U.S. MAGNET DEVELOPMENT PROGRAM

Development of REBCO dipole magnets using CORC® wires: C2 and next steps

Presented to HFM-MDP Forum

27 Feb 2025

U.S. DEPARTMENT OF ENERGY | Office of Science

Contributors and acknowledgments

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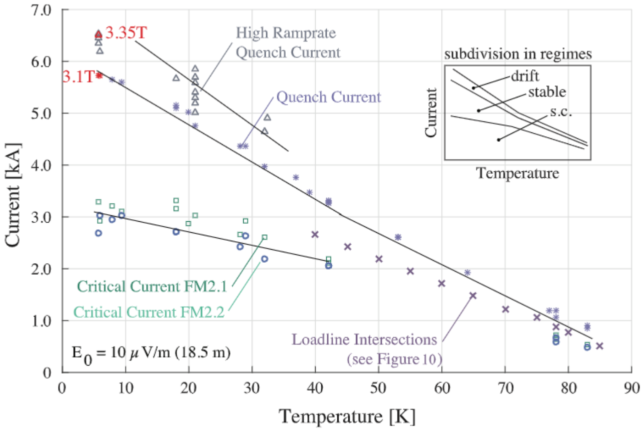
- Thanks to the U.S. MDP collaboration to provide the opportunity and financial support

- Thanks to Ken Marken, program manager at DOE for discussions and encouragement

REBCO can enable 20+ T accelerator magnets: a new paradigm for accelerator magnet technology

- The community has achieved significant progress
  - Record J_e of 5000 A/mm^2 at 4.2 K, 15 T, Univ. Houston [Majkic *et al.*, SuST, 2018]
  - 45.5 T total dc field with a non-insulation insert, ASC/NHMFL [Hahn *et al.*, Nature, 2019]
- EuCARD2 successfully demonstrated accelerator-quality REBCO dipole magnets using Roebel cable [van Nugteren et al., SuST, 2018]
- The US-MDP also sets a near-term goal to reach 5 T in HTS dipole magnets



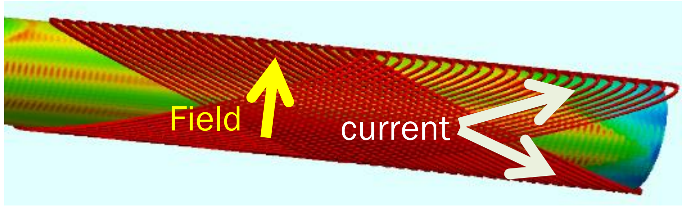
EuCARD²

We are developing CORC® CCT dipole magnets to address several driving questions for REBCO magnet technology

- How to make dipole magnets and use what kind of REBCO cables?
- What is the magnet performance and required conductor performance?
- What issues limit the magnet performance? How to address them?
- What are the impacts on the High-Energy Physics (HEP) community?

- CORC® wire is a promising configuration for HEP magnets
  - Isotropic for magnetics and mechanics
  - High current (~10 kA) at small bending radius (~30 mm)

- CCT design is attractive for high-field magnets
  - Reduce conductor stress
  - Provide good geometric field quality



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

- C1, 1.2 T at 2017. Demonstrated initial concept
- C2, 2.9 T at 2019. Used metal mandrel
- C3, target 5 T at 2021*. Develop magnet technology towards higher fields
- We are considering what's beyond 5 T

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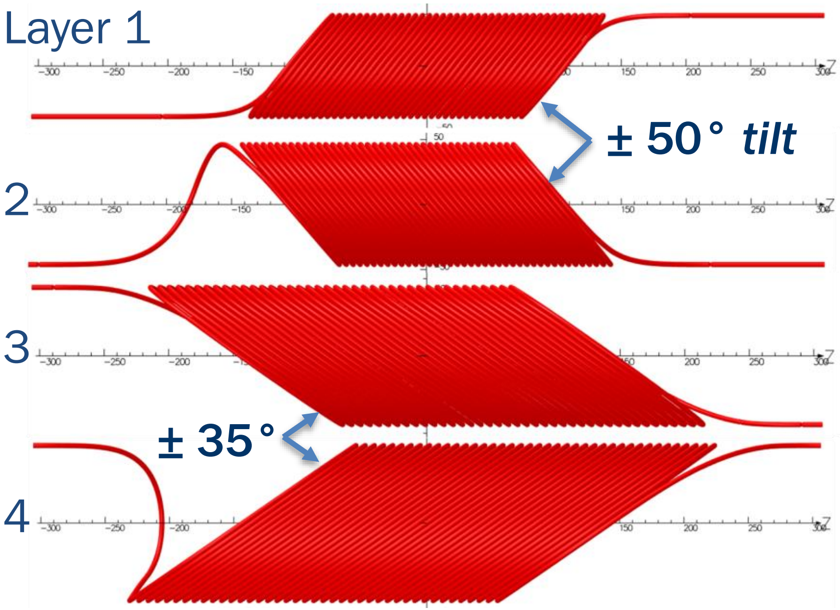
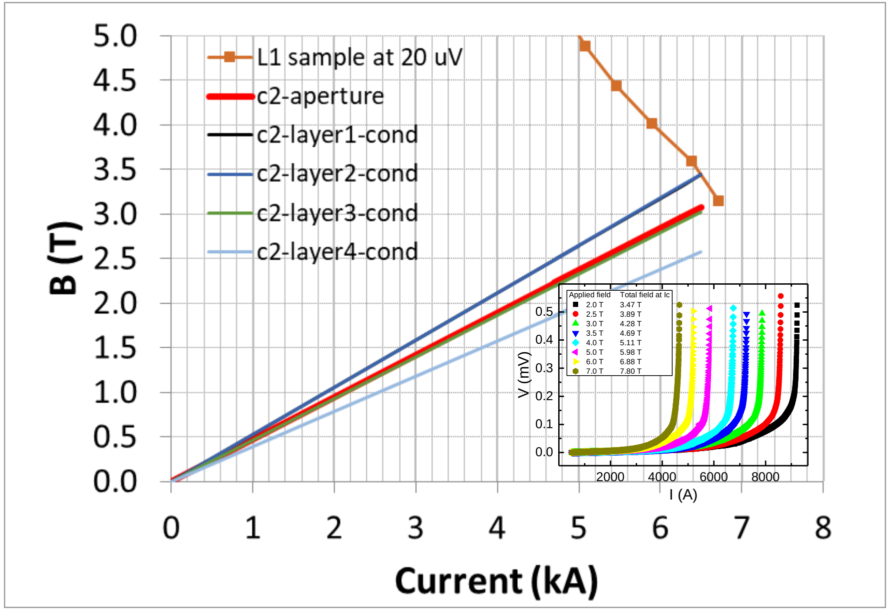
- Strongly coupled magnet/conductor work provides effective feedback to conductor development based on magnet performance
- Collaboration within MDP and broader community through MDP

C2, a four-layer CCT magnet, aims at generating a dipole field of 3 T

Minimum bending radius 30 mm





Wire sample measured by Jeremy Weiss and Danko van der Laan at ACT

C2 used the state-of-art CORC® wire with 30 µm thick substrate

- SuperPower tapes: 2 mm wide, 30 µm substrate, 5 µm surrounded Cu stabilizer
- ACT fabricated 100 m long wires (5 km long tapes) for C2
- Layer 4 CORC® wire contains high- and low-pinning tapes

Wire ID	Length (m)	Wire OD (mm)	Average tape Ic (A) 77 K, SF	Peak field on wire (T)	Min. bend radius (mm)
Layer 1	18	3.80	70	3.4	30
L2	20	3.80	70	3.4	35
L3	24	3.77	69	3.0	30
L4	28	3.67	57	2.5	35

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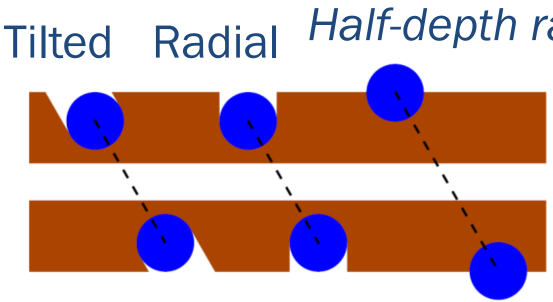
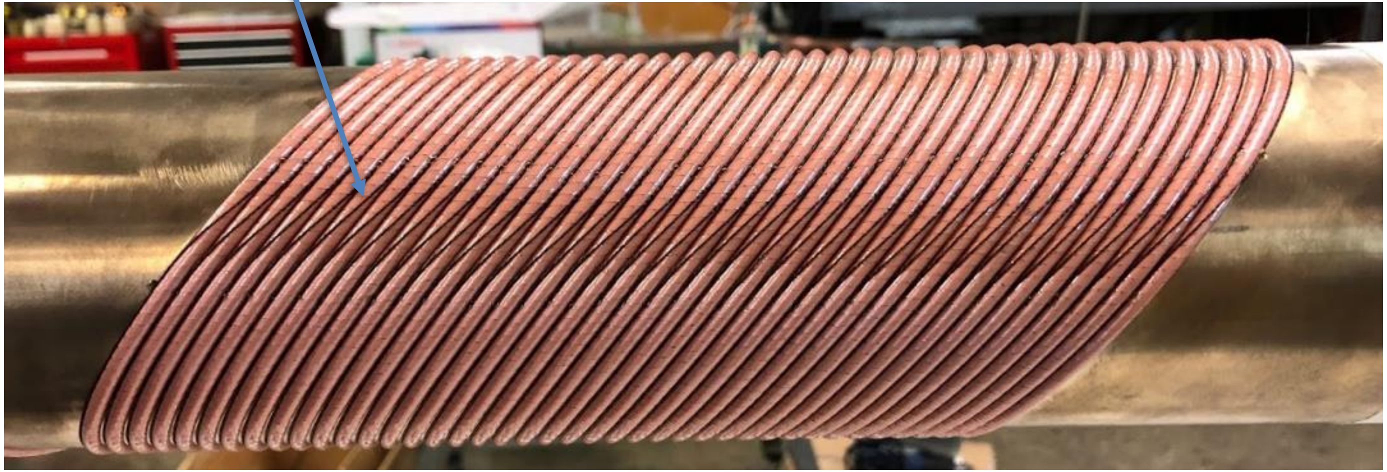
Half-depth radial grooves on aluminum-bronze mandrels helped with winding but needs improvement



- Sharp edges of mandrels damaged the wire insulation
- Electrical short between mandrel and wire
- Potential conductor degradation during epoxy impregnation
- Use conformal coating or anodized aluminum

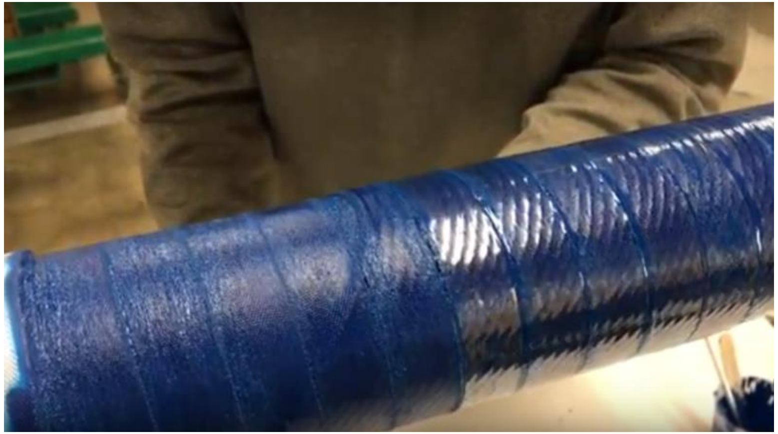
Co-wound voltage-tap wires with the conductor

Voltage tape wires



Critical to reduce the inductive pickup and to generate clean voltage signals during the tests

Application of Stycast has negligible impact on conductor transport performance (< 3% I_c reduction)

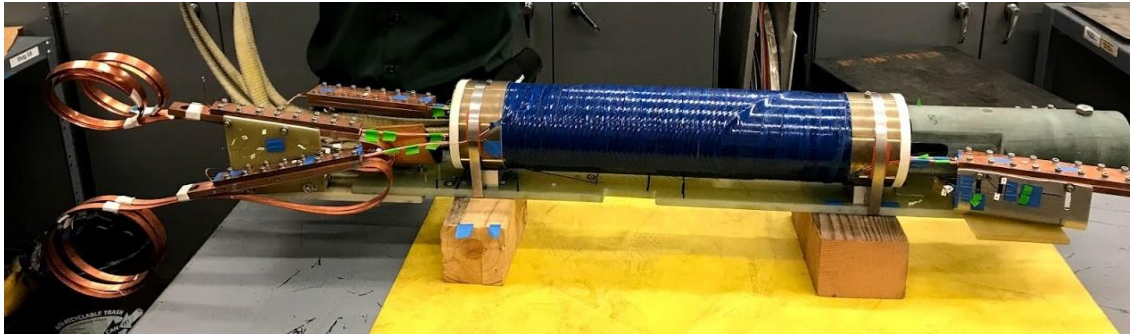


I_c retention, 20 μV, 77 K, self-field

	After winding	After stycast	Change
BS-Layer 1	n/a	71%	
BS-Layer 2	71%	69%	-2%
BS-Layer 3	68%	65%	-3%
BS-Layer 4	69%	n/a	
AB-Layer 1	81%	79%	-2%
AB-Layer 3	75%	74%	-1%

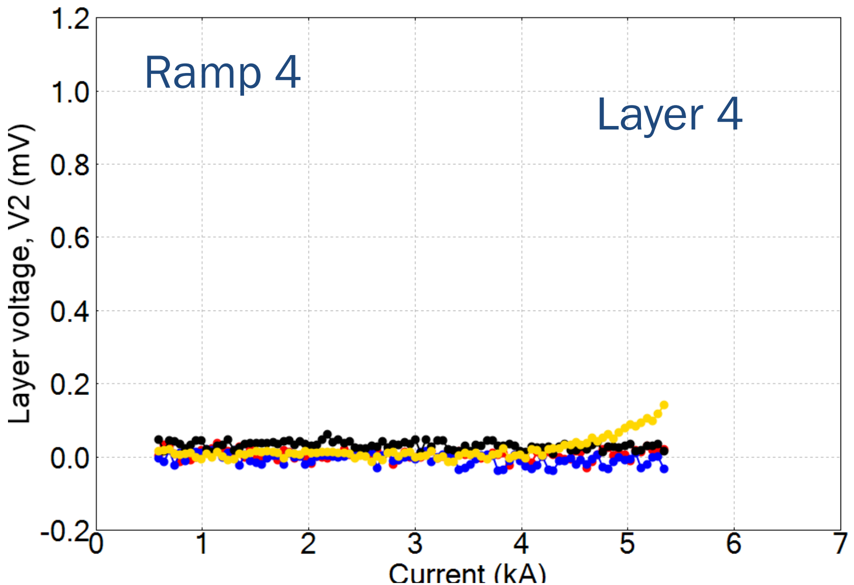
- Wrapped fiber cloth on top of conductor
- Wrapped and heated heat shrink tapes around coil before Stycast cured

Magnet assembly and test



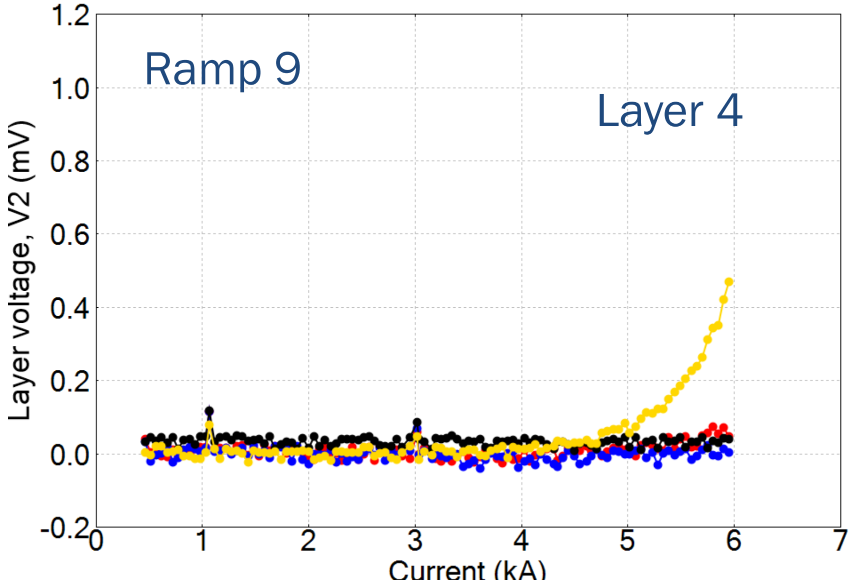
Test cryostat provided by Prof. David Larbalestier at FSU

A controlled increase in the maximum current allowed us to probe the true performance of C2



- Increasing the threshold for quench detection

A controlled increase in the maximum current allowed us to probe the true performance of C2



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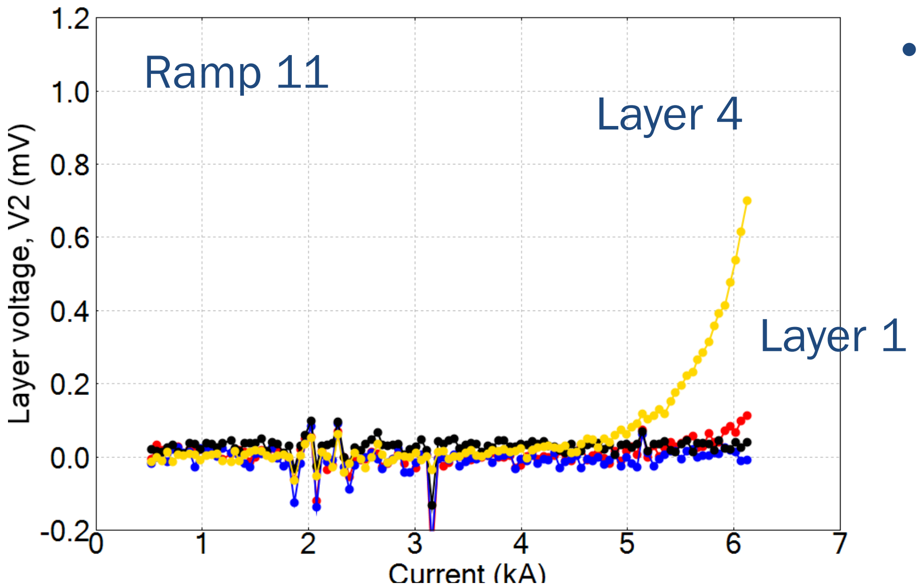

- Increasing the threshold for quench detection

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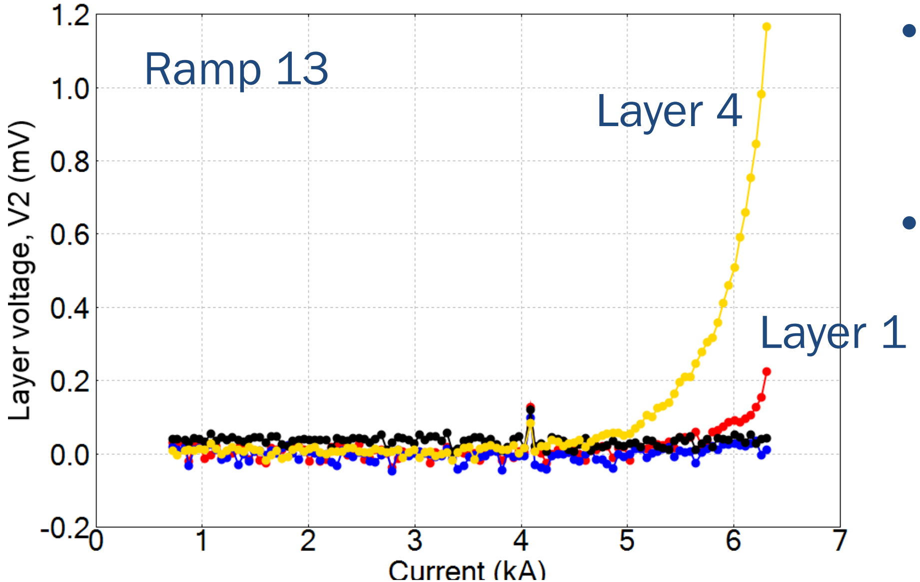
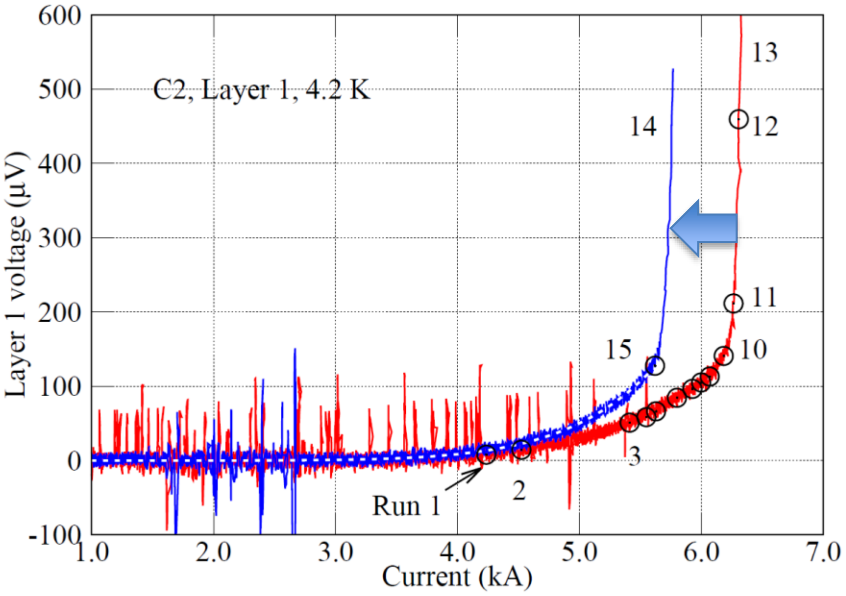
A controlled increase in the maximum current allowed us to probe the true performance of C2

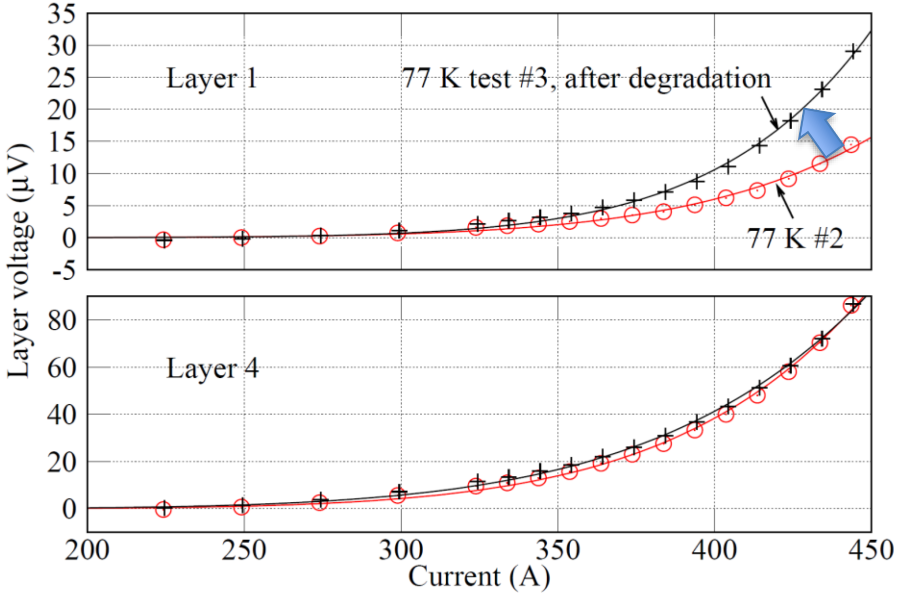


- Increasing the threshold for quench detection
- Reproducible V(I) transition between ramps
  - n = 13.1 for Layer 4
  - n = 6.8 for Layer 1, consistent with the behavior of short sample measured at ACT
- Reached 2.9 T dipole field at 6.3 kA, wire J_e = 550 A/mm^2

Layer 1 conductor degraded during the thermal runaway at a J_e of 550 A/mm^2 at 4.2 K



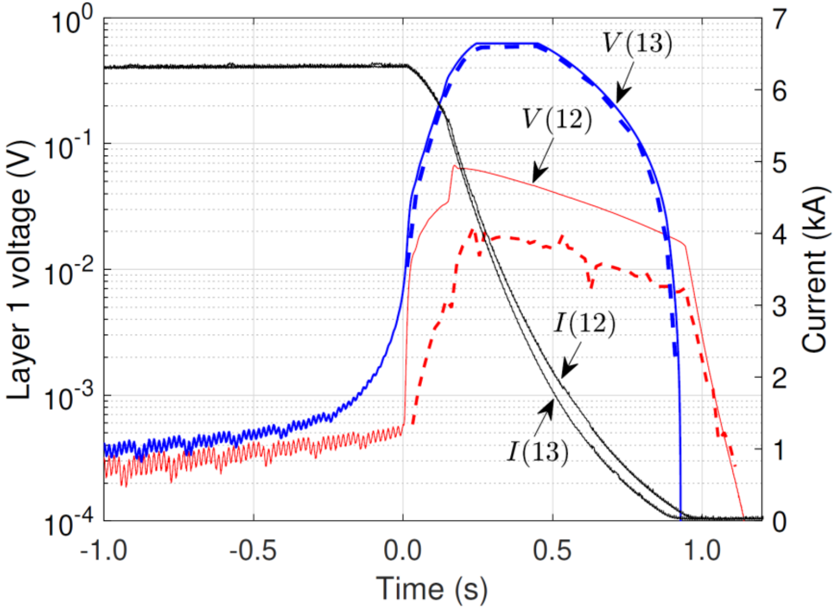
Ramp 14 showed an I_c degradation by 5% after the thermal runaway in Ramp 13



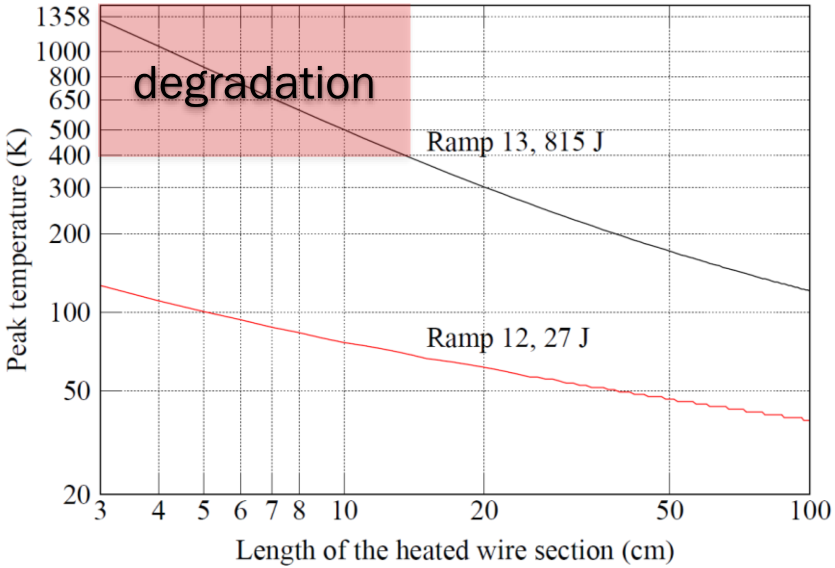
The 77 K test following the 4.2 K test also confirmed the I_c degradation in Layer 1

Joule heating during thermal runaway possibly degraded the conductors

V(t) traces for Ramps 12 and 13



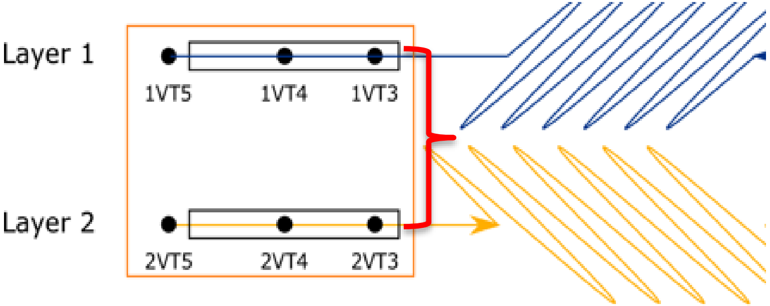
What could be the peak wire temperature?

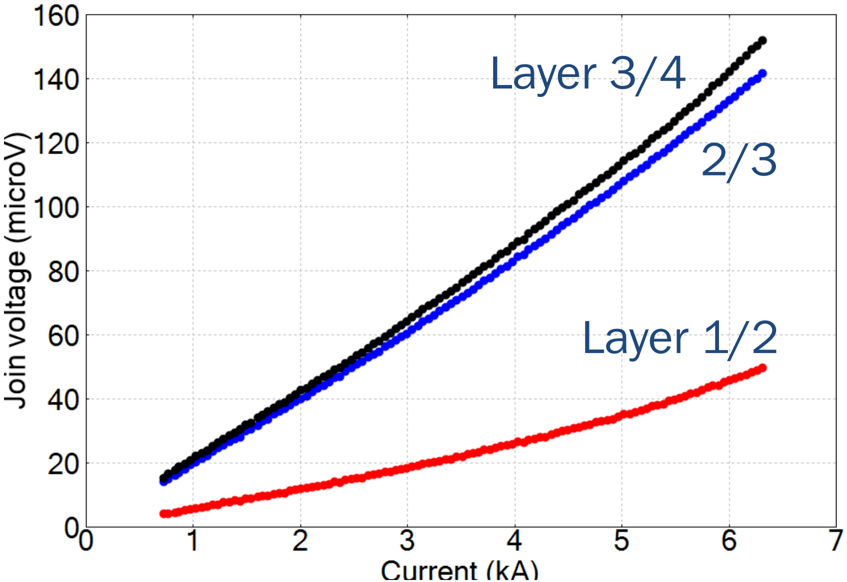


15 cm or shorter of heated section is possible due to the slow propagation of normal zones

Inter-layer joint resistance ranges from 8 to 24 nΩ at 4.2 K

Joint voltage is measured across the voltage taps in each layer

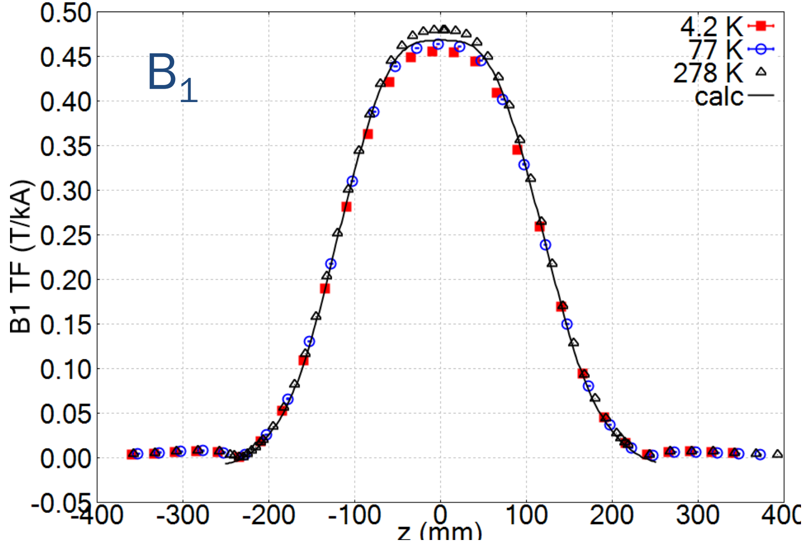


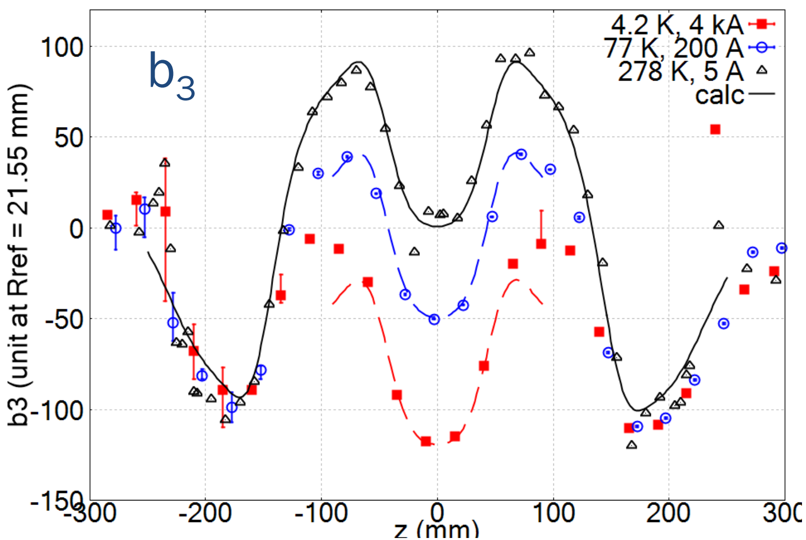


- Joint resistance is acceptable for magnet test but needs further reduction

We observed strong persistent-current effects in C2

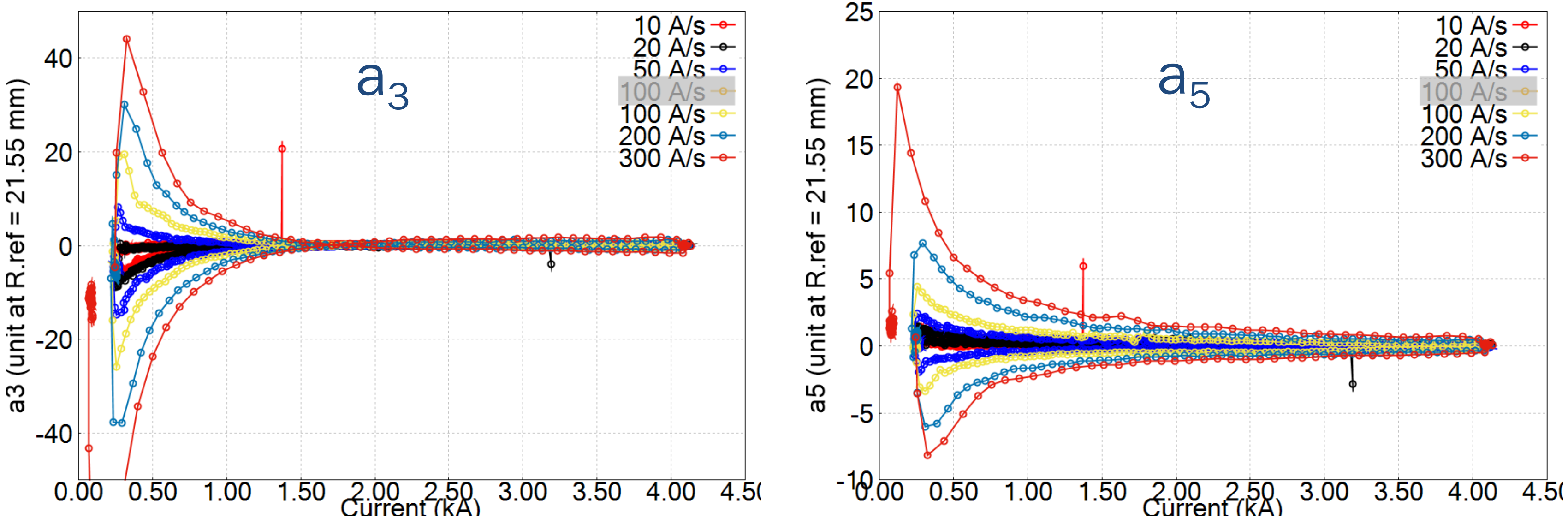
- Measurement with a 100 mm long rotating coil developed by J. DiMarco at FNAL





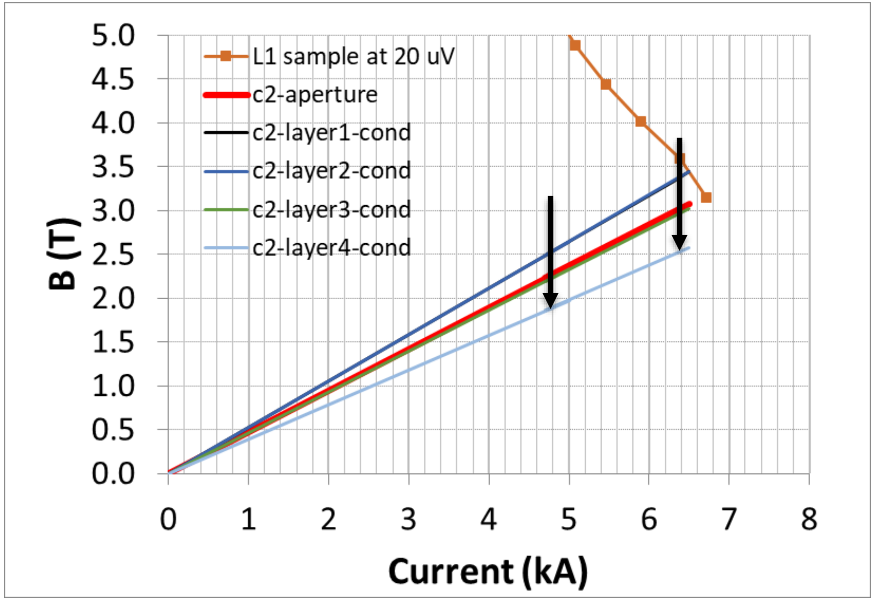
- Stronger effect at 4.2 K – large J_c in tapes with perpendicular fields

The ramp-rate dependence in the odd skewed harmonics: a mystery to be understood



- May indicate inter-tape coupling currents inside CORC® wires that are induced by varying magnetic fields

We close the chapter on C2 with a good result



- C2 reached 2.9 T, 98% of the expected value

- Why did Layer 1 started transitioning at 4.8 kA, 73% of the short-sample prediction?
- What caused the low performance of Layer 4?
- Where is the heat/voltage generated?
- How can we improve for the next magnet?

"A good result and more questions. That's what we need." – S. Gourlay

C2 magnet represents another successful step towards high-field REBCO dipole magnets

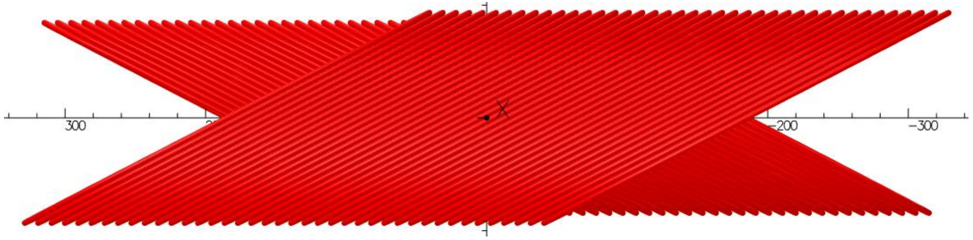
- US-MDP successfully developed C2, a CORC® CCT dipole magnet with a peak dipole field of 2.9 T
  - Used 70 m long 30-tape CORC® wires, a record conductor length
  - Conductors were wound on metal mandrels and constrained with Stycast
  - Reproducible V-I transitions with a J_e ranging from 400 – 550 A mm^{-2} that allowed reliable quench detection
  - Thermal runaway should be avoided
  - Set the stage for the C3 magnet to reach a 5 T dipole field

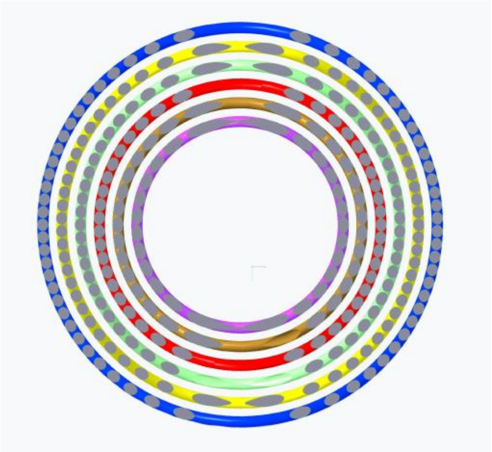
C2 magnet represents another successful step towards high-field REBCO dipole magnets

- Magnets continue requiring wires with a smaller bending radius and higher performance
  - Demonstrate 20 μm thick substrate in SuperPower tapes
  - Demonstrate narrower tapes (< 2 mm) and higher pinning at 4.2 K
- More magnet results are critical and coming – MDP (ASC/NHMFL, BNL, FNAL), CERN, …
  - Excellent opportunities to collaborate and push the REBCO accelerator magnet technology together

With the experience from C2, we start developing the next magnet C3 to reach 5 T dipole field

- A six-layer CCT dipole design. ID = 65 mm, OD = 160 mm.





Tilt angle (degree)			TF
Pair 1	Pair 2	Pair 3	T/kA
50°	35°	27°	0.72

- Ordered REBCO tapes with a minimum I_c of 350 A at 4.5 K, 6 T

C3 magnet is our latest vehicle to work with conductor vendor and to address the driving questions

- Six-layer CCT dipole aiming at the 5 T milestone
  - Built on what we learned from C1 and C2
- 145 m of CORC® wires in six pieces, maximum piece length 35 m
  - Specified the minimum tape I_c for HM tapes
- First attempt to consider mechanics
  - Aluminum shell + Stycast filling
- Test idea of machine-aided winding and distributed fiber-optic sensing

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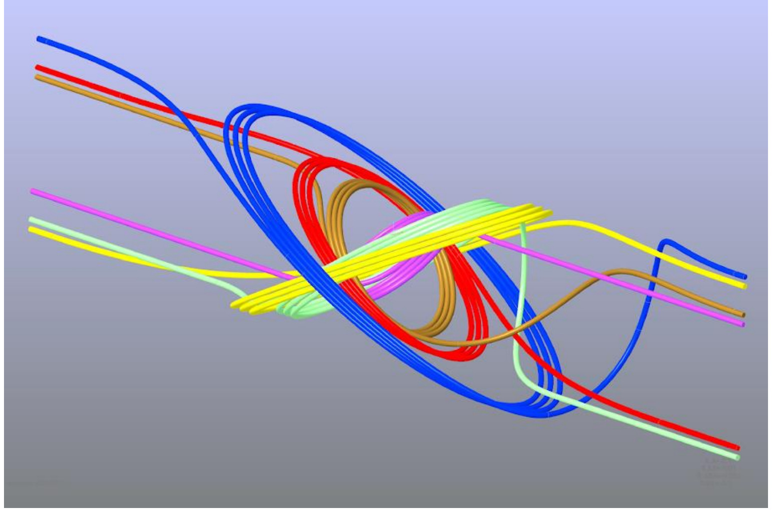
Three steps towards C3

- ~~Vendor make and deliver the conductors~~
- ~~Make, test subscale C3a and learn~~
- Make, test C3 and learn

Make a subscale version to practice and reduce risk for C3



- Conductor and magnet
  - What's the behavior of the new HM wire?
  - What's the magnet behavior?
- Technology
  - How to assemble the magnet?
  - Does the new termination concept work at high current?
  - How does the optic fiber perform? See Linqing's talk on Thursday
    - Data that can help understand the mechanics, see Giorgio's talk
- What can be improved for C3?

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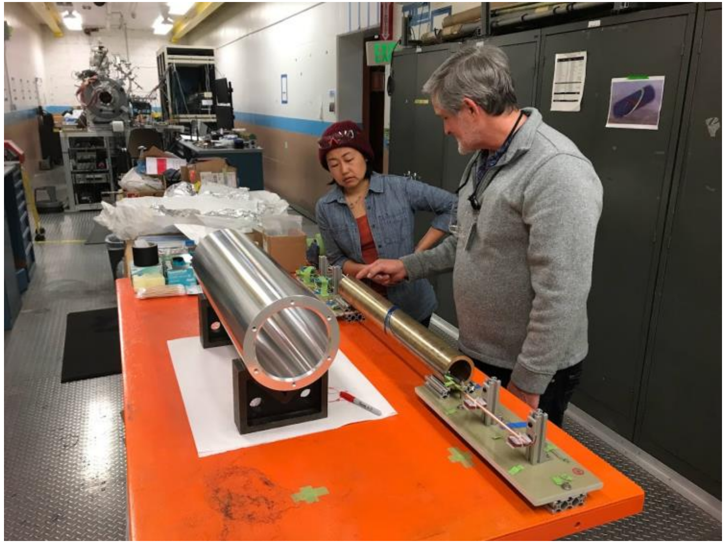
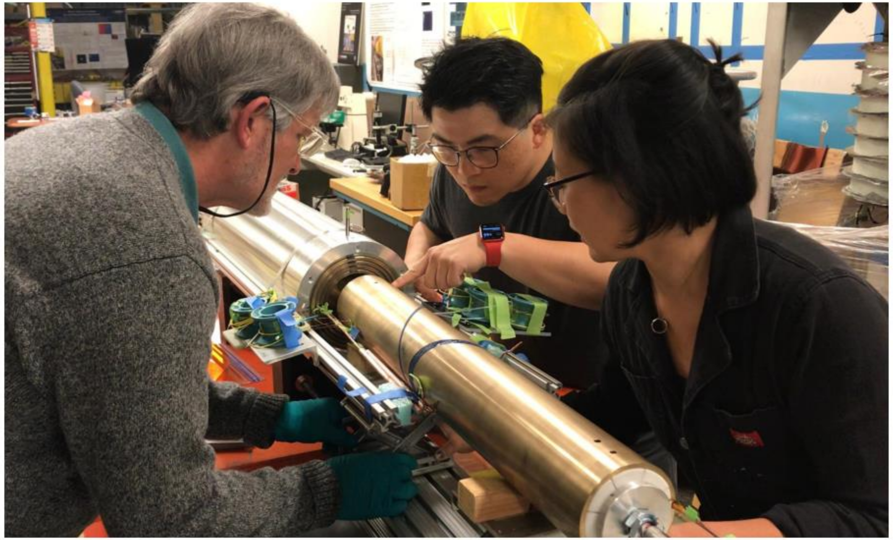
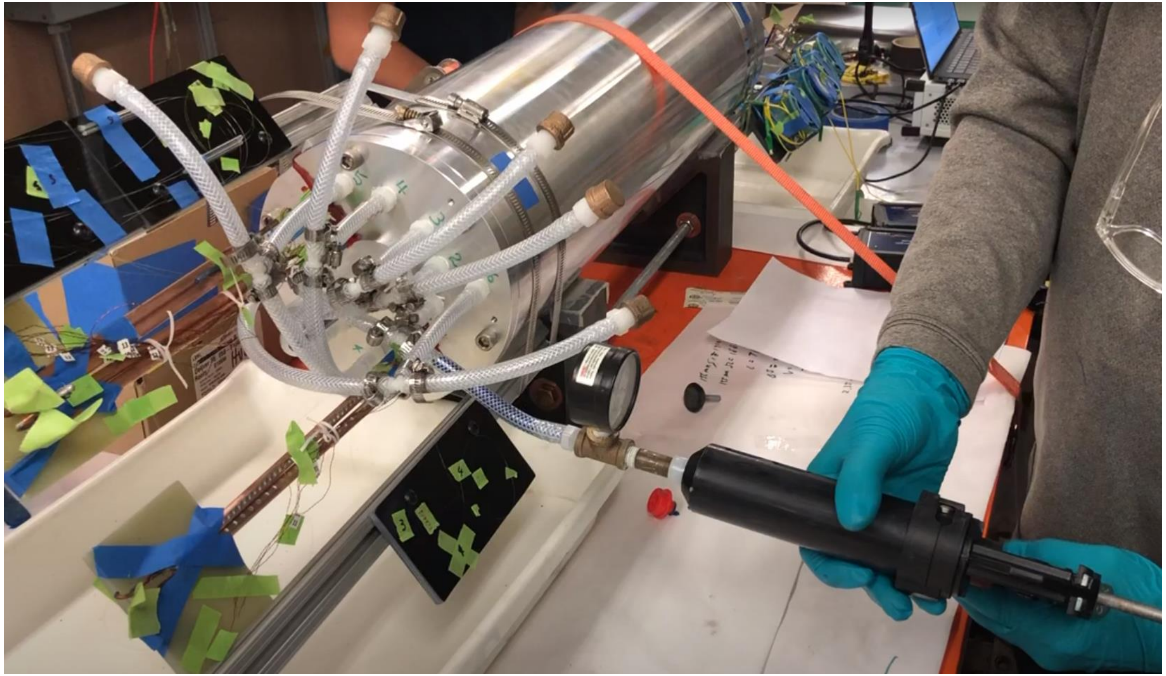
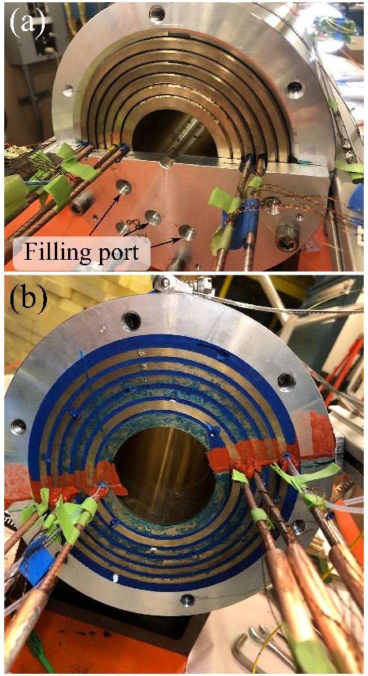
Assemble the coils



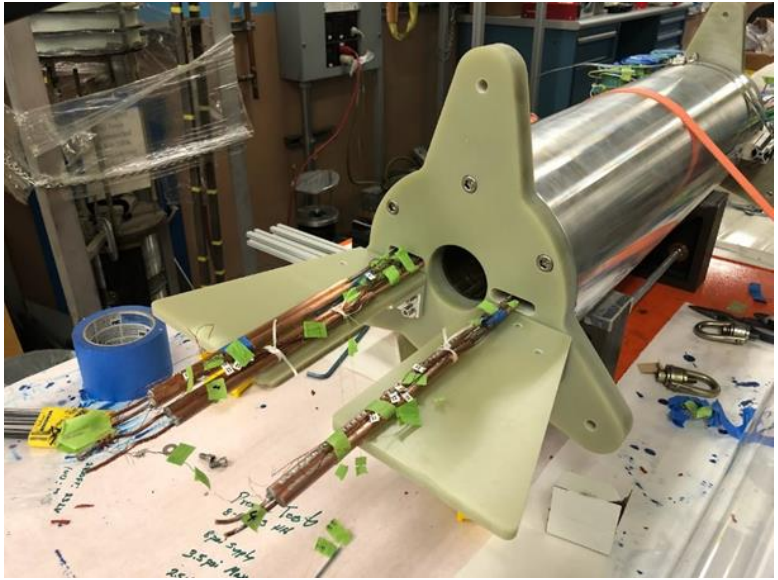


Fill the radial gaps between the layers with Stycast to mechanically couple them



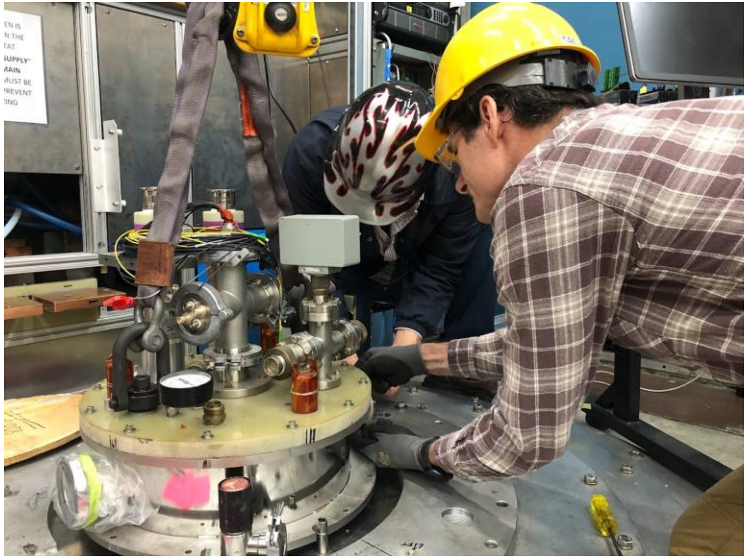


Make electrical joints



Attach to test header

Get ready to test



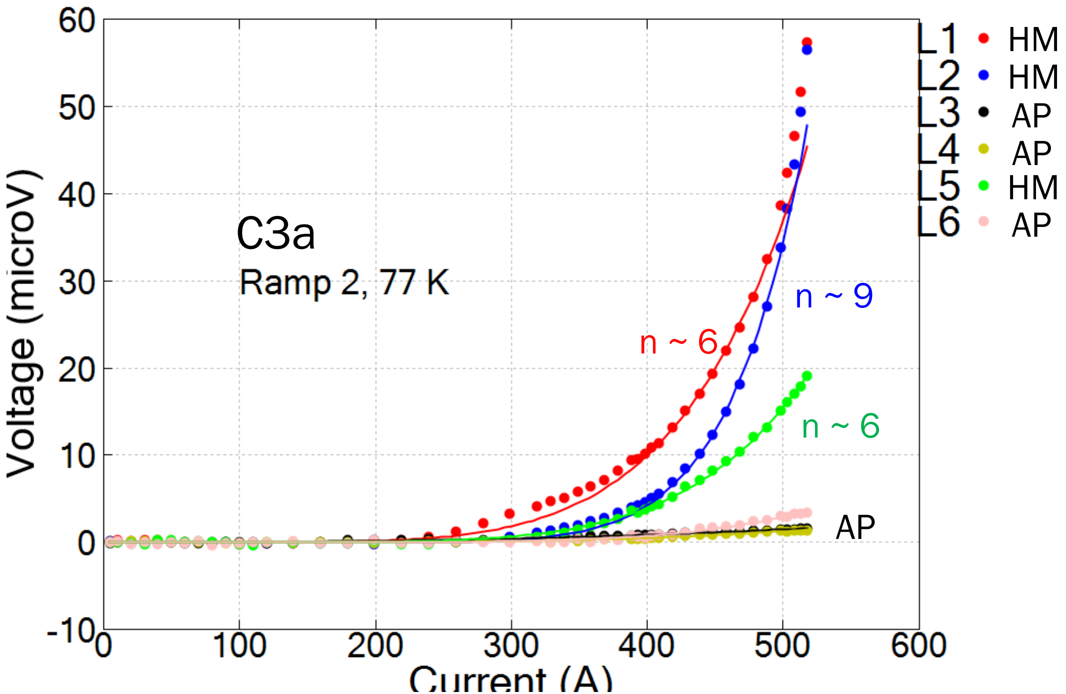
Thanks to Prof. Larbalestier and colleagues at ASC for providing the cryostat

Overview of C3a test

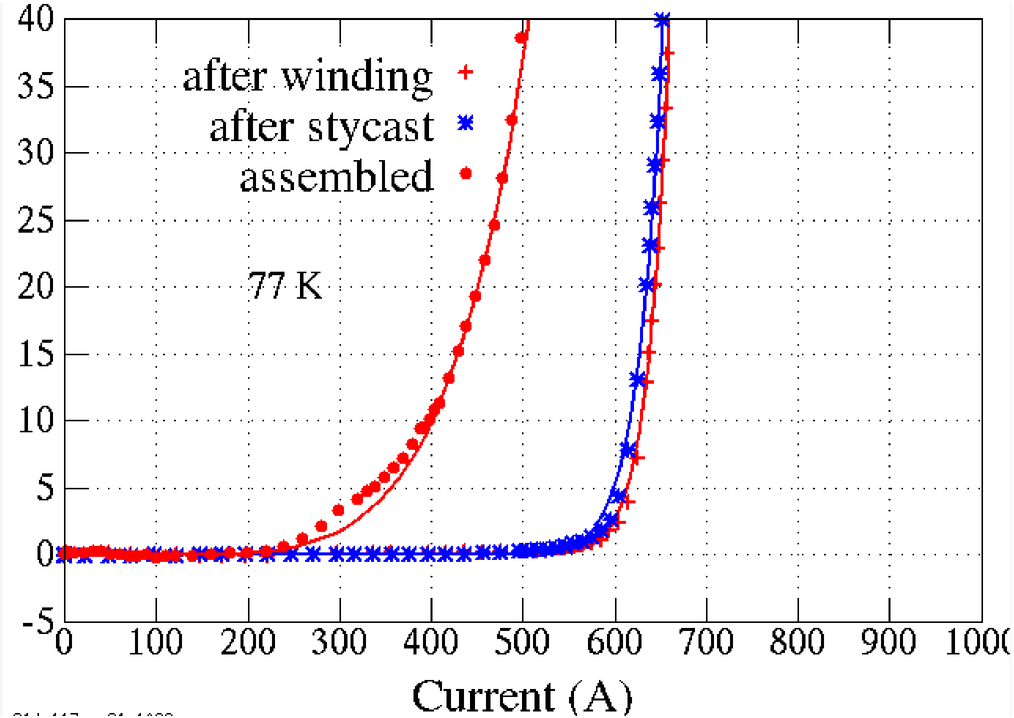
- Measured the V(I) for each layer individually at 77 K

- After being assembled into the magnet configuration
  - Tested at 77 K on 11/17/2023 and 11/21. No thermal cycle in between
    - Measured V(I) transition
  - Warmed up to room temperature to fix the spoiled vacuum in the cryostat jacket
  - Tested at 4.2 K on 11/29
    - Measured V(I) transition and ramp-rate dependence

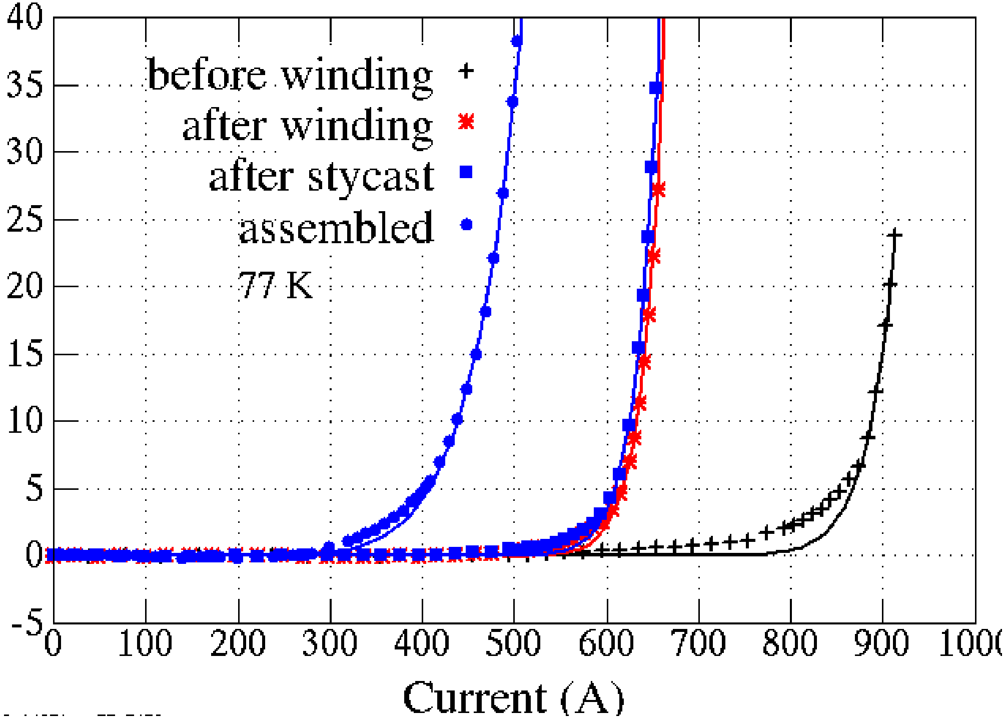
Three HM layers carried less current at 77 K, as expected



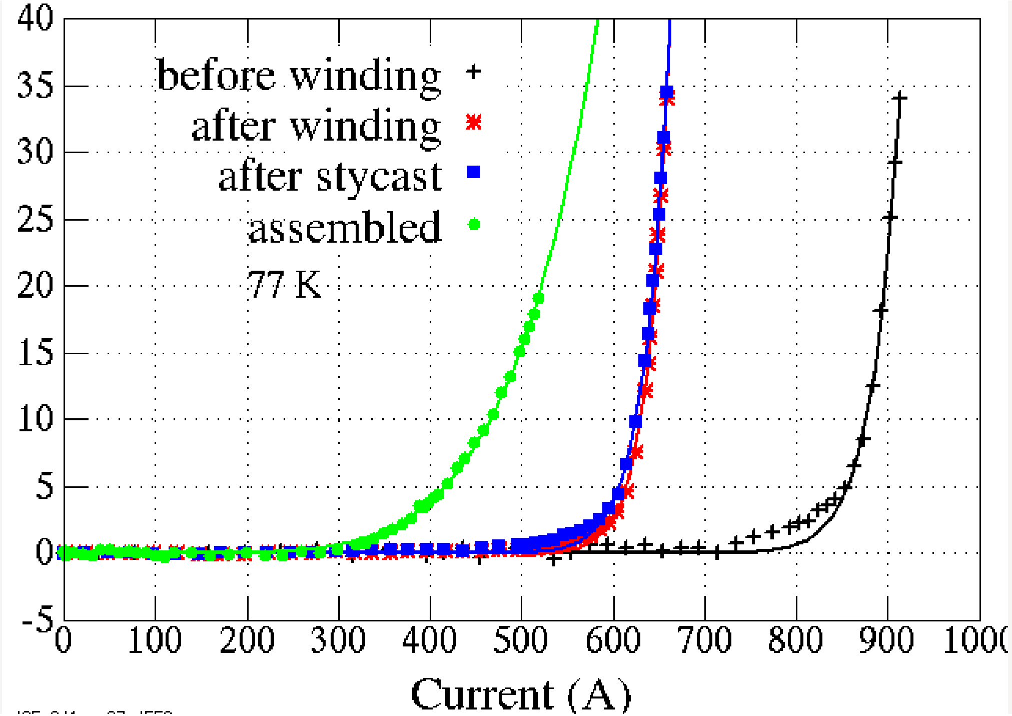
Performance evolution of Layer 1b



Performance evolution of Layer 2b



Performance evolution of Layer 5



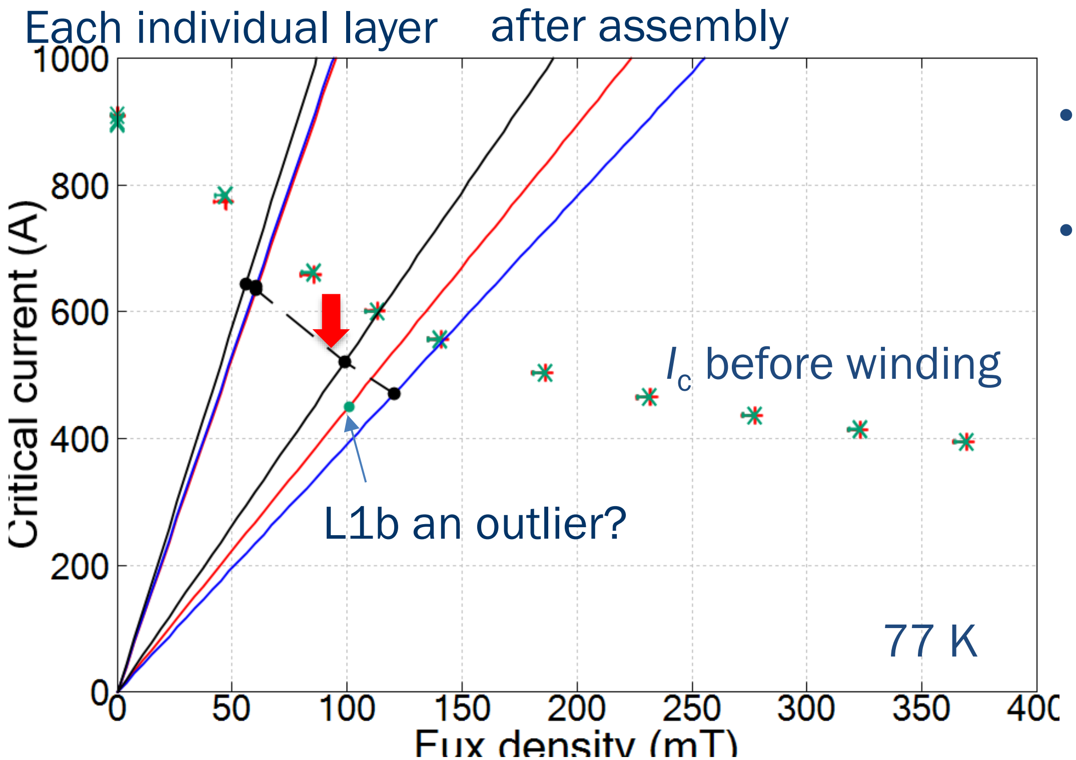
Evolution of HM performance at different stages of magnet fabrication

Normalized to the I_c before winding at 77 K, self-field

Layer	Length (m)	Expected from self-field, after winding	Measured, after winding	After assembly
1b	2.3	80%	73%	50%
2b	2.5	78%	73%	52%
5	3.6	81%	72%	58%

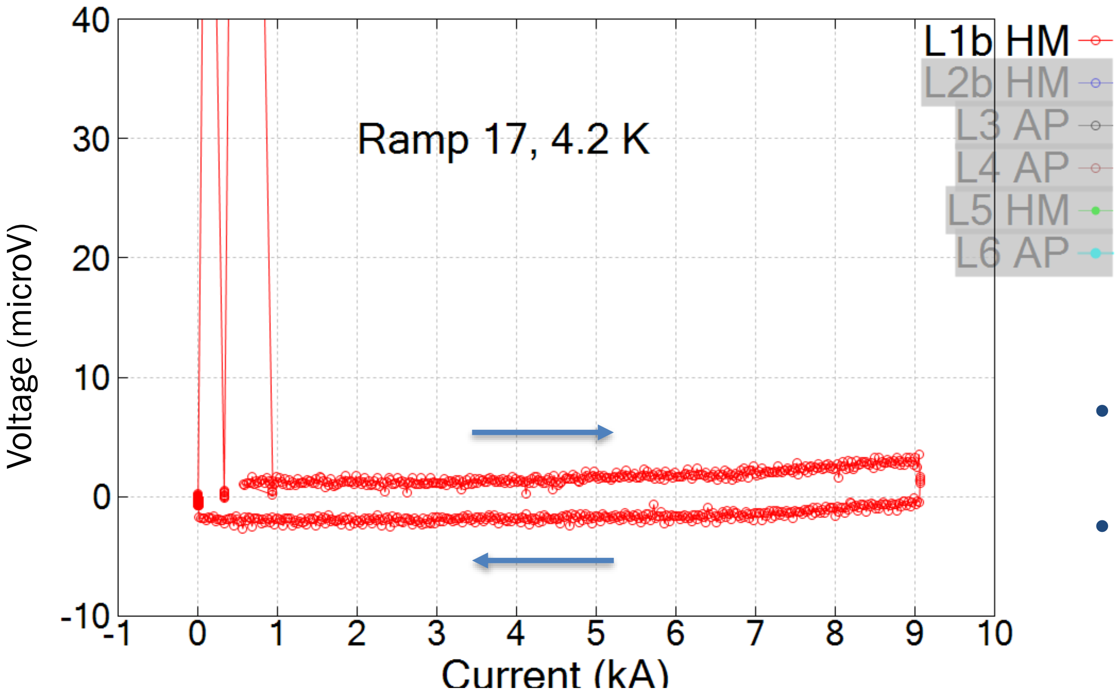
C3 data will help generate a better picture for understanding

The measurement data allowed to reconstruct the I_c(B) of HM wire after winding



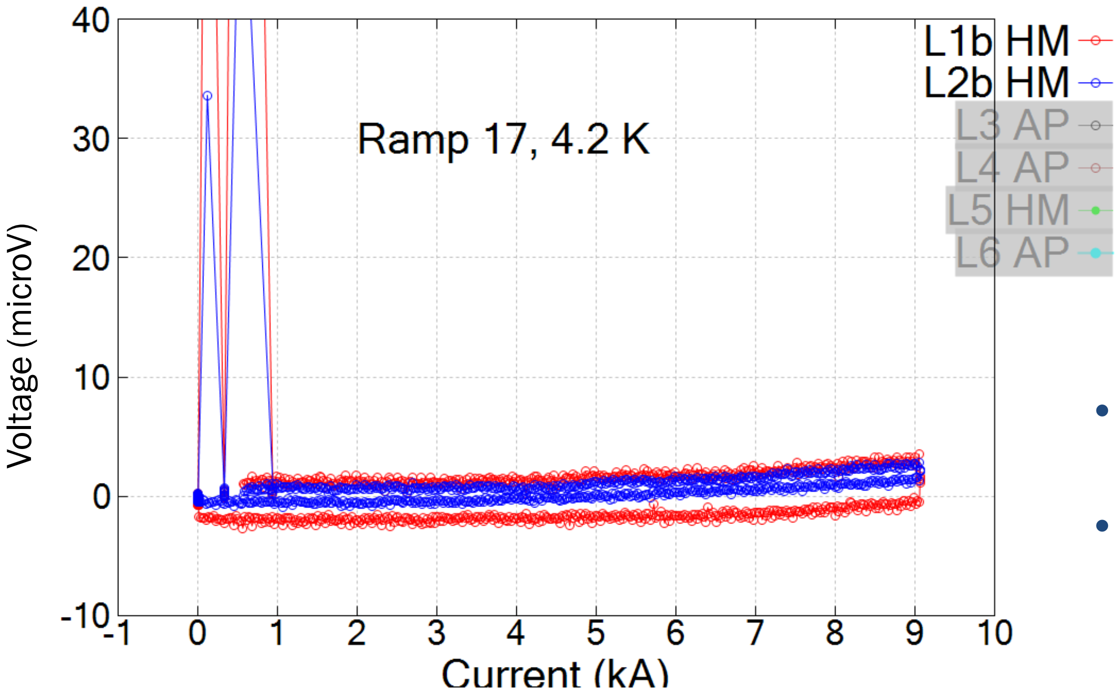
- **Data from Layers 1b, 2b, and 5**
- **After winding, the I_c(B) is about 18% lower than that before winding, at the same applied field – another way to characterize the impact due to bending?**

At 4.2 K, HM wires showed little voltage up to 9 kA, as expected



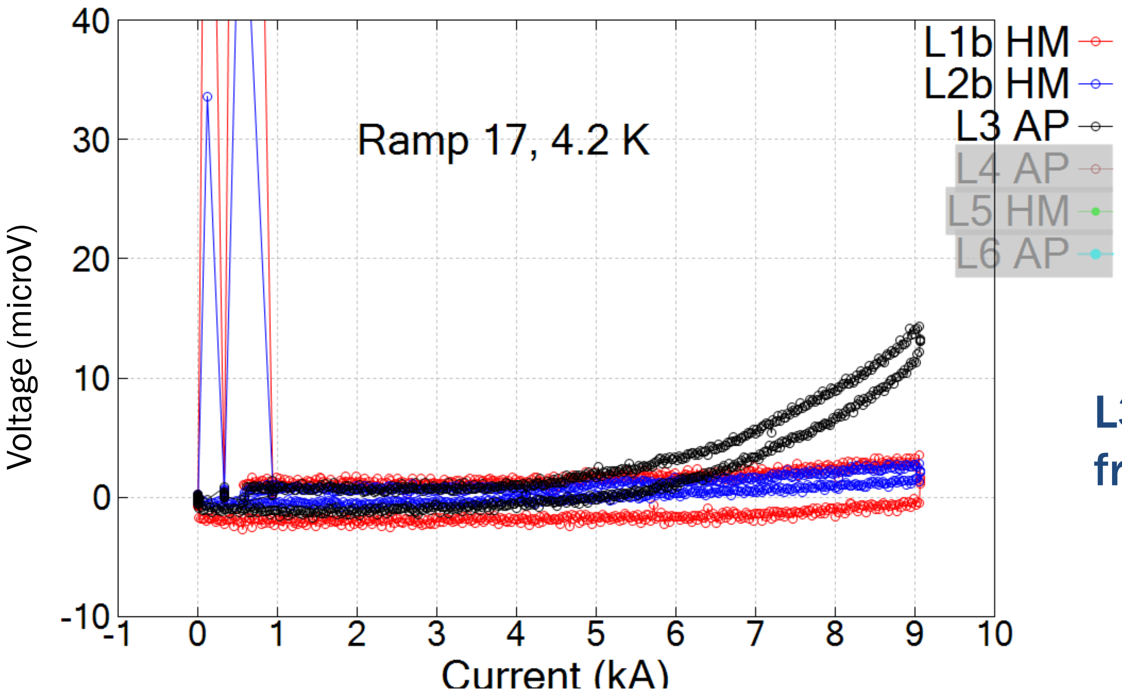
- L1b voltage increased ~ 1.6 µV from 0 to 9 kA
- x 20 higher than 77 K current

At 4.2 K, HM wires showed little voltage up to 9 kA



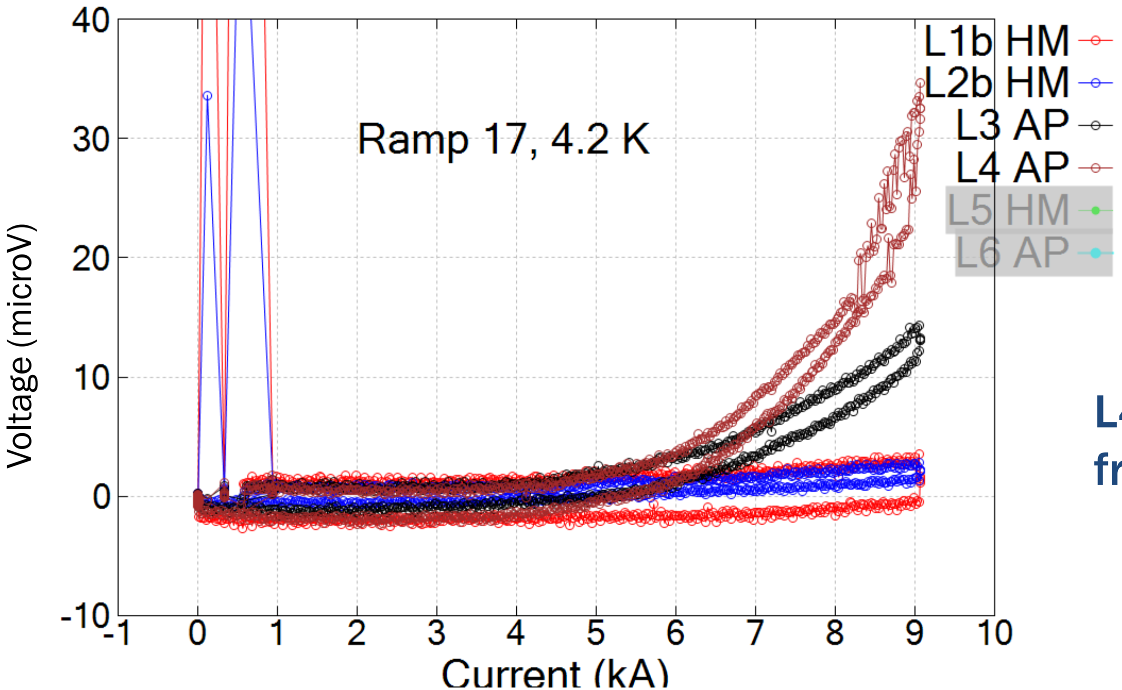
- L2b voltage increased ~ 1.6 μV from 0 to 9 kA
- x 20 higher than 77 K current

At 4.2 K, AP wires had lower current-carrying capacity than HM wires



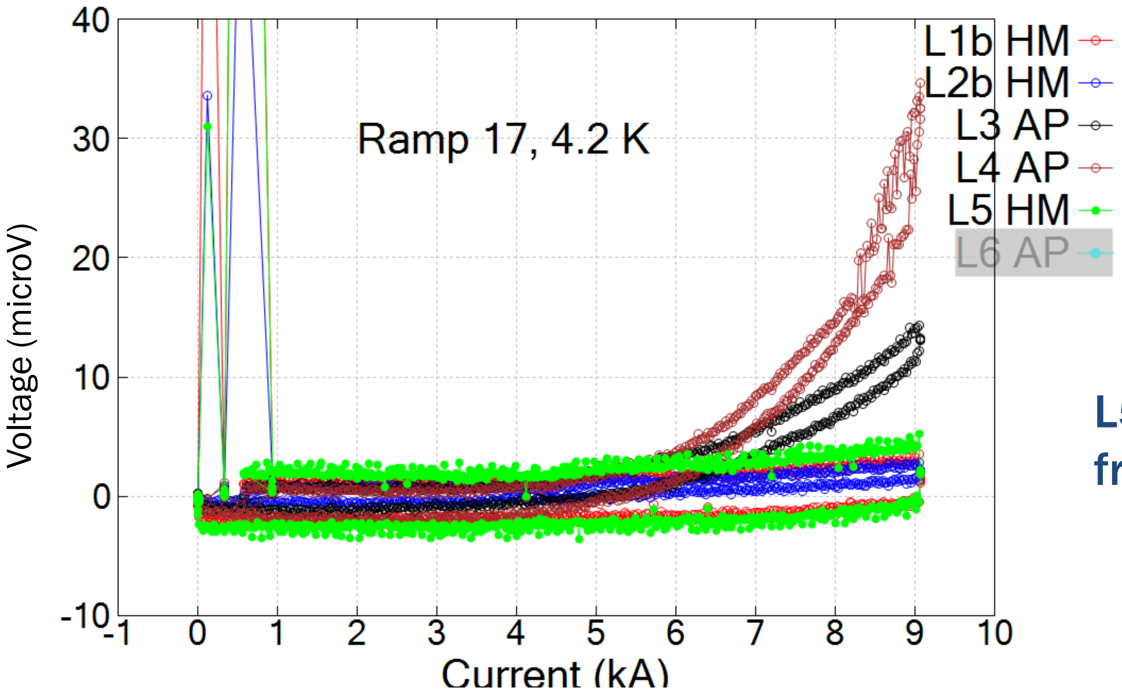
L3 voltage increased ~ 13 μV from 0 to 9 kA

At 4.2 K, AP wires had lower current-carrying capacity than HM wires – had to abort at 9 kA to avoid thermal runaway



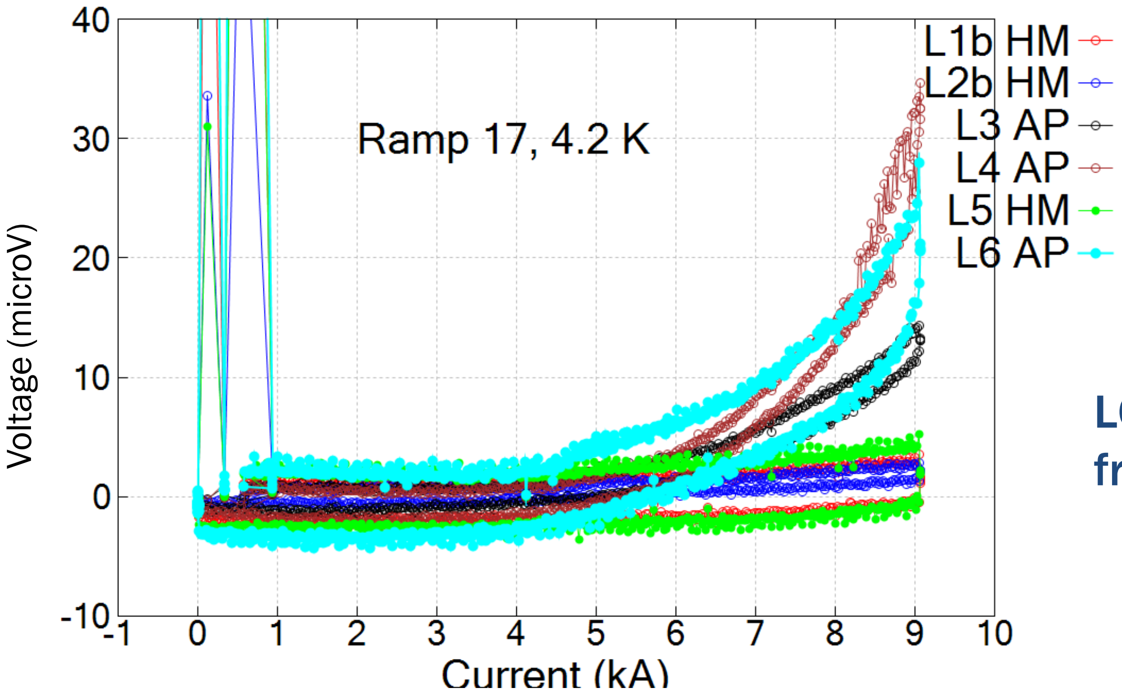
L4 voltage increased ~ 32 μV from 0 to 9 kA

At 4.2 K, HM wires showed little voltage rise up to 9 kA



L5 voltage increased ~ 2 μV from 0 to 9 kA

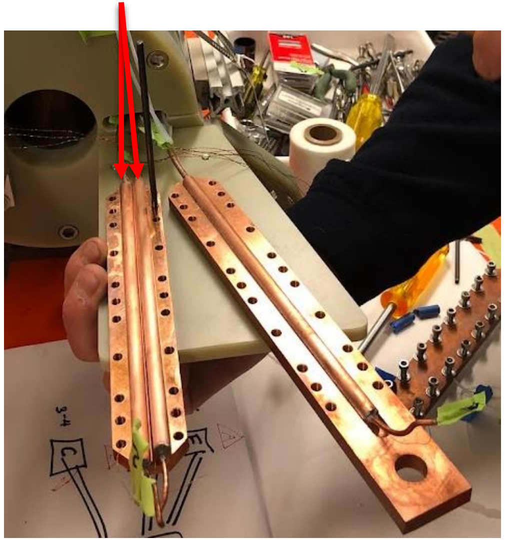
At 4.2 K, AP wires had lower current-carrying capacity than HM wires

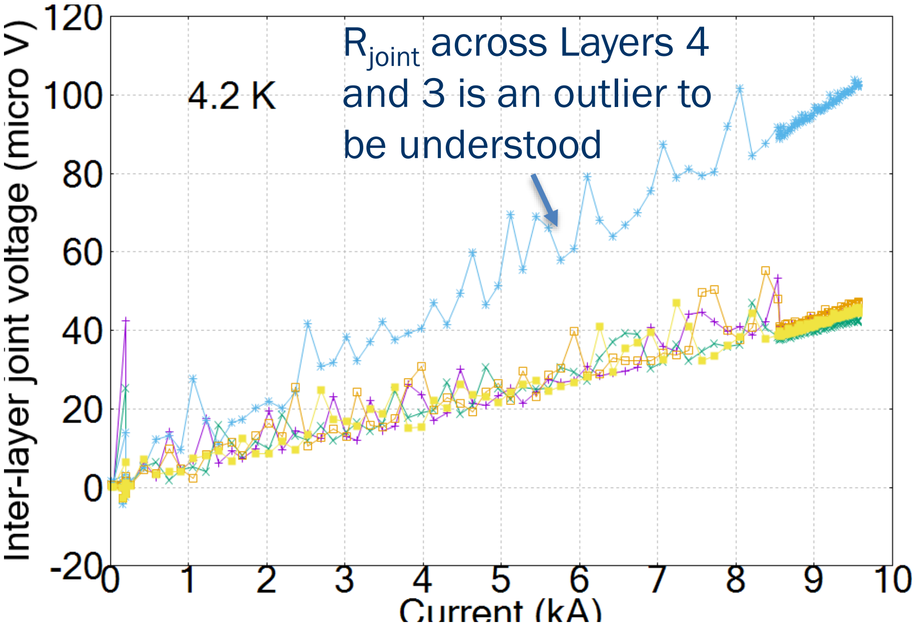


L6 voltage increased ~ 23 μV from 0 to 9 kA

The new termination technique gave reasonable performance at 4.2 K up to 9.5 kA – good enough for C3

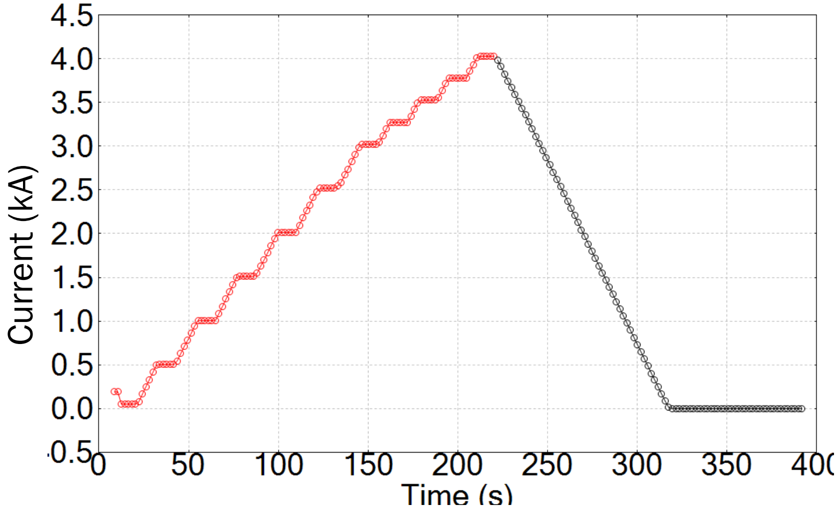
- Resistance across the inter-layer joints between 5 – 12 nΩ



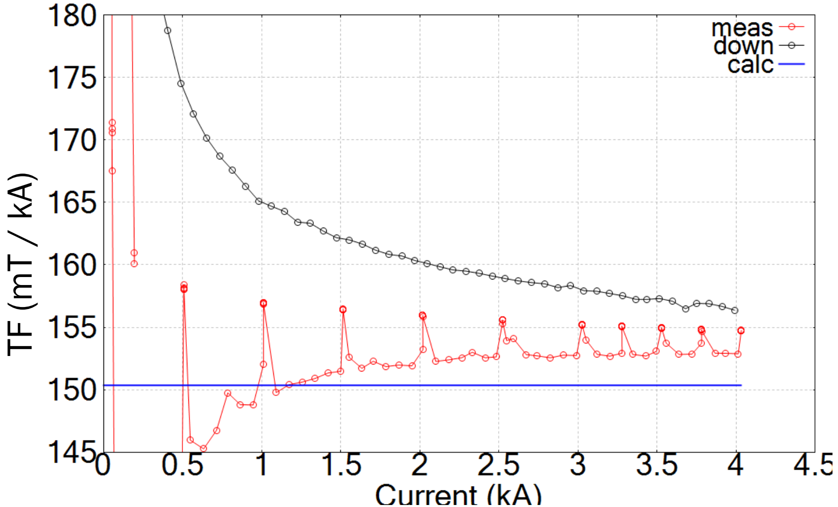


Measured dipole transfer function is within 3% of calculation, validating the magnetic design

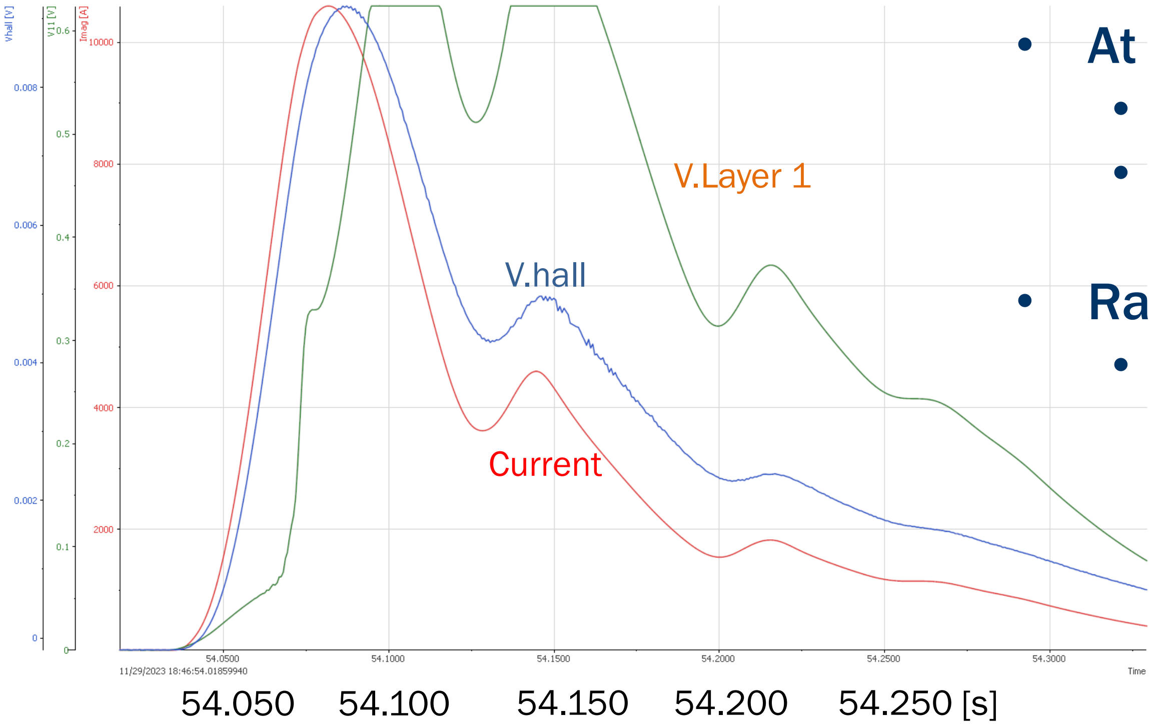
- Measurement using a calibrated cryogenic Hall probe



- Strong dynamic effects? To be confirmed with a rotating coil in C3

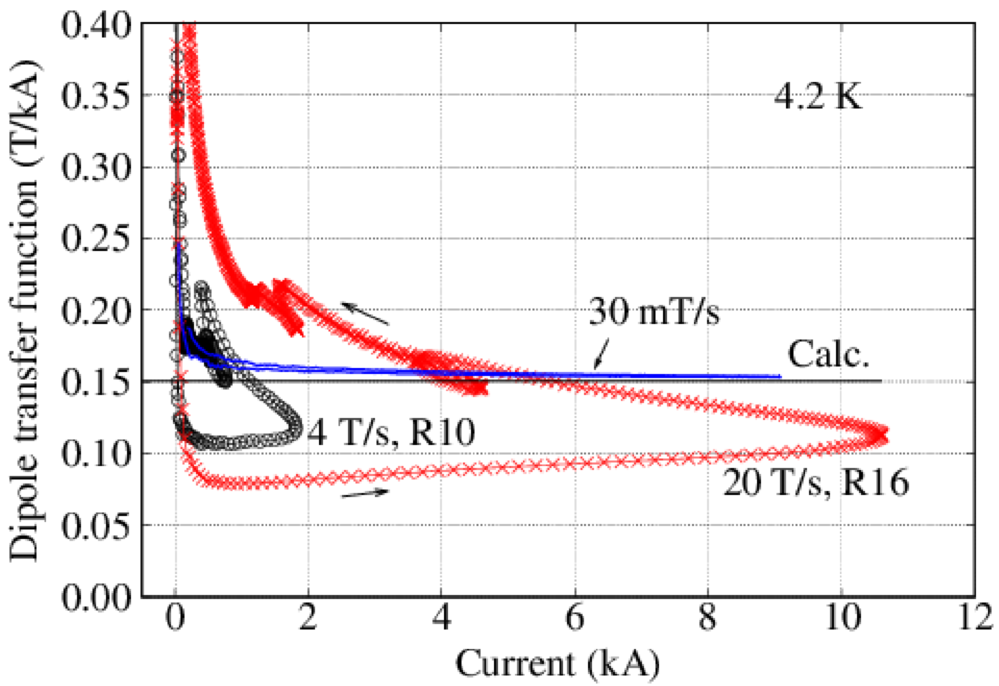


An unplanned 10.6 kA current transient occurred due to power supply control glitch…

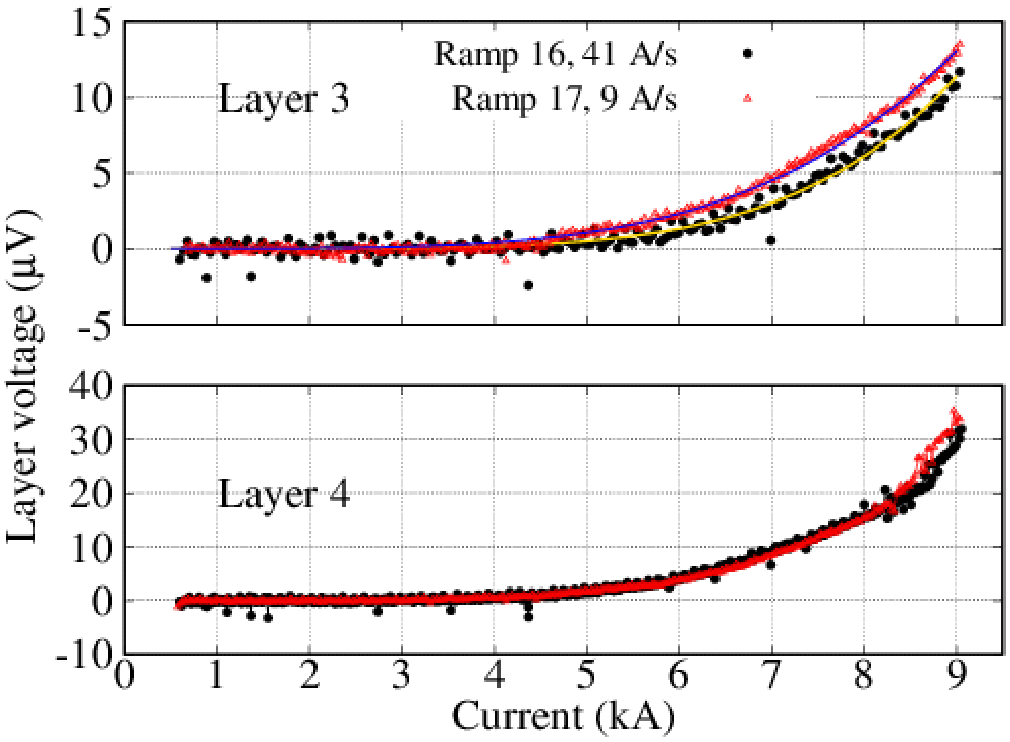


- At peak
  - I = 10.6 kA
  - Field on conductor = 2.7 T
- Ramp rate
  - 240 kA/s and 36 T/s

Dipole transfer function measured by a Hall sensor at the aperture center – a strong ramp-rate dependence



… L3 AP wire apparently degraded by 350 A after the transient. The other layers did not show significant changes in V(I) curves



Let there be light – experiments with distributed fiber-optic sensing provides insight into the magnet behavior

- Feather 2 magnet tested the Rayleigh-scattering based fiber optic sensing, the first report on application in a REBCO dipole magnet

- We started experimenting using a similar setup in the 3-turn CCT magnet. More details can be found in this paper

- A lot of open questions and opportunities
  - Limitations of commercial interrogators
  - Differentiate mechanical and thermal strain
  - High-resolution data to validate magnet mechanical models

We are making C3 – Layer 1 wound

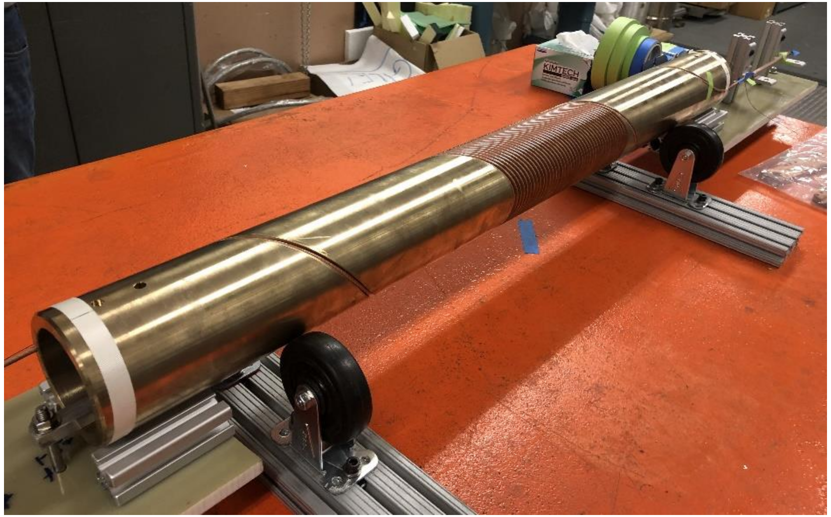
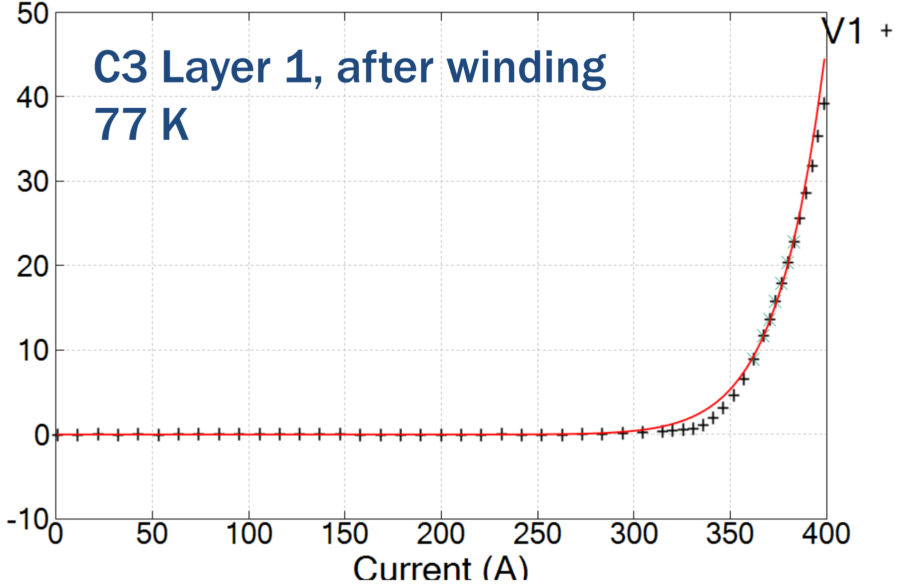


Image courtesy Paolo Ferracin

Although we practiced, there is still surprise



- I_c ~ 380 A and n ~ 15.7
- Lower than 580 A, as expected from the I_c(B) of the HM wire used in 3-turn layers
- To measure the I_c(B) of the actual Layer 1 wire

Fast forward to this week – we are testing C3

- Completed 77 K test
  - Layer 1, the innermost layer, has an I_c of 190 A, limiting the magnet performance
  - Co-wound fiber in each layer and on the aluminum shell. Collecting fiber data during the test

- Cool down to 4.2 K today
  - Will see if it can generate 5 T

Beyond C3 – we need to push toward the limit of HTS sooner

- Higher field or else
  - A key point of HTS is to go beyond the reach of Nb_3Sn. Will it do?
  - What's the performance limit of HTS?

- Two approaches
  - Hybrid and all HTS, not mutually exclusive
  - Community should pursue both simultaneously in fast paces
  - All HTS opens the door of operating at a temperature above 10 K – "a brave new world"

- Be mindful of but don't be bogged down by conductor cost
  - Cost can only become a possible issue after the technology works?

No good work is done alone

Conductor development and procurement: Dmytro Abraimov (FSU), Ian Pong, Kyle Radcliff, Danko van der Laan, Jeremy Weiss (ACT)

C3a analysis: Diego Arbelaez, Lucas Brouwer, Marika D'Addazio, Paolo Ferracin, Mariusz Juchno, José Luis Rudeiros Fernandez, Giorgio Vallone

C3a fabrication: Tim Bogdanof*, Helen Feng*, Bill Ghiorso, Hugh Higley, Derek Hochvert, Andy Lin, Anjana Saravanan

C3a test: Jean-Francois Croteau, Hugh Higley, Derek Hochvert, Simone Johnson, Linqing Luo, Maxim Marchevsky, Bob Memmo, Mike Naus, Matt Reynolds, José Luis Rudeiros Fernandez, Tengming Shen, Chet Spencer, Reed Teyber, Marcos Turqueti

*: gone but not forgotten

No good work is done alone

- Elliptic CCT design: Lucas Brouwer, Anjana Saravanan
- 20 mm bend radius coil experiment: Hugh Higley, Anjana Saravanan
- STAR® wire impregnation: Diego Arbelaez, Elaine Buron, Hugh Higley, Simone Johnson, José Luis Rudeiros Fernandez, Jim Swanson
- STAR® 6-around-1 cable: Hugh Higley, Mark Krutulis*, Andy Lin
- Collaborations with ACT and AMPeers via DOE HEP SBIR programs
- Frequent participants at the working group meeting: BNL: Anis Ben Yahia, Ramesh Gupta, Mithlesh Kumar, Vikas Teotia; FNAL: Maria Baldini, Steve Gourlay, Steve Krave, Vadim Kashikhin, Vito Lombardo, Xingchen Xu; Paolo Ferracin, Ian Pong, Reed Teyber, Yufan Yan