From 32 T to the 40 T All-Superconducting Magnet

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Muon Collider Collaboration Meeting
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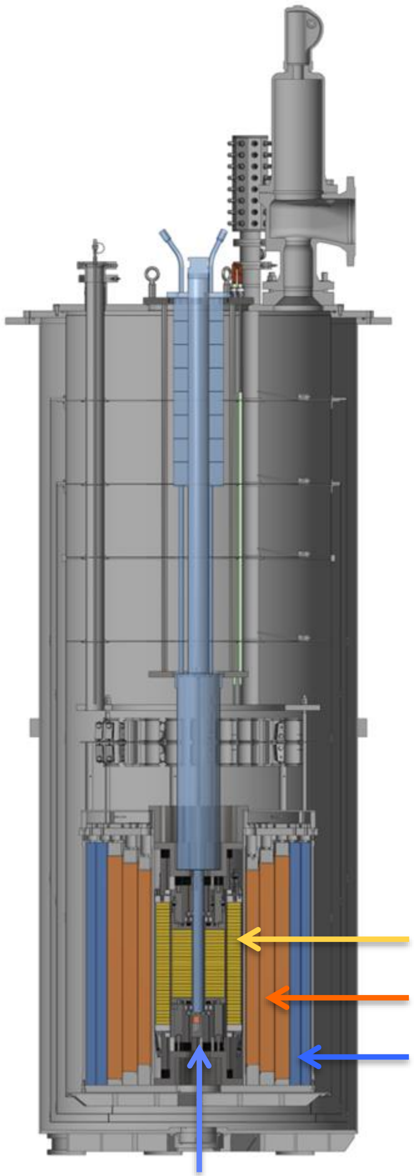
Iain R. Dixon
Dima Abraimov, Hongyu Bai, Mark Bird, Ernesto Bosque, Kwangmin Kim, Dylan Kolb-Bond, Jan Jaroszynski, Andrey Gavrilin, Jun Lu, Denis Markiewicz, Robert Walsh, Huub Weijers…

Overview

- 32 T All-superconducting magnet
  - *Timeline and development*
- 40 T All-superconducting magnet
  - *Technical challenges*
  - *Test coils*
    - *Insulated REBCO*
    - *Resistive Insulation REBCO*
- Outlook

The 32 T magnet



Key parameters:

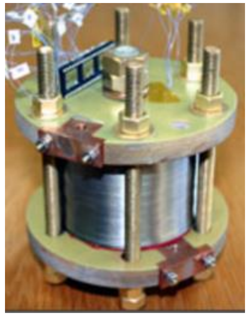
Center field	32 T
Clear bore	34 mm
Ramp time	1 hour
Uniformity 1 cm DSV	5×10^{-4}
Operating temperature	4.2 K
Stored energy	8.3 MJ
Expected cycles/20 years	50,000
System weight	2.6 ton

15 T / 250 mm bore LTS magnet
17 T / 34 mm bore REBCO coils
Separately powered, simultaneously ramped

REBCO: 2 double pancake coils
Nb_3Sn coils
NbTi coils

32 T Project Timeline and Development

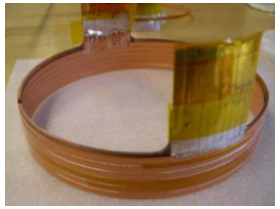
- 2007 – 2008 IGC/SP test two test coils @NHMFL to 27 T (19 T background)



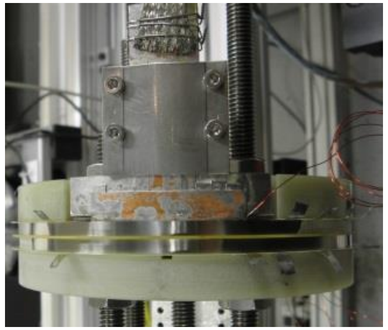
- 2008 NHMFL 33.4 T Test coil (31 T background)

31 T + 2.4 T

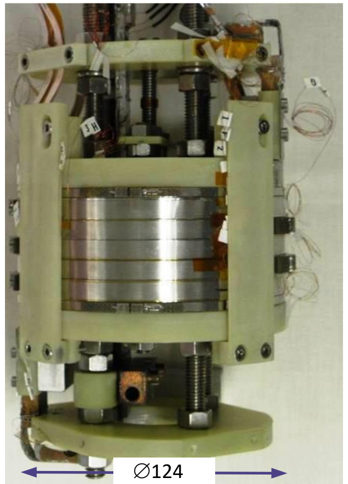
- 2009 Initial funding of 32 T
- 2009 – 2012 Additional test coils



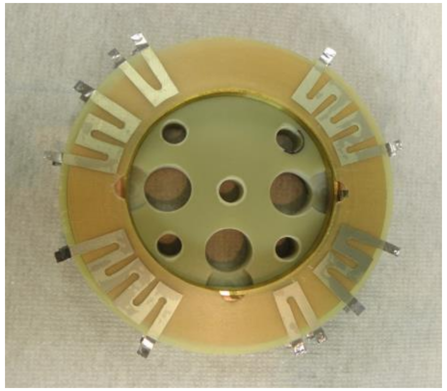
High Hoop-stress coils
>760 MPa



42-62 Mark 1:
1st test coil



42-62 Mark 2:
2nd test coil

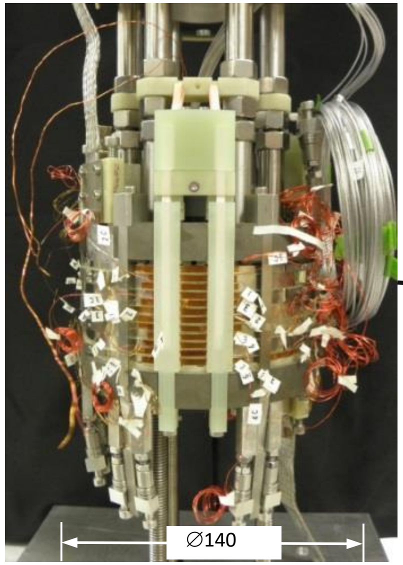


Early Heater Design

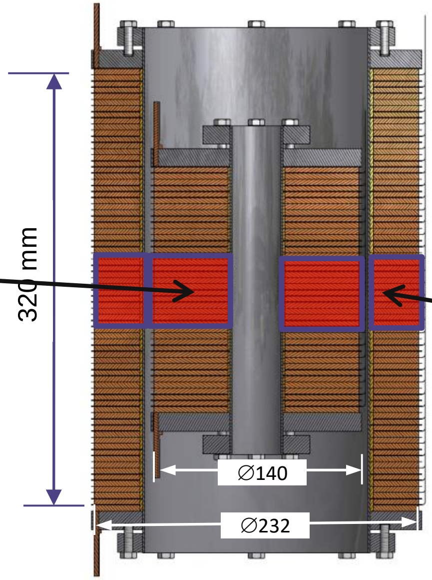
32 T Project Timeline and Development

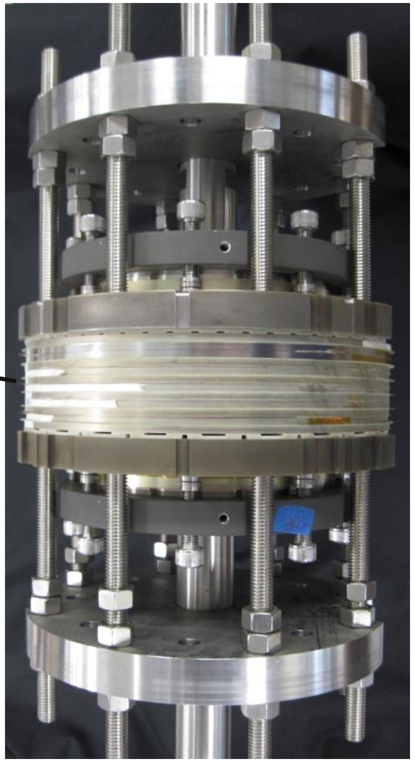
- 2013 – 2014   Prototype test coils

2013



20 - 70:
1st Full-featured Prototype



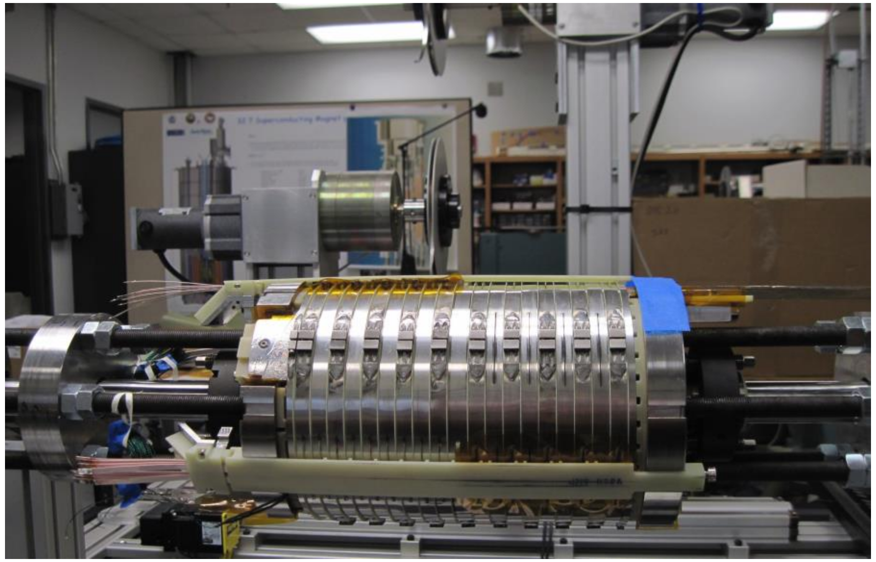


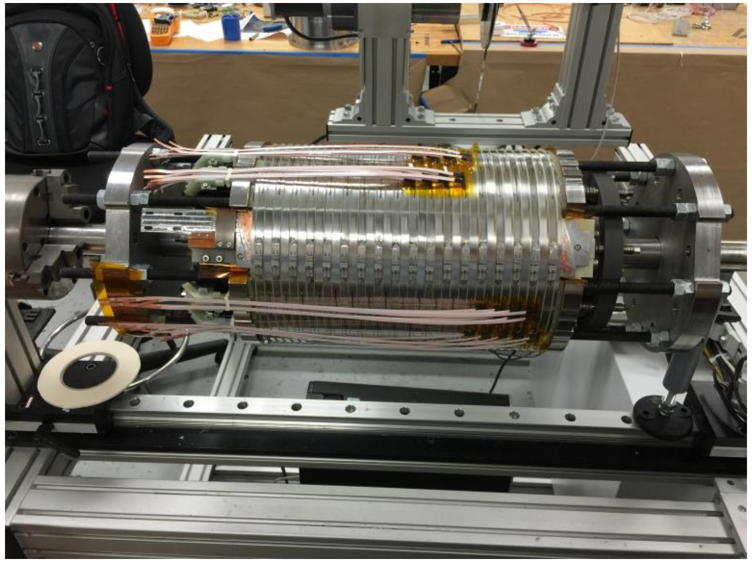
82 - 116:
2nd Full-featured Prototype

Modern Heater Design

32 T Project Timeline and Development

- 2015 – 2017 Construction and Testing

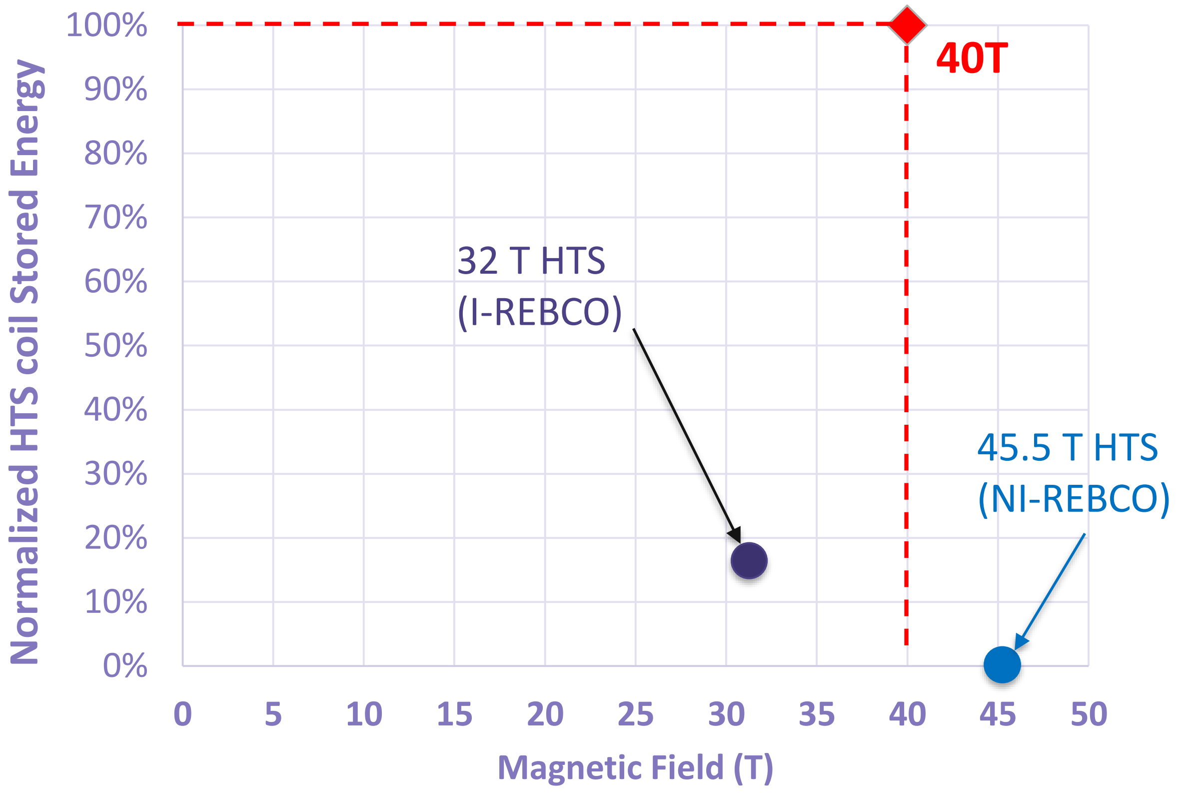




- 2020 Open for User Operations

40 T All-Superconducting Magnet Project

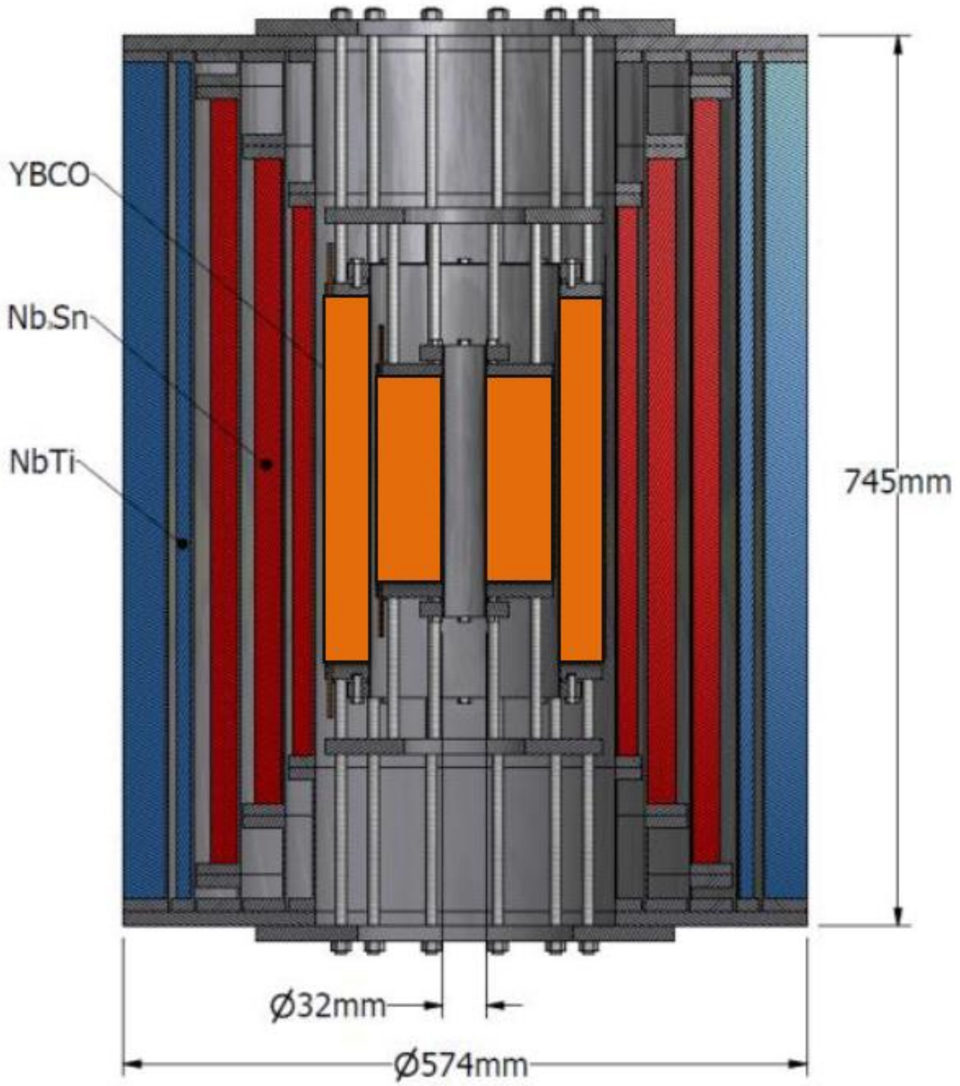
- National Science Foundation Funded Design Project through 2025
- Implementation/Construction Proposal to Follow
- Specifications:
  - Central field: 40 T
  - Operating temperature: 4.2 K
  - Cold bore diameter: ≥ 34 mm
  - Ramp rate: ≥ 0.5 T/min
  - Operating lifetime: 50,000 cycles or 20 years
  - Homogeneity: ≤ 500 ppm over a 1 cm DSV
  - 10 Gauss fringe field: < 5.4 m
  - Stabilization time: < 3 minutes
- Two design options are being considered
  - Insulated REBCO (I-REBCO)
  - Resistive Insulation REBCO (RI-REBCO)

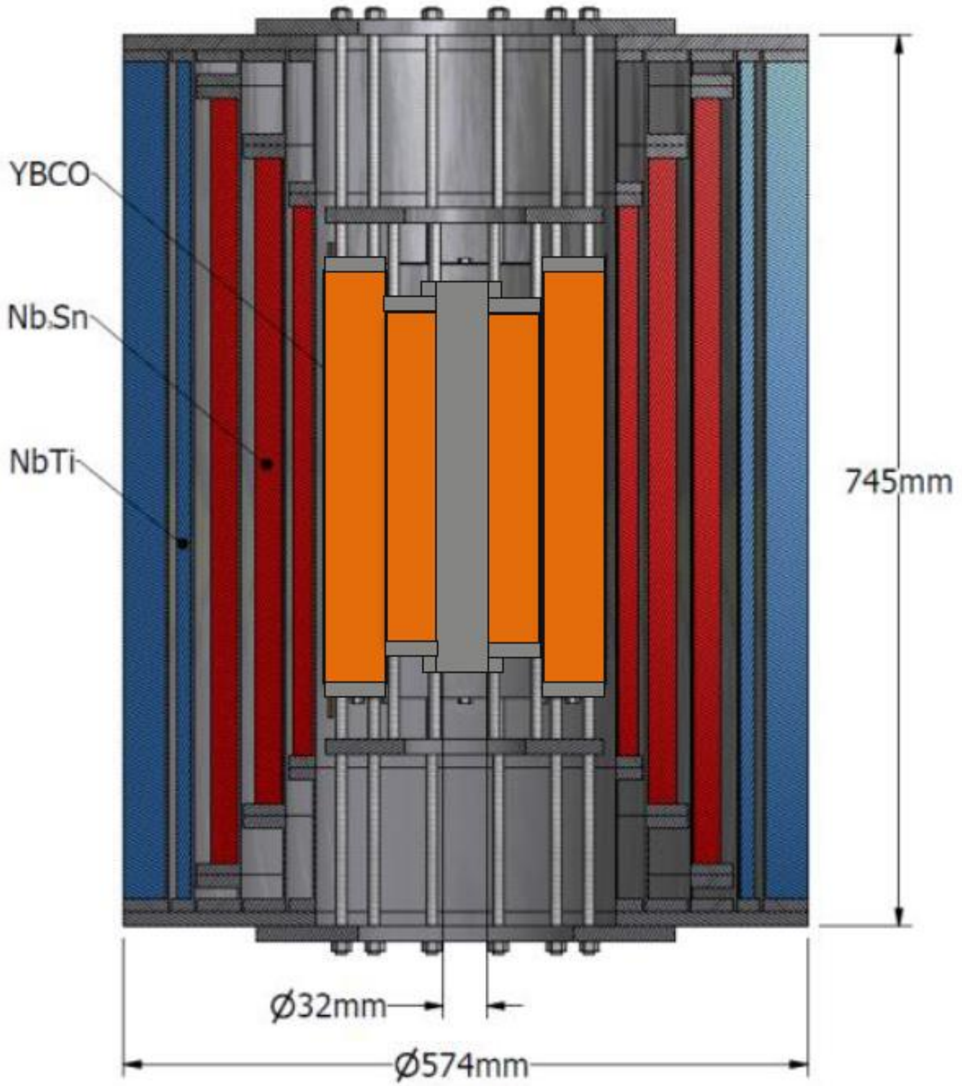


40 T Technical Challenges - Compactness

- Simple scaling of the 32 T to 40 T is not feasible
  - LTS outsert field / bore size too large
  - Most economical to design HTS coils to fit inside the commercially available 15 T LTS or 12 T LTS (with inner Nb_3Sn coil removed)
  - Need to increase current density of HTS coils, J_{eng}, J_{cu}
    - For J_{eng} we need to increase $f_{Ic} = I_{op}/I_c$
      - Reduced screening currents and better quench management
      - Higher chance of finding conductor defects
      - Better knowledge of conductor properties are required ($I_c(B,\theta)$, ab-plane)
    - For J_{cu}
      - 32 T: J_{cu} = 420 A/mm^2
      - I-REBCO goal: J_{cu} = 700 A/mm^2
      - RI-REBCO goal: J_{cu} = 1500 A/mm^2

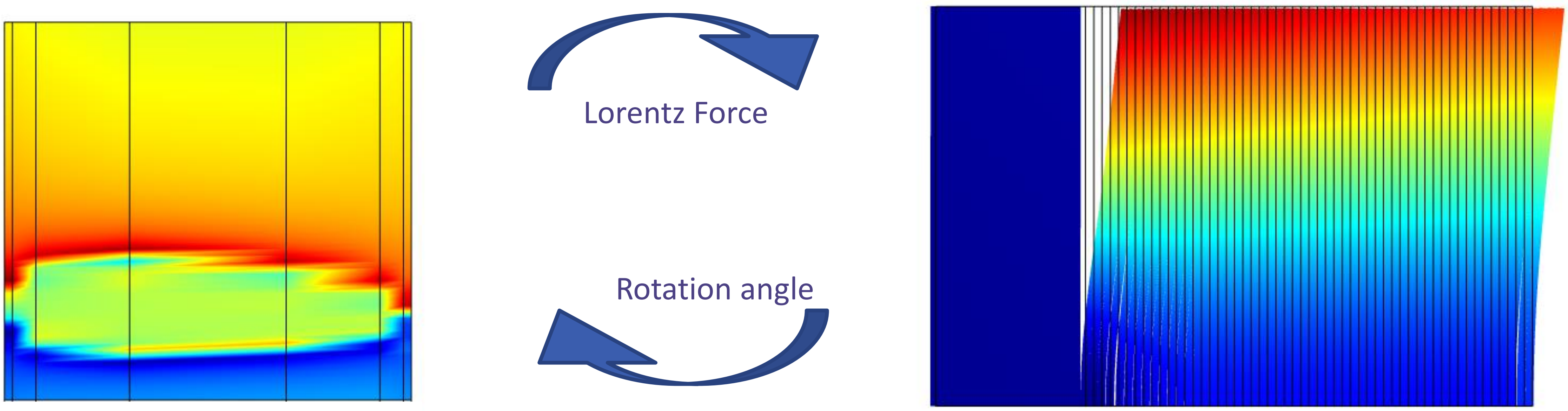
40 T Technical Challenges - Compactness





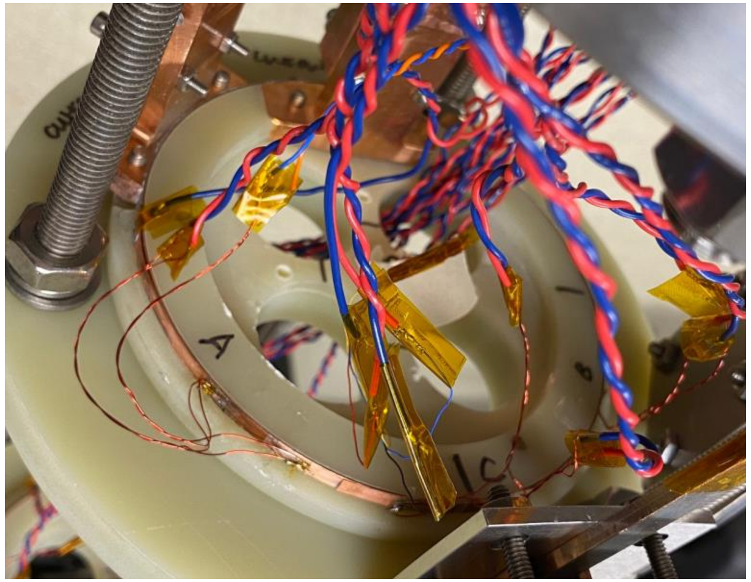
40 T Technical Challenges – Stress Management

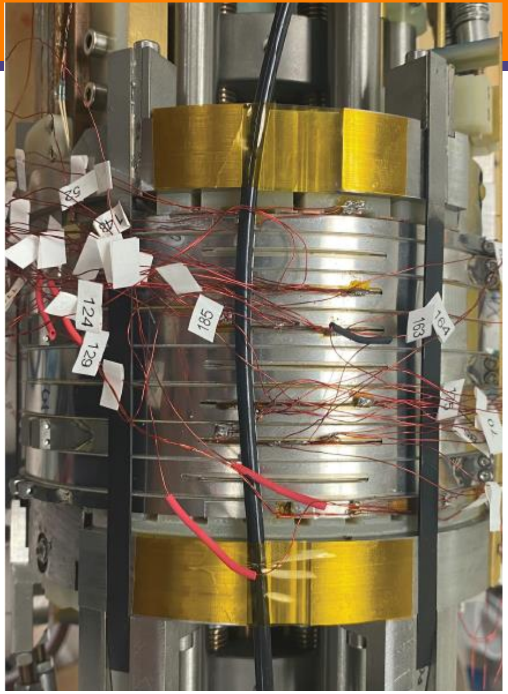
- It is critical to have precise knowledge of the conductor strain state
- We are working to improve accuracy of electromagnetic-screening current strain calculations
- An electromagnetic model (TA formulation) computes current & density is coupled with a structural model for strain and deformations. Iterated to recompute e-m with updated applied field angle from conductor deformations.



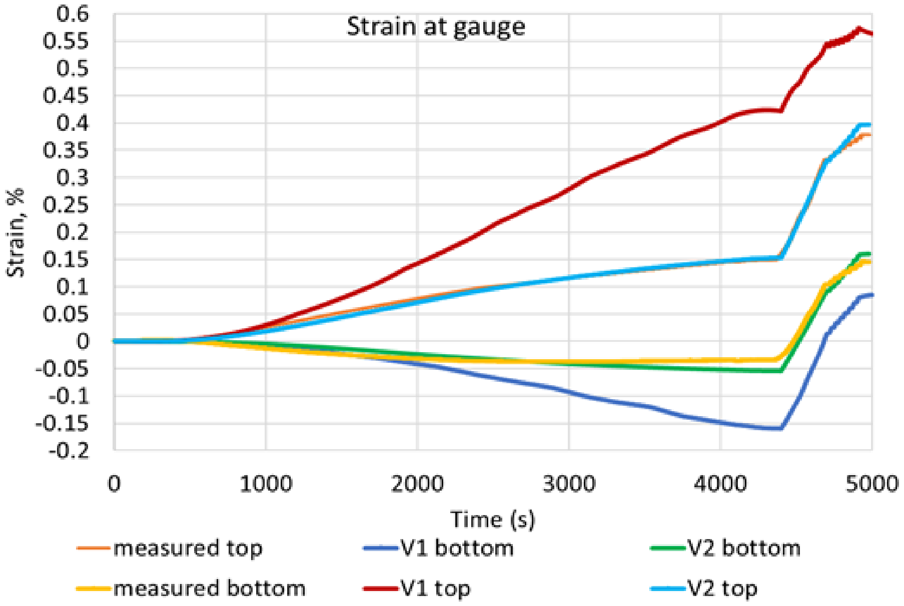
D Kolb-Bond *et al* 2021 *Supercond. Sci. Technol.* **34** 095004

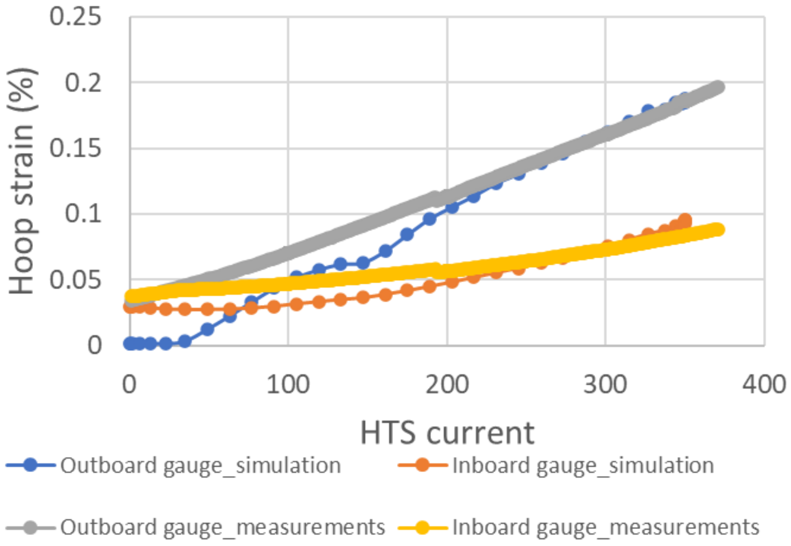
40 T Technical Challenges – Stress Management

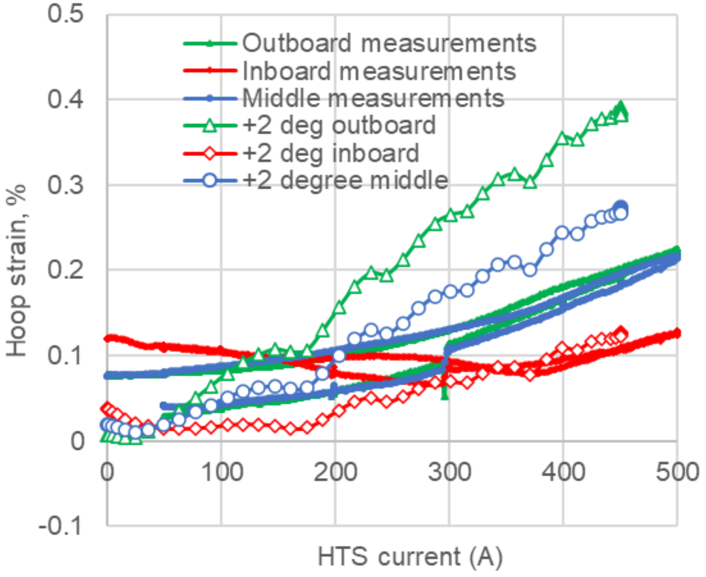




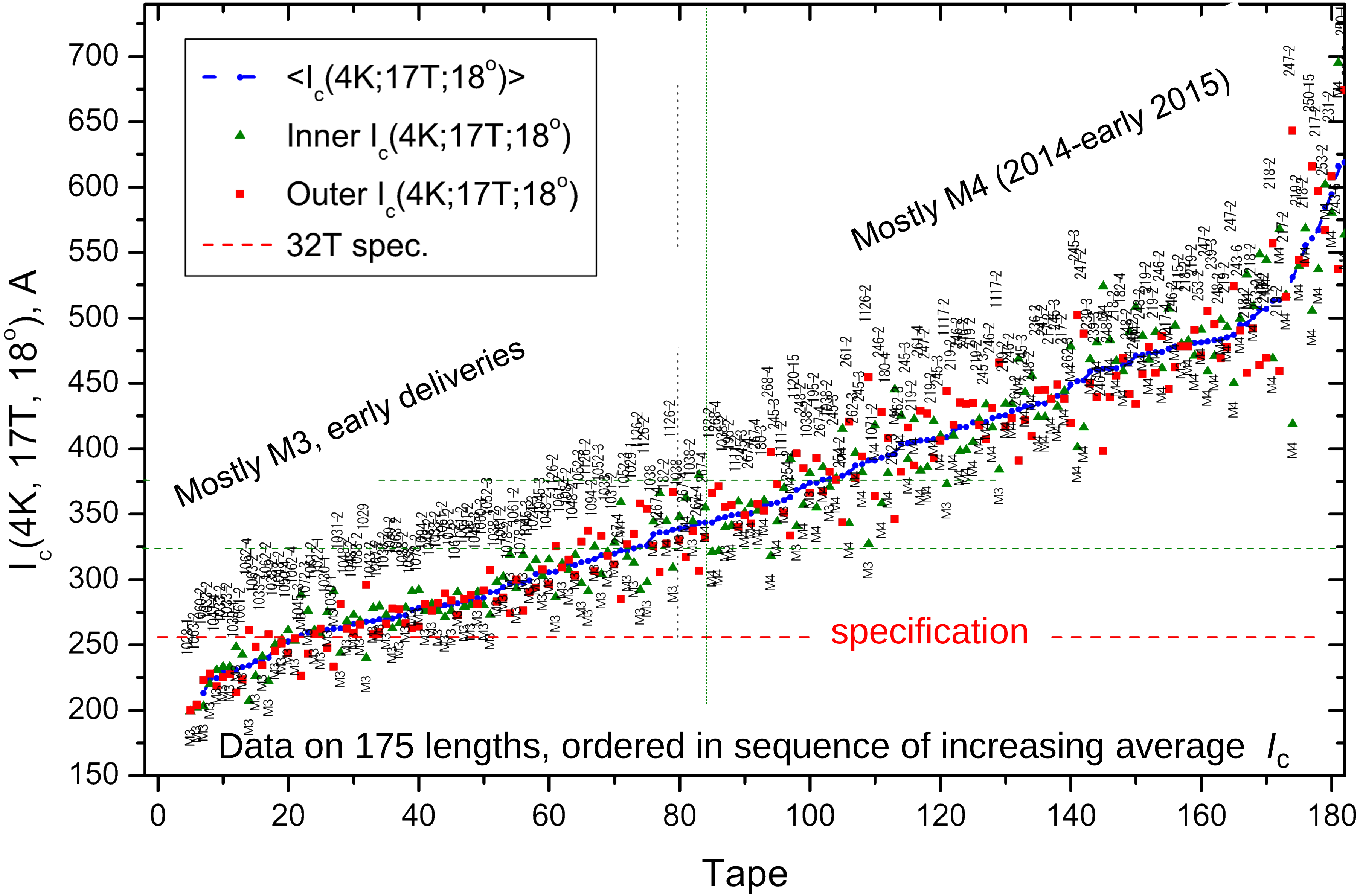
Petten Test Coil







40 T Technical Challenges - Conductor



Critical Current of Conductor for the 32 T

This conductor is "TOO GOOD"

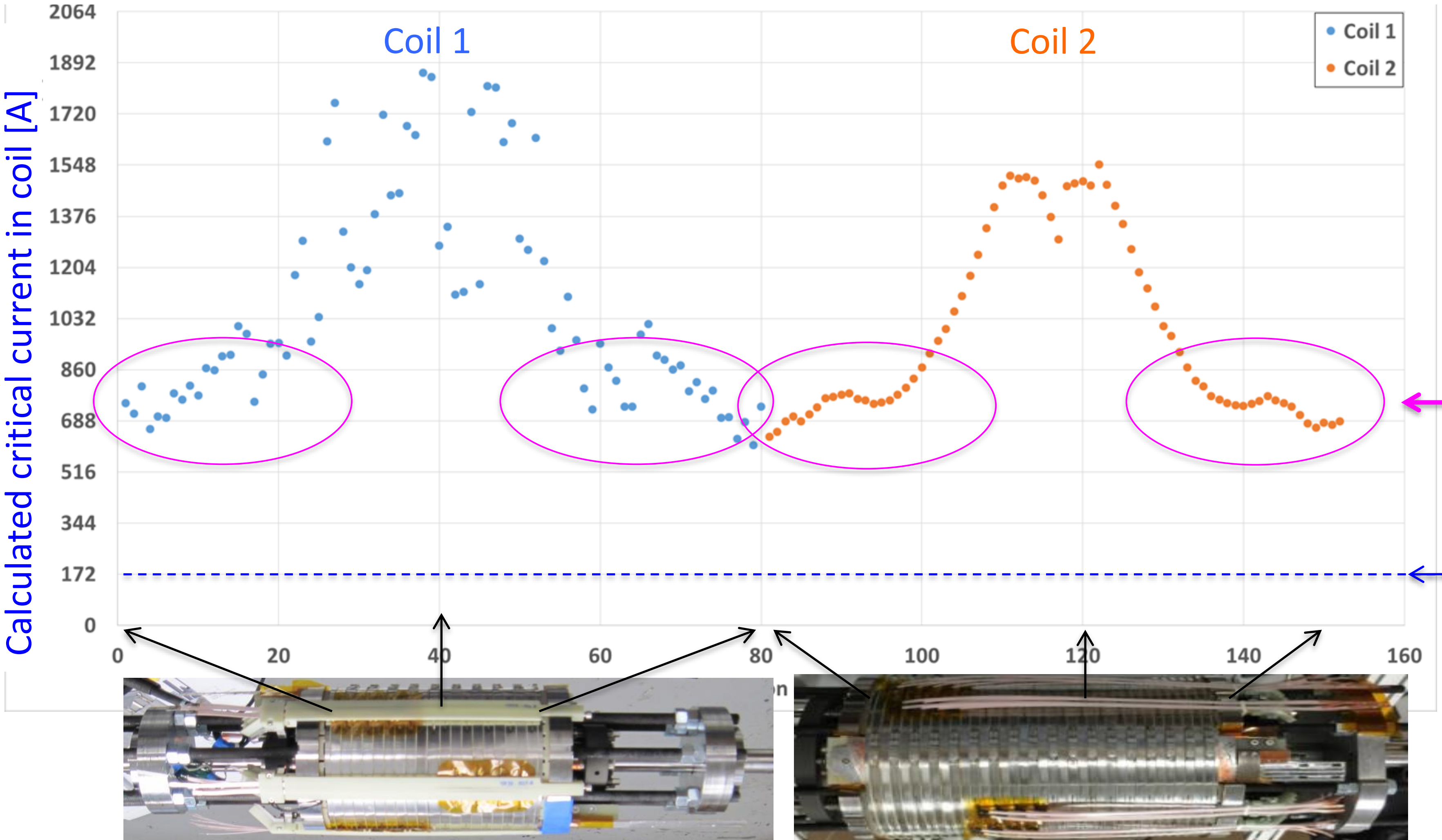
Operating margin is large:

- Exceedingly stable
- 130,000 J to protect 100 kg HTS coils
- 300 J to protect 1400 kg LTS coils

40 T Technical Challenges - Conductor

Calculated critical current (32 T) at full field

- Operating current is 1/10 to 1/3 of critical current



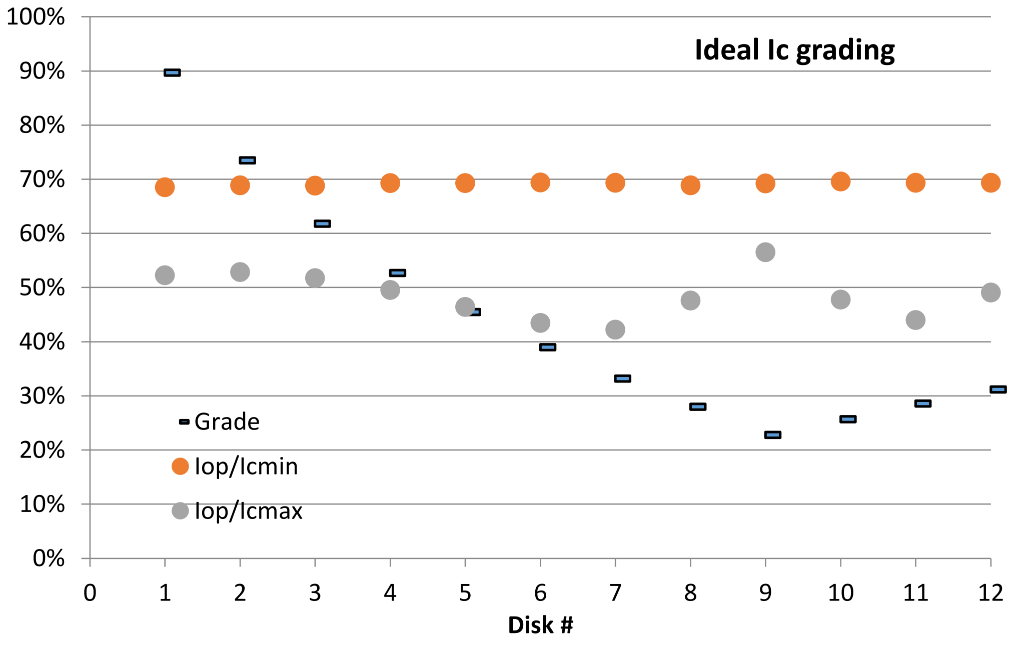
In quench at least half coil the HTS volume must be driven normal to absorb stored energy
(Hot-spot temperature < 200 K)

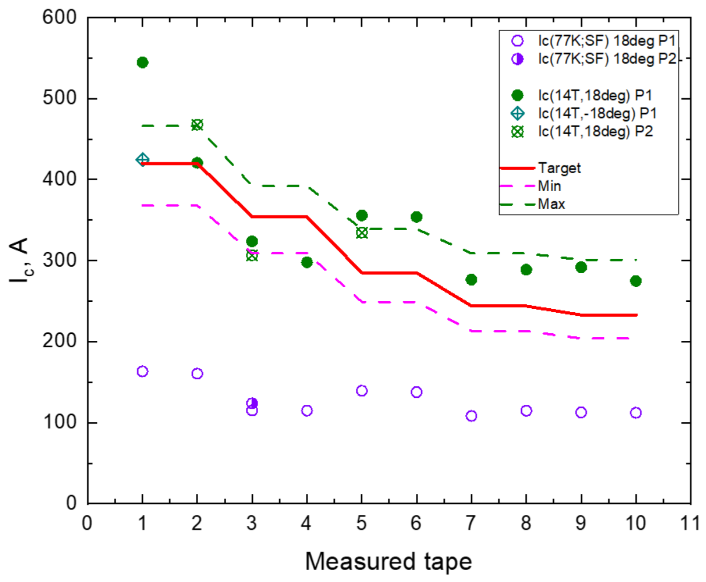
Must be driven normal at ~ same time

Operating current

40 T Technical Challenges - Conductor

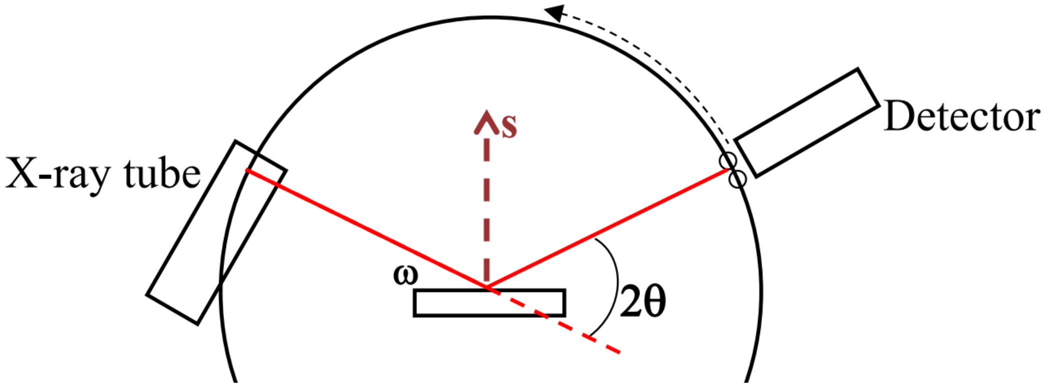
- Design approach is to maintain a constant fraction of critical current
- Example design of a 12-disk coil with maximum f_{Ic} = 0.70 within a pancake
- Constant f_{Ic} is achieved by varying a “standard” conductor critical current from 25 % - 90 %

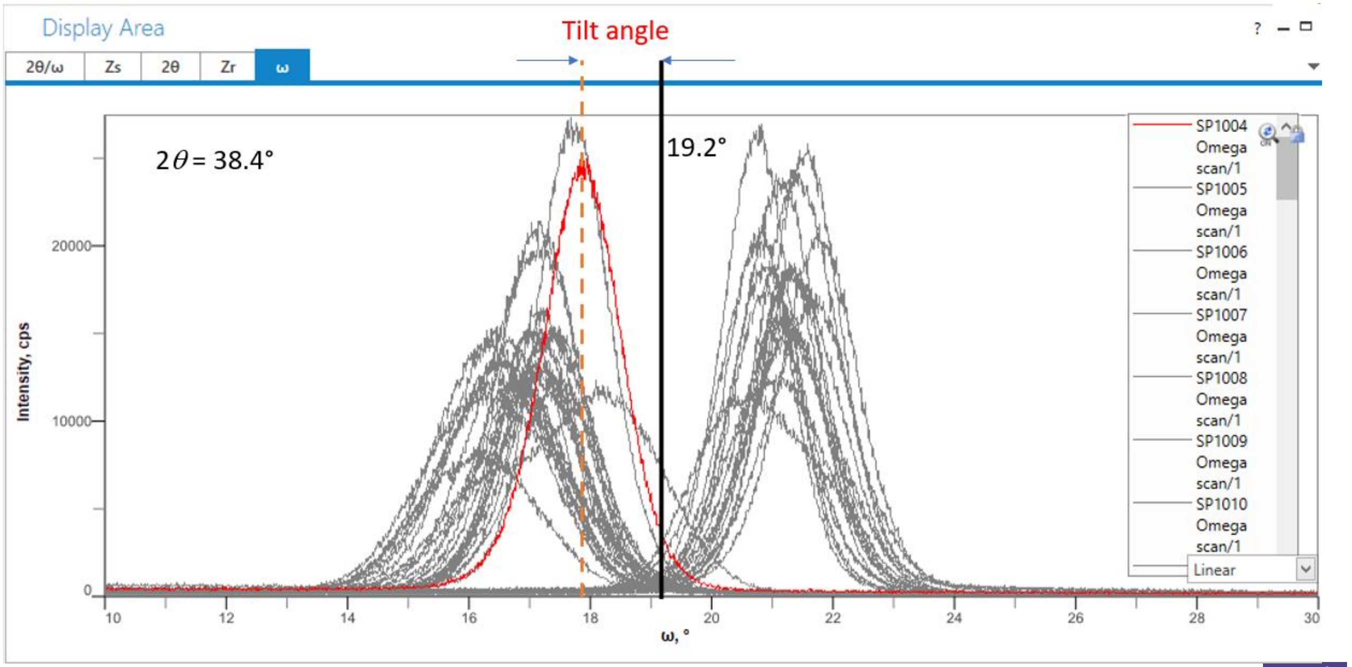


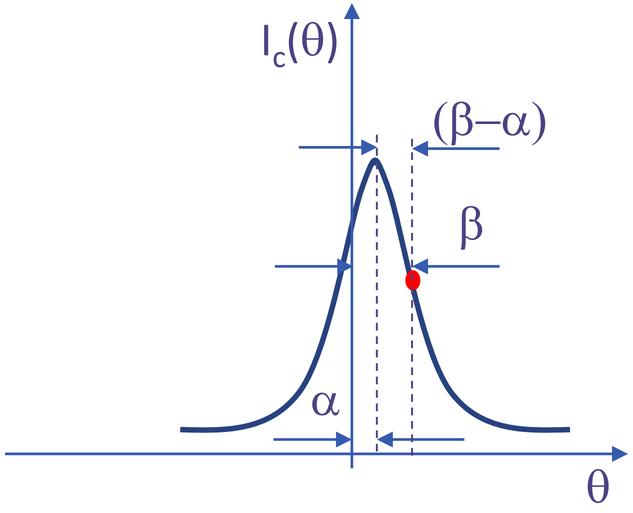


40 T Technical Challenges - Conductor

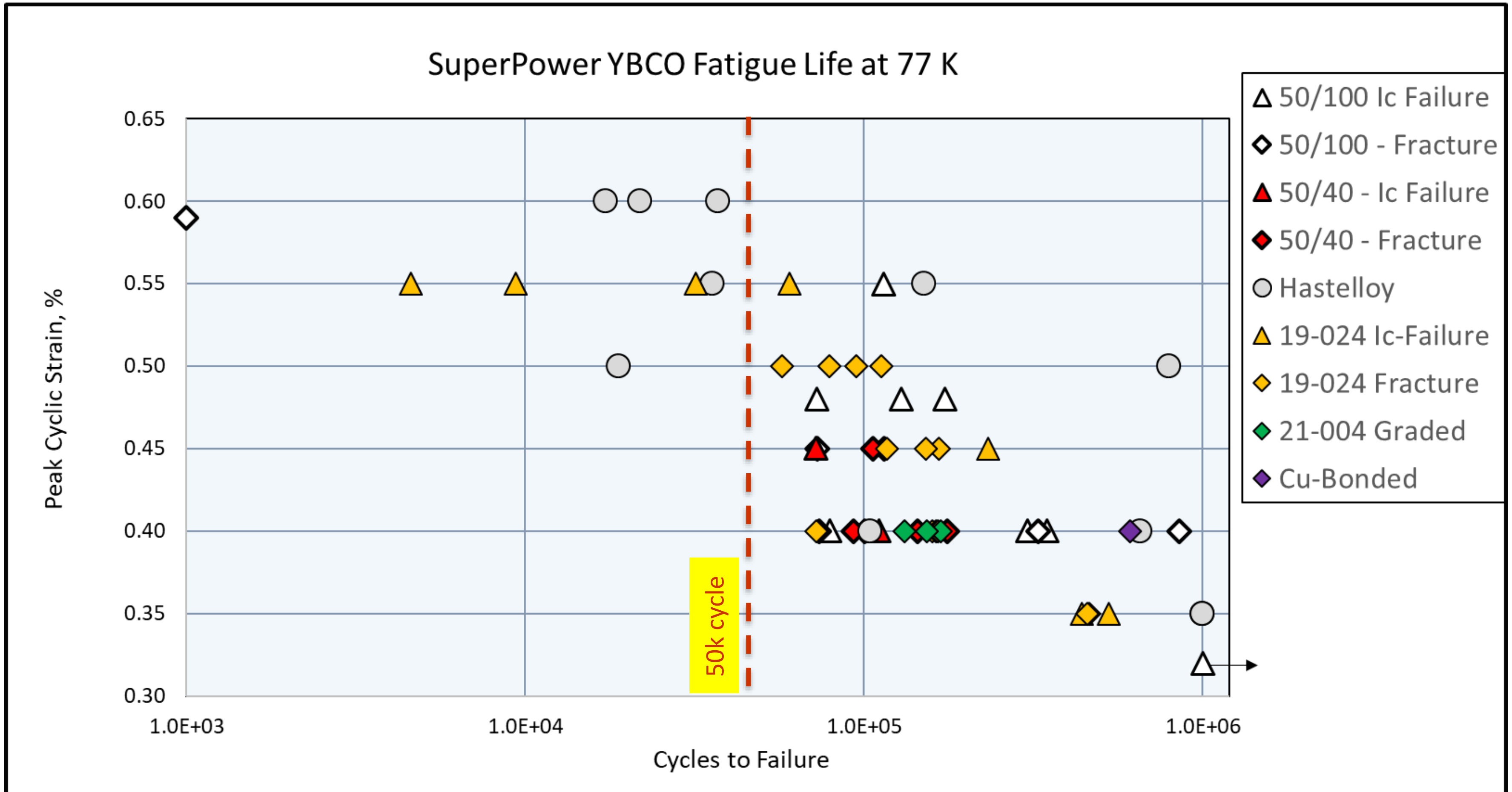
- The angular tilt of the REBCO ab-plane shifts the $I_c(\theta)$ peak
- Mixing up the "left" / "right" orientation can greatly affect the critical current of a module
- We are developing techniques to determine the angle and orientation of a tape's ab-plane
- See Lu, ASC2022 2MPo2A-04





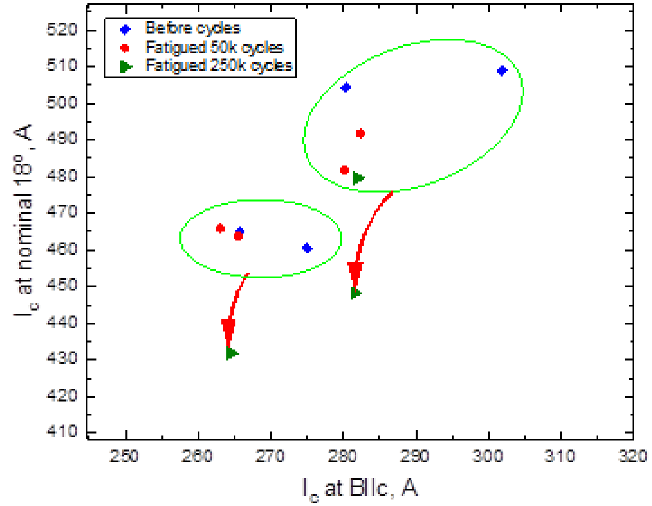


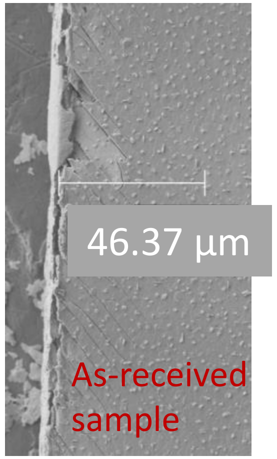
40 T Technical Challenges - Conductor

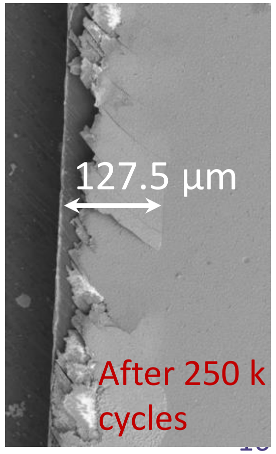


NOTES:
1. Load Control Tension-Tension Fatigue, r = 0.1
2. Ic Failure is defined as a permanent degradation of 1% reduction in Ic or more.

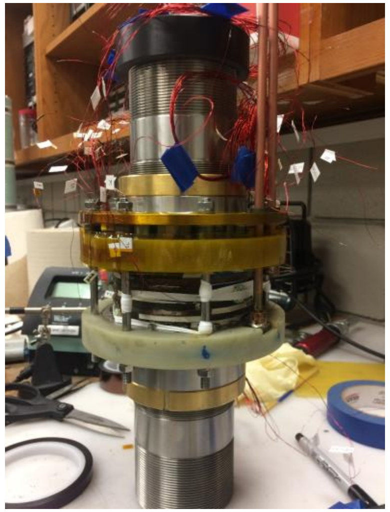
- Observed 6% Ic reduction at 4.2 K, 0.4% strain after 250 k cycles.





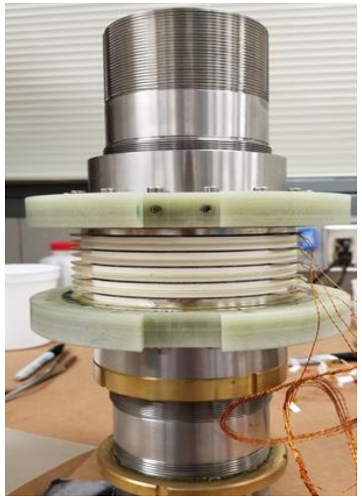


40 T, Small Scale Test Coils



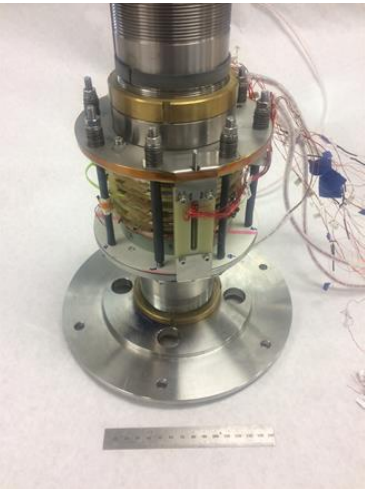
PTC1
(Apr 2019)

LBC-AR
(Apr 2019)

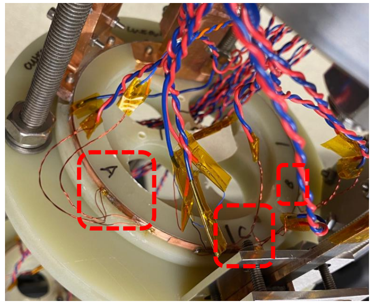


PTC2
(Jun 2019)

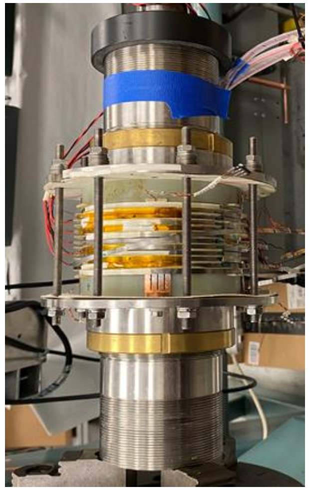
LBC-CO
(Aug 2019)



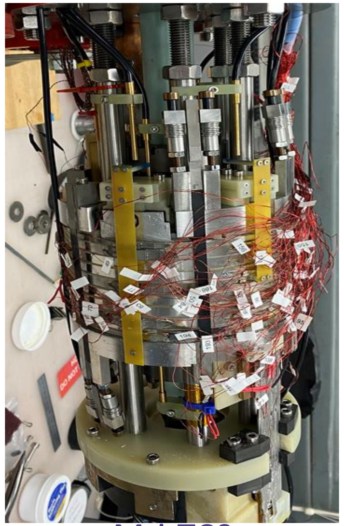
PT1R
(Oct 2019)



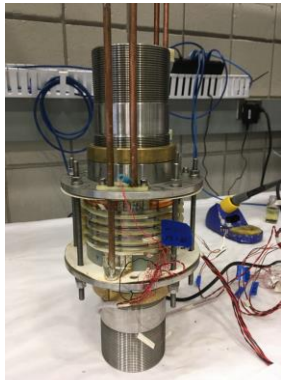
Mini fatigue coil
– Off centered
(Jun 2020)



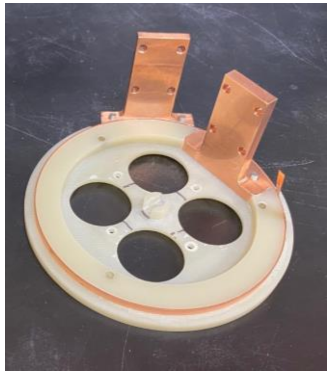
PT3
(July 2020)



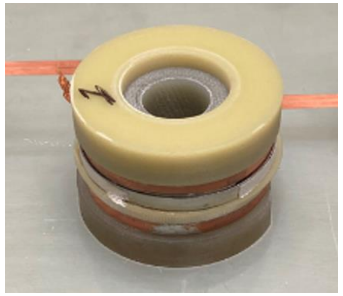
Mti-TC0
(Oct 2020)



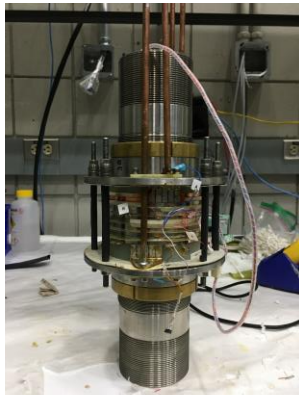
PTC4
(Dec 2020)



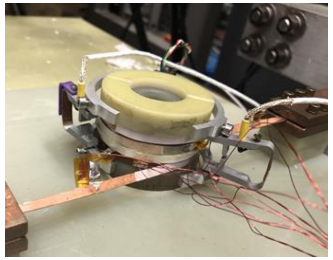
Mini fatigue coil
– centered
(Mar 2021)



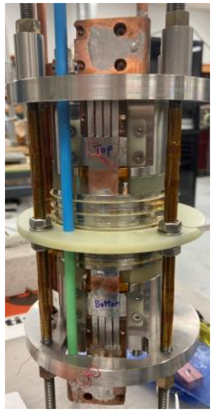
Axial pressure test coils
(Mar 2021)



PTC5
(Mar 2021)



Axial pressure test coil:
two in hand
(April 2021)



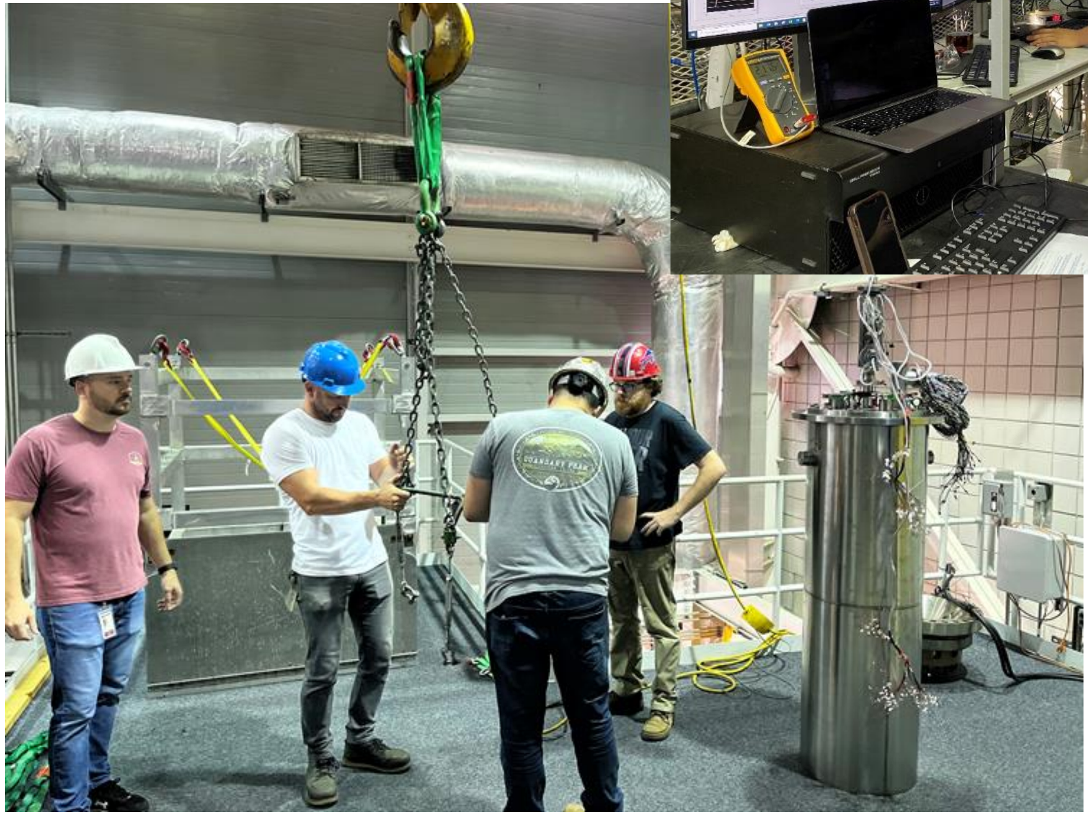
PT6
(June 202

40 T, Mid-Scale Test Coils

- Most Recent Test Coils
  - I-REBCO: “TC2”
    - Single insert coil operated in the 45 T Outsert
    - Two-in-hand REBCO winding “MTI”
  - RI-REBCO: “RI-NC”
    - Two nested coils – self field
    - Inner coil: 12 DP’s
    - Outer coil: 18 DP’s

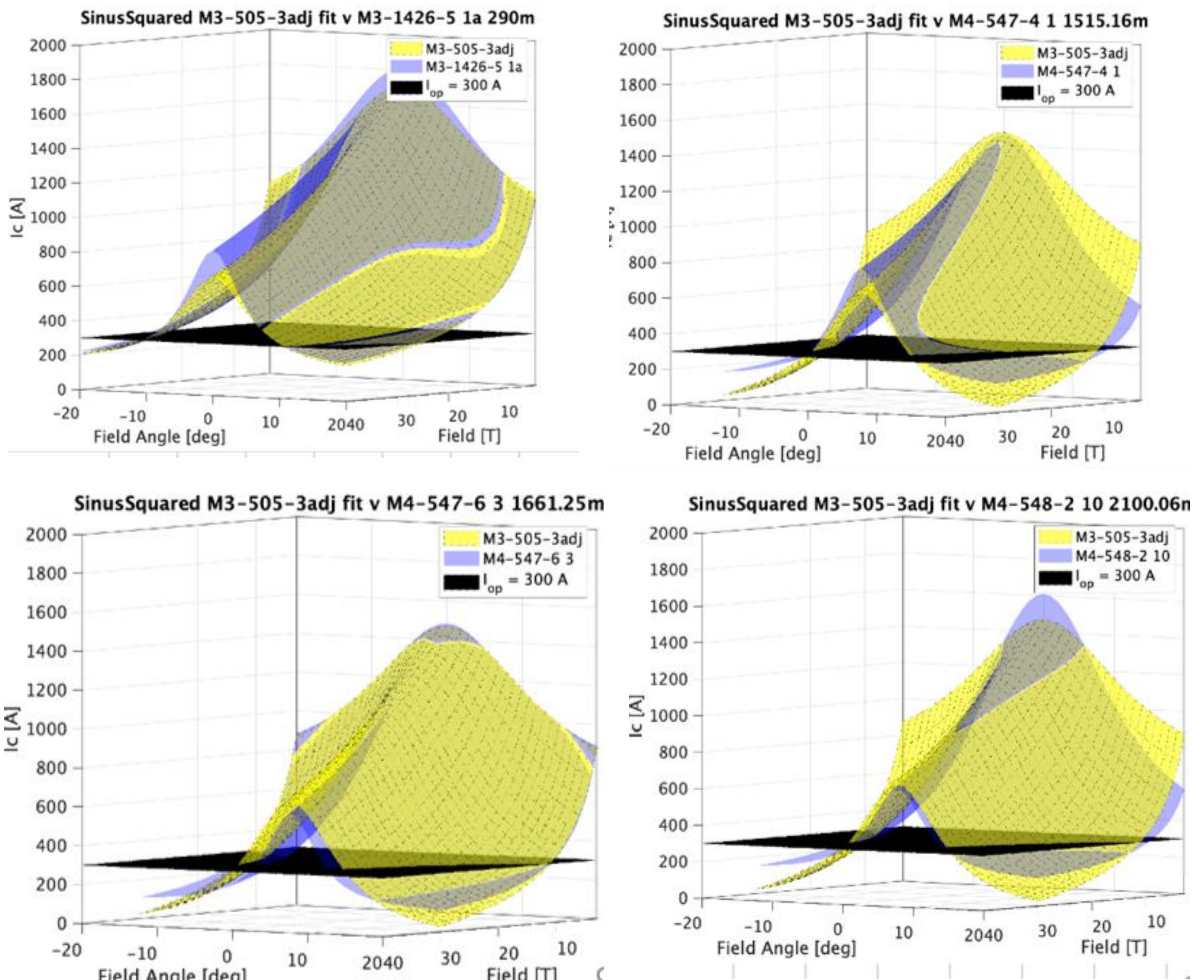
I-REBCO Test Coil – TC2

- Single insert coil operated in the 45 T Outsert
- Central field: 25.4 T (11.4 T background)
- Current: 570 A
- Stored energy: 47 kJ
- Inductance: 289 mH
- Six conductor grades
- J_{cu} = 650 A/mm^2
- Protected via pulsed forming network



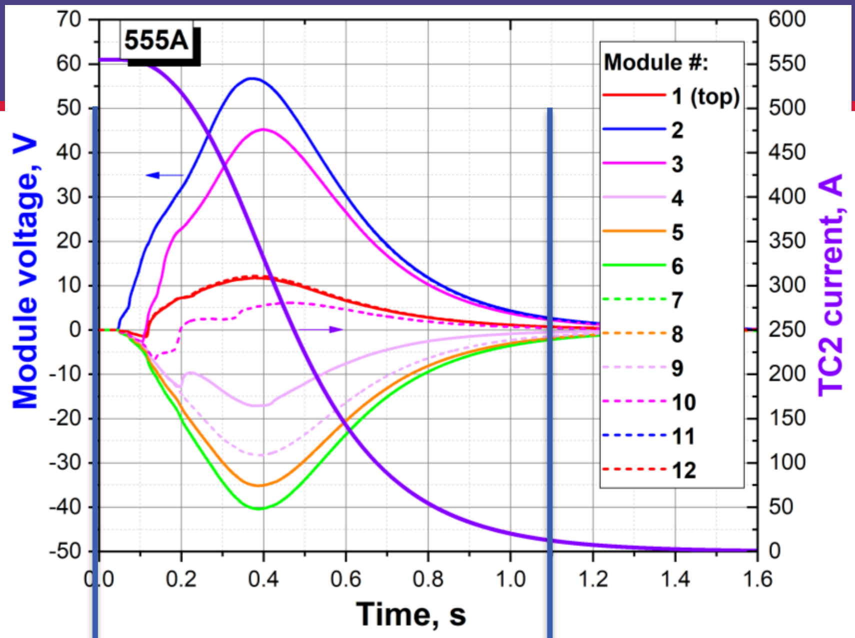
I-REBCO Test Coil – TC2

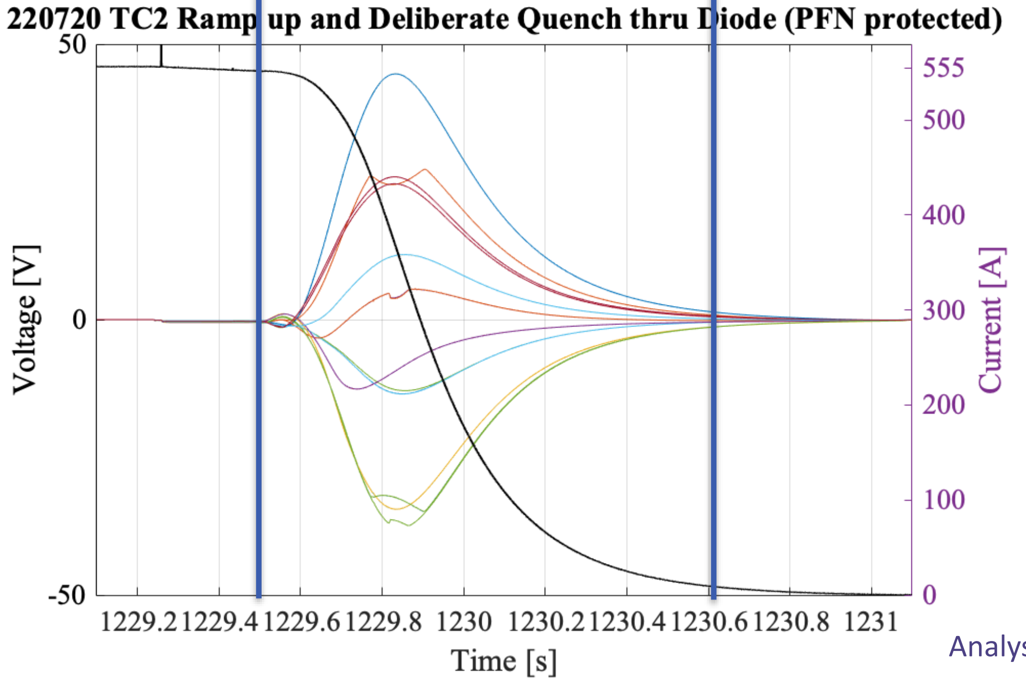
- Fully characterized I_c of each tape used in the test coil via torque magnetometry
  - See Jaroszynski ASC2022, 2MOr2B-01
- Critical surface of each spool is unique and not scalable based from single point measurements



I-REBCO Test Coil – TC2

- The main purpose of TC2 was to study quench
- Quench modeling now includes deformation of conductors from screening currents, which affects critical current
- Very good agreement between predictions and measurements





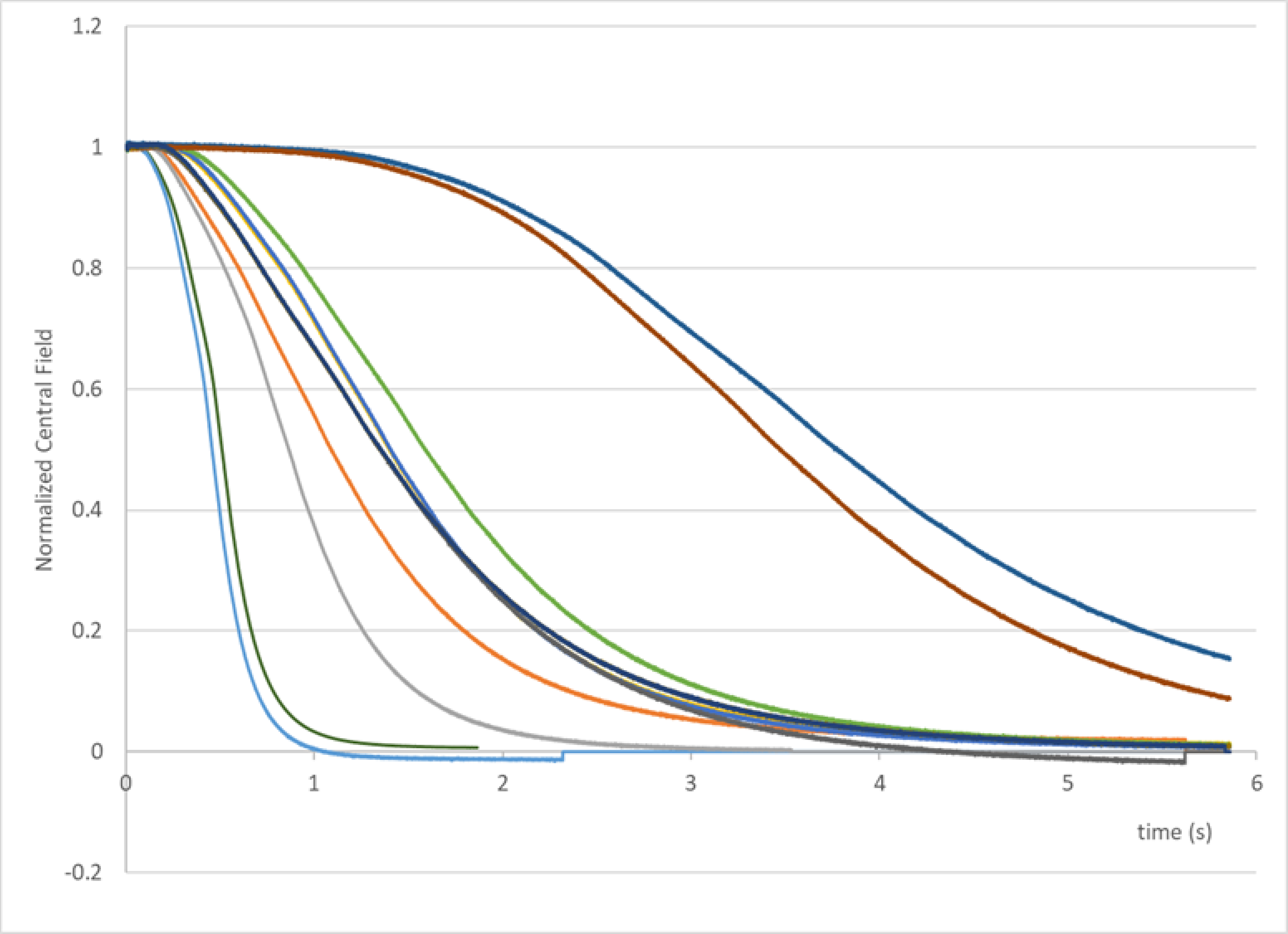
Analysis by A.V. Gavrilin

RI-Nested Coils

- Two nested REBCO Coils
- Central field: 19.2 T (225 A)
- Stored energy: 0.105 MJ
- Inductance: 4.15 H
- Target R_c = 2.7 mΩ
- Mid-plane pressure = 60 MPa (coil 2)
- Self contained axial forces, designed to 245 kN
- Testing occurred late September

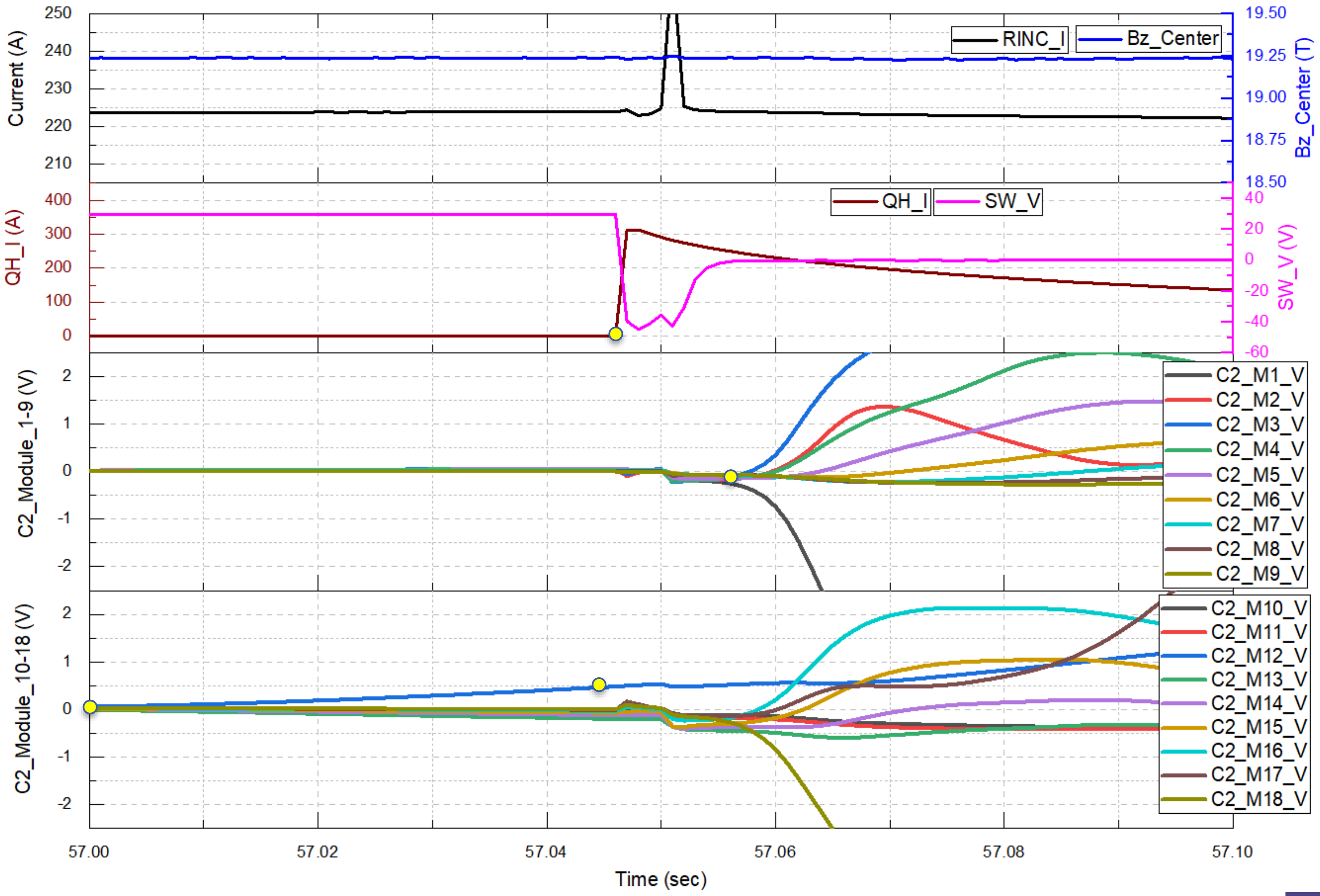
RI-Nested Coils

- Quench tests
  - Active protection system
  - Varied energy level of quench heaters to study discharge time and quench propagation
  - Quench initiated
    - Coil 2, module 12



RI-Nested Coil

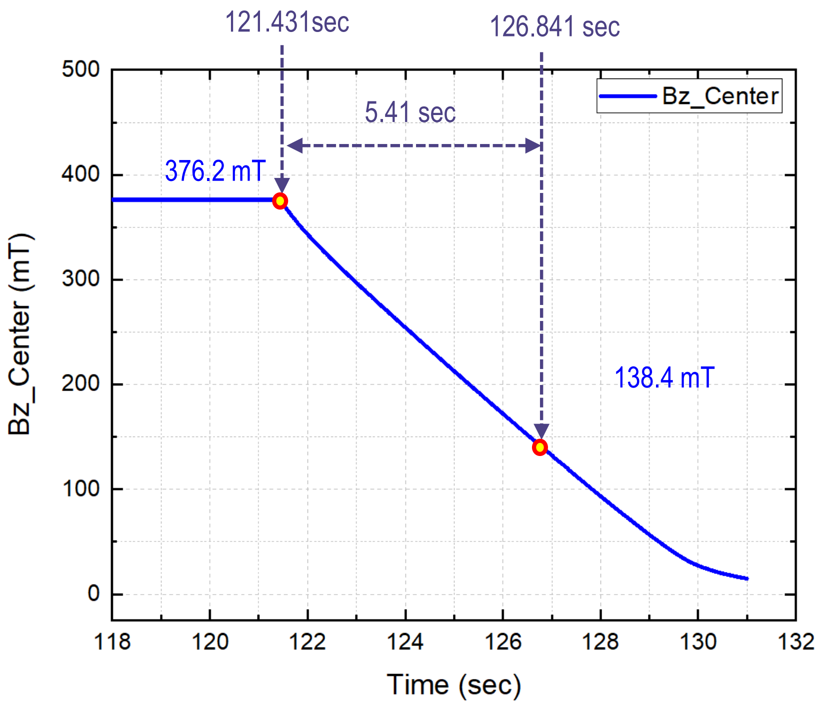
- Quench moment
  - Module starts to transition
    - t ~ 57 s
  - Voltage rises until exceeding threshold of 0.5 V for 5 ms
    - t = 57.045 s
  - Protection fires
    - t = 57.046 s
  - Other modules start to normalize within 10 ms
    - t = 57.057 s
- Comparisons with modeling are proceeding



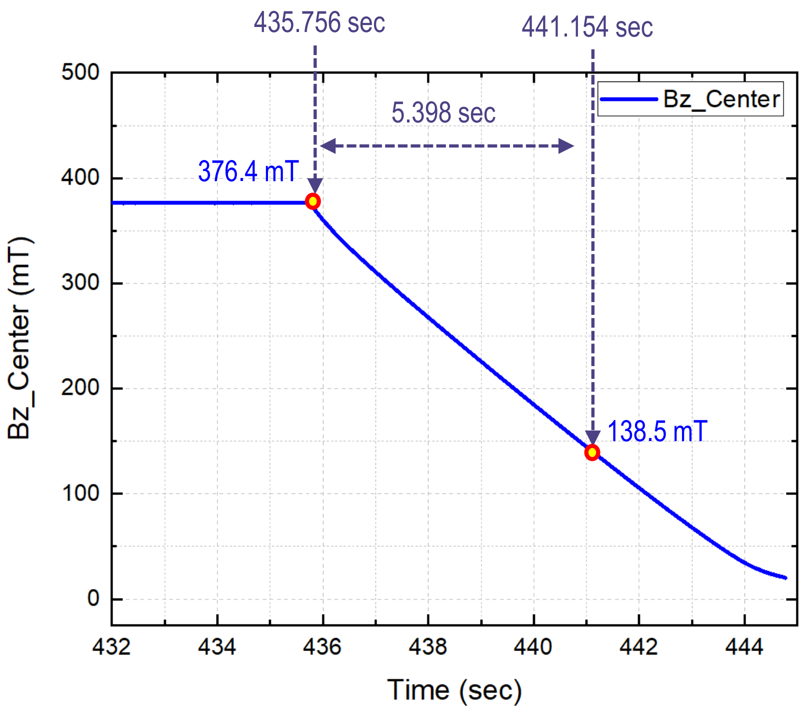
C2-M12

RI-Nested Coils

- Contact resistance
  - Target R_c = 2.7 mΩ
  - Measured: 0.74 mΩ
    - Using fast discharge method
  - Contact resistance remained constant through the testing



First discharge test



Final discharge test
(after quench tests)

Outlook

- Technical risks are being retired because of the results produced by the test coils and conductor characterizations – but there is still more to do
- Additional thermometry is being added to TC2, which will be retested in November
- RI-NC results are still being reviewed
- Within 1-year we will select the technology for the 40 T final design
- Final demonstration large scale coil testing to be performed based on final design