U.S. MAGNET DEVELOPMENT PROGRAM

REBCO magnet – LBL report and conductor needs

X. Wang

MDP Collaboration Meeting, 1 May 2024

Driving questions for a technology development program

- What performances and parameters should the conductor have? How to collaborate with vendors to meet the conductor performance targets?
- How can we make magnets using these conductors?
- What is the maximum dipole field a REBCO magnet can generate?
- What is the magnet performance? How does it quench? What is the field quality?
- How does the magnet fail? How can we avoid it?
- How can we characterize the performance for long conductors?

We make magnets to address the questions

- Pursue different magnet concepts with a focus on round wires
  - Common coil, COMB, cct, uni-layer, …
- Couple magnet and conductor development
  - Engage competent vendors to improve conductors for us to make better magnets
- Goals
  - Generate fields beyond reach of Nb_3Sn
  - Can scale to meter-long magnets
  - Machines make magnets

- Emphasize fabrication
- Be mindful but do not get bogged down by conductor cost

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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SuperPower Inc.
A Furukawa Company

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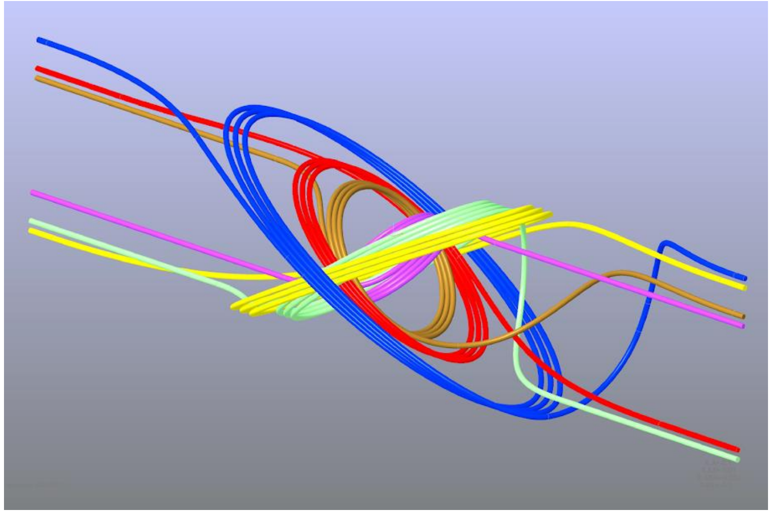
Three steps towards C3

- ~~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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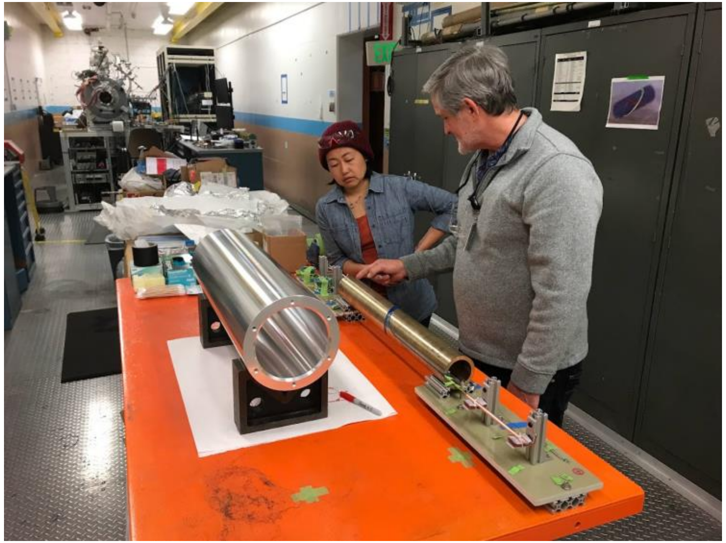
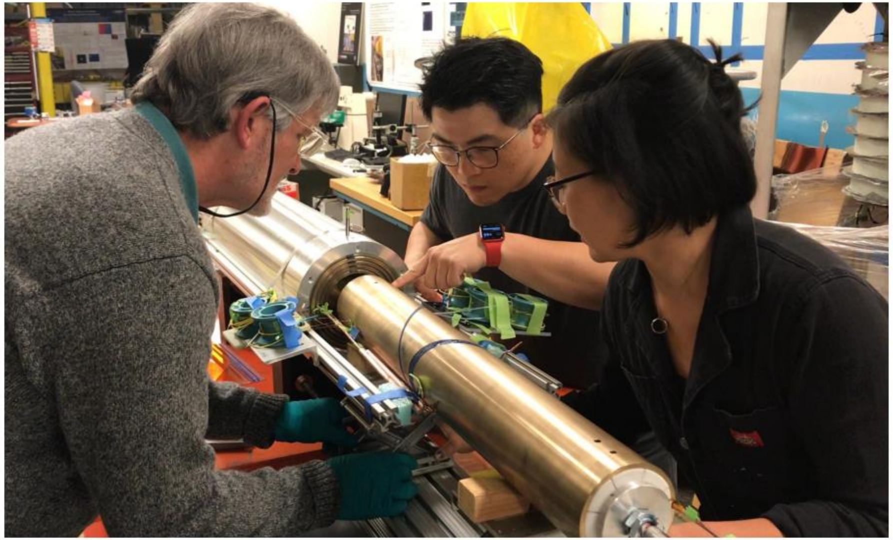
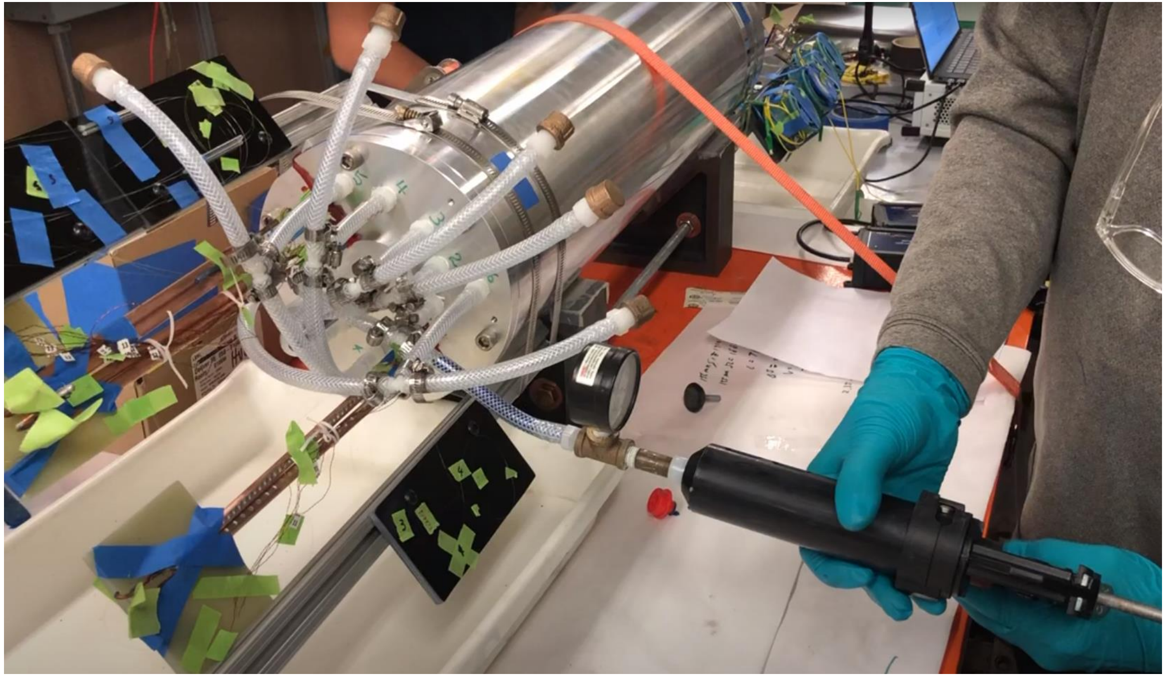
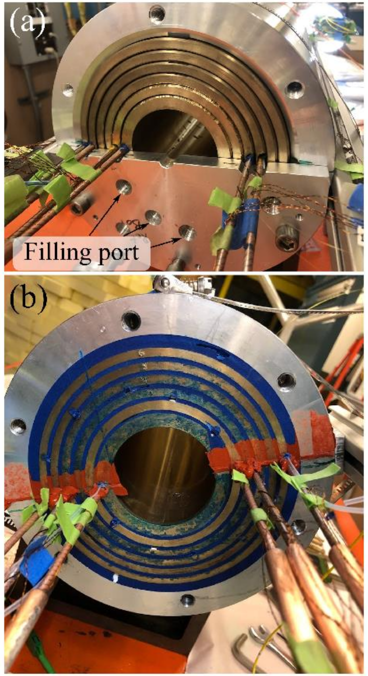
Assemble the coils



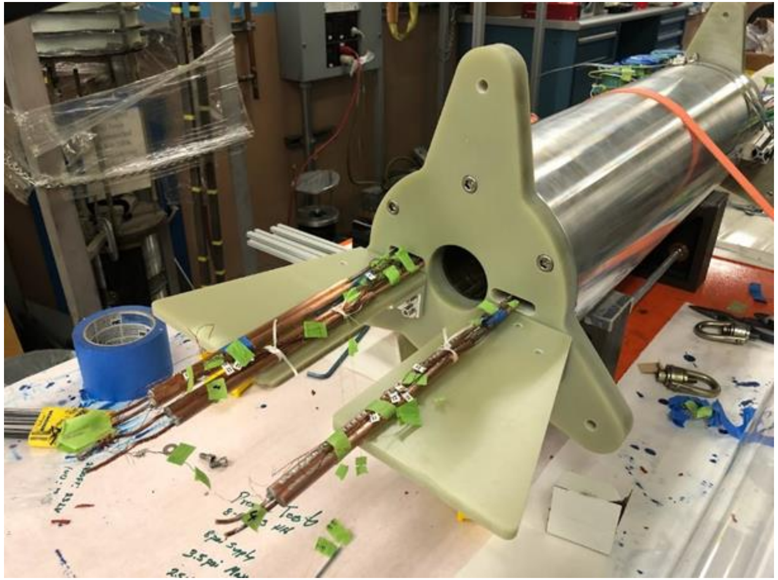


Fill the radial gaps between the layers with Stycast to mechanically couple them



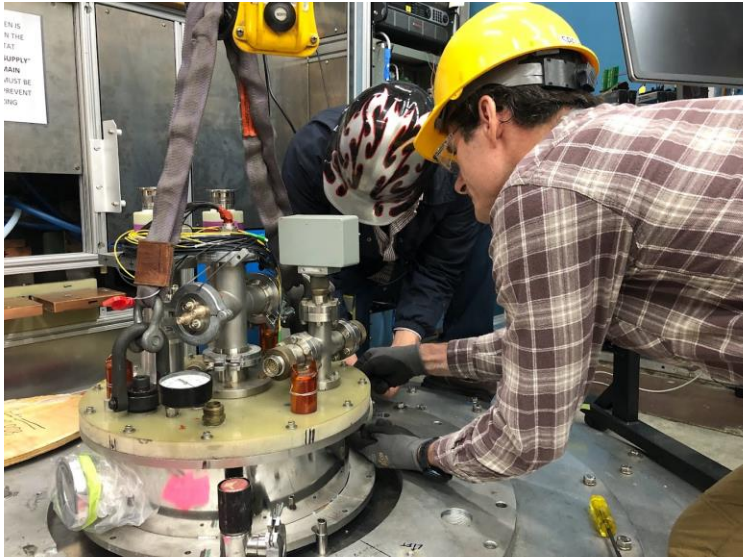


Make electrical joints



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

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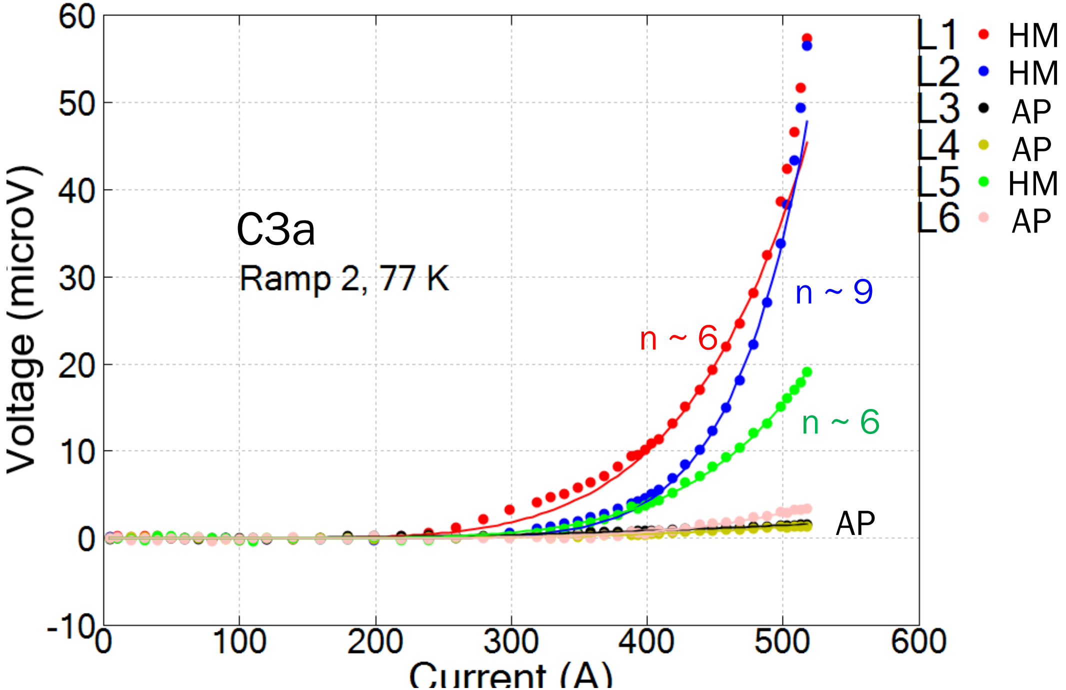
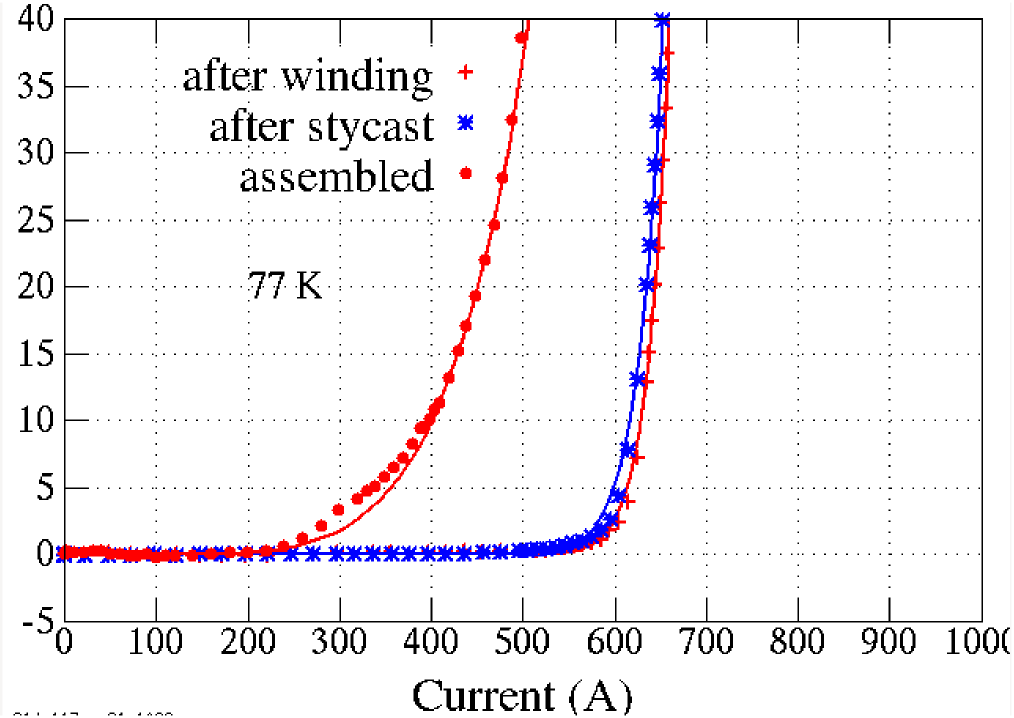
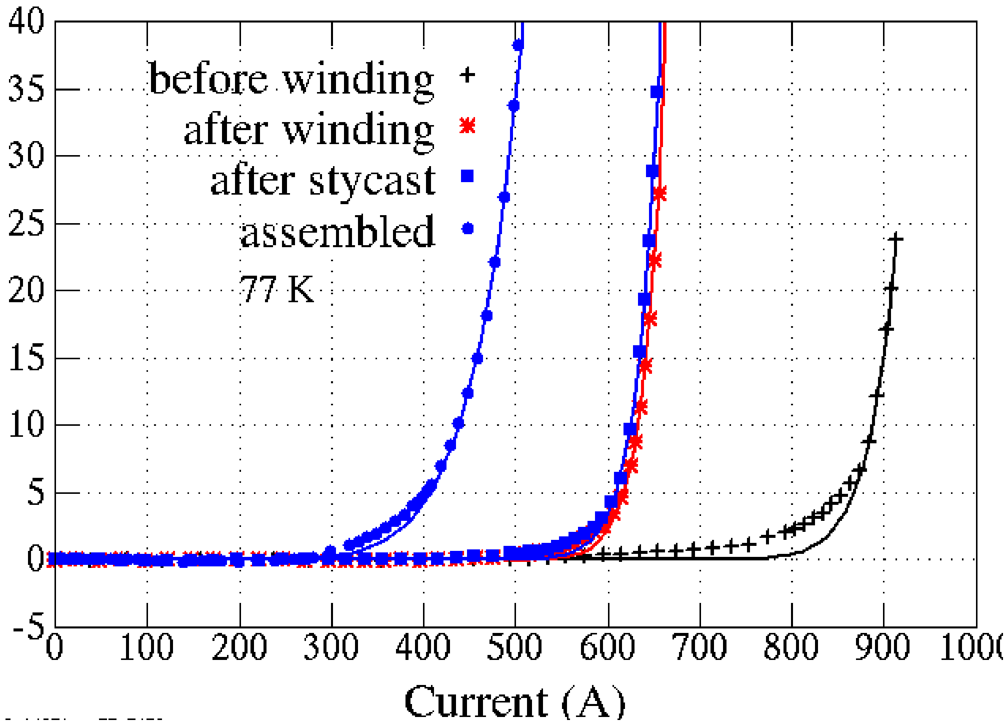
Three HM layers carried less current at 77 K, as expected



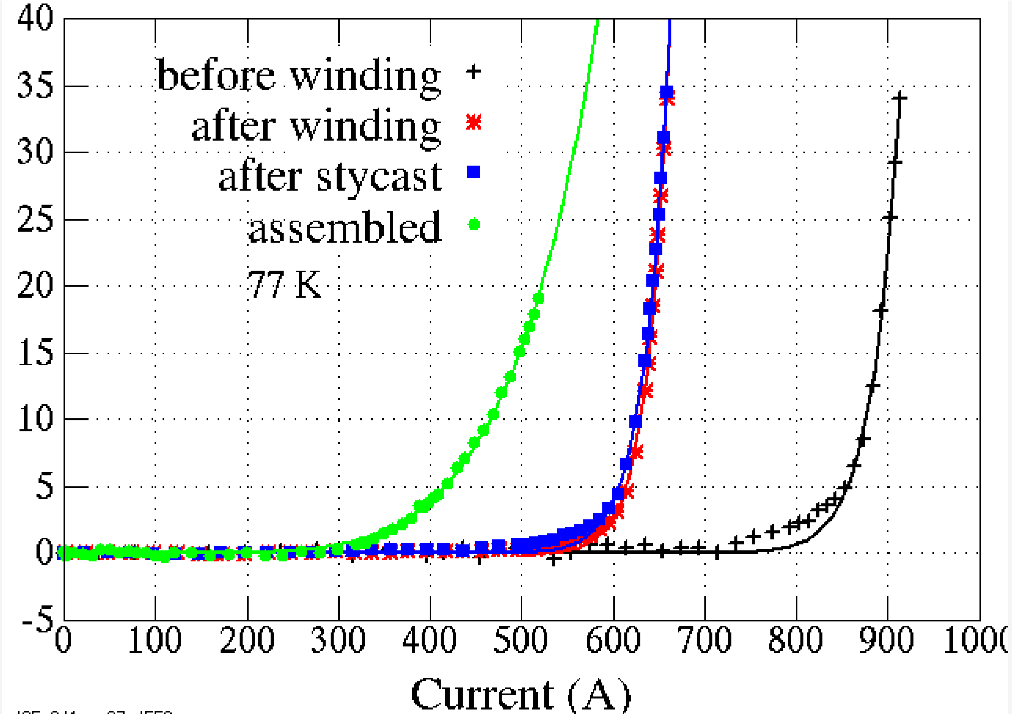
Performance evolution of Layer 1b



Performance evolution of Layer 2b



Performance evolution of Layer 5



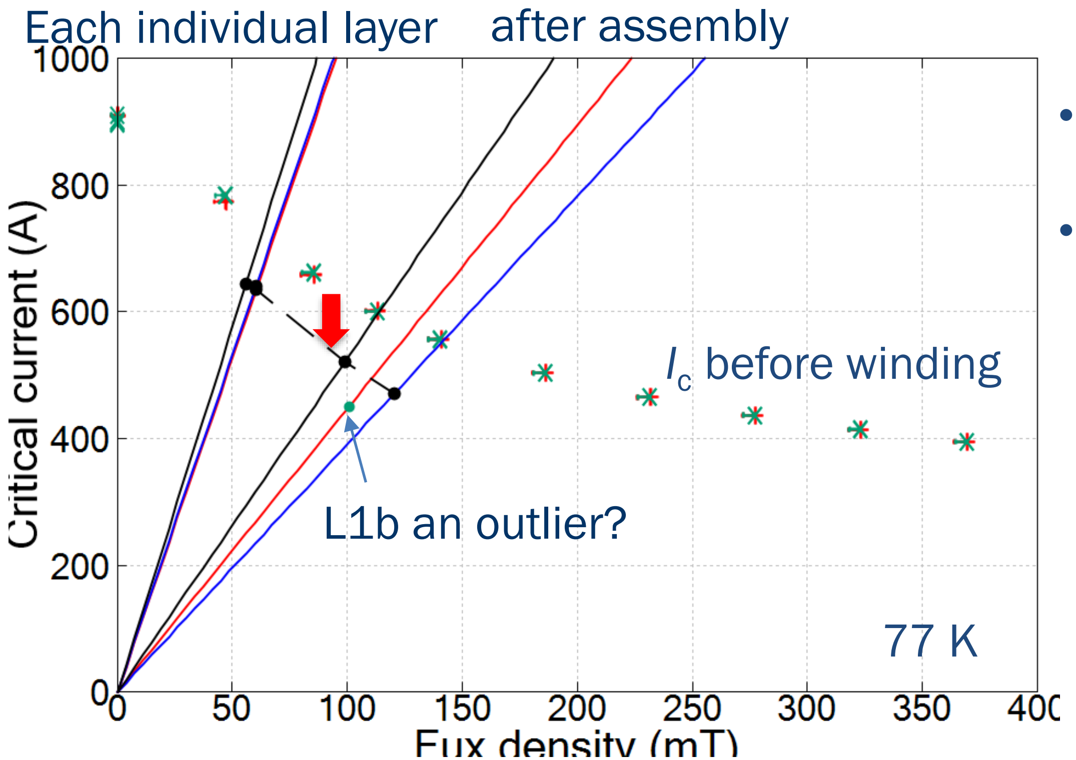
Evolution of HM performance at different stages of magnet fabrication

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%

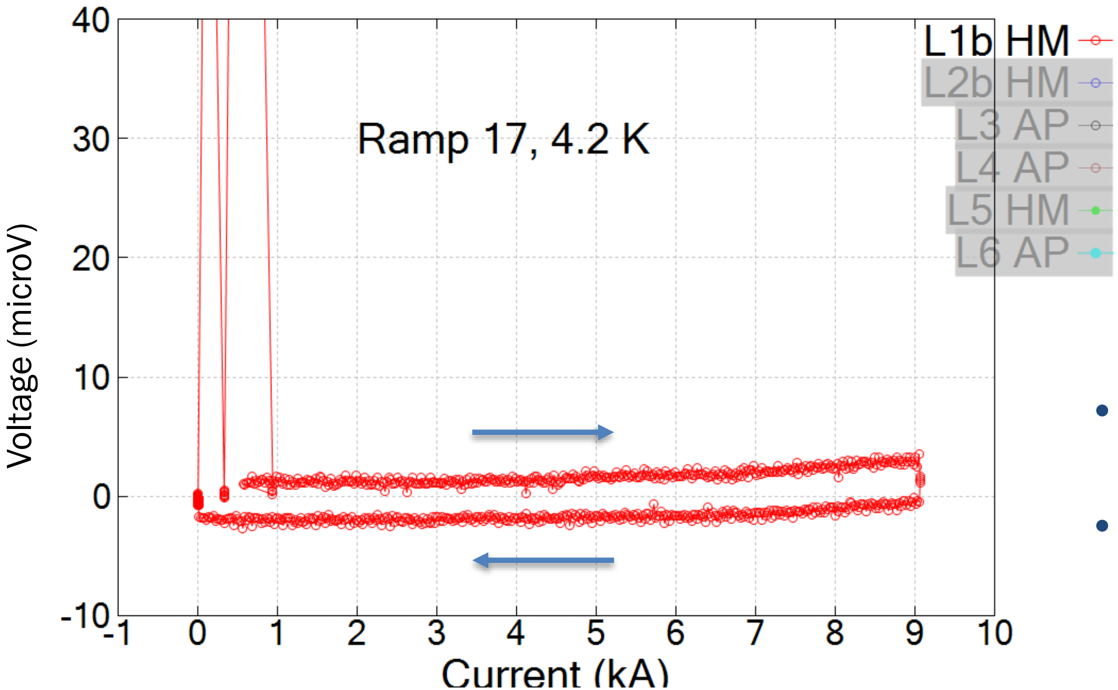
C3 data will help generate a better picture for understanding

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



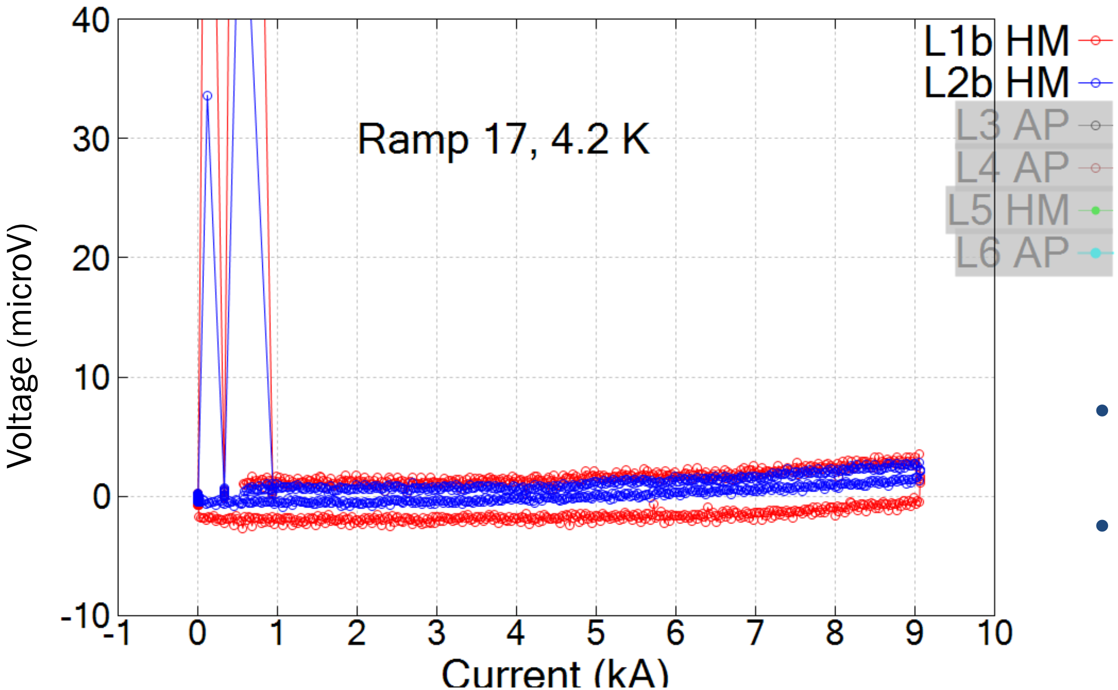
- **Data from Layers 1b, 2b, and 5**
- **After winding, the I_c(B) is about 18% lower than that before winding, at the same applied field – another way to characterize the impact due to bending?**

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



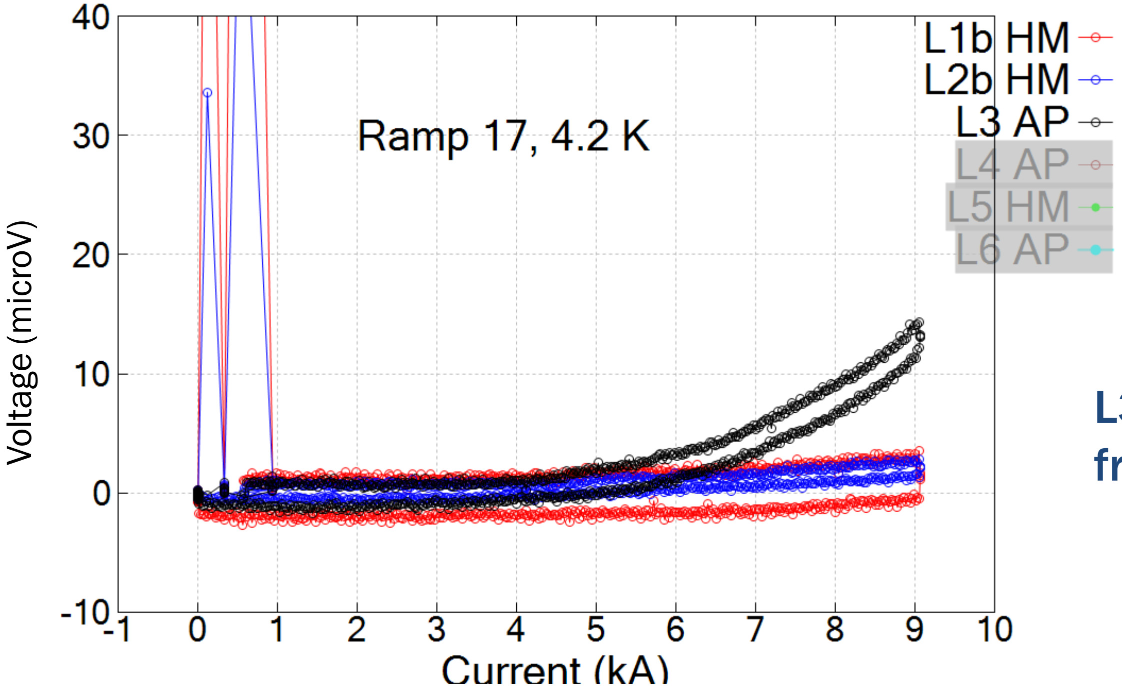
- L1b voltage increased ~ 1.6 μV from 0 to 9 kA
- x 20 higher than 77 K current

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



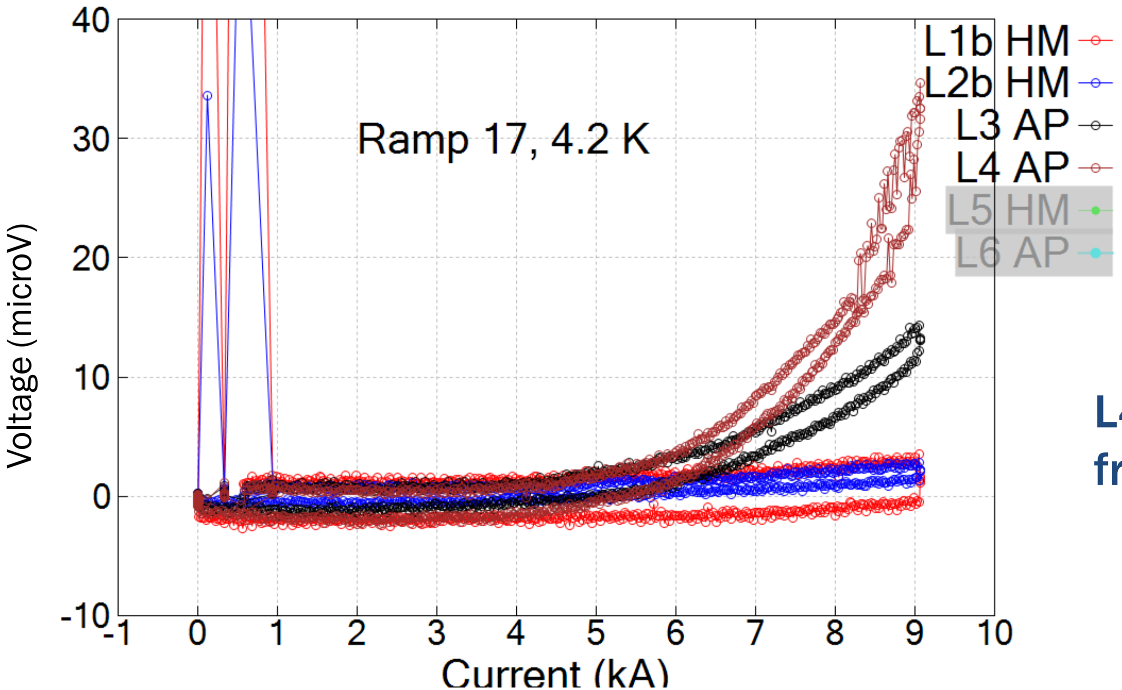
- L2b voltage increased ~ 1.6 µV from 0 to 9 kA
- x 20 higher than 77 K current

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



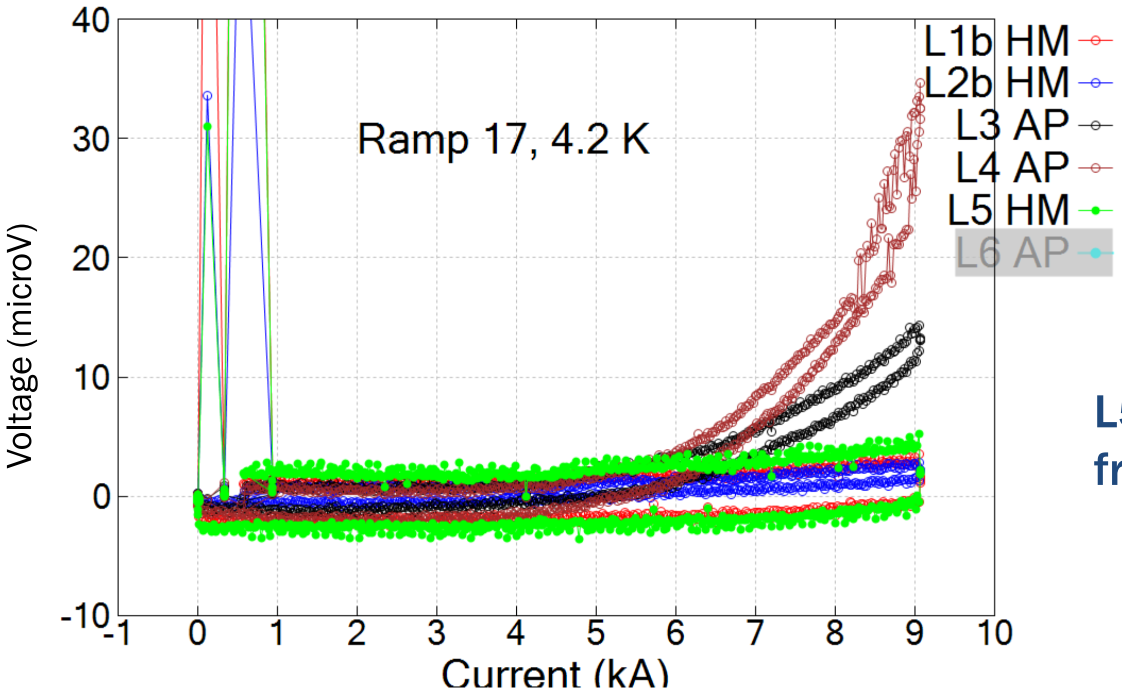
L3 voltage increased ~ 13 μV from 0 to 9 kA

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



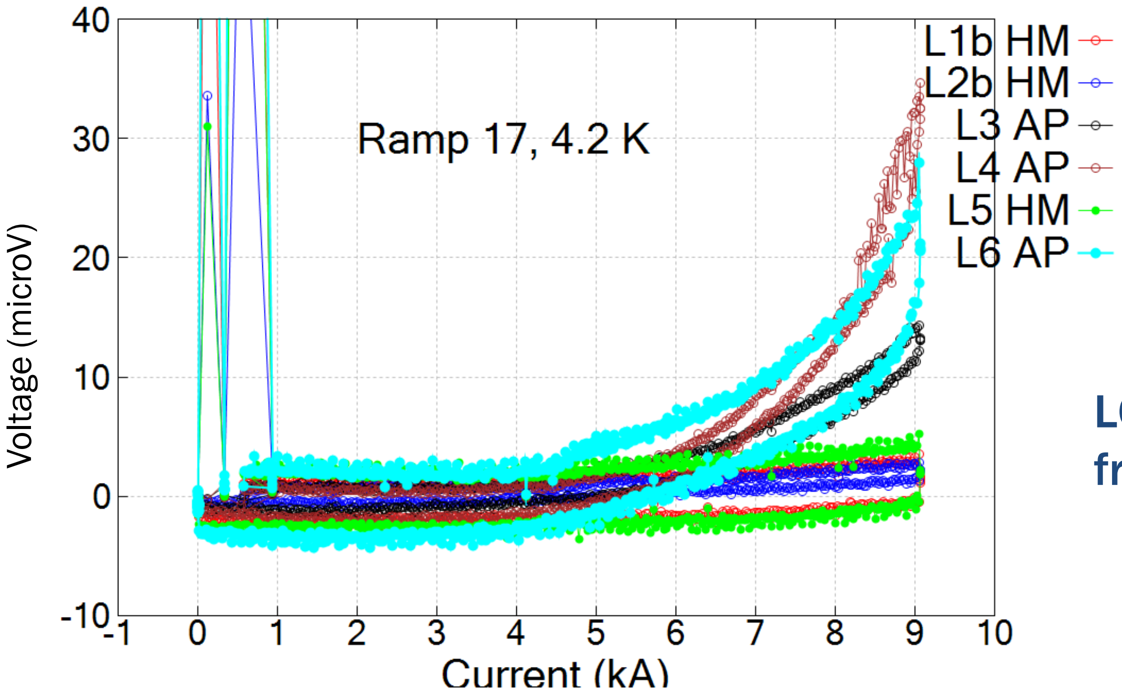
L4 voltage increased ~ 32 μV from 0 to 9 kA

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



L5 voltage increased ~ 2 μV from 0 to 9 kA

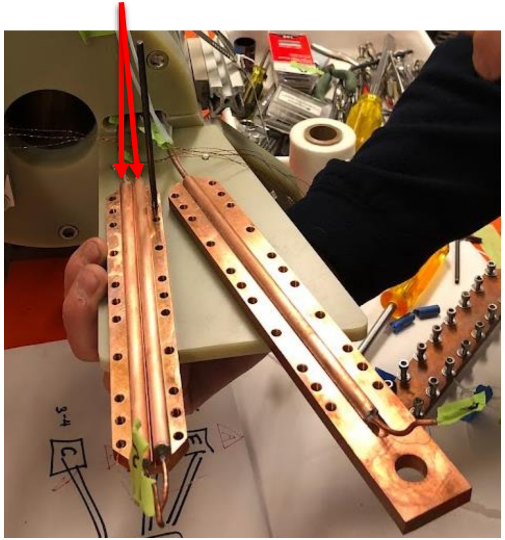
At 4.2 K, AP wires had lower current-carrying capacity than HM wires

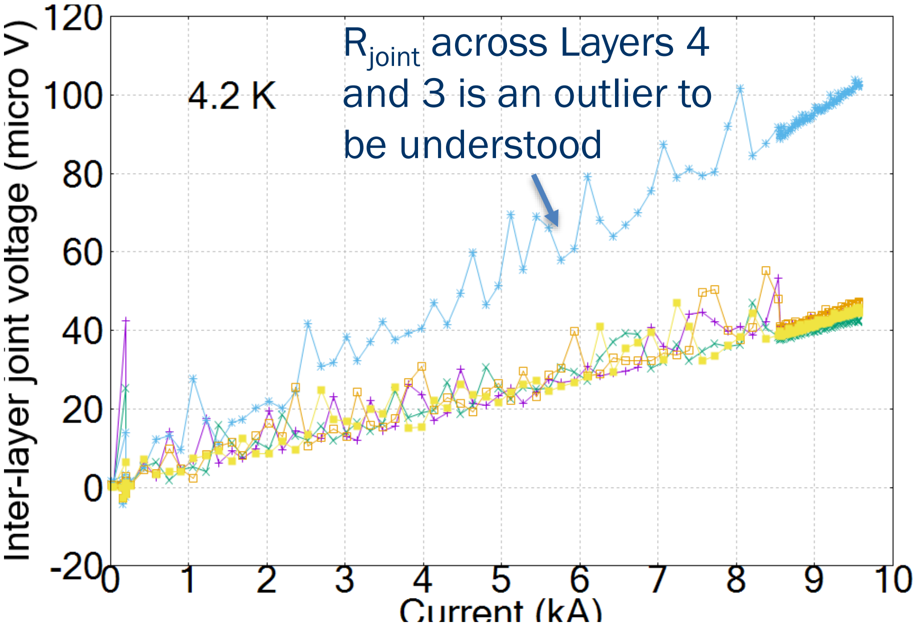


L6 voltage increased ~ 23 μV from 0 to 9 kA

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

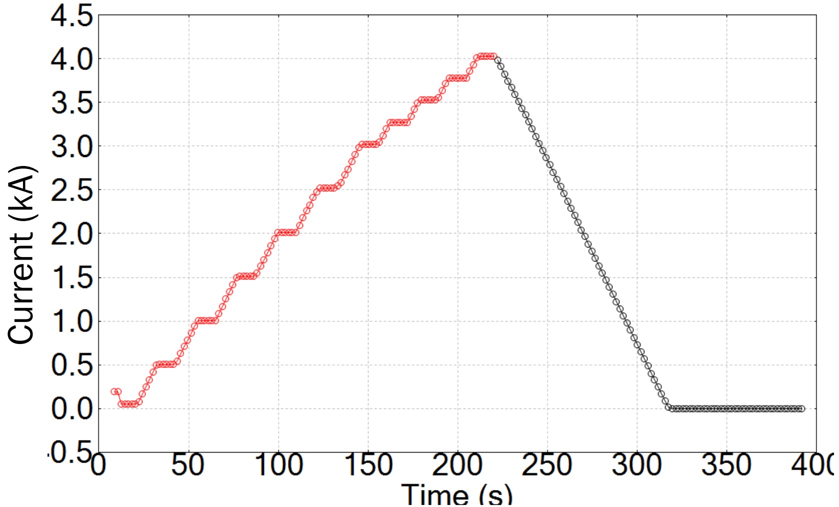
- **Resistance across the inter-layer joints between 5 – 12 nΩ**



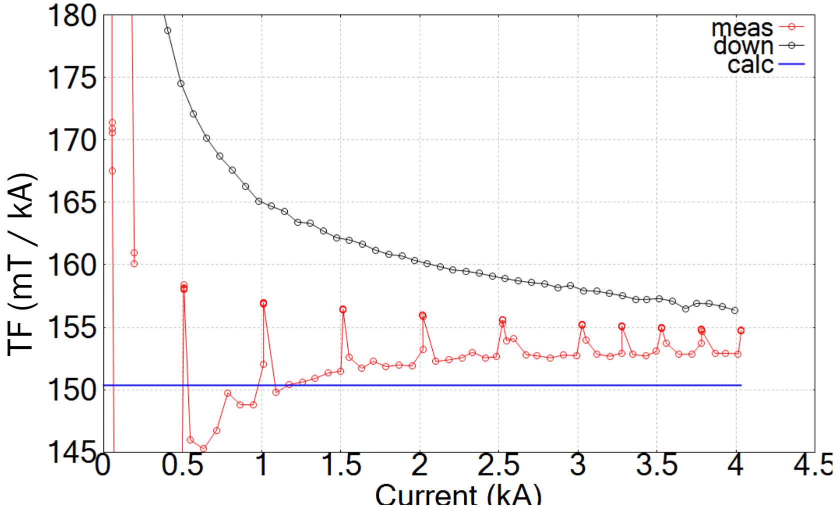


Measured dipole transfer function is within 3% of calculation, validating the magnetic design

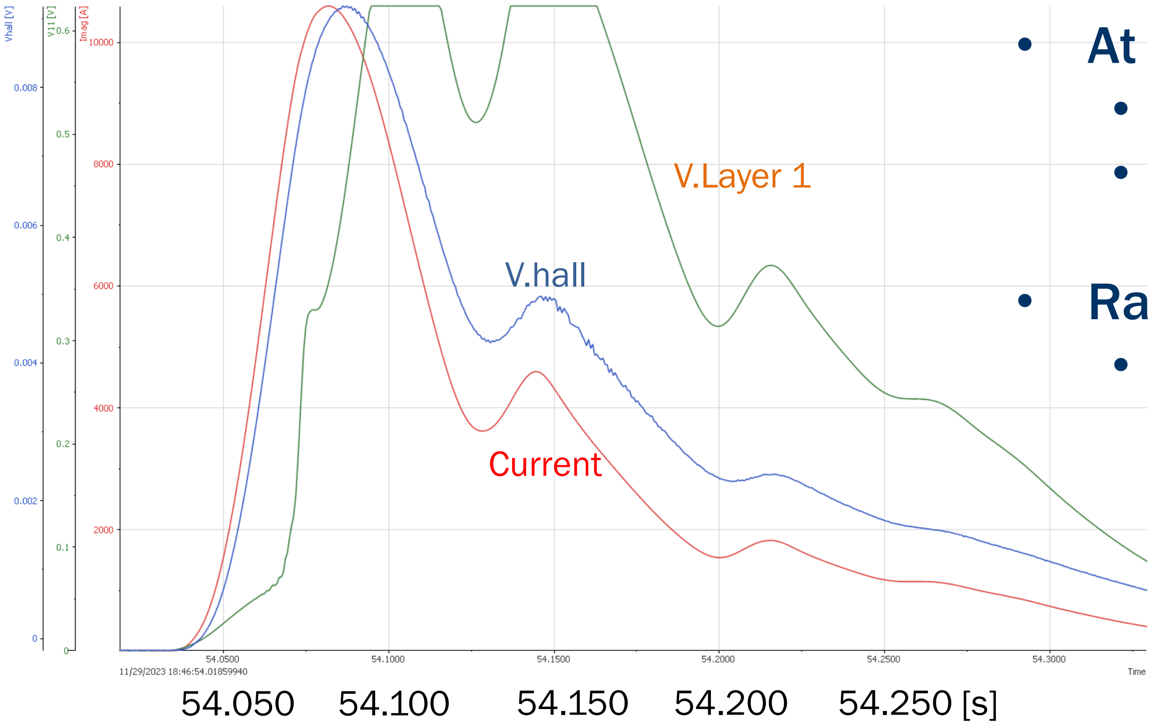
- Measurement using a calibrated cryogenic Hall probe



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

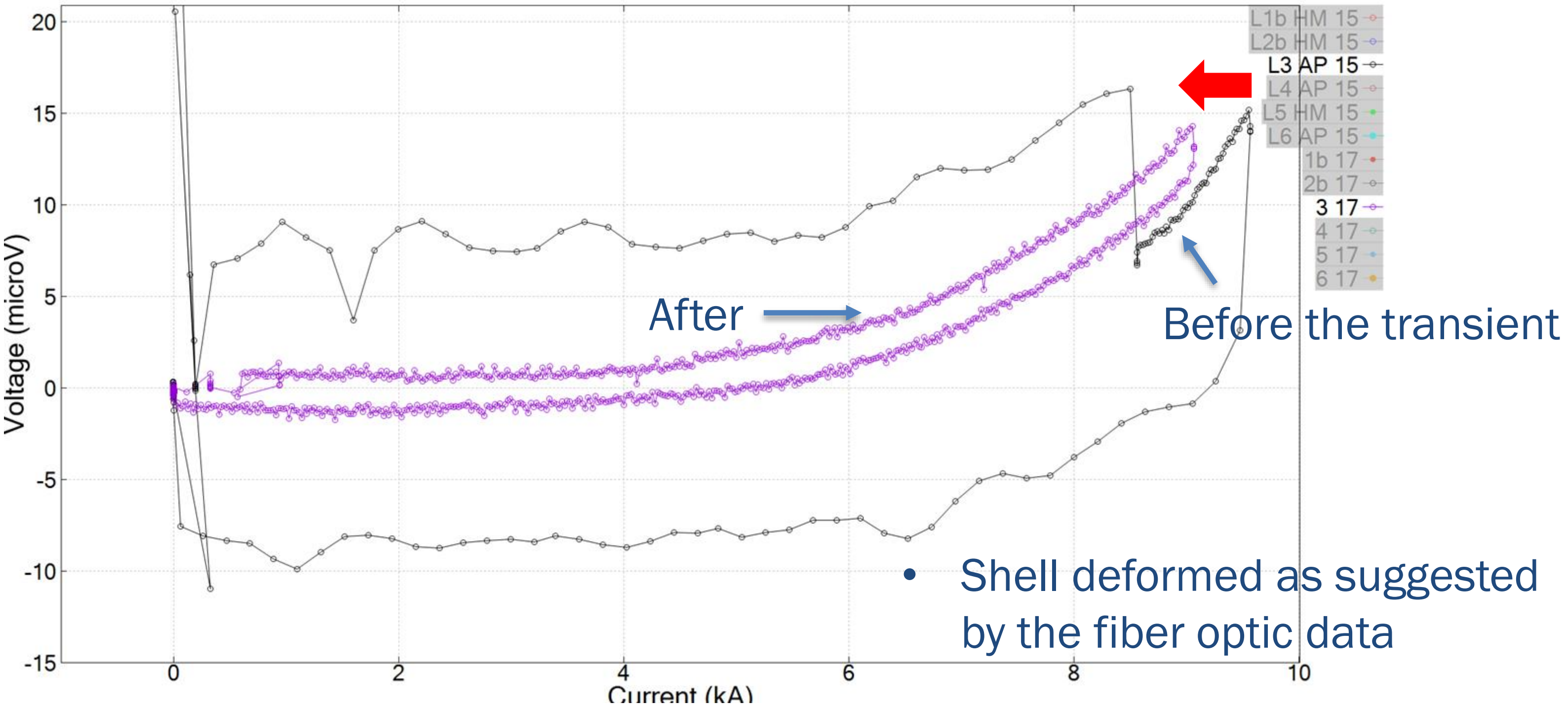


An unplanned 10.6 kA current transient occurred due to power supply control glitch…



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

… L3 AP wire apparently degraded by 800 A after the transient. The other layers did not show significant changes in V(I) curves



- Shell deformed as suggested by the fiber optic data

We are making C3 – Layer 1 wound

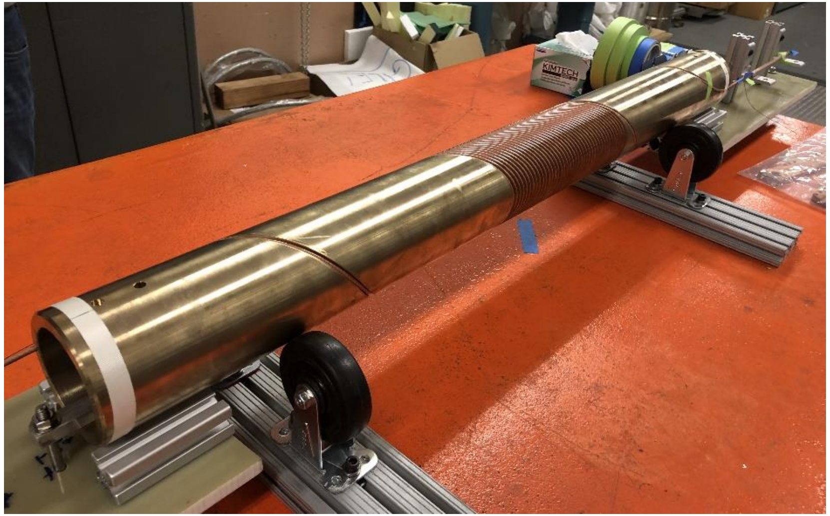
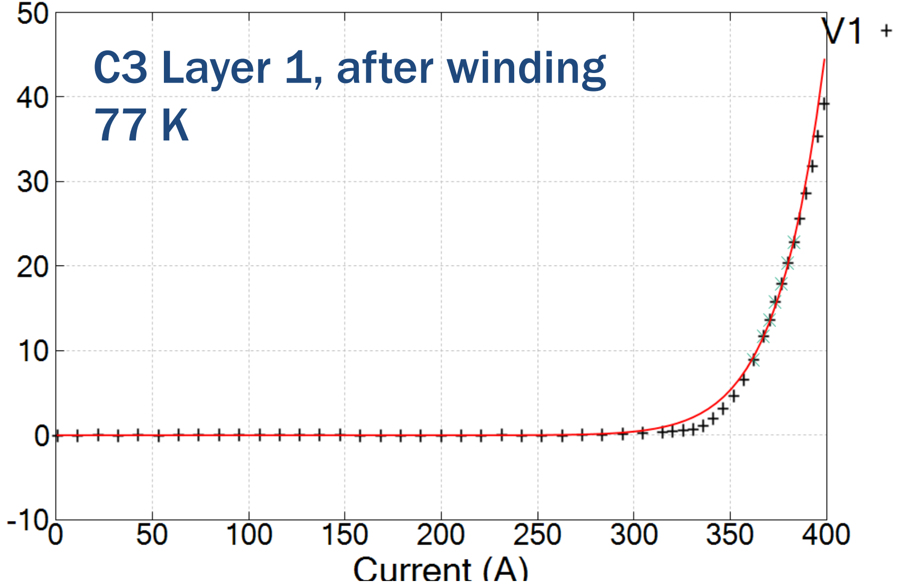


Image courtesy Paolo Ferracin

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

What do we need to make C3 by December 2024?

- Continued access to key staff
  - Contract ends in May 2024; working with the lab to keep the door open
  - Significantly reduce the risks of C3 delivery

- Make the aluminum shell in May 2024, $7 k

- *If* C3 generates a decent field, make and install an iron yoke

…, and some good luck

ACT recently improved CORC® conductor performance – Opportunities for next magnets

- Reduce the bend radius from 30 to 20 mm for 30-tape CORC® wire
  - 2 mm wide tape, 30 μm substrate
  - 3.8 mm diameter
  - Can enable several insert options for the study of hybrid magnets, see Paolo's talk and Reed's talk

- Double the current-carrying capability from CORC® wire to cable
  - 32 x 4 mm wide tape, 30 μm substrate, 40 mm target bend radius
  - 5.9 mm diameter
  - Can enable 10 T dipole field in a muon-collider relevant aperture

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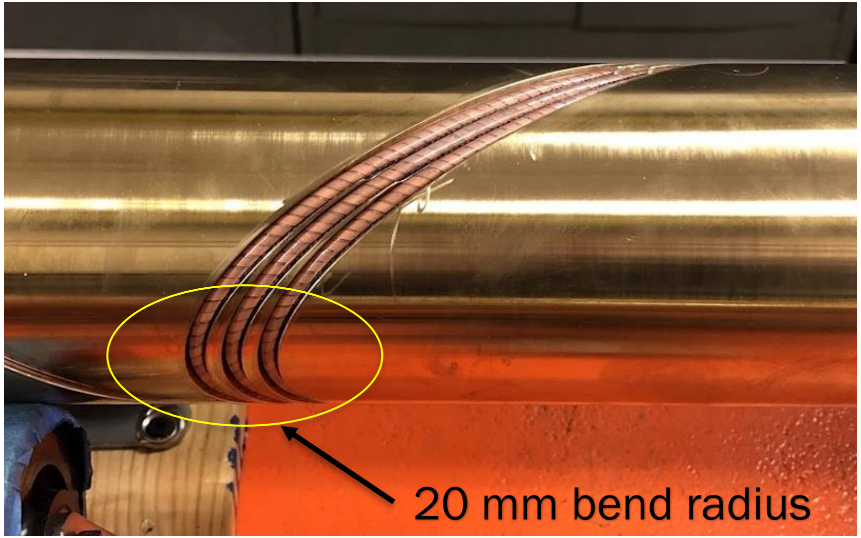
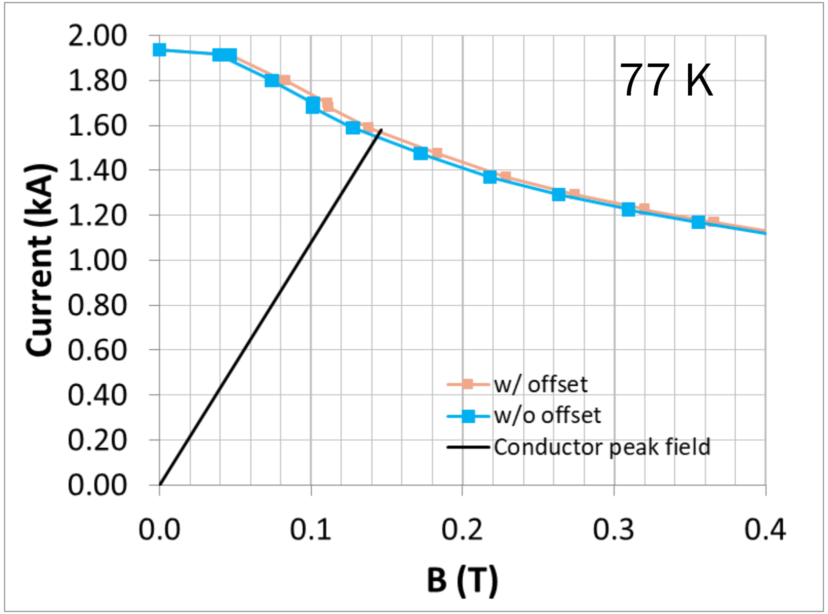
Supported by HEP SBIR Phase I

We tested the bending performance of the new CORC® wire by winding a 3-turn CCT coil

- Compared the wire performance before and after winding
- 3-turn CCT coil with six bends, each with a bend radius of 20 mm along the wire longitudinal axis
- Winding tension 25 N



Expected coil performance is 82% of the wire I_c before winding, due to the increased self-field



- Consider only the field component that is transverse to the longitudinal axis of the wire
- ~ 145 mT self-field reduces 18% of I_c
- Expected performance: 1553 – 1578 A at 40 μV criterion

Measured coil I_c is 1514 A, 96% of the expected performance, consistent with ACT's other measurements

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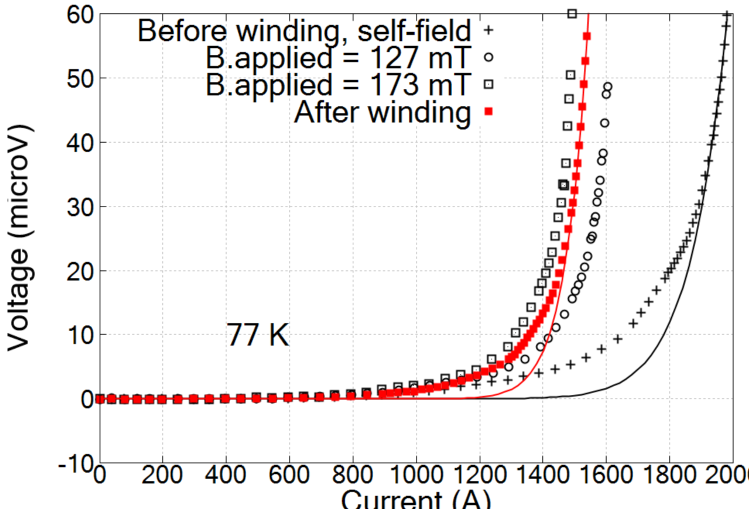
- *n* value 21.3



- **ACT measurements of similar wires**
  - 90% retention of a hair-pin sample at 20 mm bend radius
  - 100% retention of a sample bent into a COMB structure at 30 mm bend radius

Conductor needs for hybrid dipole magnet

- Make inserts for the 90-mm aperture CCT5
  - Gain early feedback on insert fabrication, test and performance, especially the impact of Lorentz forces on conductors
  - Get ready for CCT6, 120 mm aperture

- 170 m long CORC® wire, $420 k
  - 30 x 2 mm wide tape, 30 μm substrate, ~ 3.8 mm conductor OD, 20 mm bend radius
  - 65 m, 4-layer *circular* cct
  - 55 m, 4-layer *elliptic* cct
  - 50 m, uni-layer insert

Continue engaging competent small business

Conductor needs for 10 T dipole magnet

- Higher fields beyond Nb_3Sn is what matters

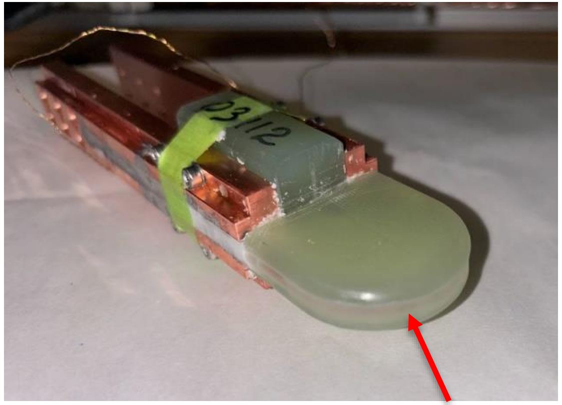
- 10 T is a stretch goal after 5 T
  - A steppingstone towards 15 T
  - 20 T hybrid needs it too

- 20 m long CORC® cable, $80 k
  - 32 x 4 mm wide tape, 30 μm substrate, ~ 5.9 mm conductor OD, 40 mm target bend radius
  - Evaluate conductor performance and fabrication of subscale elliptic CCT coils

We are also developing technology using STAR® wires

- Revised the sample holder for better wax impregnation
- Wax impregnation of five STAR® wires showed less than 1% degradation in critical current
- Next to try filled-wax. Samples will be tested at Grenoble in June up to 30 T and 4 kA.
- Contact José Luis for more details

AMPeers

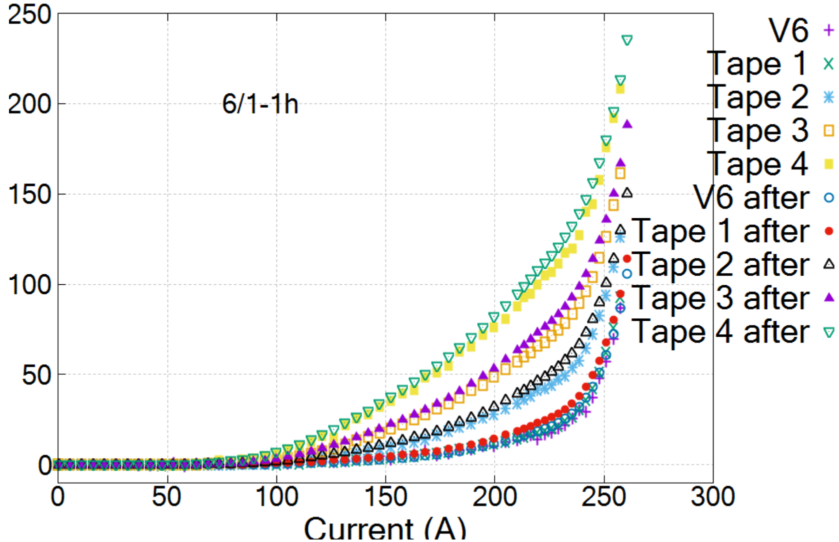


STAR® wire embedded in wax

Supported by HEP SBIR Phase II

STAR® wire retained 95% of I_c after being manually cabled into 6-around-1 configuration

- Four tapes, each 2 mm wide. 0.81 mm diameter Cu core. 1.3 mm wire OD
- Next to verify the retention in a cable made by a machine



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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; FNAL: Maria Baldini, Steve Gourlay, Vadim Kashikhin, Vito Lombardo; Ian Pong, Reed Teyber

Exciting time for collaboration and collective learning

- The working group has been working very well, exchanging results, ideas and sometimes complaints
- We still certainly miss the voices from ASC/FSU
- Thank you to Vadim for taking the lead of the REBCO working group

Higher fields or else

- We started making C3 aiming at the 5 T milestone, still much to learn
  - Access key staff to reduce the risks of delivery
- Order 170 m long CORC® wire and 20 m long cable, $500 k
  - To fuel the hybrid front
  - To get to 10 T as the next stretch goal
- Continue engaging competent vendors. Help them help us reach 20 T