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An experiment that generated a dipole field of 5.99 T at 4.2 K using high-temperature superconducting CORC® wires Presented to the ASET program at MSU

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  - FNAL: M. Baldini, S. Gourlay, V. Kashikhin, S. Krave, V. Lombardo, X. Xu

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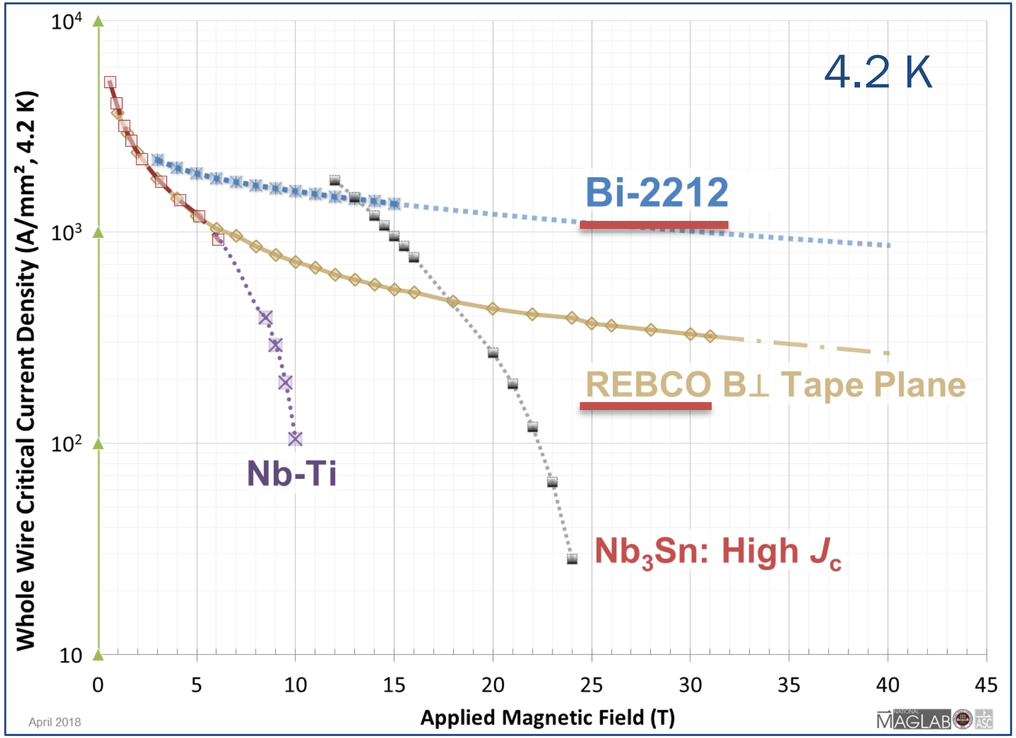
This presentation builds on two excellent ASET seminars

- **High-field superconductors and superconducting magnets for ECRIS and frontier nuclear physics**
  - Dr. Tengming Shen, 19 April 2024
- **Advances in Superconducting Magnet Technology for Future Colliders**
  - Dr. Soren Prestemon, 7 October 2022

Plan

- What's special about HTS, especially REBCO?
- What's new in the REBCO dipole magnet development?
- C3: design, fabrication and test. What can we learn?
- A question for you

HTS can generate high fields than Nb-Ti or Nb_3Sn at 4.2 K

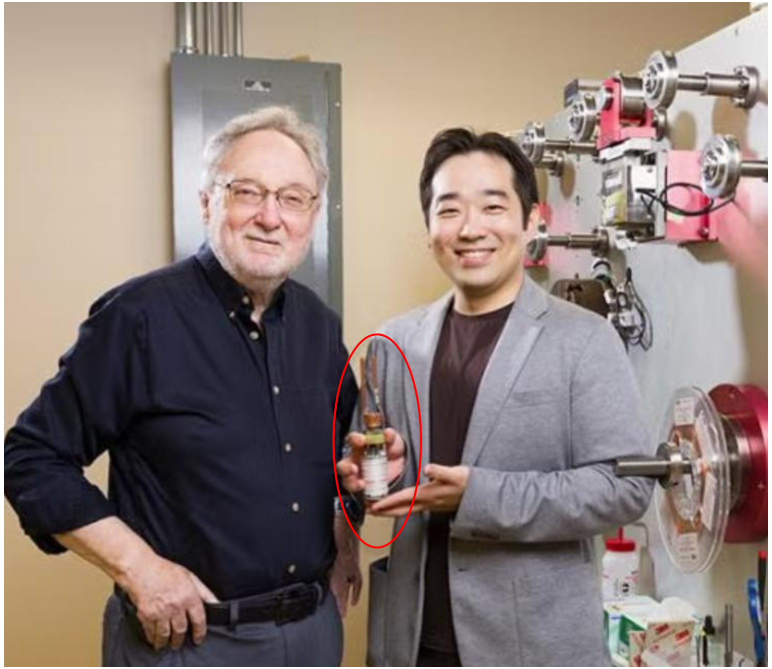


Two HTS options:

- Bi-2212
- RE-Ba-Cu-O, RE = rare earth

P. Lee's master plot

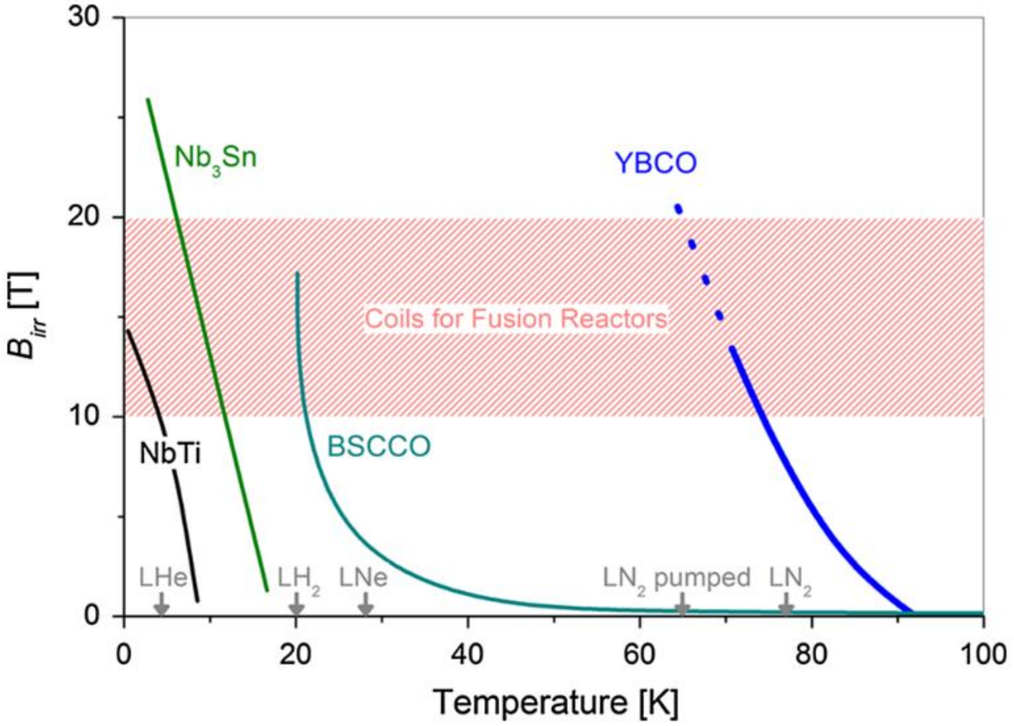
A new record solenoid field, 48.7 T, was made in October 2025



ASC / NHMFL tested a REBCO coil that generated a solenoid field of 17.6 T within a background field of 31.1 T, reaching a total field of 48.7 T at 4.2 K.

Prof. David Larbalestier and Dr. Jeseok Bang with the REBCO coil. source

REBCO can also operate at temperatures above 4.2 K



- Independent of LHe
- Higher cooling efficiency
- Higher heat capacity

[Whyte *et al.*, J Fusion Energy, 2016]

Another helium shortage

ECONOMY

The war in Iran is impacting Earth's supply of helium

MARCH 15, 2026 · 8:10 AM ET

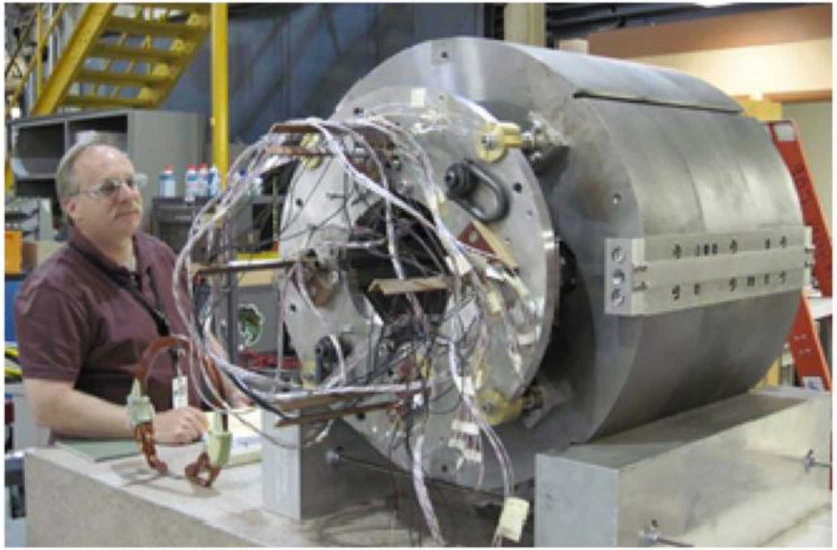
HEARD ON WEEKEND EDITION SUNDAY

By Ayesha Rascoe, Margaux Bauerlein

npr

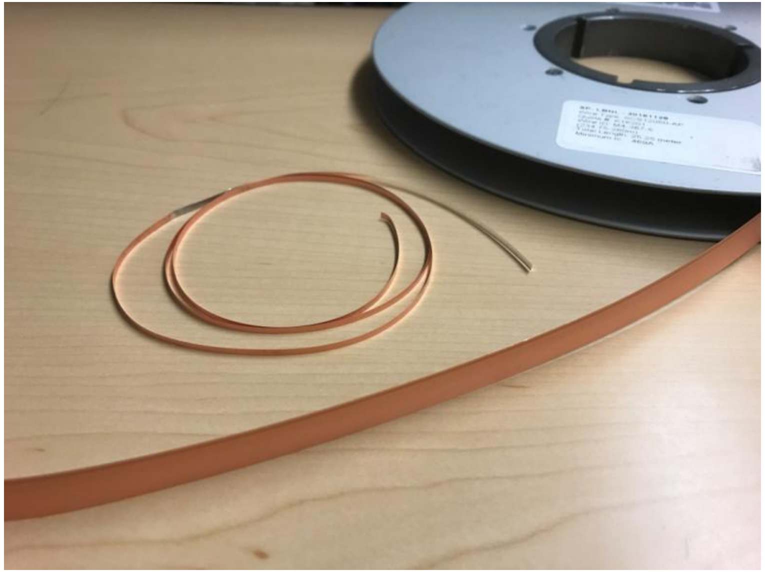
An email from the lab on 3/19,
"Airgas declared a Force Majeure for helium effective this week so orders may or may not come in."

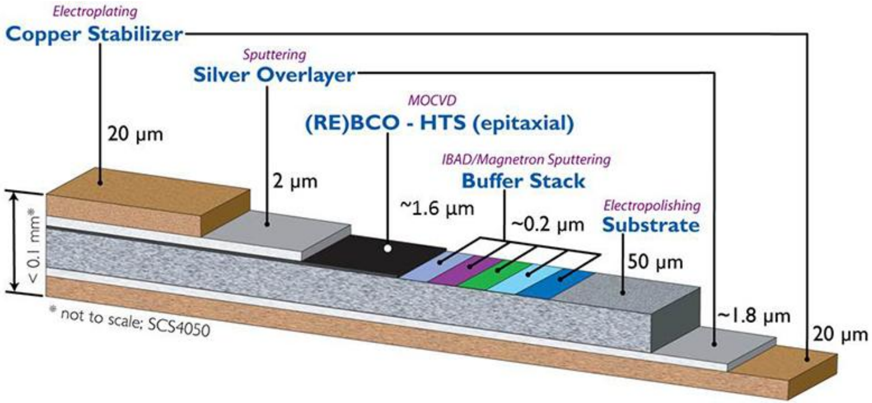
HTS technology can address high heat load to magnets – an example related to FRIB



- Motivation: to address the high radiation and high heat load at the fragment-separator region
- BNL developed a conduction-cooled REBCO quadrupole magnet [Gupta, IEEE TAS, 2015]

REBCO is produced in tape form to carry a useful amount of current





Several vendors are competing to offer REBCO

SuperPower Inc.

METOX

上海超导™
SHANGHAI SUPERCONDUCTOR

FARADAY FACTORY JAPAN

Fujikura

Zero to Infinity
SuNAM

THEVA

- Volume up, cost down
- Strengthen the U.S. domestic supply chain

Advantages of REBCO can also cause problems

One the hand …	One the other hand …
No reaction needed	Tricky to wind and handle the brittle tapes
High current in high field	Strong magnetization, high loss, large field errors
High thermal stability	Difficult to detect a resistive zone

Driving questions

- How to make accelerator magnets using REBCO?
  - Coupled choices in magnet design and conductor option
- How do the magnet and conductor perform?
  - Does the magnet quench? Can we protect the magnet?
  - How reproducible is the field? What's the field error?
- What issues limit the magnet performance? How to address them?

What are the impacts on HEP and NP programs?

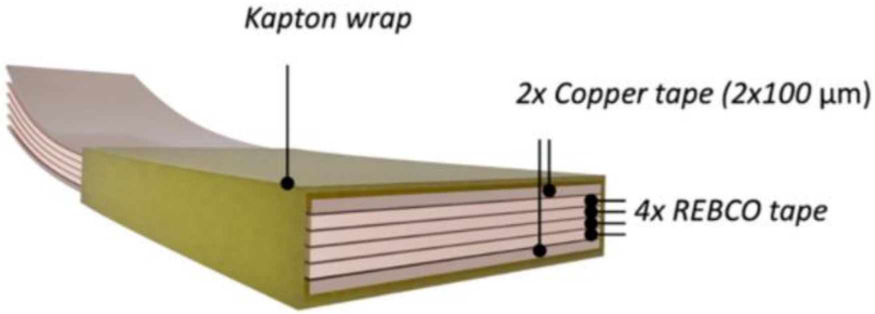
European programs have led the development of REBCO technology

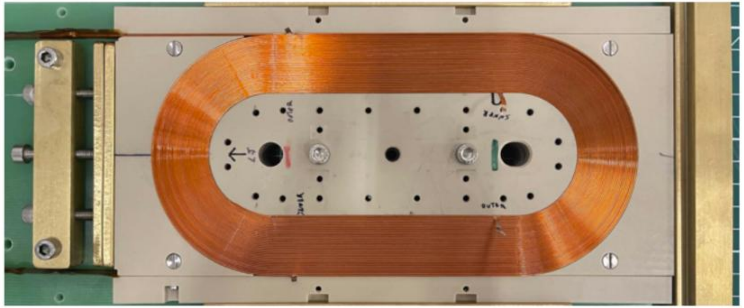
- **EuCARD2 successfully demonstrated accelerator-quality REBCO dipole magnets using Roebel cable: 4.5 T at 4.5 K** [van Nugteren *et al.*, SuST, 2018; Rossi and Senatore, Instruments, 2021]

HFM program is focused on common coil based on modular REBCO racetrack coils

- A common coil using 4 racetrack coils recently generated 5.4 T in the 20-mm-diameter apertures
- As part of a road map toward 14 T and beyond

[Baskys, IEEE TAS, 2026, also HiTAT-2 workshop]





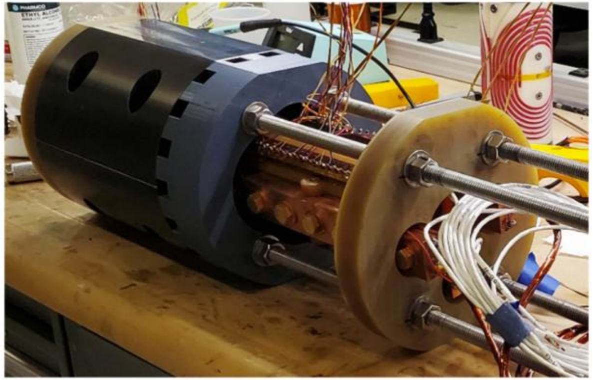
U.S. MDP has been focused on round REBCO cables

- REBCO tapes wrapped around a solid core
- Round wire eases winding and magnetic analysis
- Two U.S. vendors

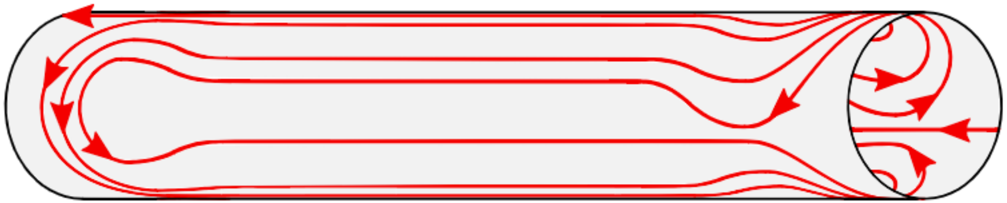
STAR® wires from AMPeers LLC

CORC® wires from ACT

MDP is pursuing several dipole magnet concepts to address high stress on conductors



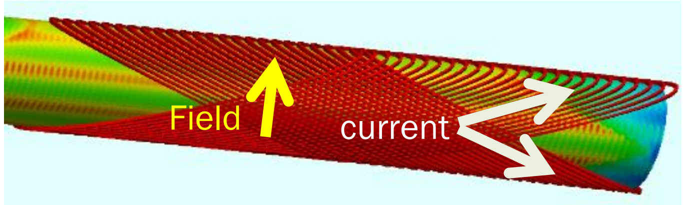
COMB at Fermilab [Kashikhin *et al.*, IEEE TAS, 2025]

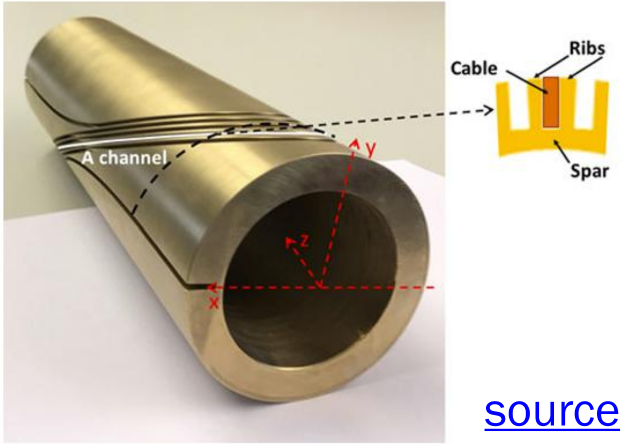


Uni-layer at LBL [Rudeiros Fernández and Ferracin, SuST, 2023]

C3 magnet uses the canted cosθ design

Example: dipole magnet





source

- Meyer and Flasck proposed the concept in 1970 [NIM]

- Embed conductor in the mandrel to support the conductor
- Generate good geometric field quality

- Use more conductor than traditional design
- Difficult to machine 10 m long mandrel

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Together with industry partners, we are developing CORC® CCT dipole magnets with increasing fields and complexities

- C1, 2-layer, 1.2 T in 2017. Demonstrated initial concept
- C2, 4-layer, 2.9 T in 2019. Used metal mandrel
- C3, this talk

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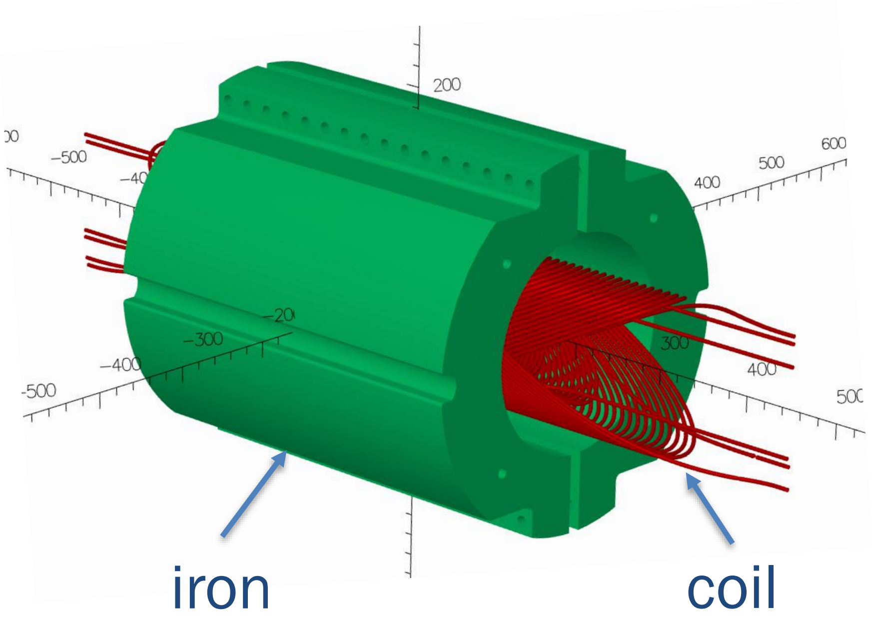
Advanced Conductor Technologies LLC
www.advancedconductor.com

SuperPower Inc.
A Furukawa Company

Couple magnet & conductor work to progress on both fronts

C3 target: generate a dipole field of 5 T at 4.2 K



- Machine-aided winding
- Distributed fiber-optic sensing
- Transfer function of 0.72 T/kA without iron; 0.93 T/kA with iron
- Clear bore 65 mm; stored energy 51 kJ at 6 T

Iron design by L. Brouwer, R. Norris and D. Arbelaez, following Nb_3Sn CCT5

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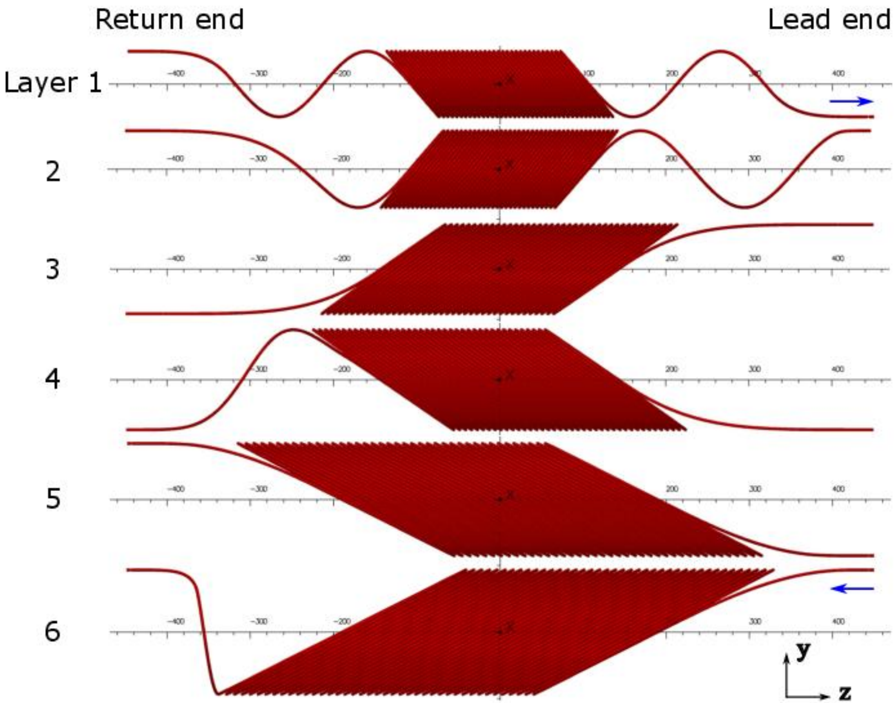
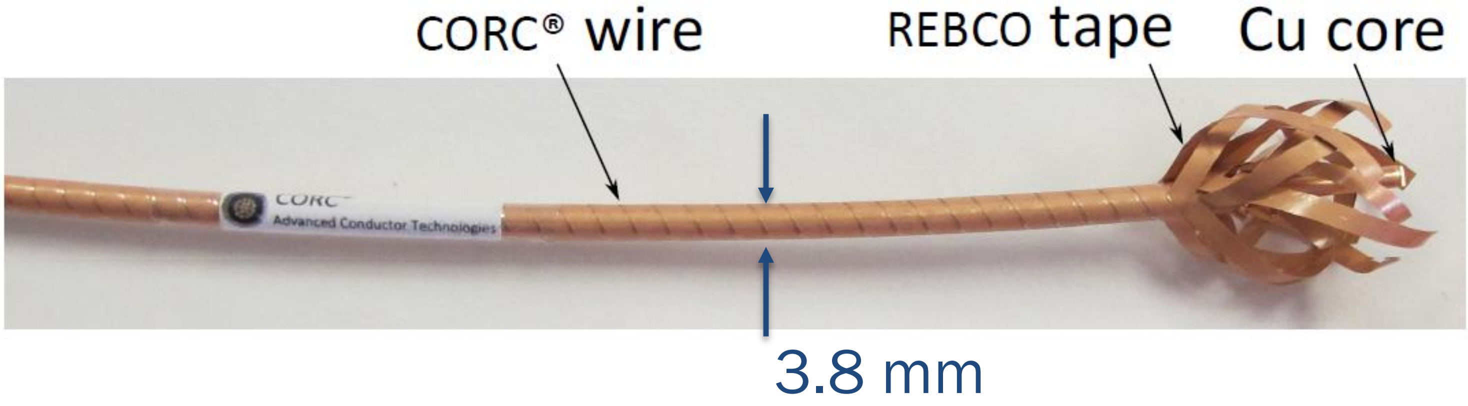
Coil layout – six tilted solenoid coils



- 145 m of CORC® wires in 6 pieces, maximum piece length 35 m
- 7.5 km long REBCO tapes

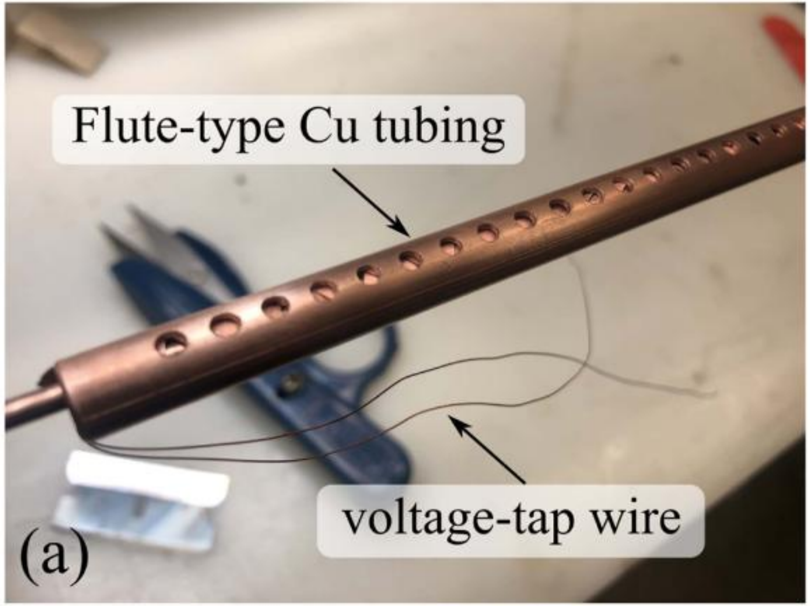
C3 magnet uses the latest-generation CORC® wire

- 30 tapes in 12 layers
- 2 mm wide commercial tapes from SuperPower



Advanced Conductor Technologies LLC
www.advancedconductor.com

Flute-type electrical termination



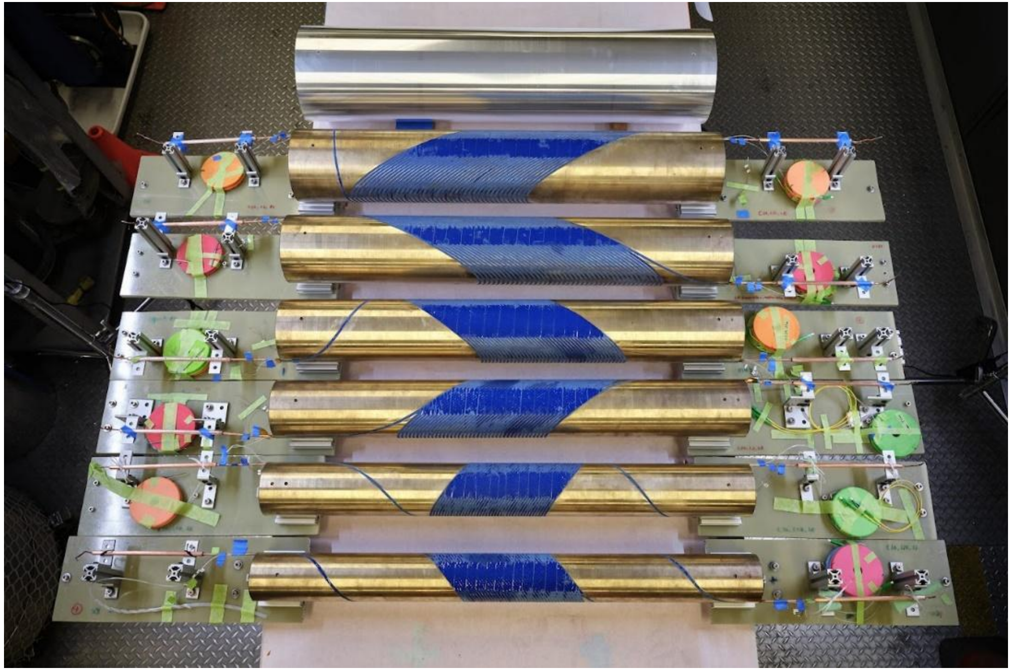
- Developed by H. Higley [Abraimov *et al.*, IEEE TAS, 2025]
- Joint resistance 10 – 50 nΩ at 4.2 K

We used a semi-automated machine to wind the C3 coils

- Inspired by G. Kirby's CCT winding machine circa 2018
- Developed by B. Ghiorso, H. Higley and T. Lipton during the pandemic
- Automated winding is key for REBCO magnets

A short video on winding

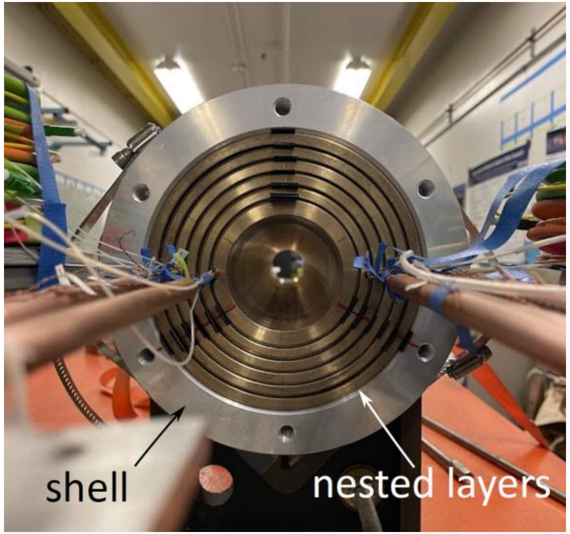
Coils and shell before assembly, November 2024

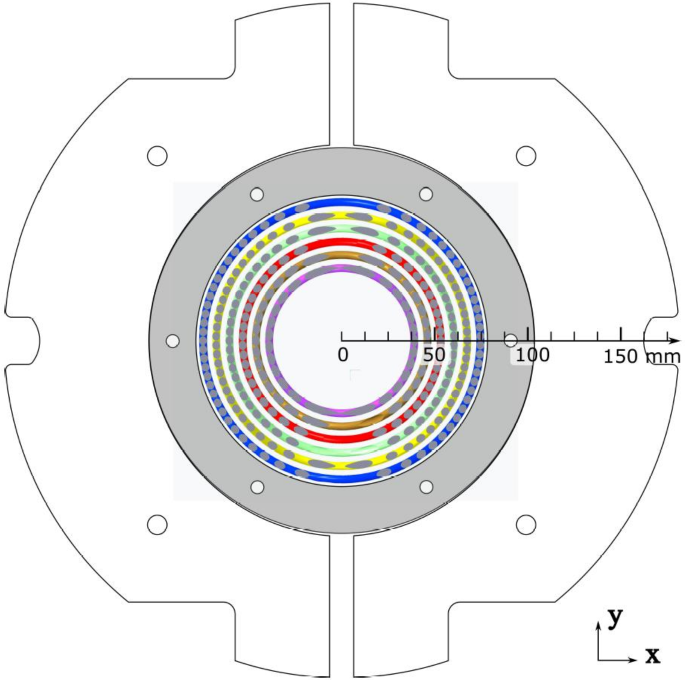


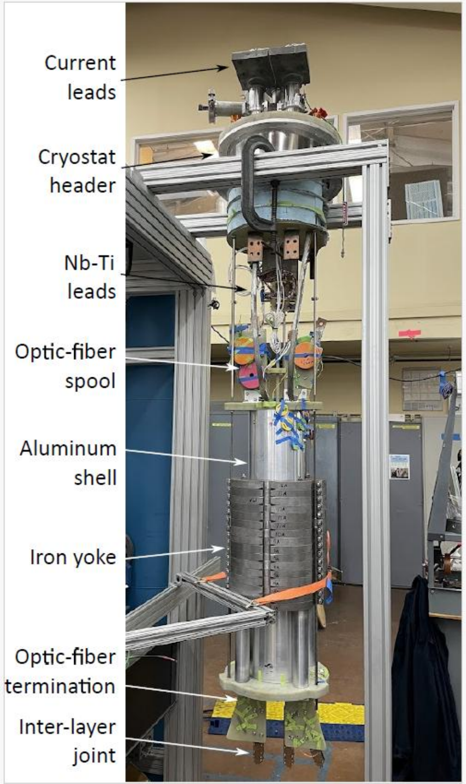
- Co-wound two optic fibers with the CORC® wire in each layer [Luo *et al.*, SuST, 2025]
- Mandrel design: A. Saravanan
- Shell design: R. Norris

Image courtesy of A. Lin

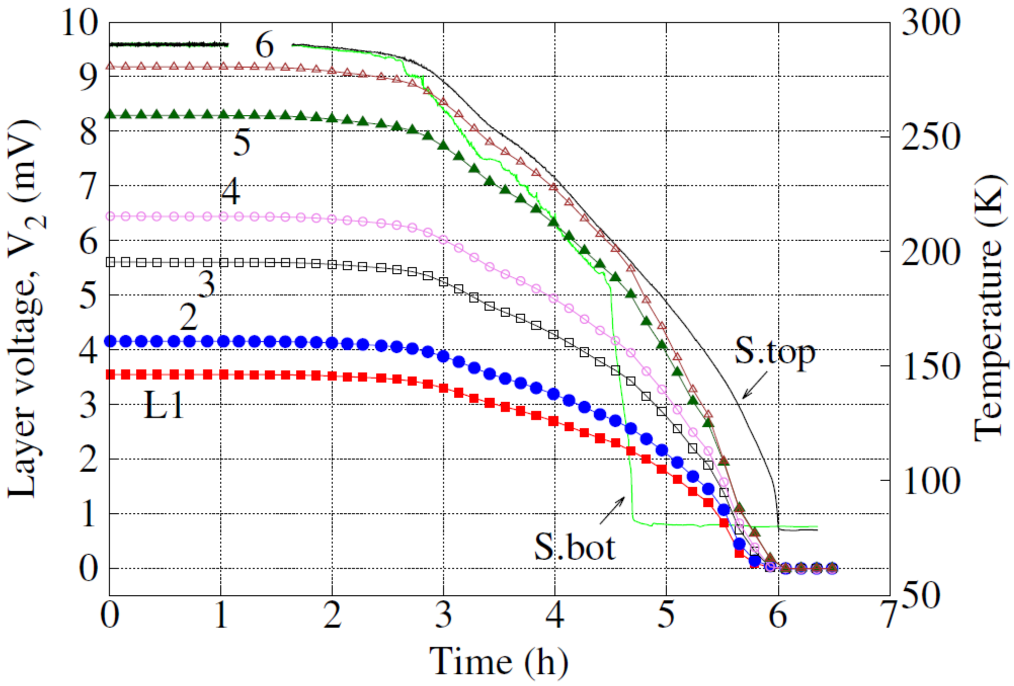
The magnet during and after assembly





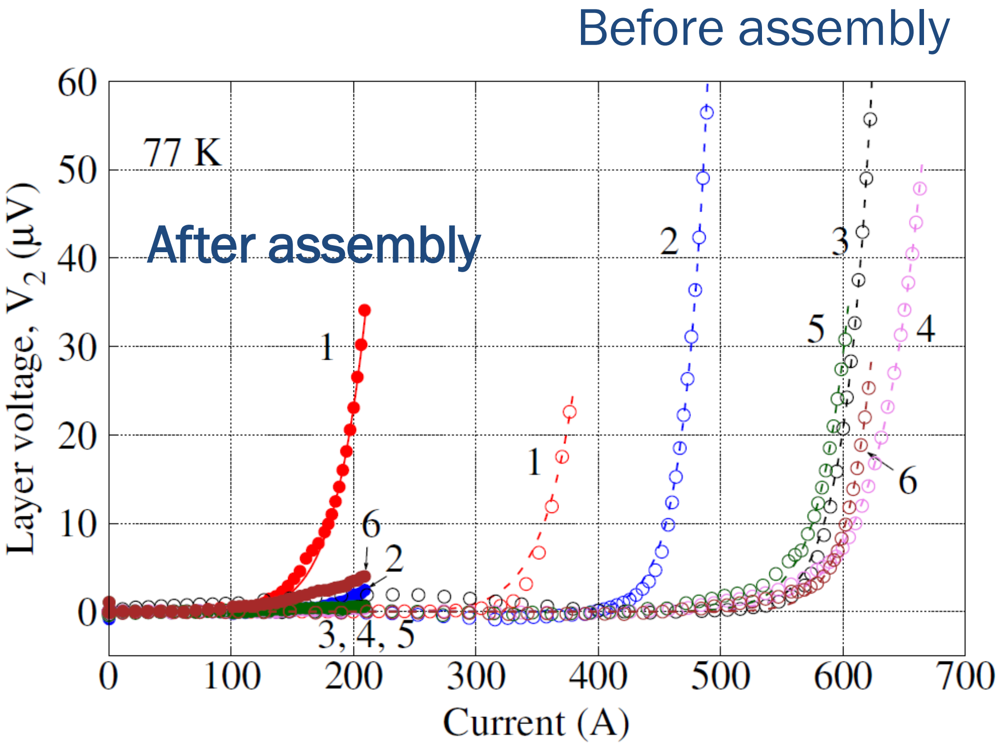


Magnet transitioned to superconducting state during a slow cooldown to 77 K



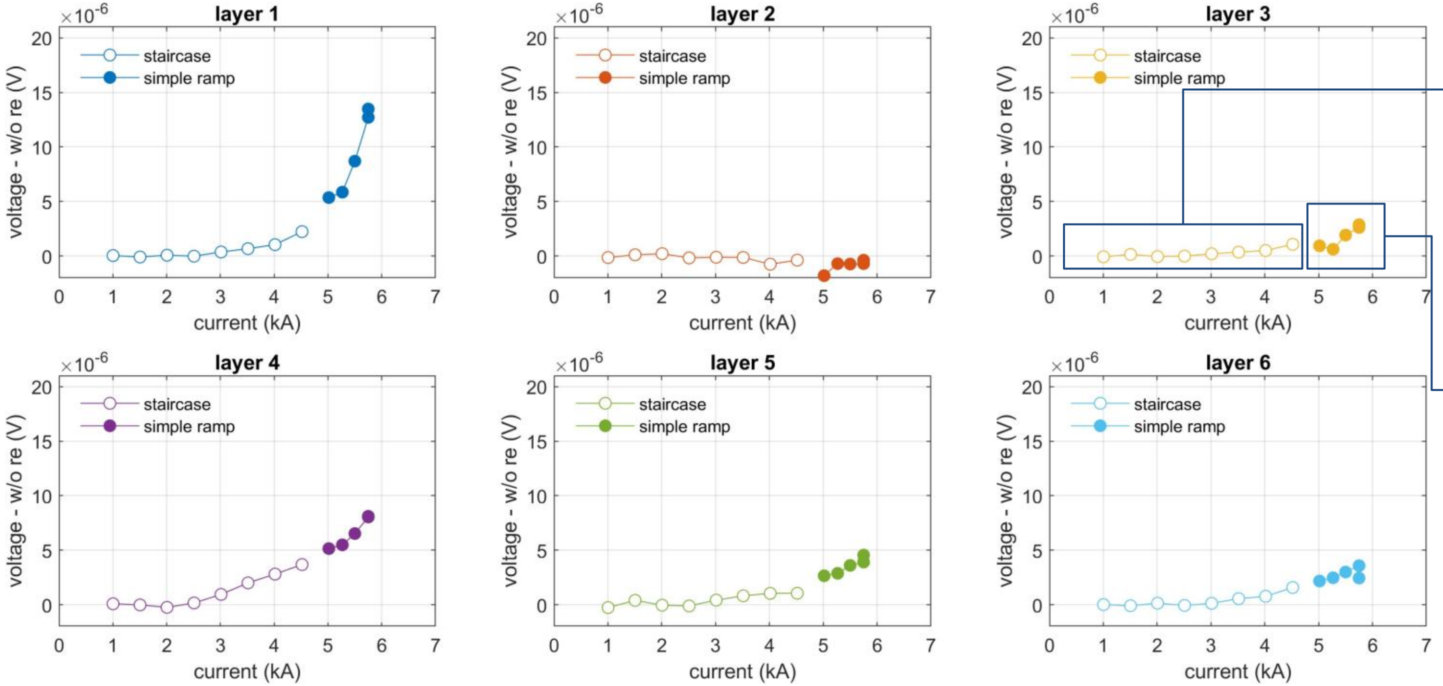
100 mA in the magnet

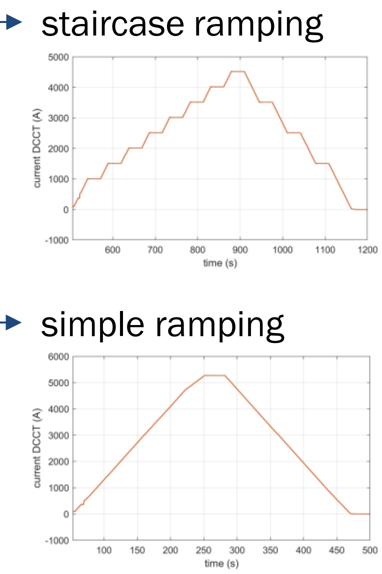
Individual layers showed 50% - 60% lower critical current after assembly



- Higher self field
- Any other causes?

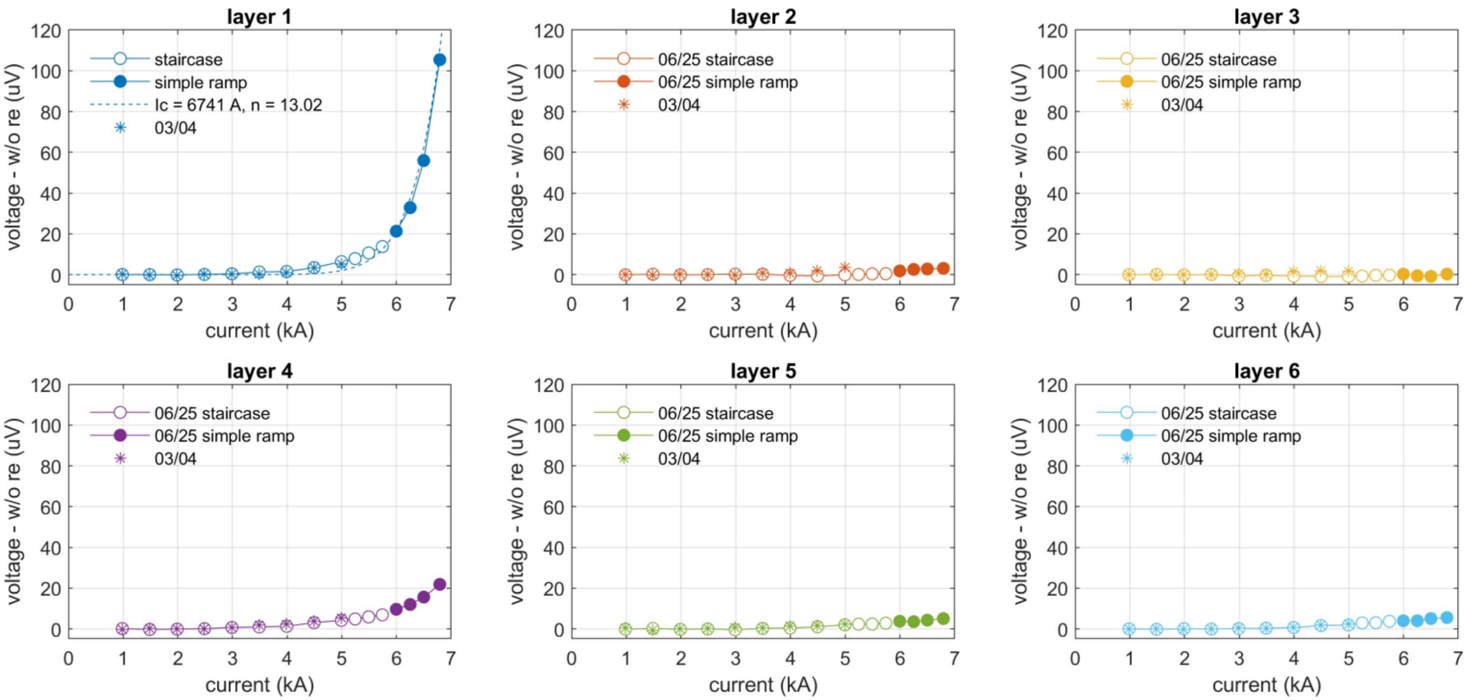
3/4/2025, reached 5.75 kA (5.2 T) with Layer 1 voltage at 14 μV during the 1[st] test at 4.2 K





Y. Yan

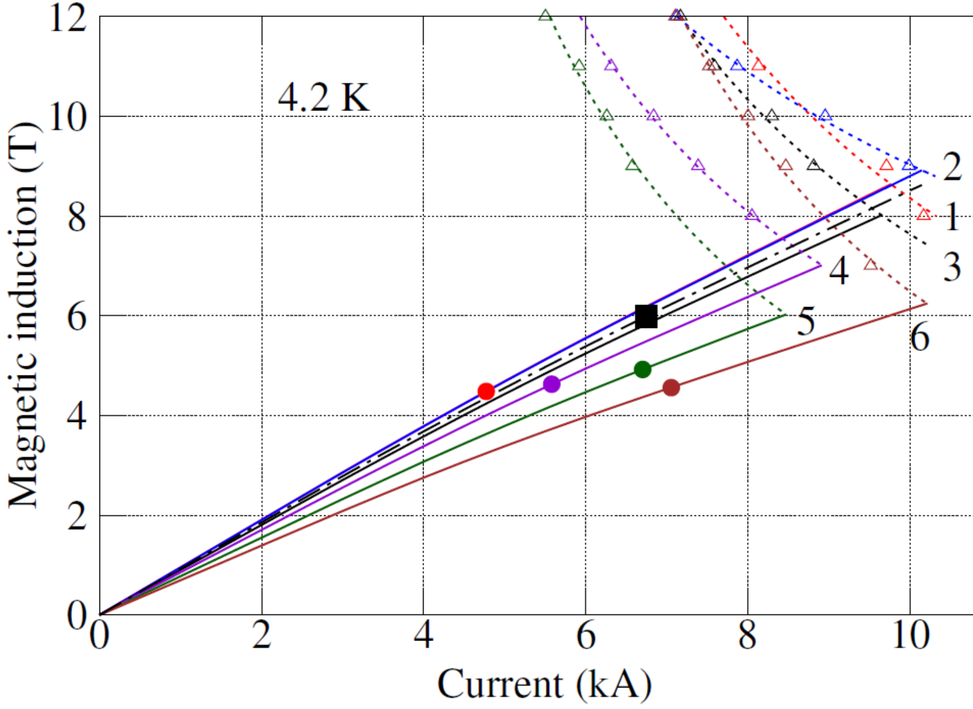
6/25/2025, reached 6.75 kA, 5.99 T, at 4.2 K with Layer 1 voltage at 105 μV, no thermal runaway



- No degradation after thermal cycle
- No training
- Voltage rise also in Layer 4

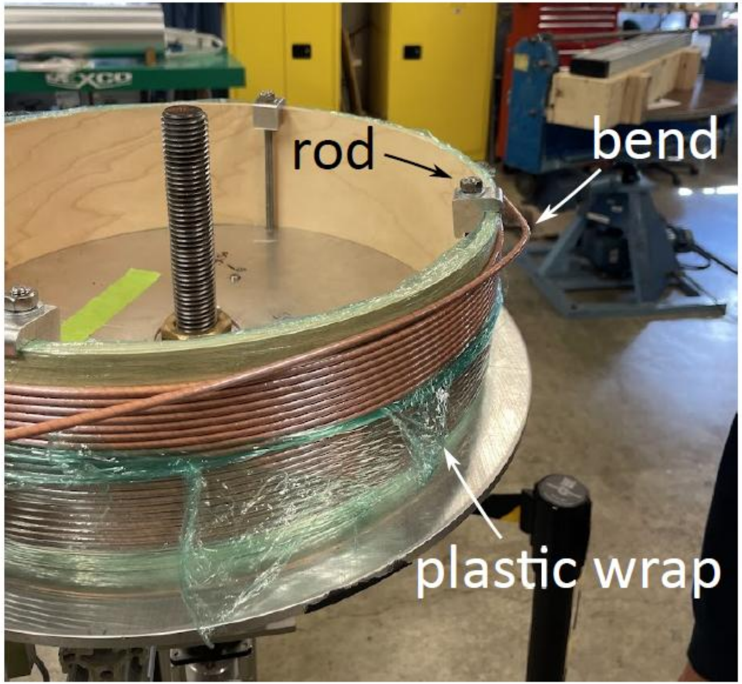
Y. Yan

We expected C3 to generate 7.4 T



- **Did the conductor degrade during fabrication?**

We did have issues when making Layers 1 and 4

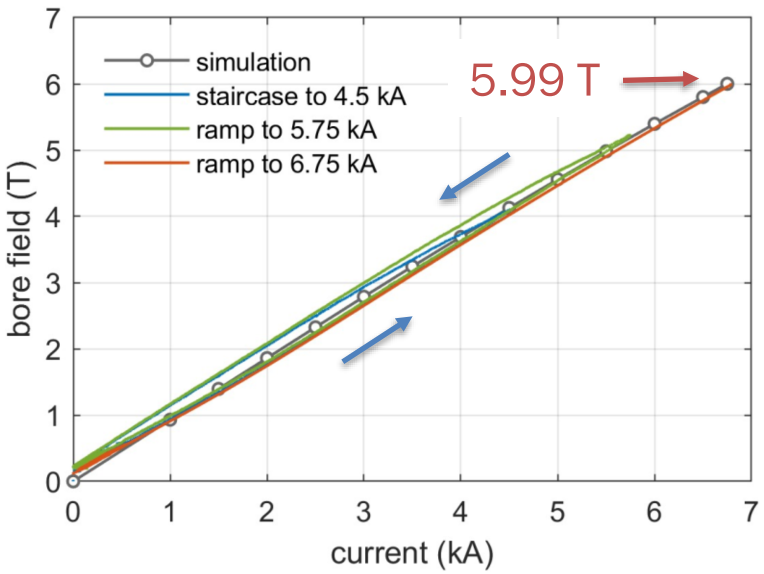


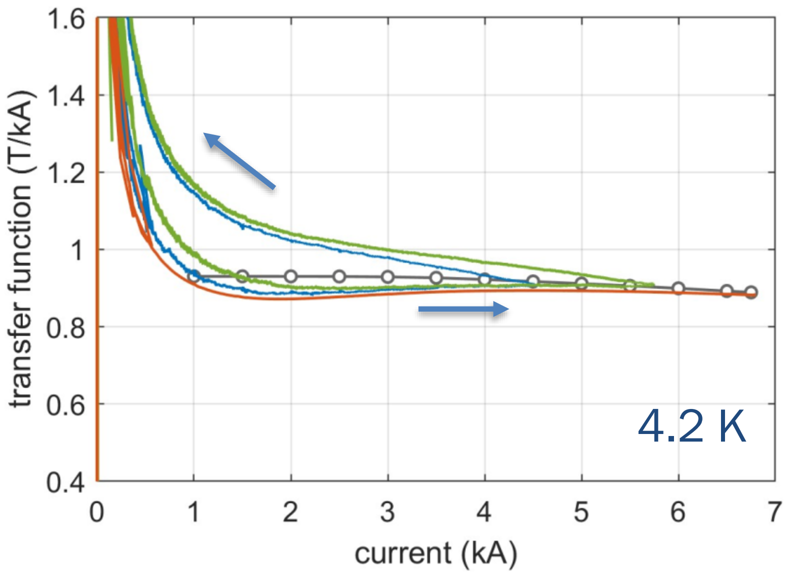
- Unwound a segment in Layer 1
- Layer 4 wire got bent during winding

Handling the reacted REBCO conductor is not trivial

Dipole TF approached the calculation, with a measured dipole field of 5.99 T at 6.75 kA

Iron contribution ~ 1.1 T, 19% of the total field

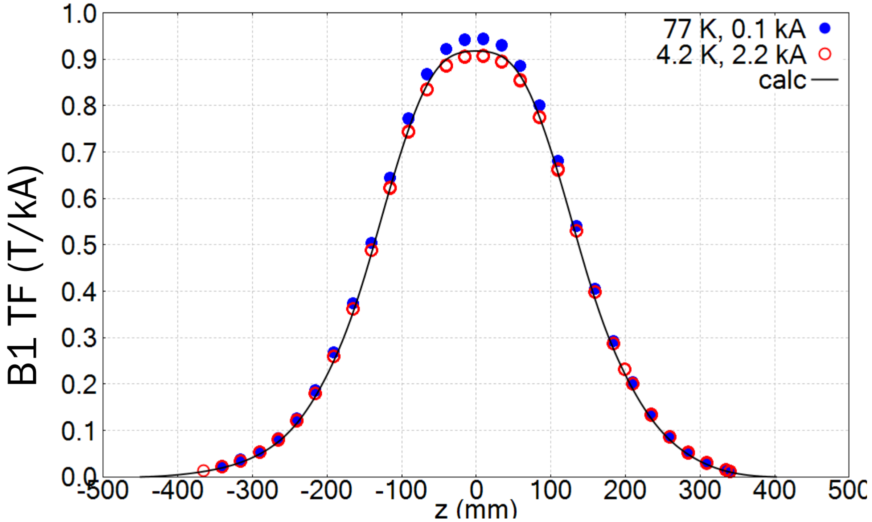


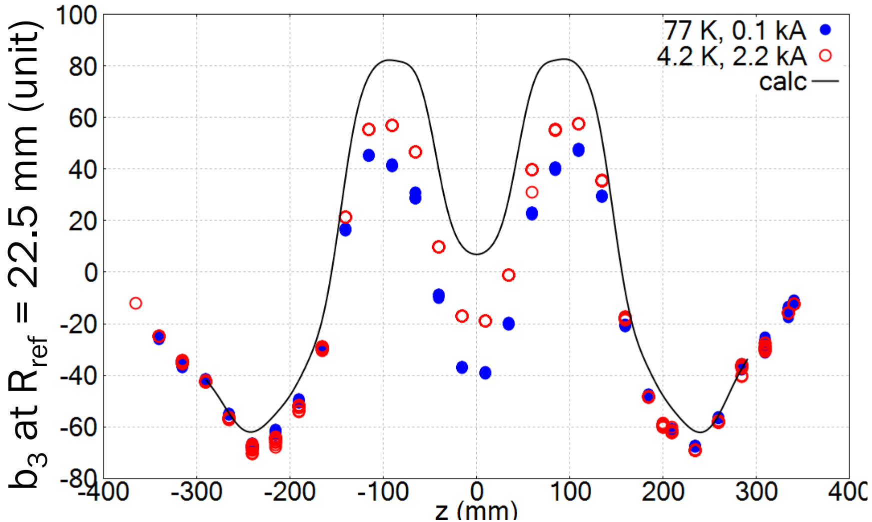


Calculation by L. Brouwer and Y. Yan

We observed strong persistent-current effects in C3

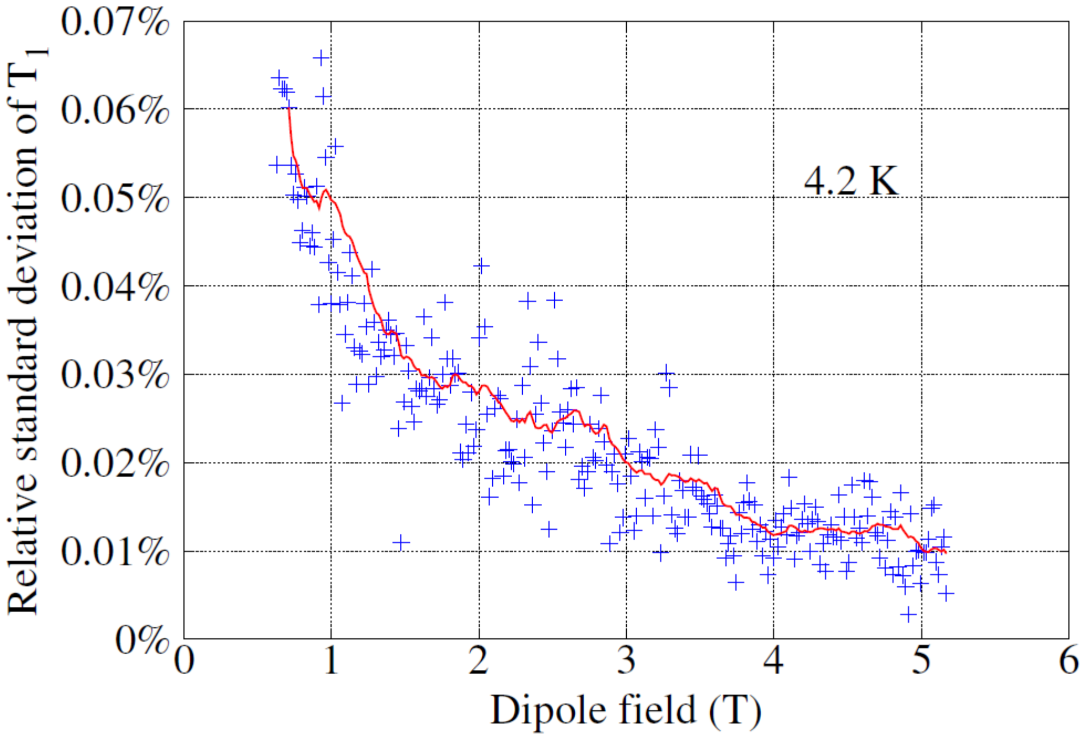
Field profile roughly matches that from simulation (w/o magnetization)



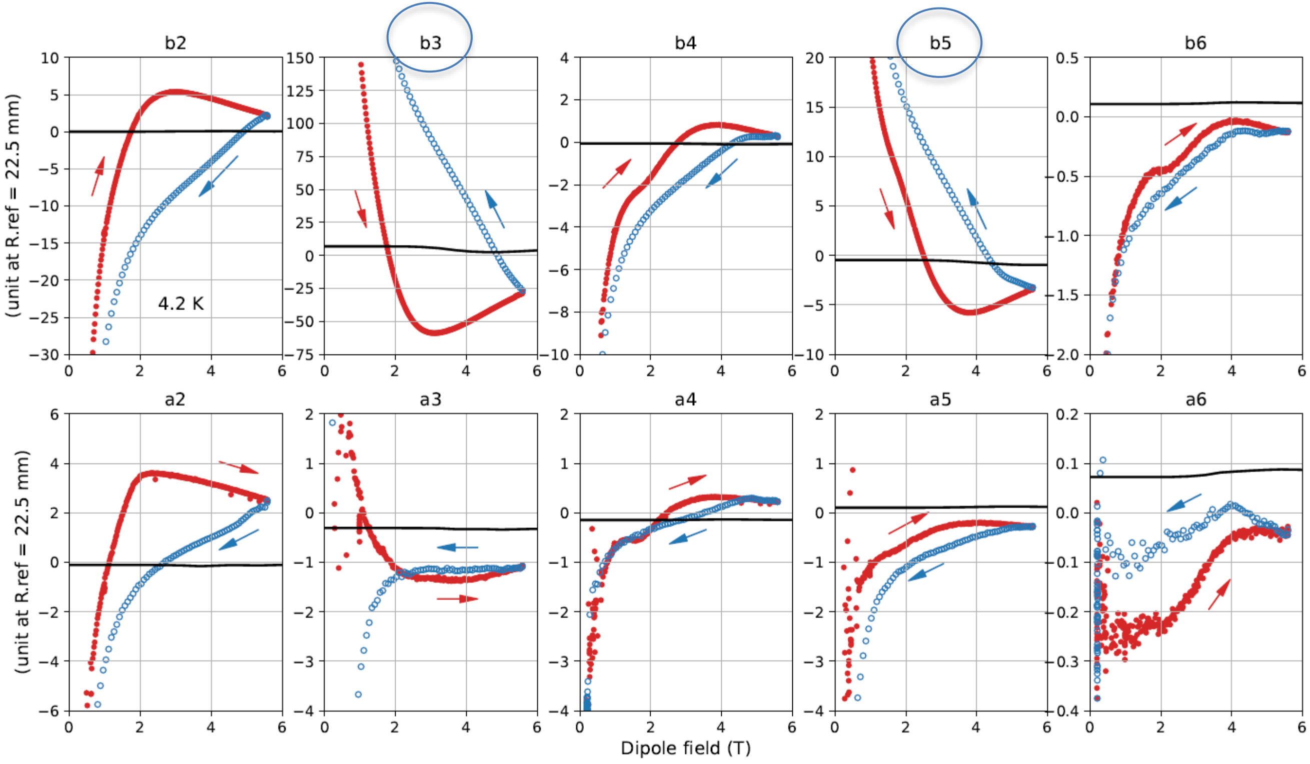


Rotating coil developed by J. DiMarco; Measurement system by B. Ghiorso and R. de Leon.

Reproducibility of the dipole transfer function reaches 0.01% at 5 T dipole field



Field errors less than 3.3 units at 6 T, except for b_3



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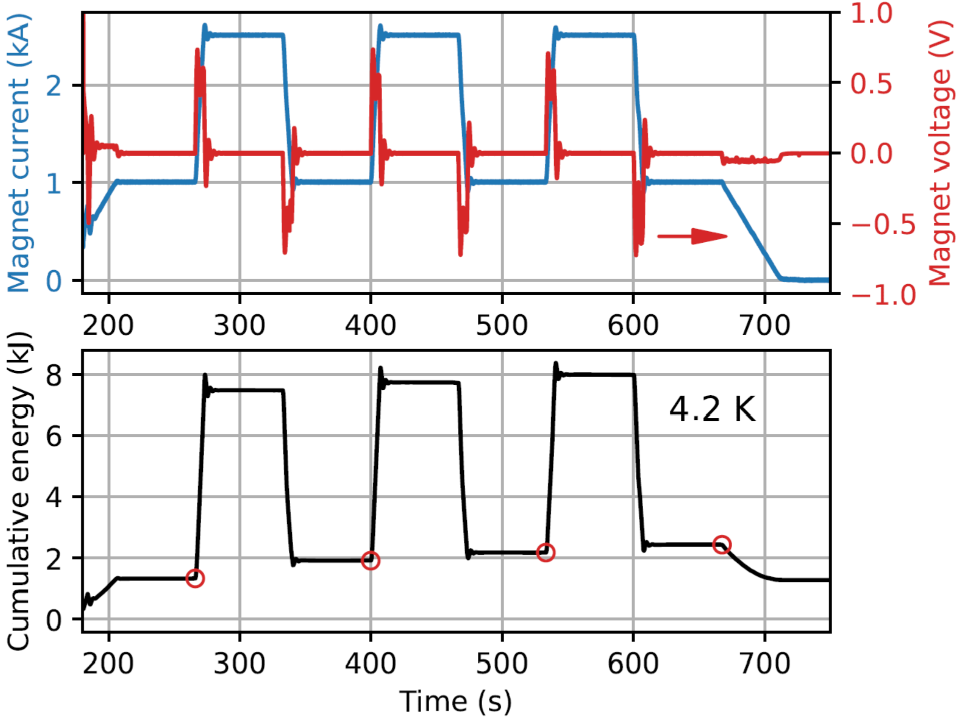
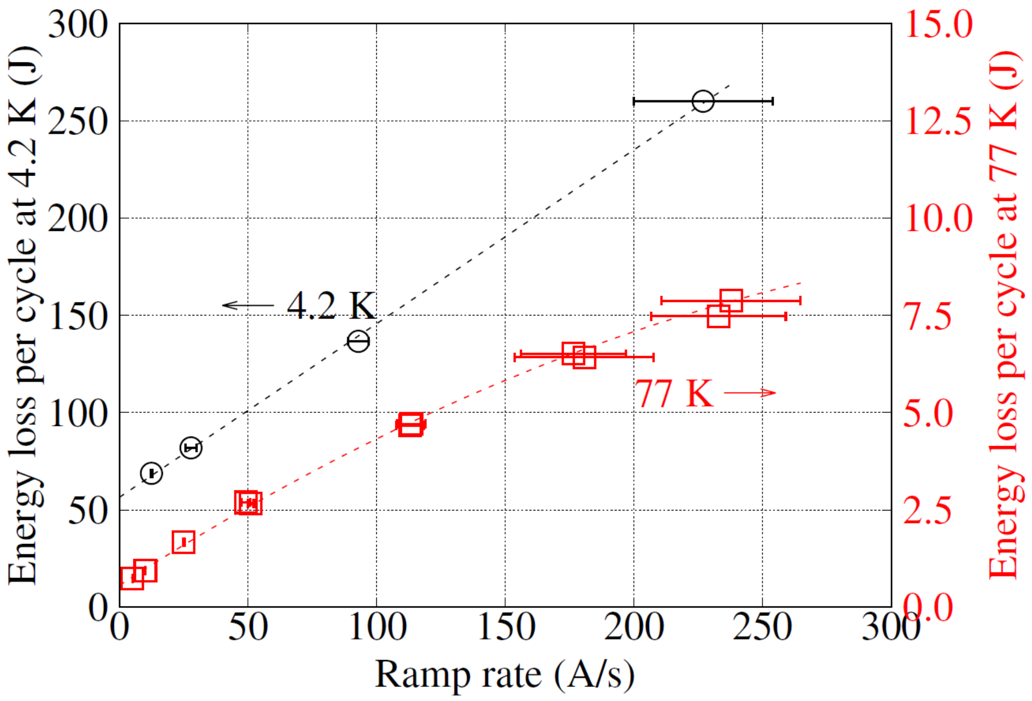
Energy loss is a key issue for ramping REBCO magnets

- **Lower loss reduces heat load to cryogenic system**
- **Main concern: hysteresis loss due to magnetization in REBCO**
- **Electrical measurement [A. P. Verweij et al. 1994]**



Hysteresis loss per cycle is several times higher than SSC Nb-Ti dipole magnets

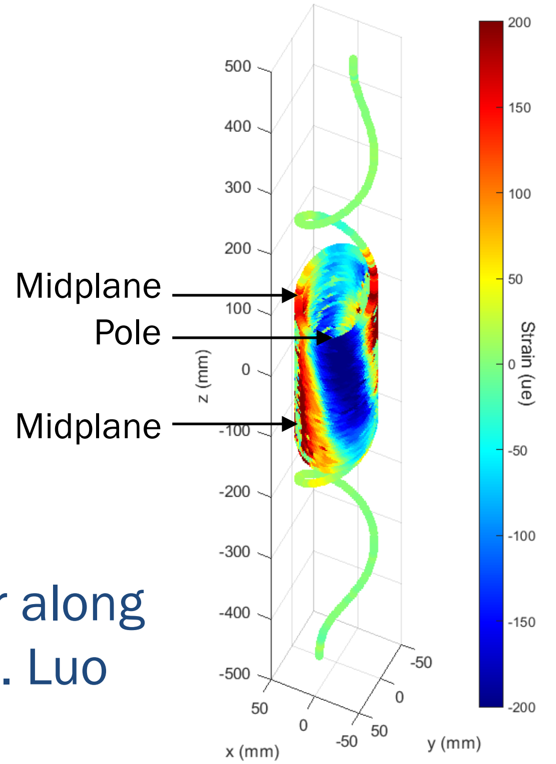


- 57 J at 4.2 K, 0.57 J at 77 K
- 6 – 10 times higher than the SSC Nb-Ti dipole magnets
- Striation in REBCO layer can reduce the hysteresis loss
  - Need to quantify

We are exploring distributed sensing to gain more insight into the magnet behavior

- **Can we use distributed fiber optic sensing to measure the strain and temperature profile along the conductor?**

- **Real-time monitoring as a way to operate future REBCO magnets?**



Strain response from the fiber along the CORC® in C3 Layer 1 by L. Luo

C3 magnet sets the stage for further development towards a useful REBCO magnet technology

- A successful collaboration with conductor vendor
- 5.99 T dipole field at 4.2 K, with a peak J_e of 595 A mm^{-2}
- No training, reproducible V-I behavior. Slow transition over several kA of current
  - Possible to avoid thermal runaway and protect the magnet
- First attempt of distributed fiber-optic sensing toward real-time monitoring

Several open questions require further investigation

- How to minimize the impact of conductor handling and coil degradation?
- How to address the energy loss and strong magnetization effect?
- How does the magnet behave with a higher field and stored energy?
- How to continue engaging conductor vendors to develop the technology?
- How can HTS technology meet the requirements of specific applications?

A question to you

- How can REBCO technology help FRIB enable new high-impact research opportunities?

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Thank you!