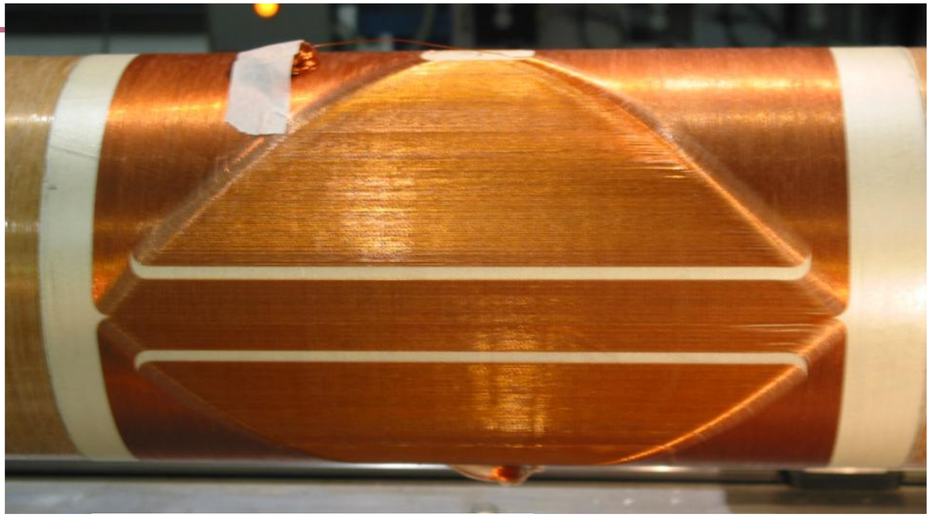
Optimize cross-section and ends together in a single step. And obtain a cosine theta current distribution in an integral sense:

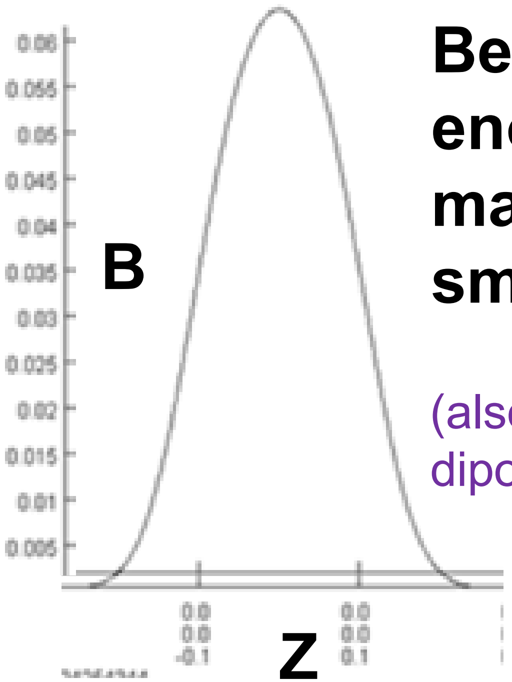
$$I(\theta)\ .\ L(\theta)\ =\ I_o\ .\ L_i\,(\theta)\ \propto\ I_o\ .\ L_o\ .\ \cos(n\theta)$$

(a) Midplane turns extend full-length and (b) length of turns decreases linearly with the angle to help create a *cos(nθ) function*

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

✓ **Loss due to ends essentially eliminated**



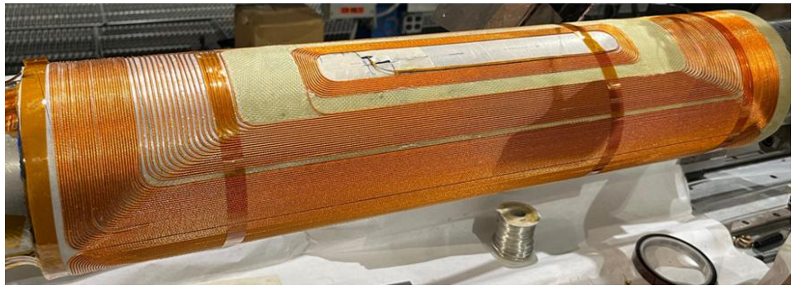


Benefits are enormous in a magnet with small flat-top

(also, built and tested dipole with coil length < coil diameter)

Special Design Code for Rapid 3-d Optimization

- Most codes first compute field (or vector potential) at several places along the length and then compute and integrate field harmonics and then optimize them.
- Optimum integral code works differently. It directly computes and optimizes 3-d integral harmonics for each wire of length "*L*" at *(a,φ)*

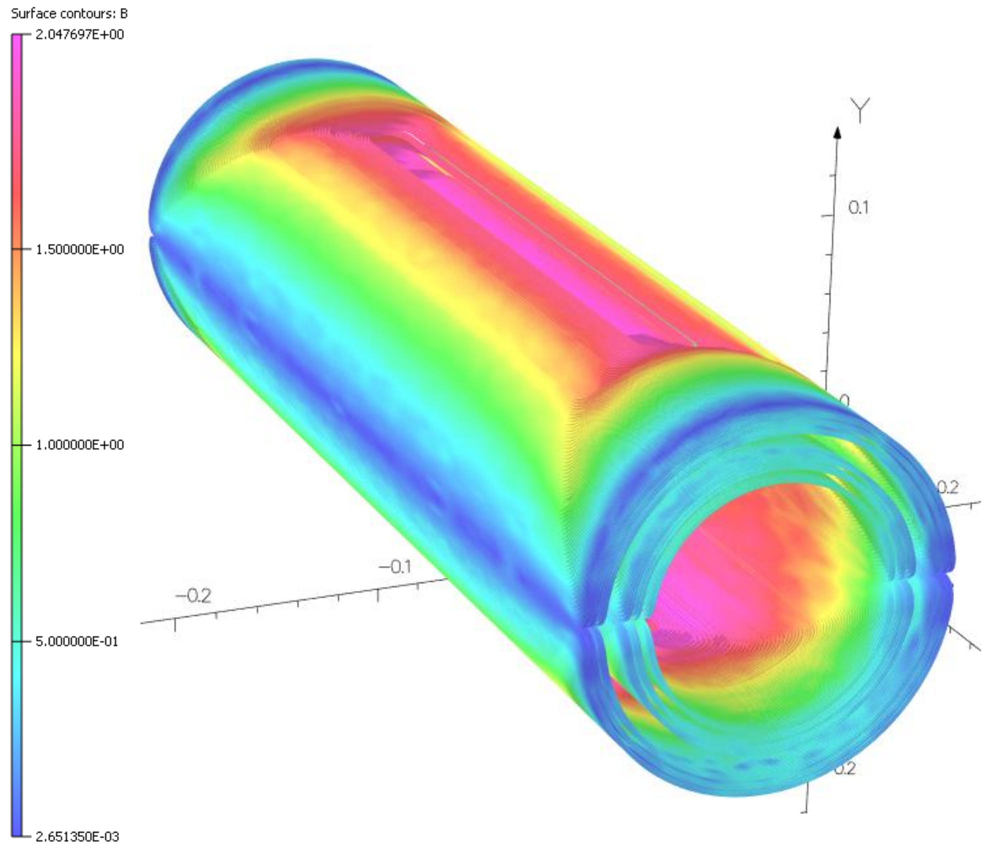


Integral harmonics: $B_n = 10^4 \left(\frac{R_0}{a}\right)^n . L . cos\left[(n+1)\,\phi\right]$

- ➢ Above formula is valid for 2-d and for 3-d when the field is integrated over the entire space (length). Iron is included in the software as the image current.
- ➢ This works fast. A 3-d optimization of multi-layer coil typically takes a few minutes (199 parameters allowed). Input files for OPERA3d, coil winding software created.
- ➢ A new GUI based code (MADEO) is almost ready that has a better pre- and post-processors, and performs peak fields and many other useful calculations, as well.

Key Parameters of the PBL/BNL OID B0ApF for EIC

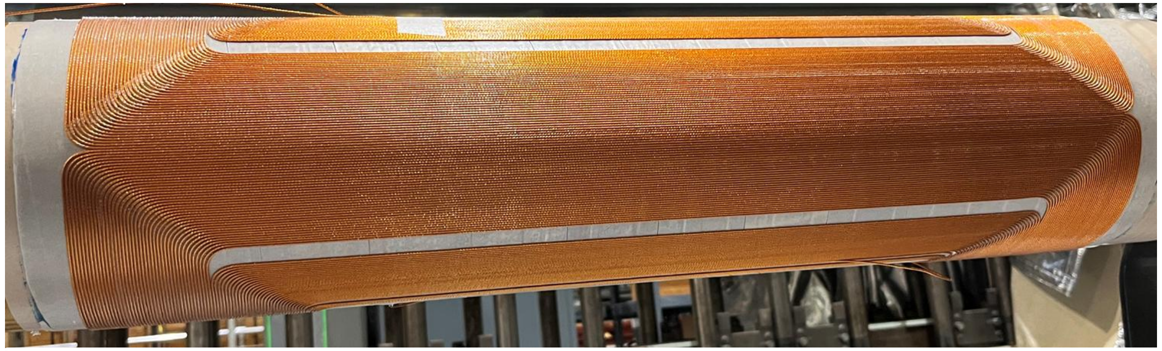
- **Coil inner diameter: 114 mm**
- **Coil length: 600 mm**
- **Field Integral: 1.98 T.m**
- **B_o, B_{pk}: 3.9 T, 4.3T @ 470 A**
- **Short Sample: 480 A @ 4.2K**
- **Number of layers: 12 (6 inner + 6 outer)**

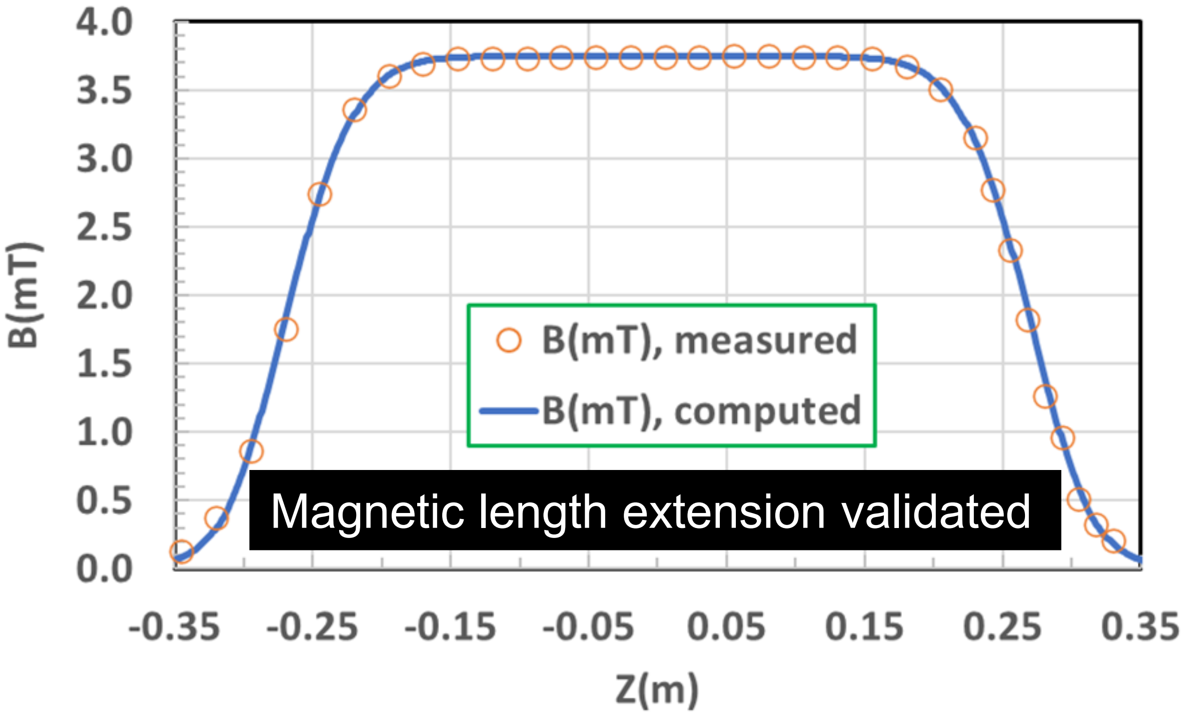


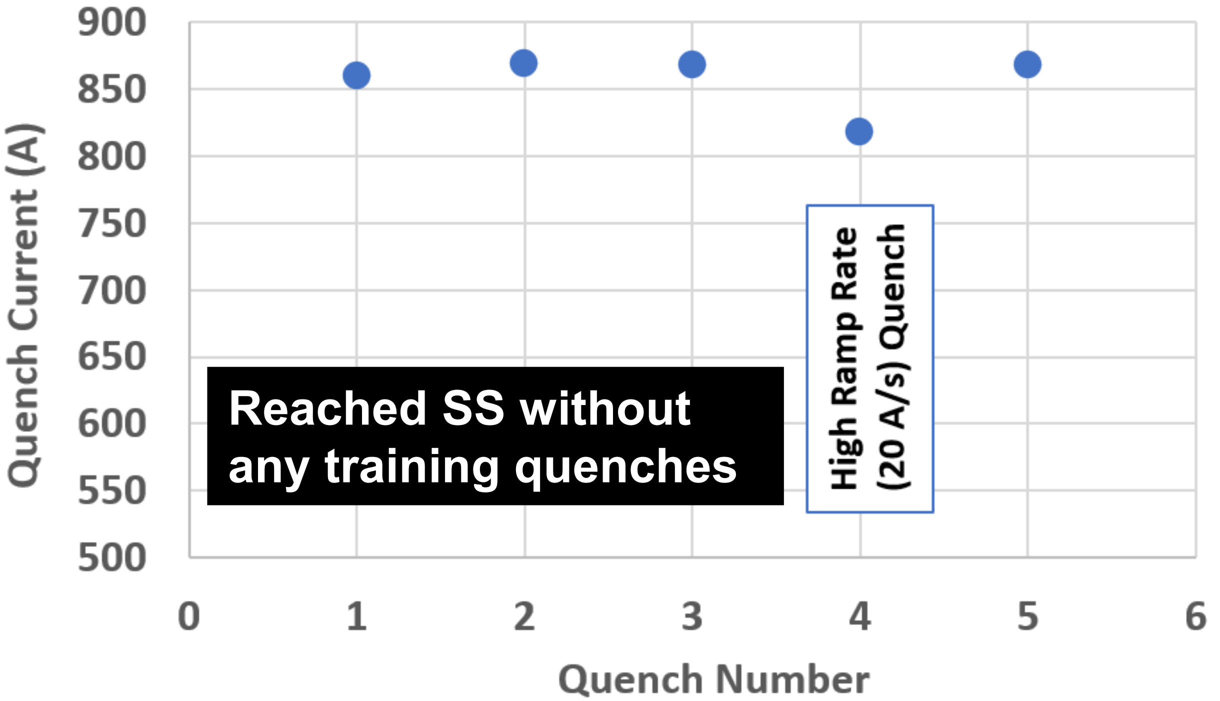
Phases of B0ApF R&D Program with Primary Goals

- **Phase I: Two layers**
  - ➢ **Validate the design principle**
- **Phase II (intermediate) : Six layers**
  - ➢ **Validate the field quality**
- **Phase II (final): Twelve layers**
  - ➢ **Validate the performance for EIC**

Phase I : Validation of the Optimum Integral Design







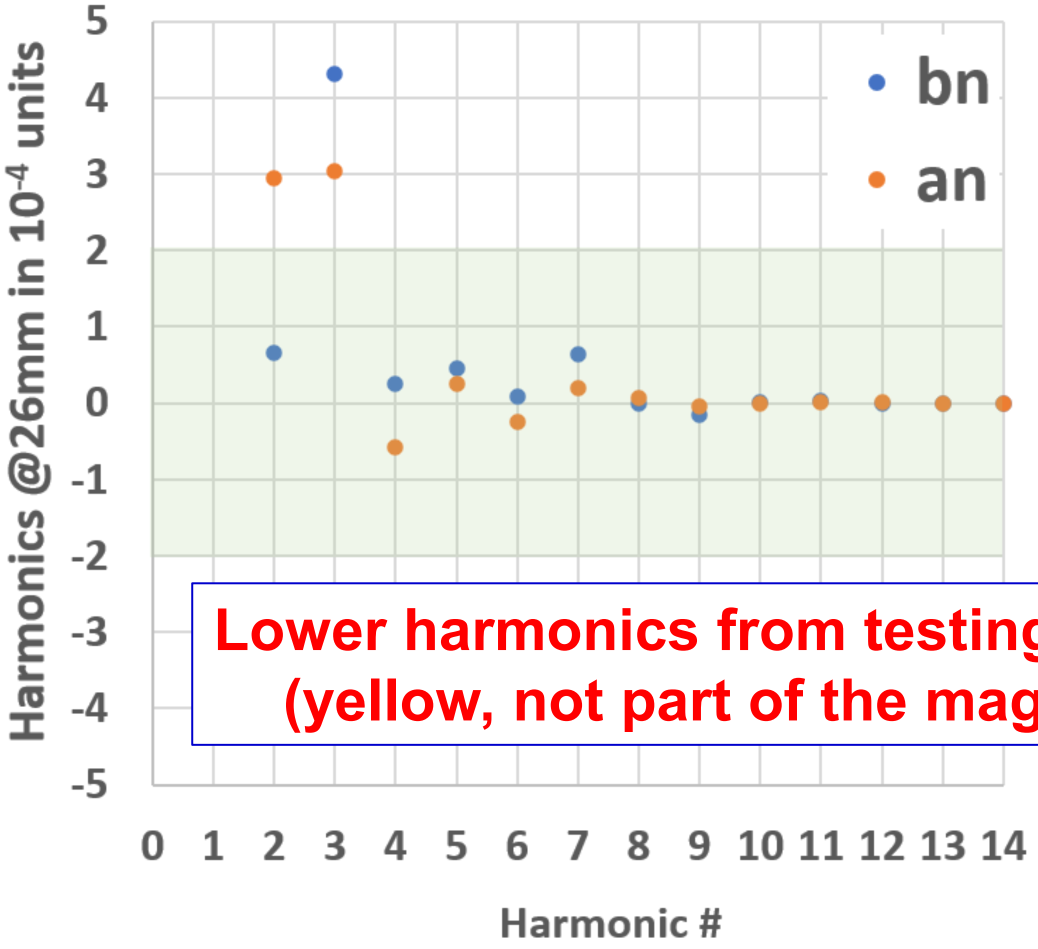
B_o ~1.7 T

B_{pk} ~2.2 T

id 114 mm

Phase II (Intermediate)
Field Quality Validation of the Design and of the Code

Specifications: +/- 2



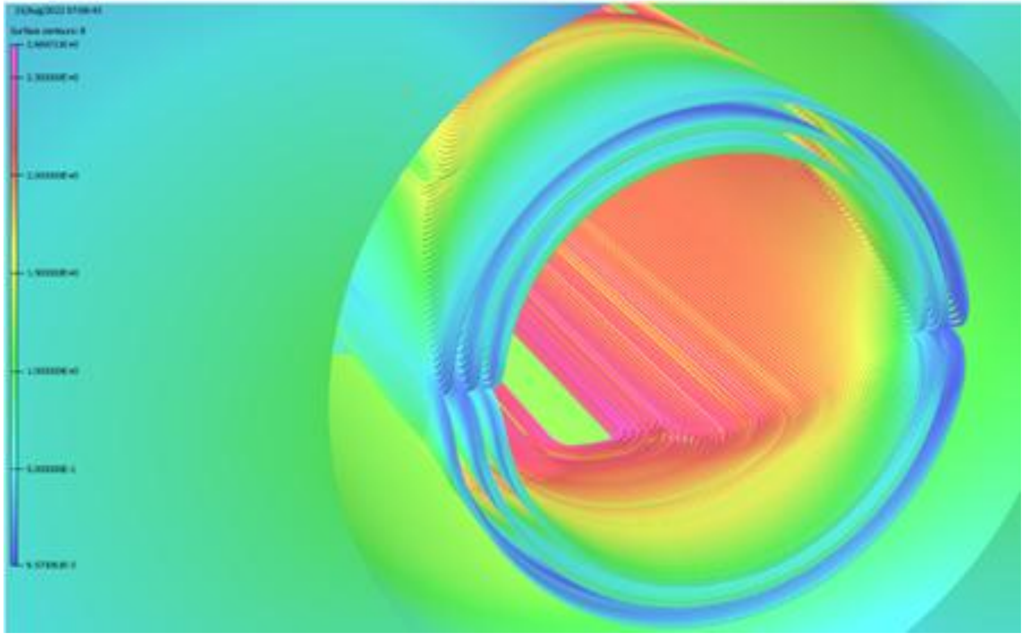
Lower harmonics from testing leads (yellow, not part of the magnet)

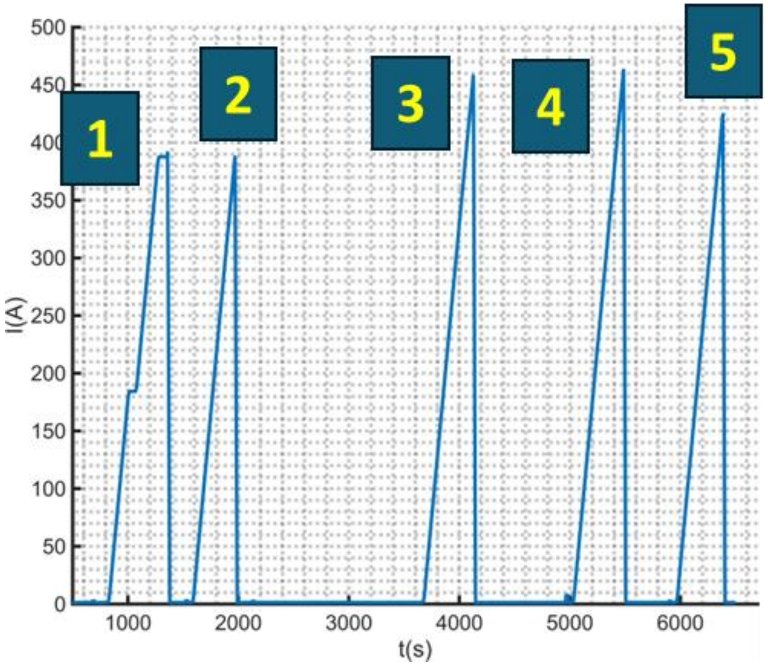
Warm measurements of 6 layers

Good field quality despite many changes on the fly

➢ **Non-zero harmonics can be compensated in subsequent layers**

Testing of the Intermediate 6-layer Optimum Integral Dipole



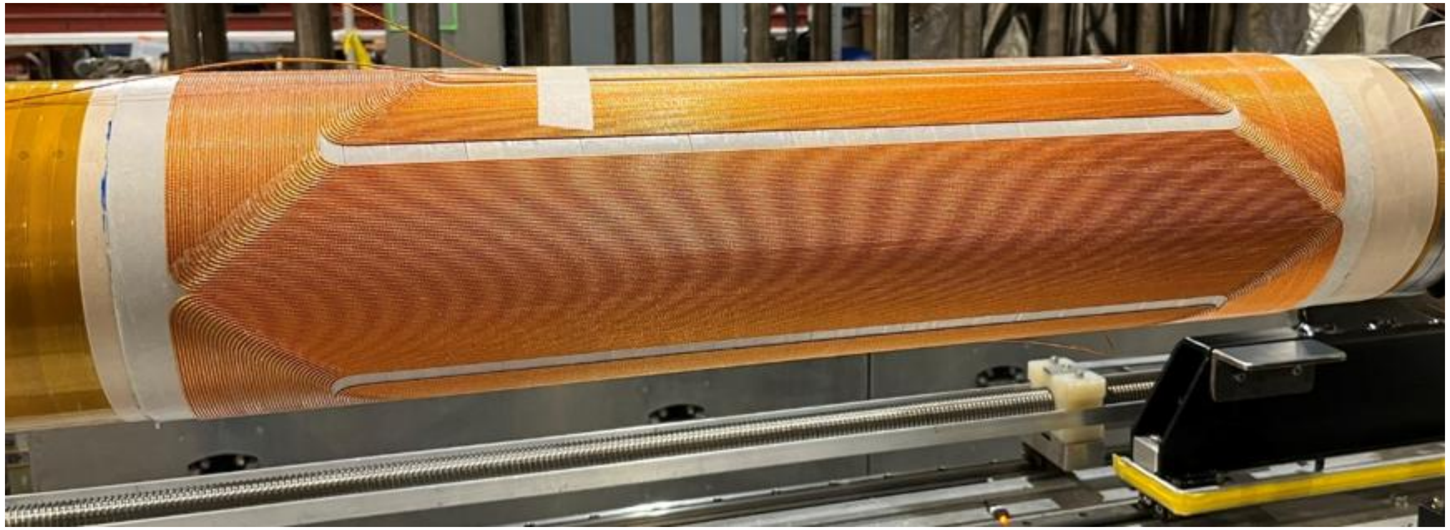


- **Magnet reached 470 A (~70% of the short-sample)**
- **Quench performance was limited by leads "external to the magnet"**
- **These issues have since been resolved (both in 6-layer and in 12 layer magnet).**

Design, Construction and Test of the Completed 12-layer Magnet

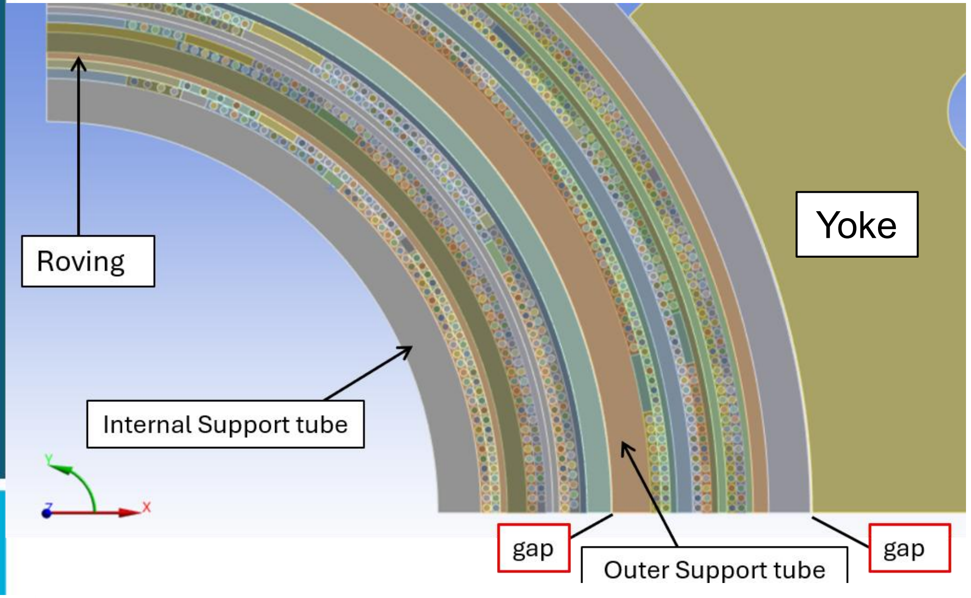
Final Validation for EIC

6 layers each on two tubes installed in the yoke



Support Structure and ANSYS Analysis

- **Key components of the original support structure concept:**
  - ➢ **High tension roving on coil set, three stainless steel tubes and yoke**
- **Support structure segmented with an intermediate tube to avoid stress build-up (stress management)**
- **Third outer SS tube not installed due to budget and schedule limitation of the STTR program (not included in the ANSYS model either)**
- **ANSYS calculations show separation at 420 A (Short Sample 480 A)**
- **Yoke outside, moreover, was not straight (additional gap)**

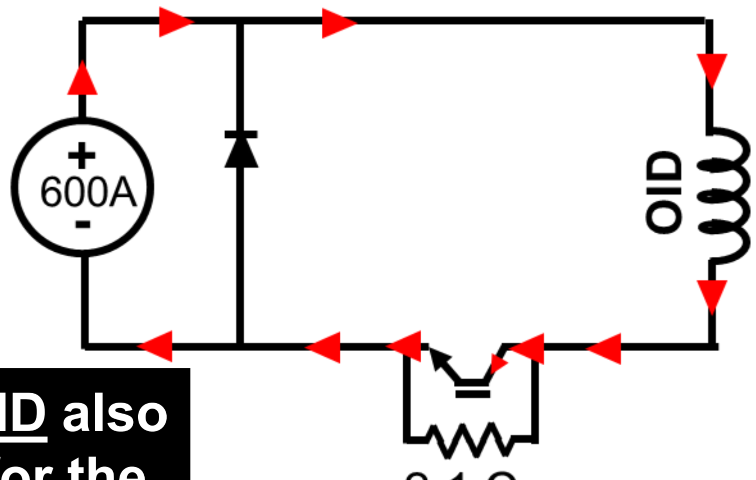


Measurement	Result @ I=470A	Result @ I=420A	Limit	Units
Maximum Radial Displacement Differential at center of coil (Thermal step to Excitation step)	0.67	0.63	N/A	mm
Maximum Radial Gap from Support Tube to First Coil Layer at Excitation Step	0.028	~0	~0	mm
Max. Von Mises Stress on Support Tube after roving installed at Room Temperature	96.28	96.28	206.8	MPa
Max. Von Mises Stress on Support Tube at Excitation Step	409.05	373.13	482.6	MPa
Max. Von Mises Stress on Coil at Excitation Step	35.18	31.98	150.0	MPa
Max. Shear Stress on Coil at Excitation Step at Excitation Step	20.27	18.44	50	MPa
Max. Normal Azimuthal Stress on Coil at Excitation Step	29.29	24.50	180	MPa

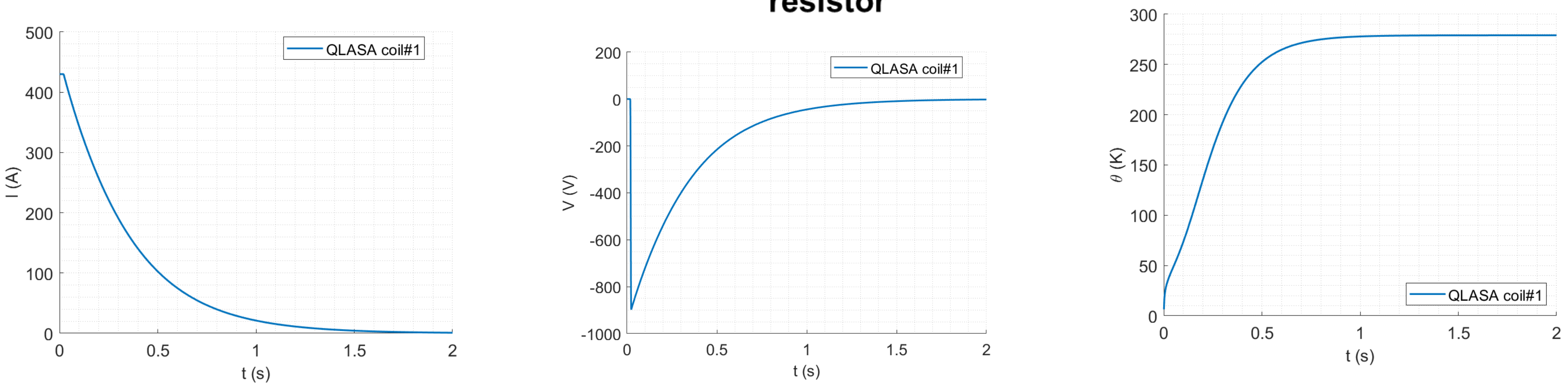
Quench Protection with External Energy Extraction

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

Simulations performed with SQUID also (BNL code specially developed for the Direct Wind magnets)

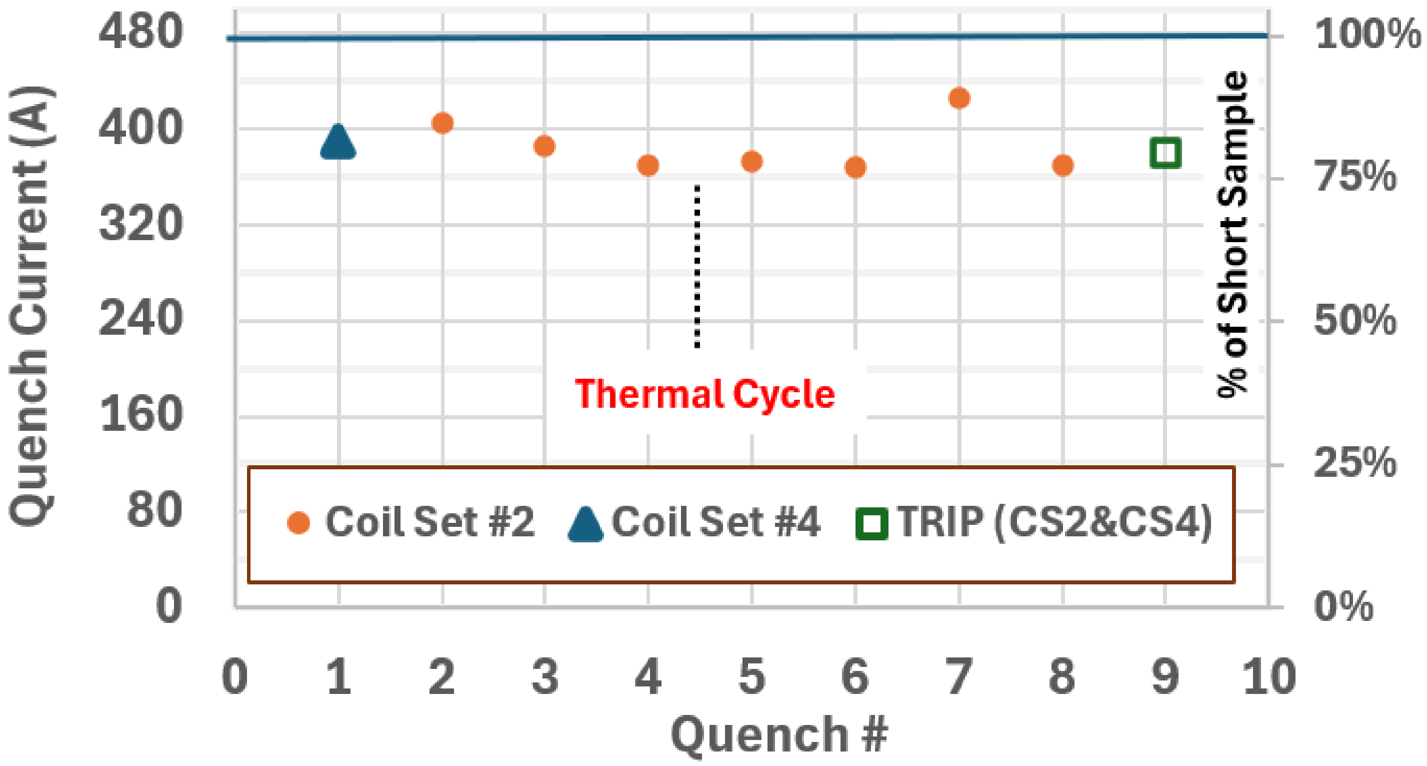


Parameter	Value
MIITs	0.0353
Hotspot temperature	279 K
Voltage total	898 V
Voltage to GND	449 V
Decay time constant	337 ms



Test Results of the Final Magnet (1)

- All quenches were above 367 A (>76% of SS), highest at 426 A (89% of SS)
- B_o ~3.6 T, B_{peak} ~4 T, 114 mm aperture (RHIC arc dipole: 3.5 T, 80 mm aperture)
- An important demonstration of Direct Wind technology (achieved in a low-cost STTR program with limited engineering). The focus was on demonstrating OID



Speculation on what could be limiting beyond 89% of SS

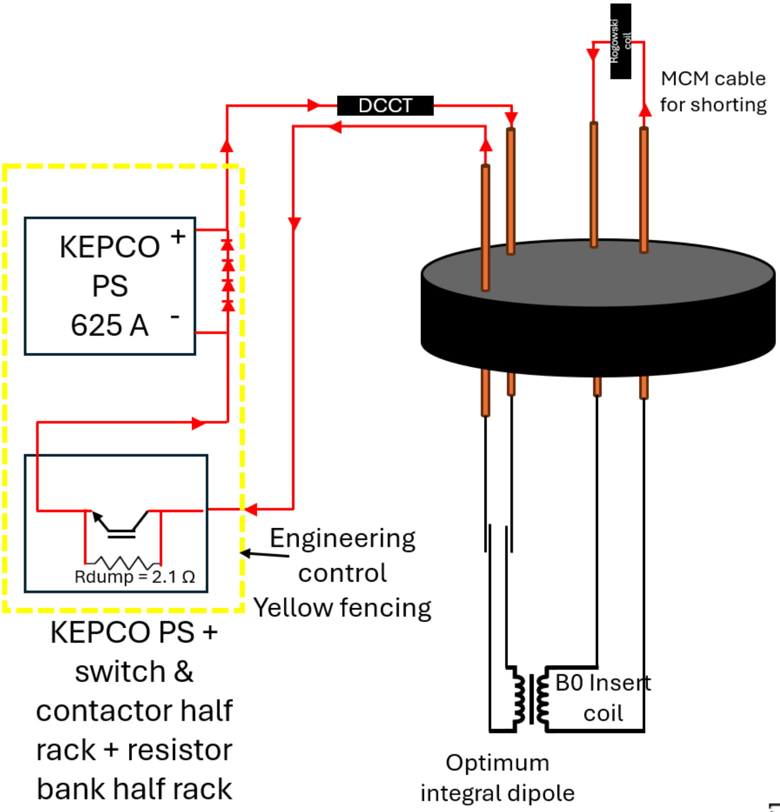
- Something still external?
- Gap inside the yoke?

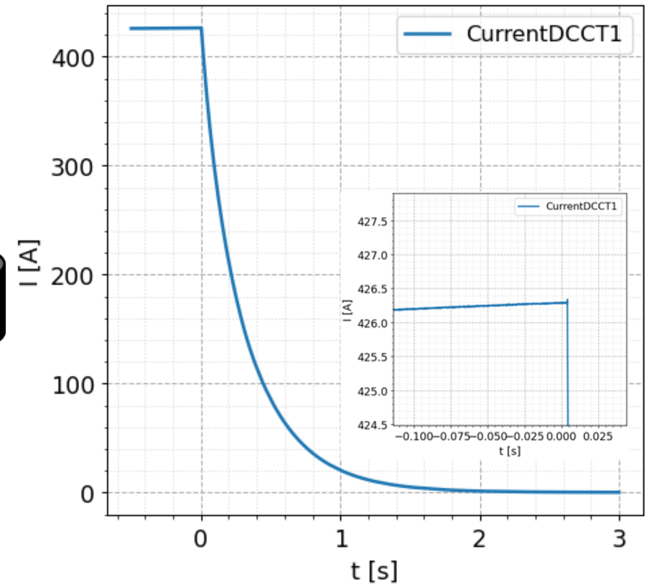
Next step (this or other magnets)

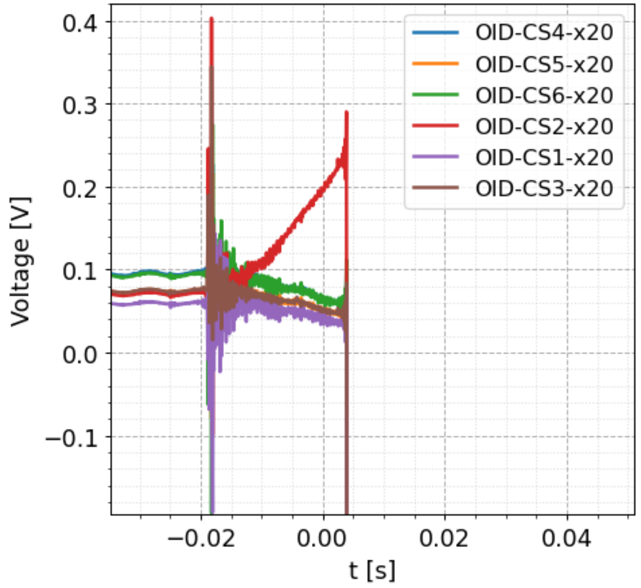
- Outside SS support tube?
- Close the gap inside the yoke?
- Test at 1.9 K?

Meets the EIC requirement

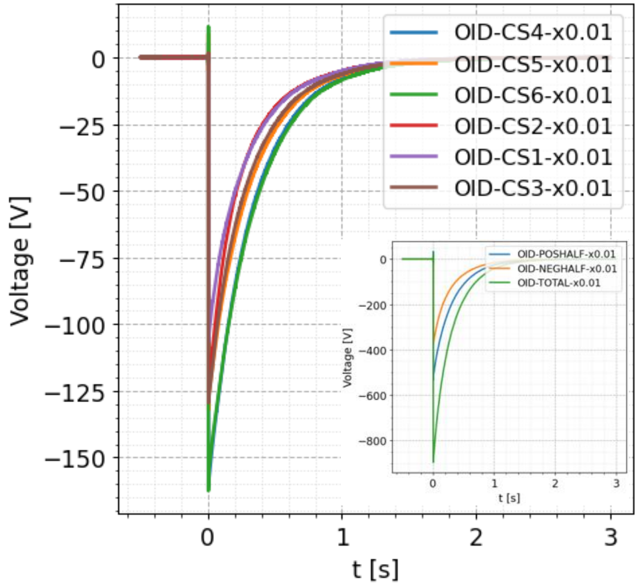
Test Results of the Final Magnet (2)

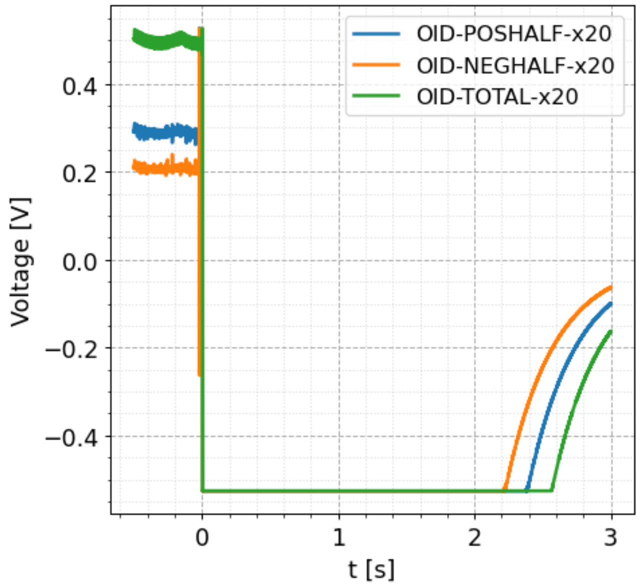






Signal before the quench @ -0.02 sec?





These tests helps validate SQUID

Application of the Optimum Integral Design in Other EIC Direct Wind Magnets

- Optimum Integral Design is retained in the updated design of B0ApF with shorter length (also used in the skew dipole and skew quadrupole in the same package)
- It is being used in Q3-B2pF package (normal and skew quads, normal and skew dipoles) where less space for correctors made a significant impact on the B2pF
- **A game changer in B0pF** (the most challenging magnet in EIC). Compared to the original serpentine design, various options of the optimum integral designs:
  1. Reduced the number of layers from 10 to 6 (range: 5 to 8)
  2. Reduced the operating current from 1143 A to 889 A (up to 671 A)
  3. Reduced the peak field on conductor from 5.3 T to 4.2 T
  4. Reduced strain on conductor (IXB) and less accumulated Lorentz forces
  5. Improved load line fraction from 70% to 60% (up to 50%)
  6. Allowed a possible operation at 4.2 K instead of 1.92 K (or central wire Cu)
  7. Reduced demand on quench protection (voltage to ground 950 V to 535 V)
  8. Reduced the number of external energy extraction circuits
  9. Eliminated the absolute need of the quench heaters

Summary

- Optimum integral design minimizes the loss in magnetic length due to the ends.
- It has a major impact in short magnets, as is the case for several magnets in EIC.
- PBL/BNL STTR dipole has validated the optimum integral design and has produced 3.6 T in a coil of 114 mm aperture. It meets the 65% of load line requirement.
- With the design validated, benefits of the optimum integral design are now being used in several EIC magnets, including the challenging B0pF magnet.

Acknowledgments

- Demonstration of the Optimum Integral Design (OID) and its incorporation into EIC was made possible from the funding and support from the DOE SBIR/STTR office.
- Additional quench studies were performed with the internal LDRD funding.
- Final support for the testing and system upgrade was directly provided by the EIC.
- We acknowledge the contributions of our technicians who worked hard and long hours. The outcome of R&D like this, carried out with limited engineering, depends on their skills, experience and finding practical solutions.
- We wish to thank support and encouragement of the program manager and the EIC project management.