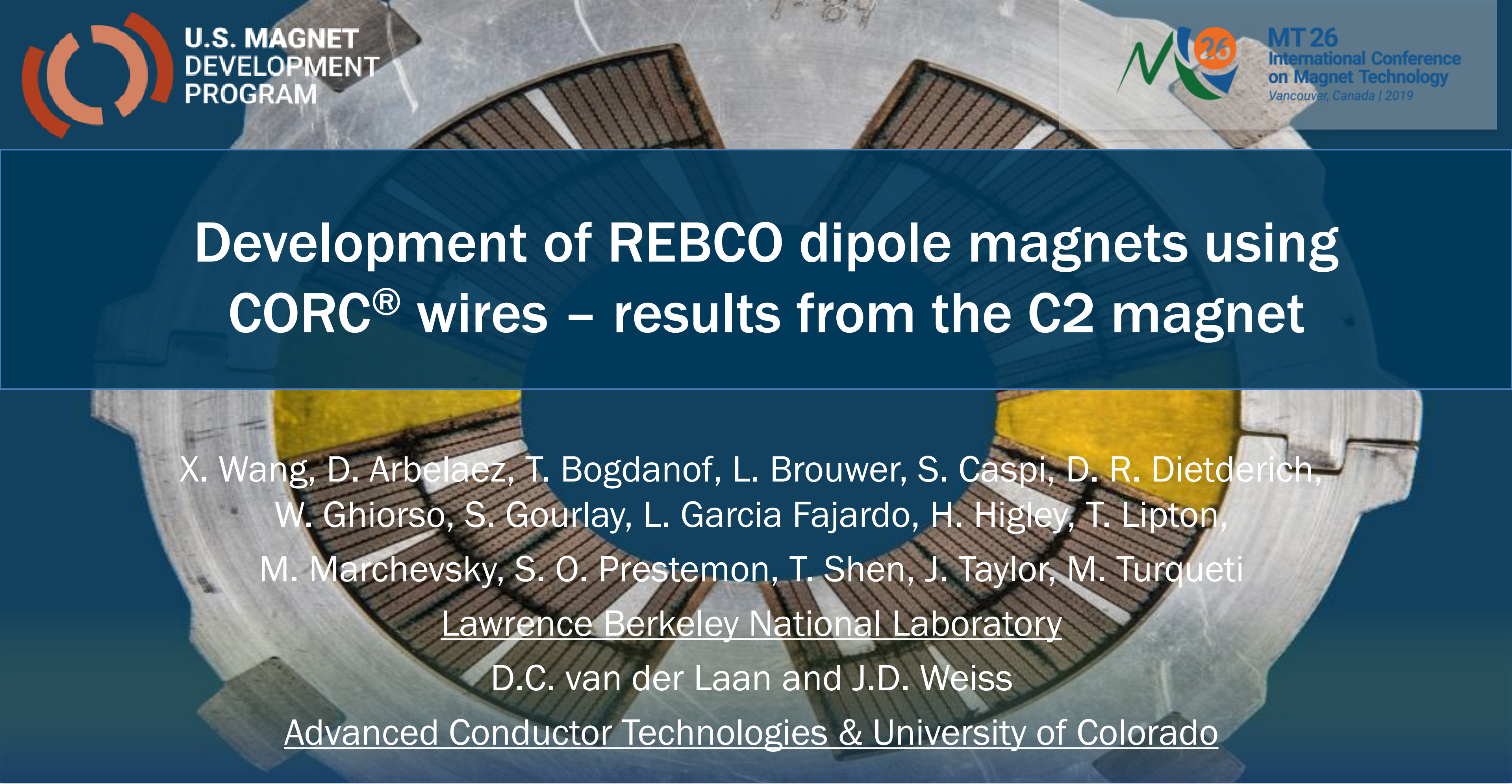


U.S. MAGNET
DEVELOPMENT
PROGRAM

MT 26
International Conference
on Magnet Technology
Vancouver, Canada | 2019

Development of REBCO dipole magnets using CORC® wires – results from the C2 magnet

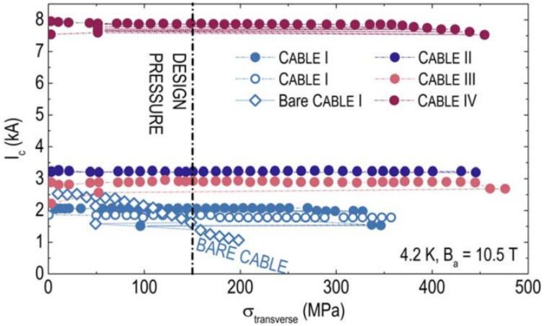
X. Wang, D. Arbelaez, T. Bogdanof, L. Brouwer, S. Caspi, D. R. Dietderich,
W. Ghiorso, S. Gourlay, L. Garcia Fajardo, H. Higley, T. Lipton,
M. Marchevsky, S. O. Prestemon, T. Shen, J. Taylor, M. Turqueti
Lawrence Berkeley National Laboratory
D.C. van der Laan and J.D. Weiss
Advanced Conductor Technologies & University of Colorado

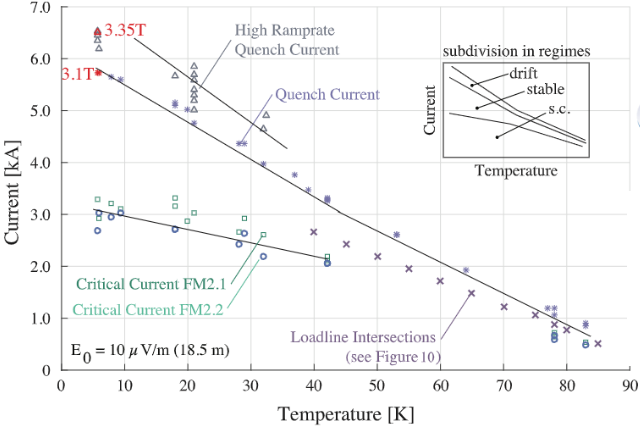
REBCO can enable 20+ T accelerator magnets: a new paradigm for magnet technology

- **The community has achieved significant progress**
    - **Record J_e of 5000 A/mm^2 at 4.2 K, 15 T, Univ. Houston**
    - **40 T total dc field with non-insulation insert, ASC/NHMFL**

- **EuCARD2 successfully demonstrated accelerator-quality REBCO dipole magnets using Roebel cable withstanding 350 MPa transverse stress. ARIES will double the conductor performance and reduce cost**

- **The USMDP also set a near-term goal to reach 5 T in HTS dipole magnets**

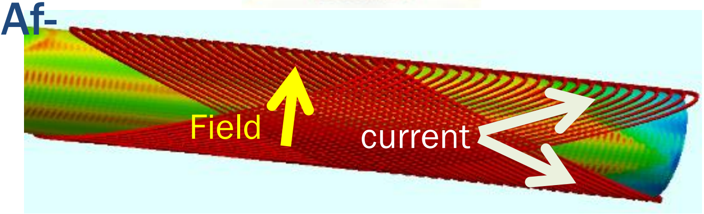




We are developing CORC® CCT dipole magnet technology to address key driving questions

- How to make dipole magnets using REBCO conductors?
- What is the magnet performance and required conductor performance?
- What issues limit the magnet performance? How to address them?
- What are the implications for the HEP community?

- CORC® wire is a promising HEP cable option
  - Isotropic for magnetics and mechanics
  - High current (~10 kA) at small bending radius (30 mm)
- CCT design is ideal for insert [D. Arbelaez, Thur-Af-Or24-05]
  - Low conductor stress
  - Excellent geometric field quality



Together with industry partners, the USMDP chooses a systematic and phased approach towards 5 T and beyond

- Develop dipole magnets with increasing fields and complexities
  - C1, 1.2 T at 2017. Demonstrated initial concept
  - C2, 2.9 T at 2019. Demonstrated metal mandrel
  - C3, target 5 T at 2020. Demonstrate magnet technology towards higher fields
  - We are formulating roadmaps beyond 5 T

U.S. MAGNET
DEVELOPMENT
PROGRAM

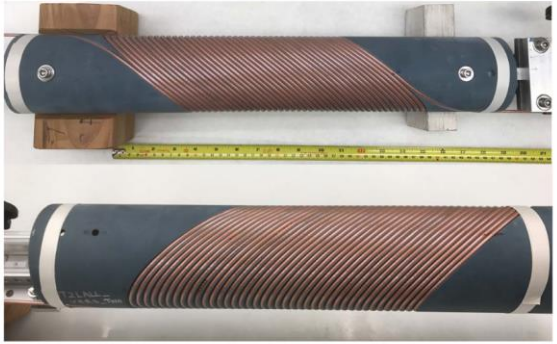
Advanced Conductor Technologies LLC
www.advancedconductor.com

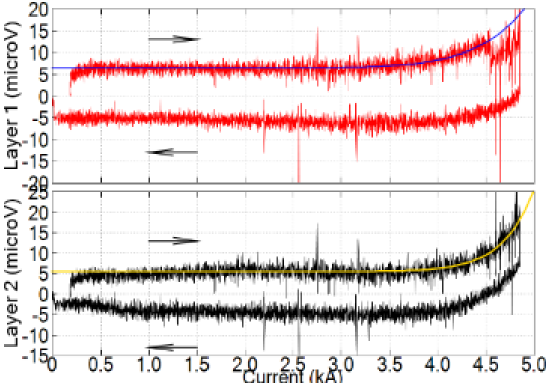
SuperPower Inc.
A Furukawa Company

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

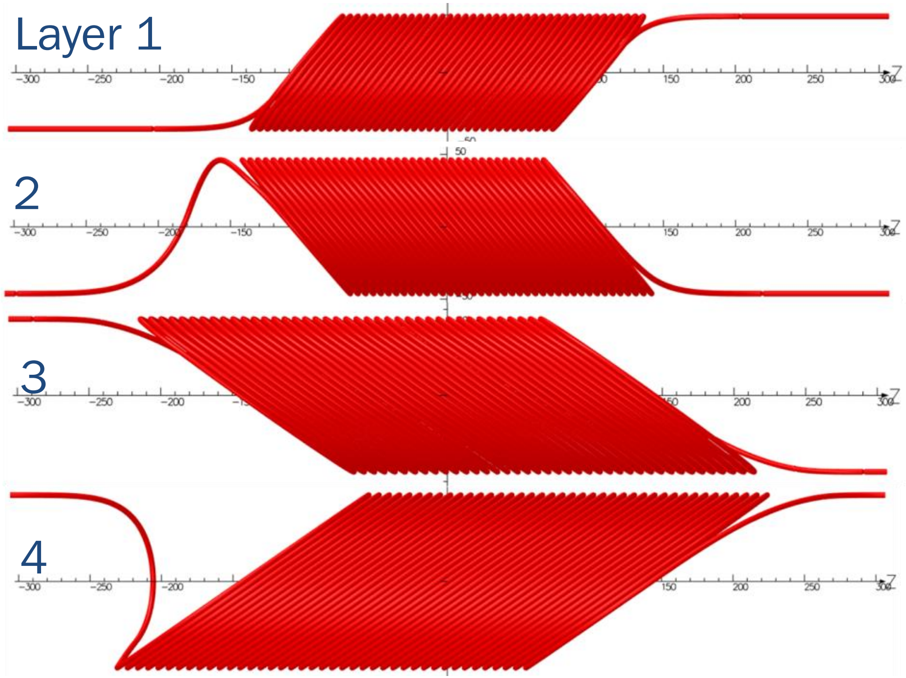
The success of the 2-layer C1 laid a solid foundation for C2

- Successfully wound 30 m long CORC® wire
- Developed praying-hand joints with 10 – 100 nΩ joint resistance
- Detected voltage rise and showed high thermal stability at J_e of 620 A/mm^2
- Generated 1.2 T dipole field at 4.2 K with printed plastic mandrels





C2 aims to generate 3 T with longer conductors, metal mandrels and Stycast to constrain the conductors



Parameters	value
Tilt angle, L1/2	50°
Tilt angle, L3/4	35°
Min. bending radius	30 mm
Transfer function	0.47 T/kA
Target dipole field	3 T

C2 used the state-of-art 30-tape CORC® wire to boost the magnet current

- SuperPower tapes: 2 mm wide, 30 µm substrate, 5 µm surrounded Cu stabilizer
- Layer 4 wire contains high- and low-pinning tapes – conductor grading
- Measurements at ASC/FSU detected deviation from expected tape performance, allowing the quick feedback to SuperPower and wire design at ACT

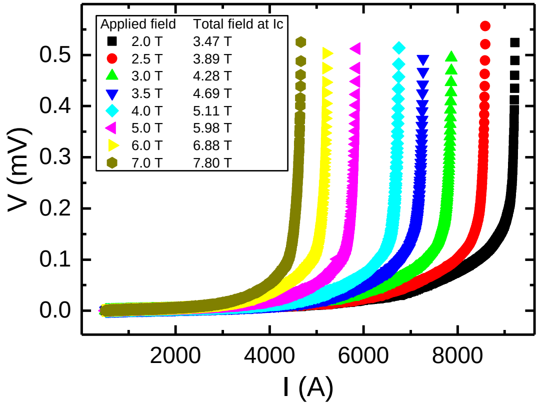
Wire ID	Length (m)	Wire OD (mm)	Average tape Ic (A) 77 K, SF	Peak field on wire (T)	Min bend radius (mm)
C2-L1	18	3.80	70	3.6	30
C2-L2	20	3.80	70	3.6	35
C2-L3	24	3.77	69	3.2	30
C2-L4	28	3.67	57	2.8	35

Advanced Conductor Technologies LLC
www.advancedconductor.com

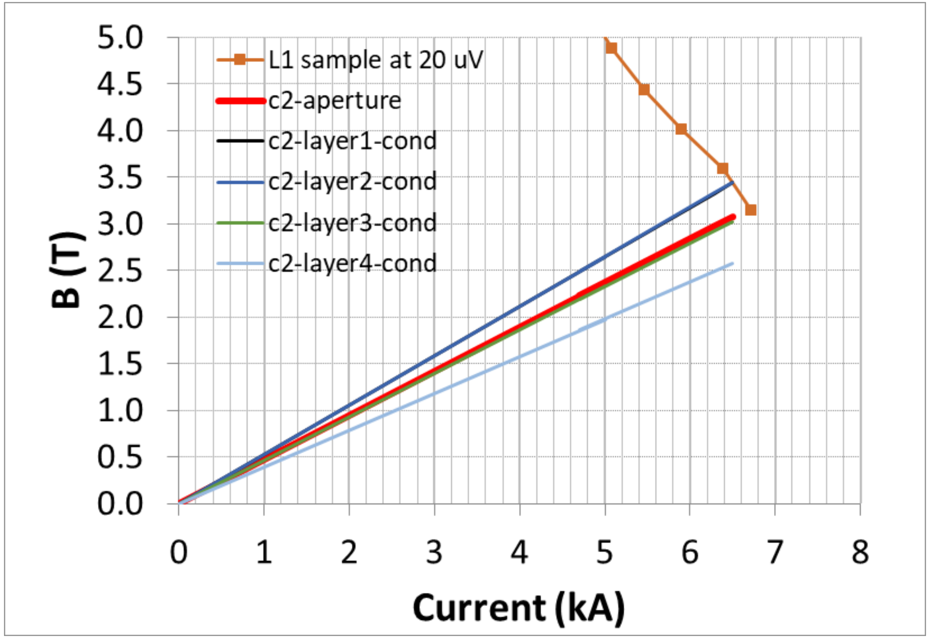
SuperPower Inc.
A Furukawa Company

We expect C2 to reach 3 T at 4.2 K based on the in-field performance data of a Layer 1 sample

- V(I) transition of a Layer 1 sample measured by ACT at different background fields
- Bending radius close to C2



Jeremy Weiss and Danko van der Laan



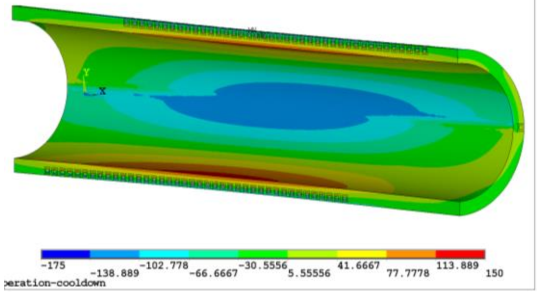
U.S. MAGNET
DEVELOPMENT
PROGRAM

Mechanical analyses confirm that C2 and beyond needs a metal mandrel

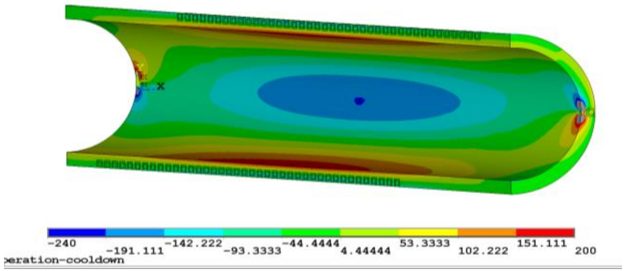
- Mandrel stresses of 150-200 MPa is too high for 3D printed Bluestone that was used for C1 mandrel

Lucas Brouwer

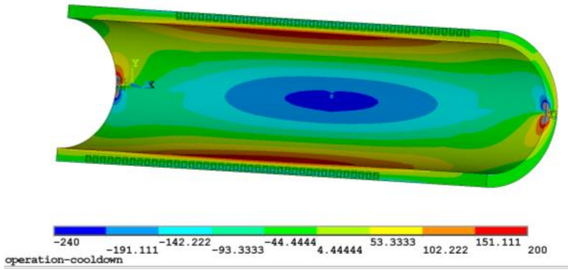
Bluestone



Aluminum



Aluminum Bronze

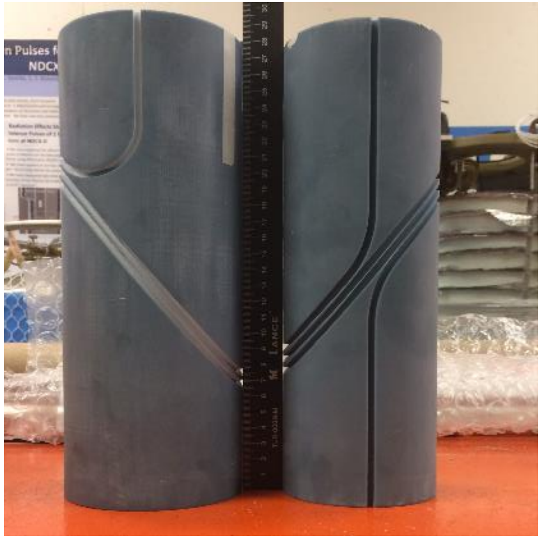


- C2 mandrel used Aluminum Bronze to leverage the experience of the CCT program at LBNL [D. Arbelaez, Thur-Af-Or24-05]

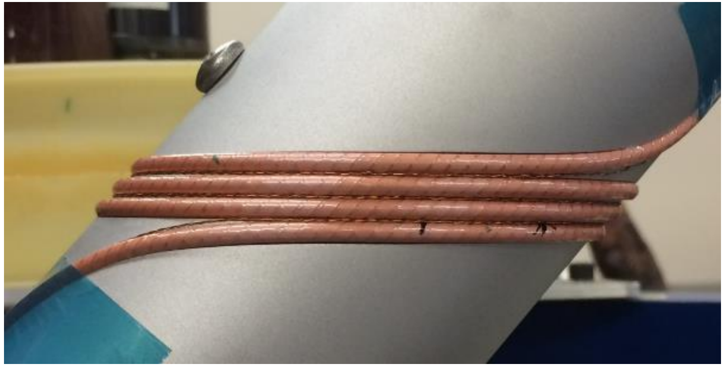
We reduced groove depth on mandrels as an interim solution to continue the magnet development

Laura Garcia Fajardo
Bill Ghiorso, Hugh Higley

- Full-depth radial groove: Straightforward to machine but challenge to wind with tension
- We will continue investigating this



Meanwhile, we used half-depth groove to help with winding



We used a systematic and progressive approach to develop and understand the fabrication technology for C2

3-turn

Test at 77 K → Wind → Test at 77 K → Apply Stycast → Test at 77 K

Assembly → Test at 77 K → Test at 4.2 K

40-turn

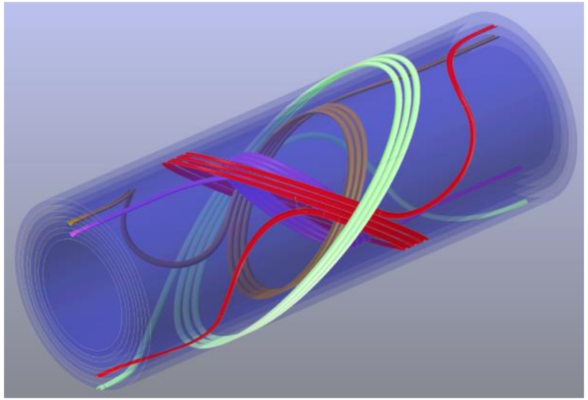
Layer 1 → Wind → Test at 77 K → Apply Stycast → Test at 77 K

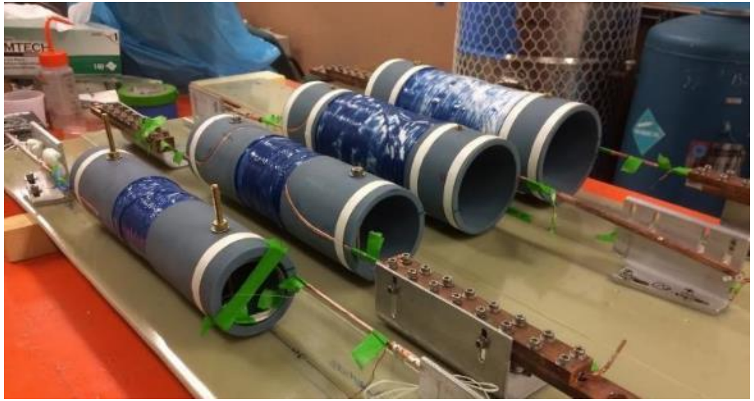
Layers 2 – 4 → Wind → Apply Stycast → Test at 77 K

Assembly → Test at 77 K → Test at 4.2 K

We learned several important things by developing 3-turn models and addressed issues not foreseen

- Used 30-tape prototype wire, 3.81 mm diameter
- Developed fabrication techniques (winding, joints, assembly, applying Stycast, …)
- Modified exit lead design to reduce conductor handling
- Co-wound voltage tape wires covering all turns





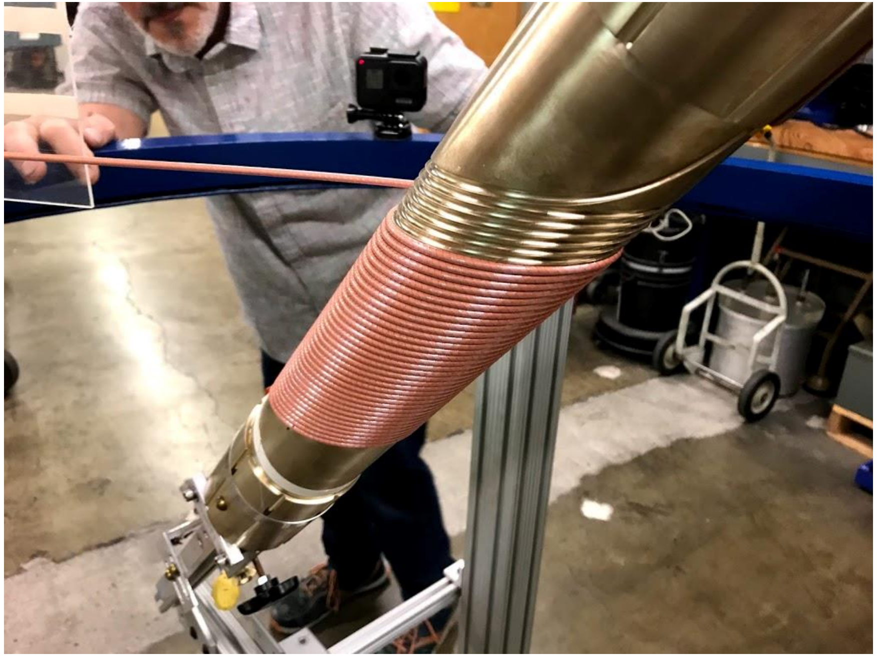
… and also gained further confidence to develop C2

- **Systematic tests on six coils showed negligible impact of Stycast (< 3% I_c reduction)**

Data wrt I_c before winding. 10 μV, 77 K, self-field

	After winding	After stycast	Change
BS-Layer 1	n/a	-29%	
BS-Layer 2	-30%	-33%	-3%
BS-Layer 3	-28%	-31%	-3%
BS-Layer 4	-30%	n/a	
AB-Layer 1	-12%	-14%	-2%
AB-Layer 3	-23%	-24%	-1%

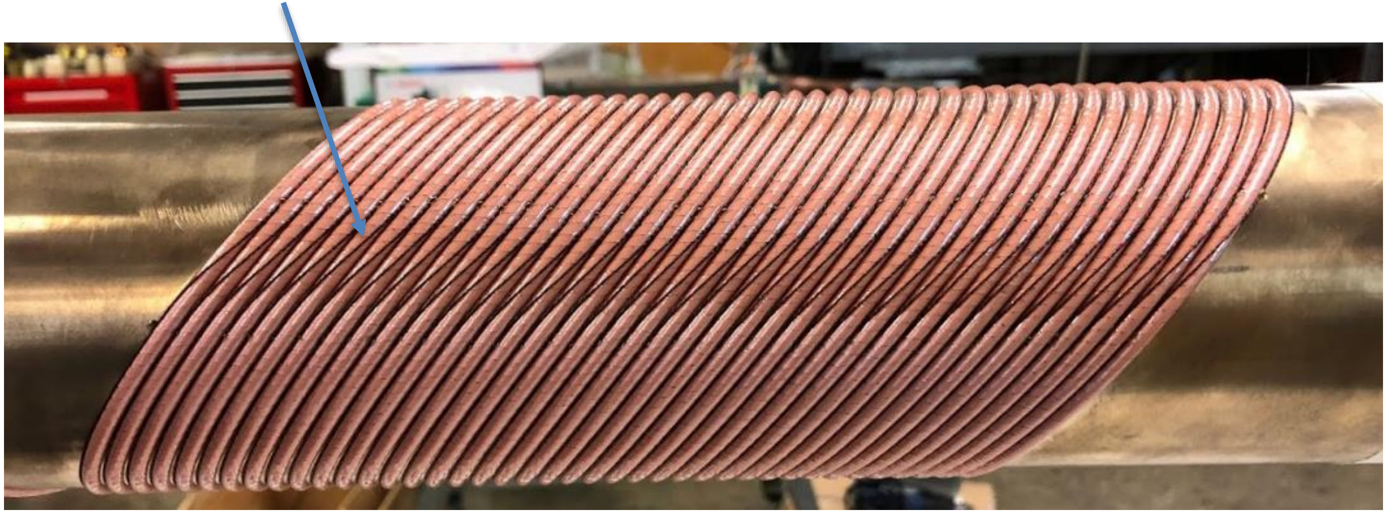
So we started



Winding with Hugh’s winding table

Mandrel designed by Bill Ghiorso and machined by Maxwell Maruszewski

Co-wound voltage-tap wires with the conductor to reduce the inductive pickup during tests



Voltage tape wires

Painted Stycast 2850MT after winding to constrain the conductors

Hugh Higley

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

We measured the transport performance of each layer at 77 K before making the next layer

Hugh Higley and
Timothy Bogdanof

Few months layer, four layers of C2 oriented for a dipole configuration

Terminals

Aluminum Bronze mandrel

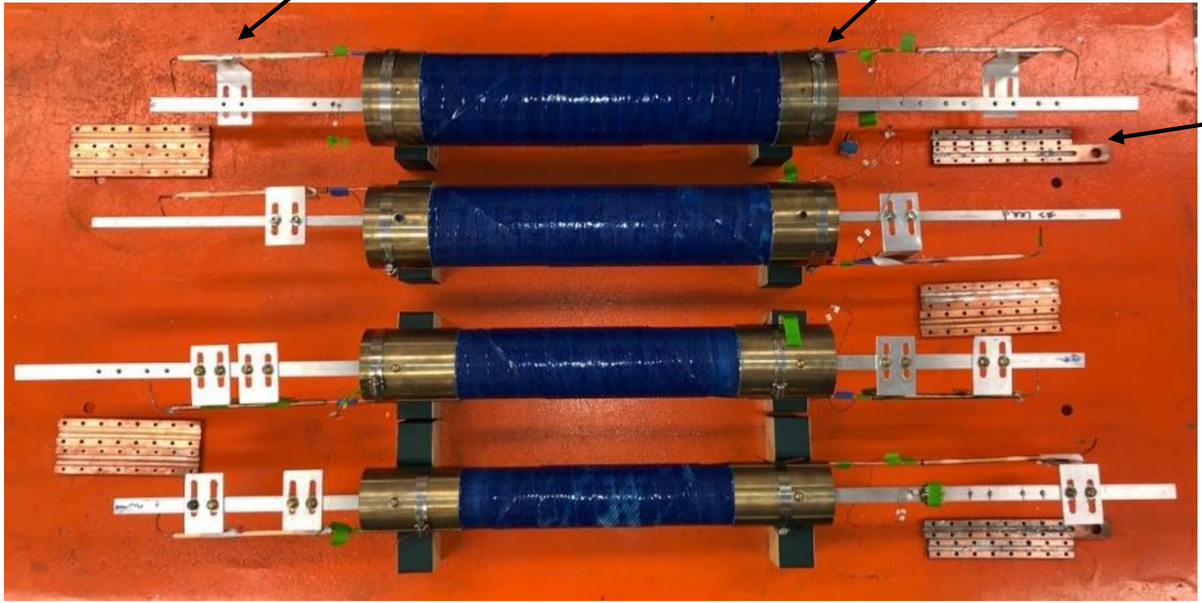
Cu blocks covering terminals

Layer 4

3

2

1

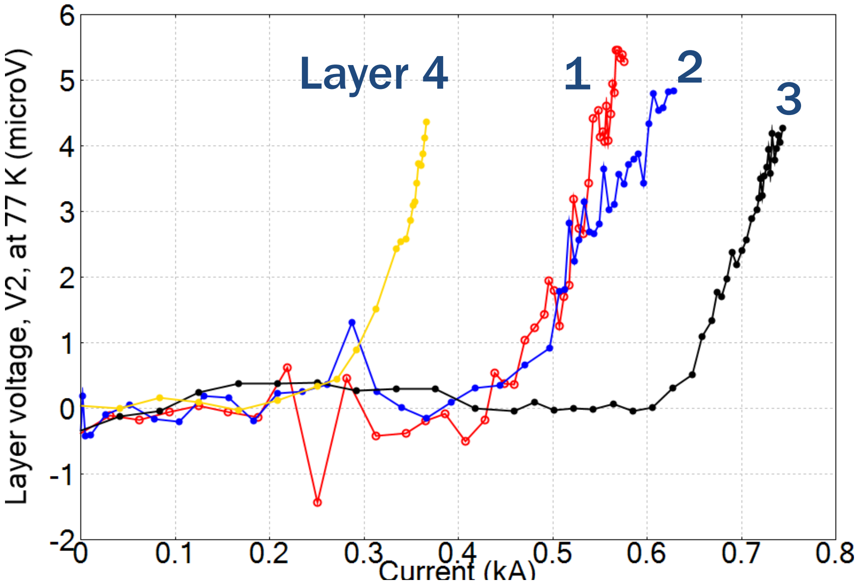


Assembly and insert into the cryostat

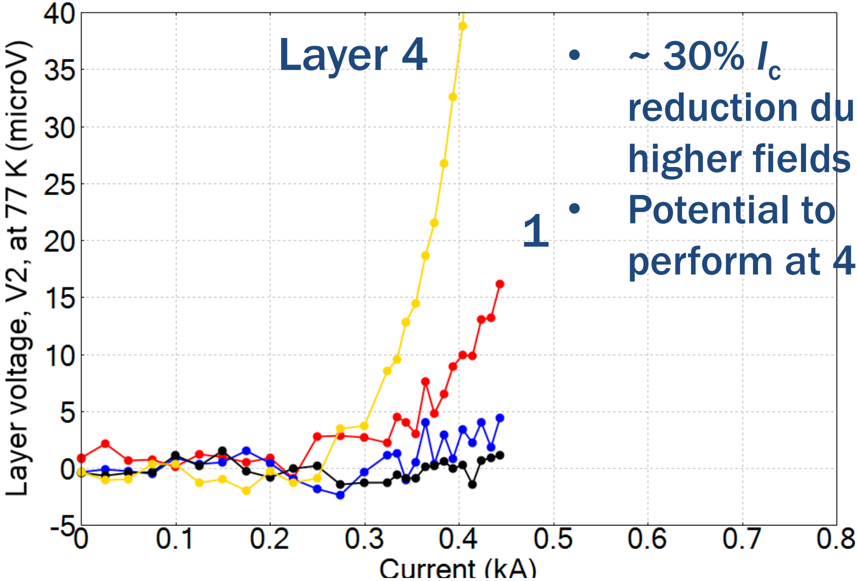
Prof. D. Larbalestier at ASC/NHMFL loaned the cryostat
R. Hafalia, R. Lee, T. Lipton, and L. Wang developed the adaptor

Layer 4 showed lower performance than the other three layers at 77 K but get closer to Layer 1 after assembly

Before assembly

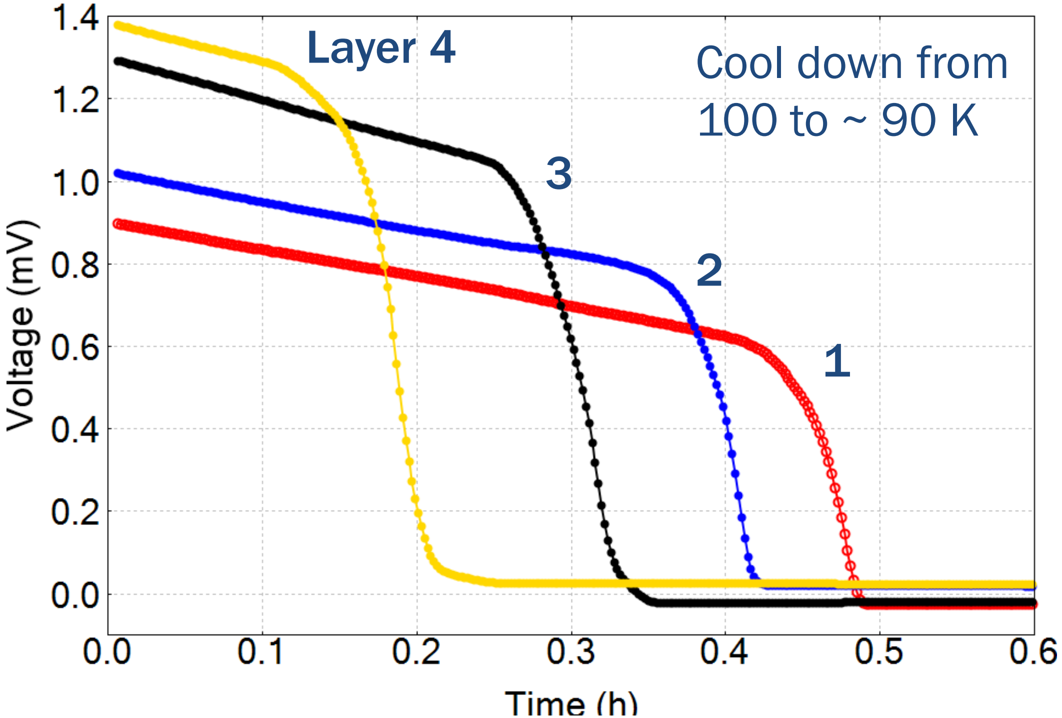


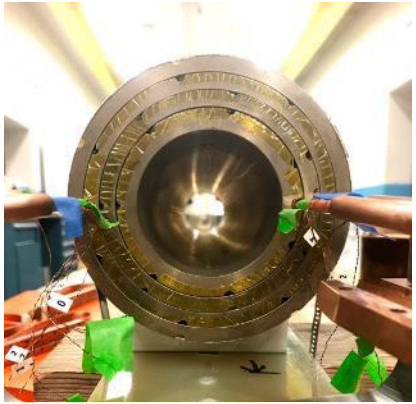
After assembly



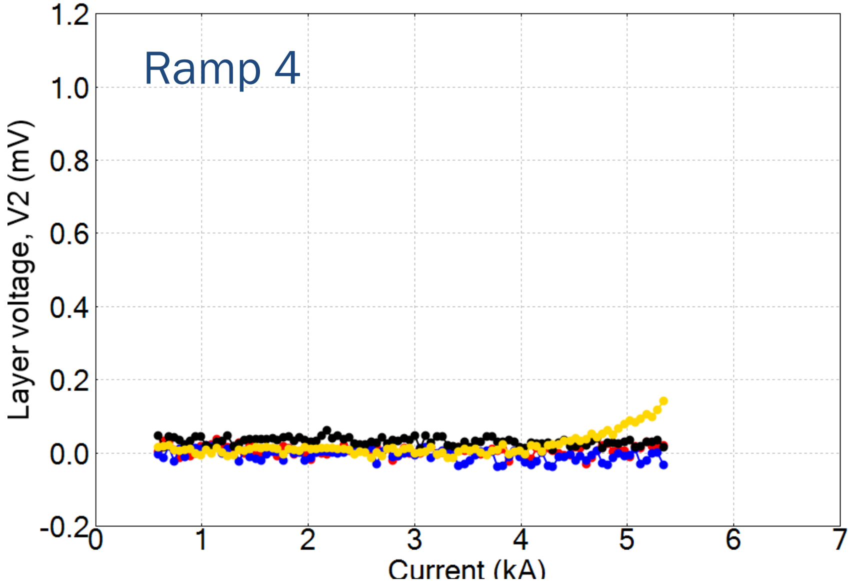
- ~ 30% I_c reduction due to higher fields
- Potential to perform at 4.2 K

Layers became superconducting in sequence, indicating cooling from outer to inner layers



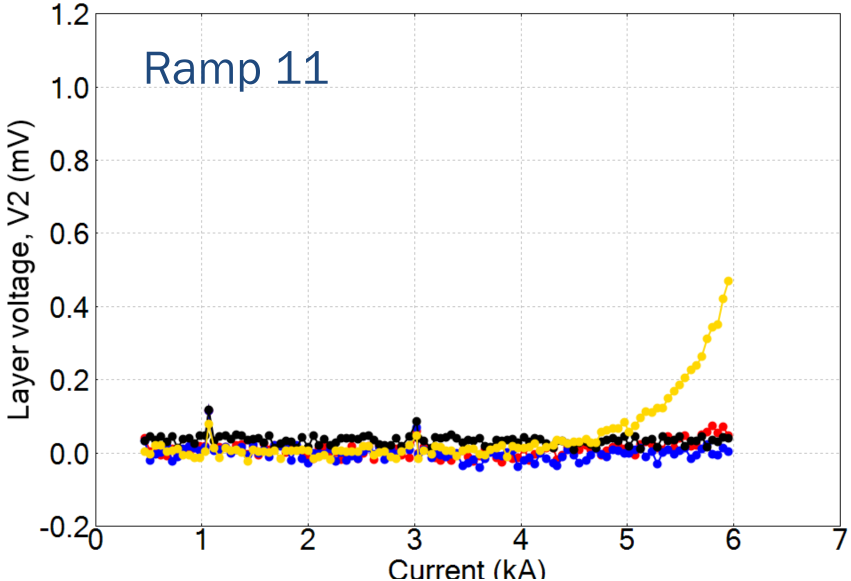


A controlled increase in the maximum current allowed us to probe the true performance of C2



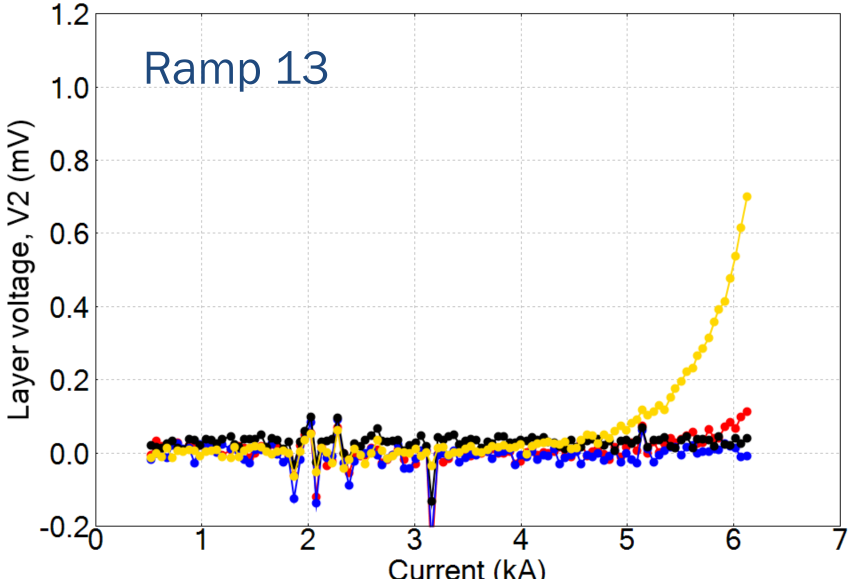
- Increasing the threshold for quench detection

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



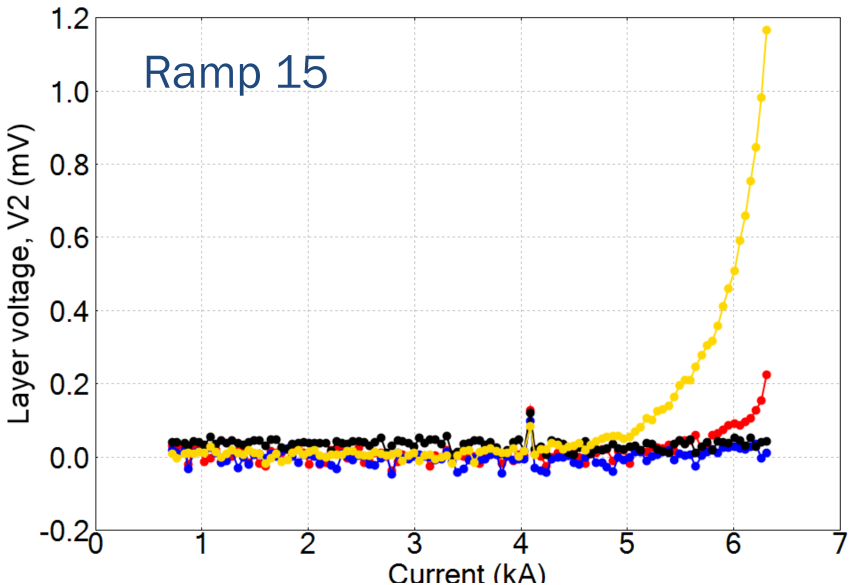
- Increasing the threshold for quench detection

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



- Increasing the threshold for quench detection

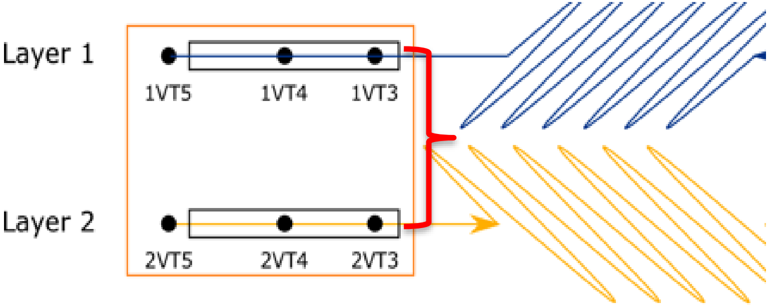
A controlled increase in the maximum current allowed us to probe the true performance of C2

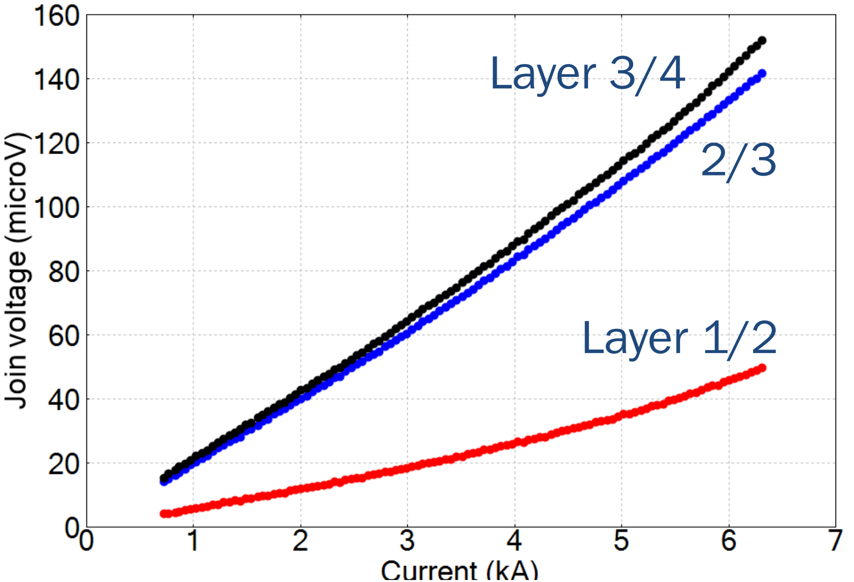


- Increasing the threshold for quench detection
- Reproducible V(I) transition between ramps
  - n = 13.1 for Layer 4
  - n = 6.8 for Layer 1, consistent with the behavior of short sample measured at ACT
- Wire J_e = 595 A/mm^2 at 6.3 kA

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

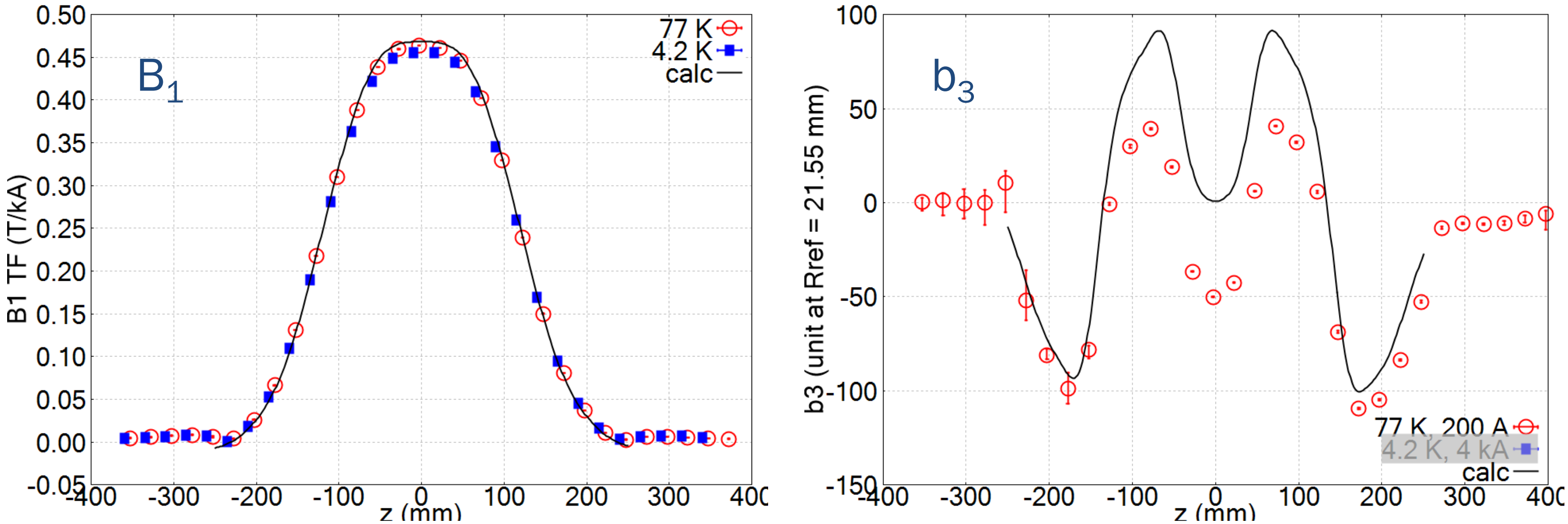
Joint voltage is measured across the voltage taps in each layer





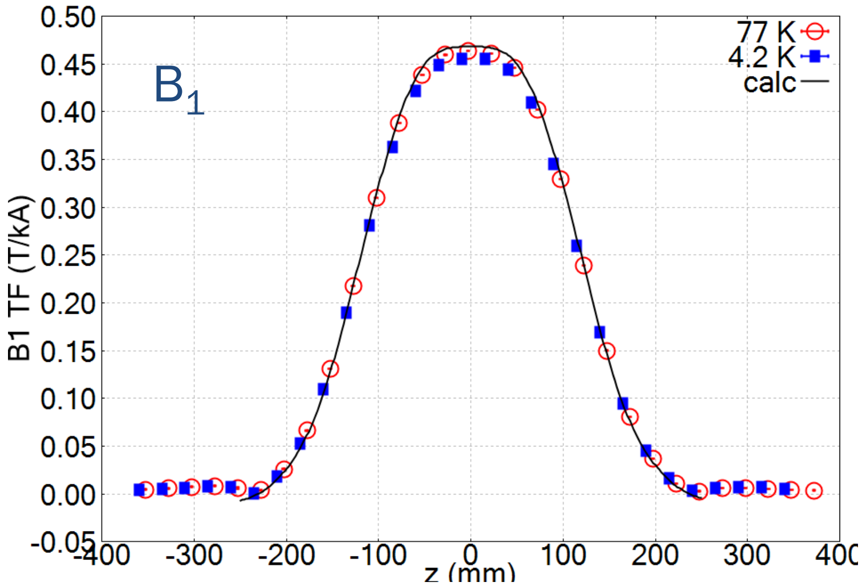
We measured the field quality of C2 and observed strong persistent-current effects at the magnet center

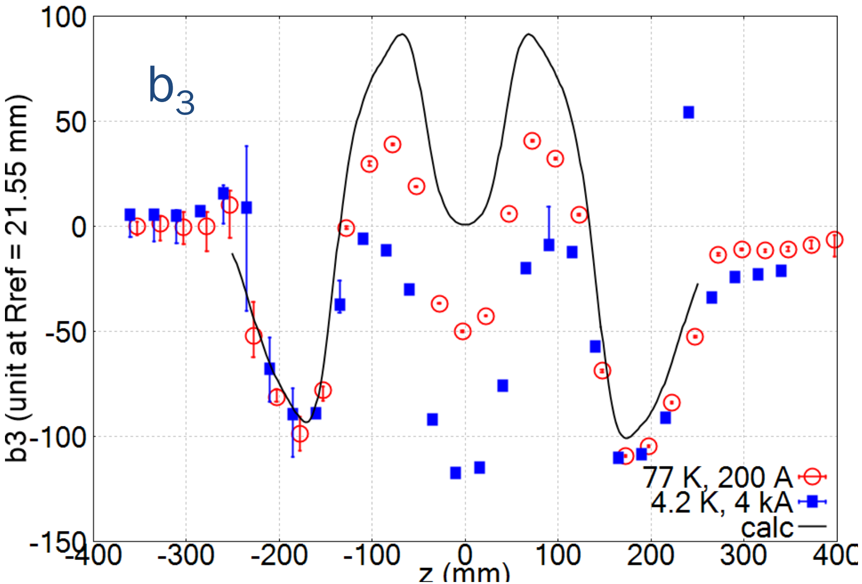
- Measurement with a 100 mm long rotating coil developed by J. DiMarco at FNAL



Stronger effects at 4.2 K – 30 tapes with large J_c

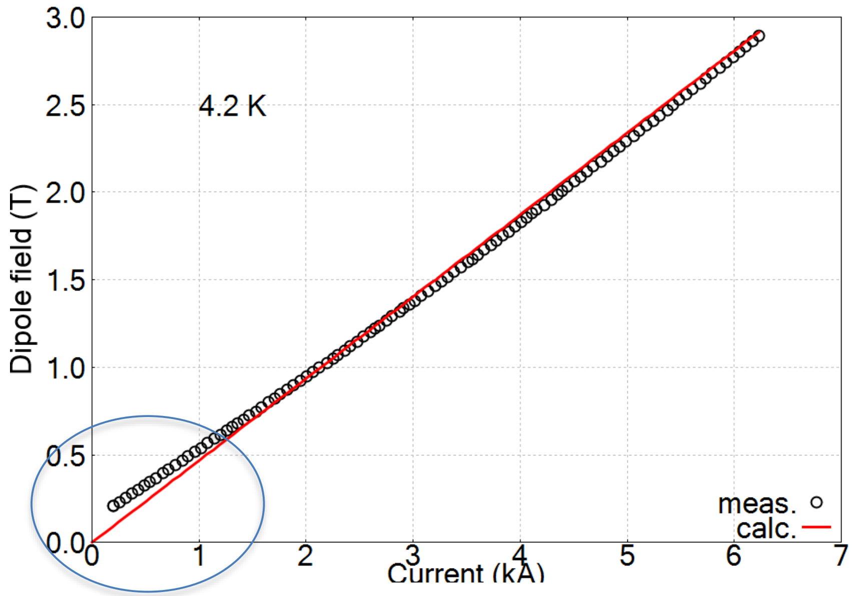
- Cory Myers from OSU will present detailed field quality study, Thu-Mo-Po4.07-05





Can we use the persistent-current effects to identify the normal zones and transition locations?

Ramp 19, measurement at the magnet center

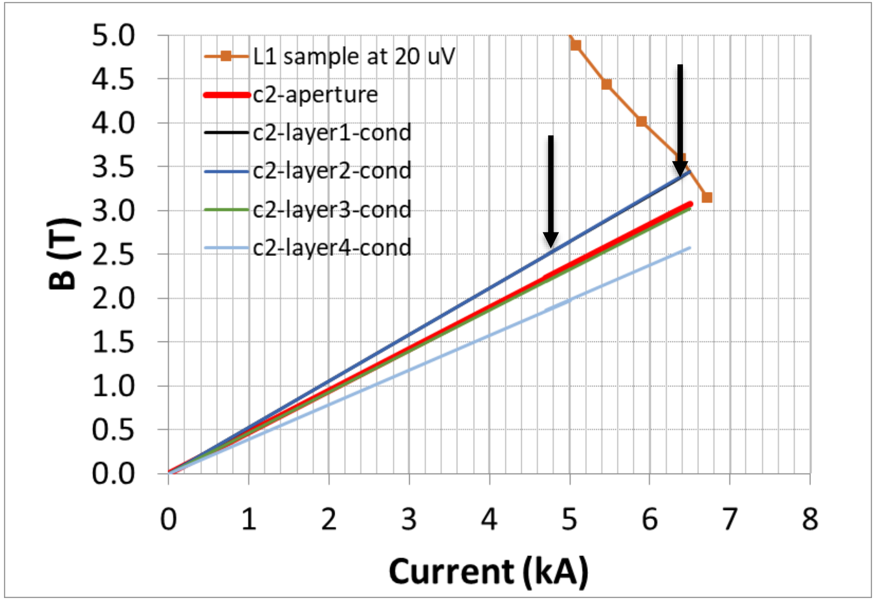


- Temperature can erase persistent currents
- Local thermal history due to transitions may leave a signature in magnetization → PC effects at the center may indicate the normal zones are outside the center

- Will test the idea at 77 K

We close the chapter on C2 with a good result

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



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

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

We start the chapter on C3 to address the challenges to reach 5 T and beyond

- USMDP is progressing consistently with a phased approach towards 5 T for REBCO
  - C1, 1.2 T, demonstrated initial concept
  - C2, 2.9 T, demonstrated metal mandrel and supporting conductor with Stycast
  - C3 to demonstrate 5 T magnet technology and higher Lorentz force

- Magnets continue desiring wires with smaller bending radius and higher performance
  - 20 µm thick substrate as the next target
  - Narrower tapes and higher pinning at 4.2 K

- More magnet results are critical and coming – ASC/NHMFL, BNL, CERN, FNAL
  - Great opportunity to collaborate and push together

A great team effort

- Team at LBNL – H. Higley, T. Bogdanof, B. Ghiorso, M. Maruszewski, S. Prestemon
  - D. Arbelaez, L. Brouwer, S. Caspi, D. Dietderich, L. Garcia Fajardo, S. Gourlay, R. Hafalia, R. Lee, A. Lin, T. Lipton, M. Marchevsky, S. Prestemon, T. Shen, L. Wang, J. Taylor, R. Teyber, M. Turqueti

- Advanced Conductor Technologies LLC and DOE HEP SBIR programs – Danko van der Laan and Jeremy Weiss

- ASC/FSU for testing the samples for ACT with quick turn-around – D. Abraimov
- ASC for loaning a cryostat to test C2 – D. Larbalestier

- SuperPower Inc. – Drew Hazelton

- U.S. Magnet Development Program/Collaboration supported by DOE Office of Science, Office of High Energy Physics, Office of Fusion Energy Sciences
  - L. Cooley at ASC/FSU
  - J. DiMarco at FNAL
  - C. Myers and M. Sumption at OSU