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U.S. MAGNET DEVELOPMENT PROGRAM

Develop high-field accelerator magnet technology using REBCO CORC® conductors

Coated Conductors for Applications Virtual Workshop 2021

X. Wang
Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. MAGNET DEVELOPMENT PROGRAM

Acknowledgment

- U.S. Magnet Development Program
  - ASC: D. Abraimov, L, Cooley, A. Francis, X. Hu, D. C. Larbalestier
  - BNL: A. Ben Yahia, R. Gupta
  - FNAL: J. DiMarco, V. Kashikhin, V. Lombardo
  - LBL: D. Arbelaez, T. Bogdanof, L. Brouwer, S. Caspi, D. R. Dietderich, P. Ferracin, L. Garcia Fajardo, W. Ghiorso, S. Gourlay, H. Higley, T. Lipton, M. Marchevsky, S. Prestemon, T. Shen, J. Taylor, R. Teyber, M. Turqueti
- Advanced Conductor Technologies
  - D. van der Laan and J. Weiss
- SuperPower
  - D. Hazelton, Y. Zhang
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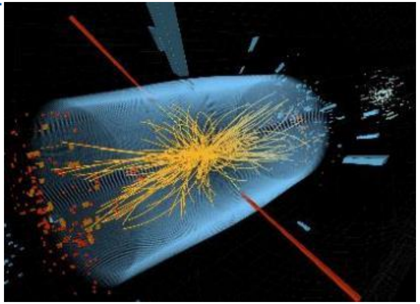
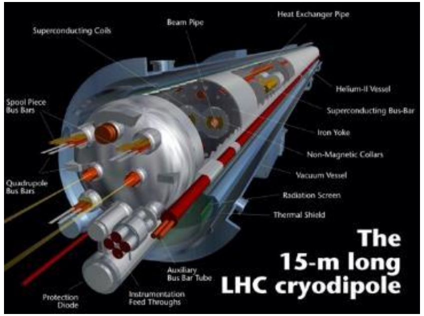
To study the origin of the Universe, circular colliders need stronger magnetic fields to collide particles at higher energy





Images courtesy of CERN

$$E \propto B \cdot R$$

Beam energy [TeV]

Dipole field [T]

Radius of beam trajectory [km]

Superconducting magnets are the only choice

- Bottura *et al*., Superconducting Magnets for Particle Accelerators, IEEE Trans. Nuclear Sci., 2016
- Rossi and Bottura, Superconducting Magnets for Particle Accelerators, Rev. Accelerator Sci. and Tech., 2012

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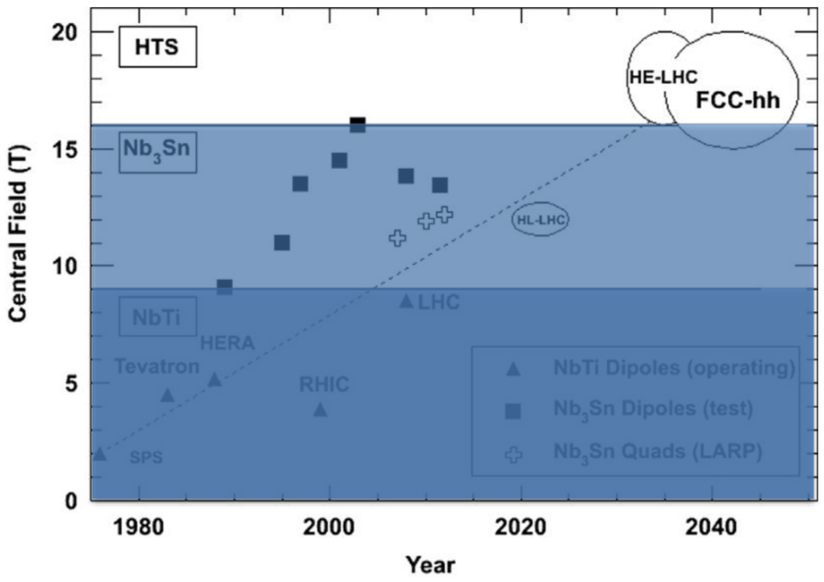
We need HTS to generate dipole fields beyond 16 T



Barletta *et al*., NIMA, 2014
Gourlay, NIMA, 2018

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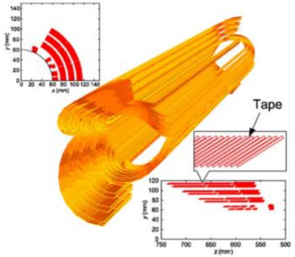
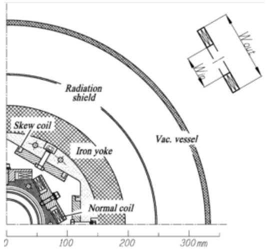
Various programs successfully developed accelerator magnets using REBCO tapes – examples from Japan, Korea and Russia

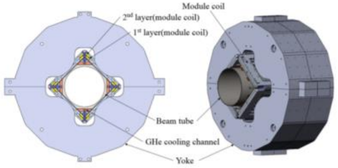
- Kyoto Univ., KEK, NIRS, Tohoku Univ., and Toshiba: saddle-shaped coil for medical applications



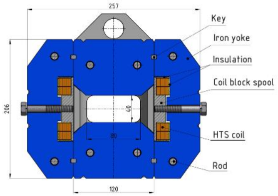
- KEK, NIMS and Fujikura: a REBCO sextupole magnet for superKEKB



- IBS, KERI, Changwon National Univ.: a REBCO quadrupole magnet used in a heavy-ion accelerator



- IHEP and SuperOx: a dipole magnet

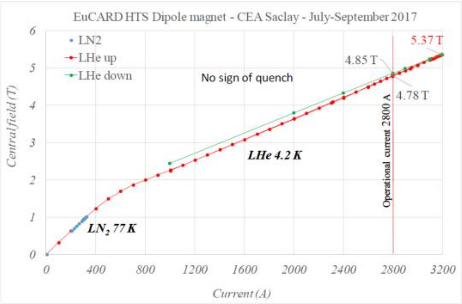


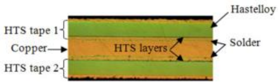
Takahashi *et al*., IEEE TAS, 2011, Tsuchiya *et al*., IEEE TAS, 2016, Hyun Chul Jo *et al*., IEEE TAS 2018, Bogdanov, SuST 2016

U.S. MAGNET DEVELOPMENT PROGRAM

The EuCARD and EuCARD2 collaborations, led by CERN, significantly advanced the high-field REBCO accelerator magnet technology based on multi-tape REBCO cable conductor

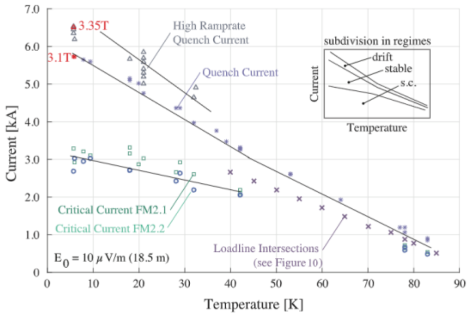
- EuCARD demonstrated a REBCO dipole field of 5.4 T at 4.2 K with a double-tape conductor





EuCARD

- EuCARD2 demonstrated accelerator-quality REBCO dipole magnets using Roebel cable, reached 4+ T dipole field at 4.2 K



EuCARD²

Rossi *et al.*, [IEEE TAS, 2018], Durante *et al.*, [IEEE TAS, 2018], van Nugteren *et al.*, [SuST 2018], Araujo *et al.*, [IEEE TAS, 2020]

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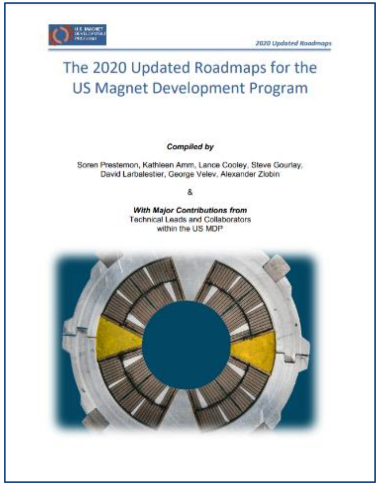
The U.S. Magnet Development Program, supported by DOE Office of High-Energy Physics, is addressing the technology needs for future high-field accelerator magnets, including REBCO

A long-range R&D program


2020 Updated Roadmaps

The 2020 Updated Roadmaps for the US Magnet Development Program

Compiled by

Soren Prestemon, Kathleen Amm, Lance Cooley, Steve Gourlay, David Larbalestier, George Velev, Alexander Zlobin

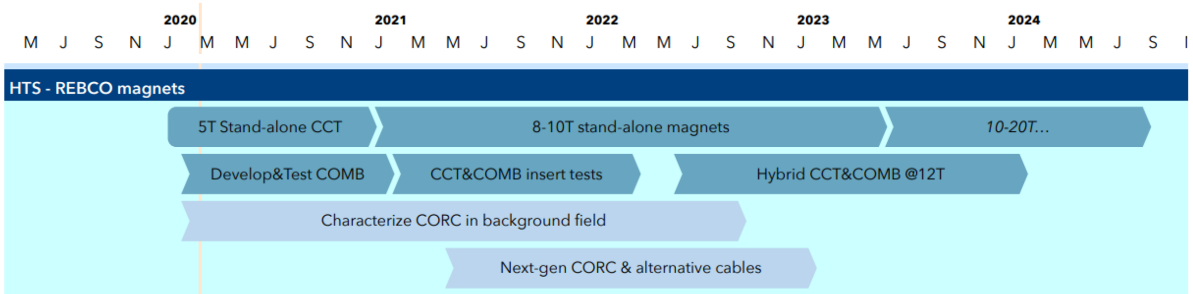
&

With Major Contributions from
Technical Leads and Collaborators within the US MDP

U.S. MAGNET DEVELOPMENT PROGRAM

The MDP is collaborating with industry and university partners to make REBCO magnets with increasing dipole fields in the coming years to address several driving questions

- How to make REBCO dipole magnets and what kind of multi-tape cables works best?
- What is the magnet performance and required conductor performance? What issues limit the magnet performance? How to address them?
- What is the maximum dipole field a REBCO magnet can generate?
- What are the impacts on magnet community and user community?



Overarching goal: REBCO dipole magnets to enable 20 T dipole field at LHe temperature

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We started using the round CORC® wires as a magnet conductor

- **CORC® wire is a promising conductor configuration**
  - *Multi-tape* cable. High current, O(10 kA), 4.2 K
  - Isotropic for magnetics and mechanics

- **Enabling characteristics of commercial tapes from SuperPower**
  - Thin substrate, 30 μm currently
  - Narrow tape, 2 mm currently
  - High I_c at 4.2 K, background fields

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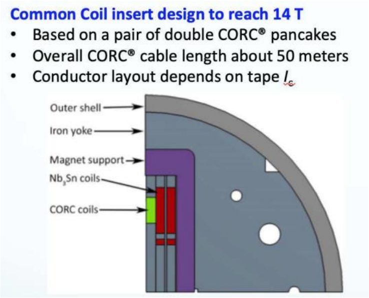
We are investigating three different dipole magnet concepts featuring stress management for high-field applications

Common coil

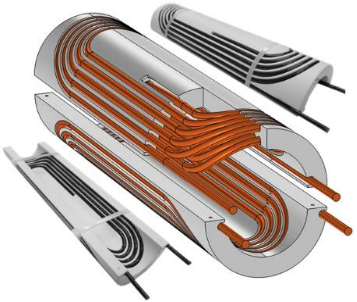
Brookhaven National Laboratory



van der Laan and Gupta EUCAS19, supported by a DOE STTR program

Conductor On Molded Barrel (COMB)

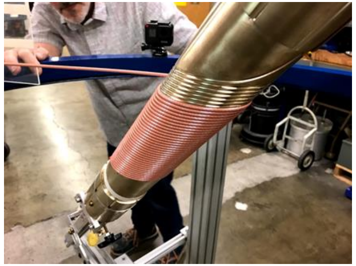
Fermilab



Kashikhin *et al.*, IPAC19

Canted cosθ (CCT)

BERKELEY LAB



Wang *et al.*, SuST, 2018

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Together with industry partners, we develop CORC® CCT magnets as a technology vehicle towards 5 T and beyond

- Develop dipole magnets with increasing fields and complexities
  - C1, 1.2 T, 2017. Demonstrated initial concept
  - C2, 2.9 T, 2019. Used metal mandrel with Stycast impregnation
  - C3, target 5 T at 2022. Develop magnet technology towards higher fields
  - We also have a road map beyond 5 T

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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

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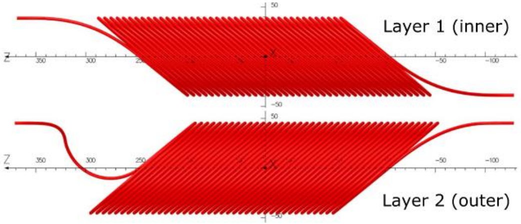
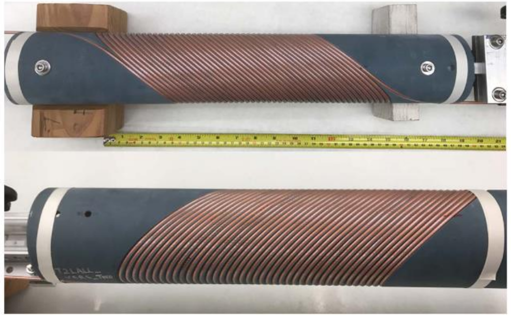
C1: first attempt to make a magnet with 15 m long CORC® wires





- 2016 – 2017
- 70 mm ID, 94 mm OD, 0.5 m long
- 1 T designed dipole field at 4.2 K at 4 kA

- 3D printed plastic Bluestone® mandrels
- No impregnation

- Magnet used 30 m long 16-tape CORC® wire
  - 16-tape architecture; prioritized low technical risk over high transport performance
  - 25 mm minimum bending radius
  - *1.3 km* of 2 mm wide SuperPower tapes with 30 µm substrates

Ref: SuST, 2019

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Careful winding and handling two magnet layers

Test winding with Cu dummy wire

A short video on the winding process

C1 magnet on testing header

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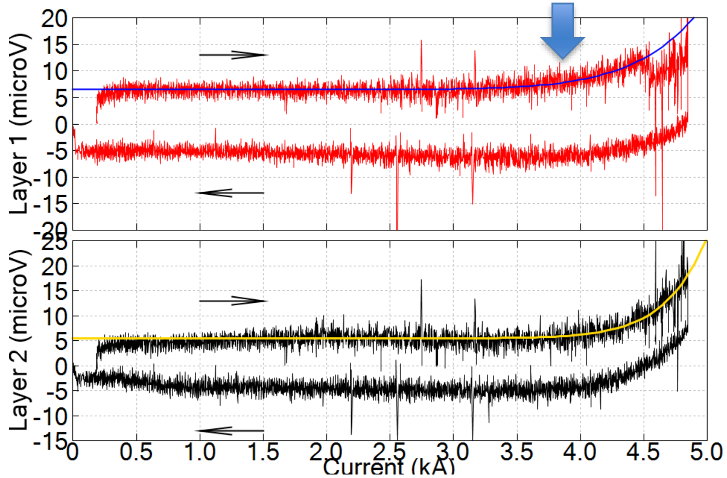
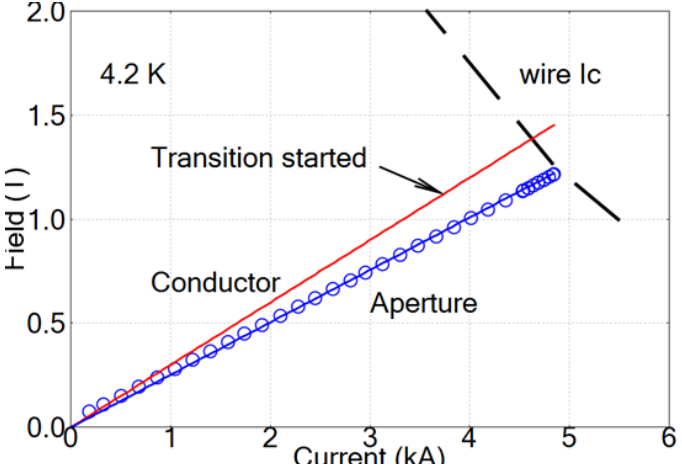
C1 generated 1.2 T dipole field at 4.2 K, a first successful step for CCT magnet using REBCO conductor

Transition started





- Inner layer transitioned at 81% of prediction
- No obvious or significant defect over 30 m long CORC® wires

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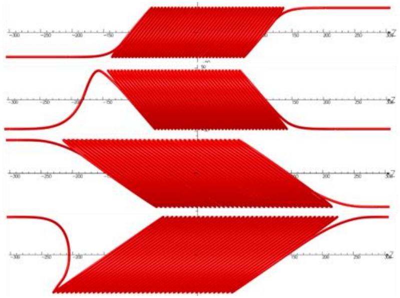
C2: generate 3 T with longer conductors, metal mandrels and Stycast to constrain the conductors



- 2018 – 2019
- 65 mm ID, 127 mm OD, 0.6 m long
- 3 T designed dipole field at 4.2 K at 6.4 kA

- Aluminum bronze machined mandrels
- Painted Stycast after winding

- Magnet used 100 m long 30-tape CORC® wire
    - *5 km* of 2 mm wide SuperPower tapes with 30 µm substrates
    - 30 mm minimum bending radius

Ref: SuST 2021

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C2 used another record length of CORC® wire: issues were encountered and addressed

- The transport measurement at ASC/FSU showed some tapes with lower than expected performance
- ACT increased tape count in CORC® wires to boost the wire performance

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

- Layer 4 wire has the lowest field, opportunity for grading

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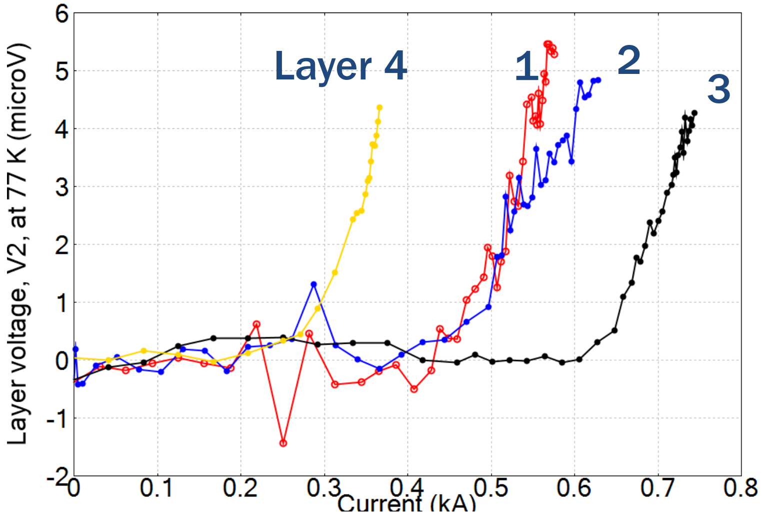
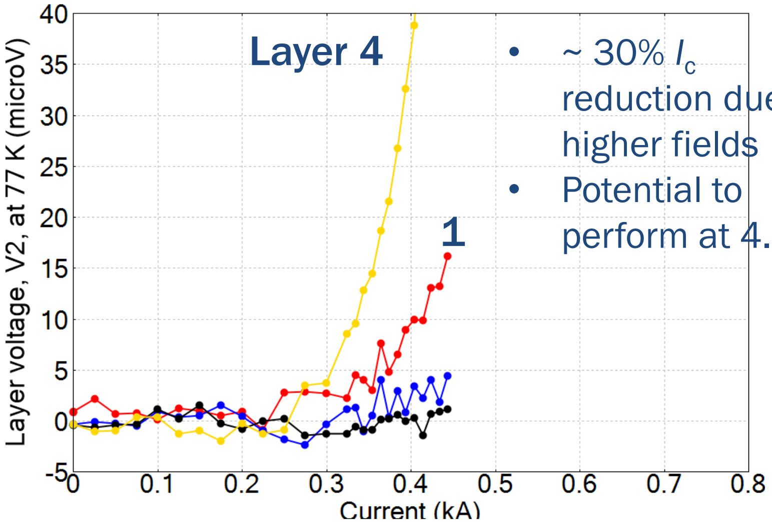
Layer 4 shows the lowest performance at 77 K – an interesting mystery

Each layer tested individually



After assembling all layers together



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

- Layer 4 wire contains high- and low-pinning tapes
- Local current sharing between the tapes or not?

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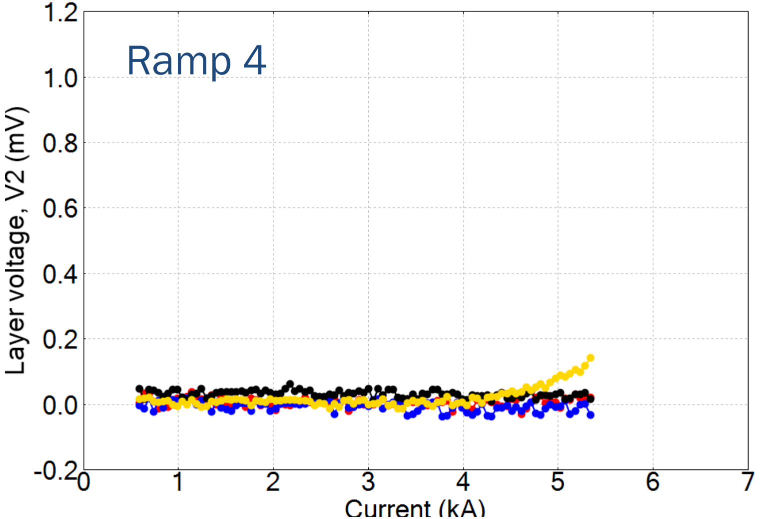
Reproducible transition behavior allowed a controlled increase in the maximum current to probe the true performance of C2



- Increasing the threshold for quench detection
- Conductor J_e = 460 A/mm^2

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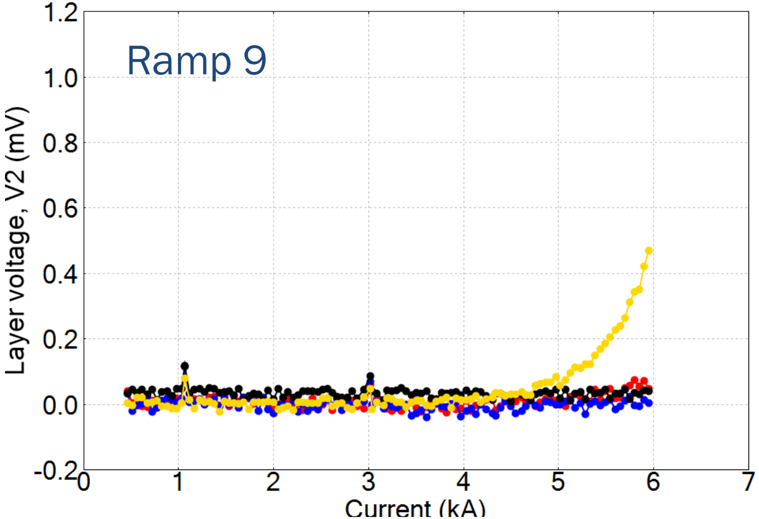
Reproducible transition behavior allowed a controlled increase in the maximum current to probe the true performance of C2



- Increasing the threshold for quench detection
- Conductor J_e = 520 A/mm^2

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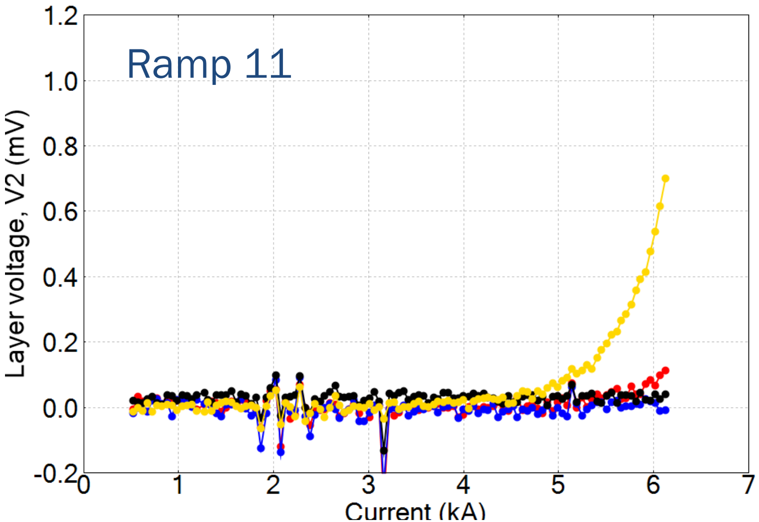
Reproducible transition behavior allowed a controlled increase in the maximum current to probe the true performance of C2



- Increasing the threshold for quench detection
- Conductor J_e = 530 A/mm^2

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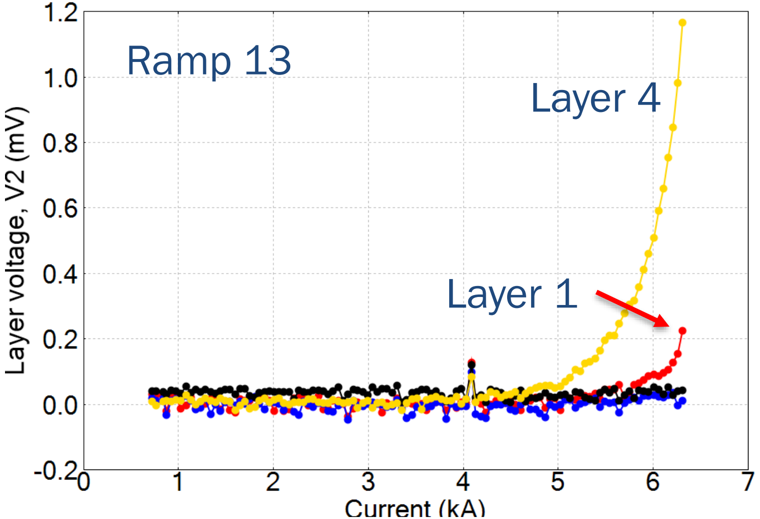
Reproducible transition behavior allowed a controlled increase in the maximum current to probe the true performance of C2



- Reached 2.9 T dipole field at 6.3 kA
- Conductor J_e = 550 A/mm^2
- Also paid a price by pushing for higher current …

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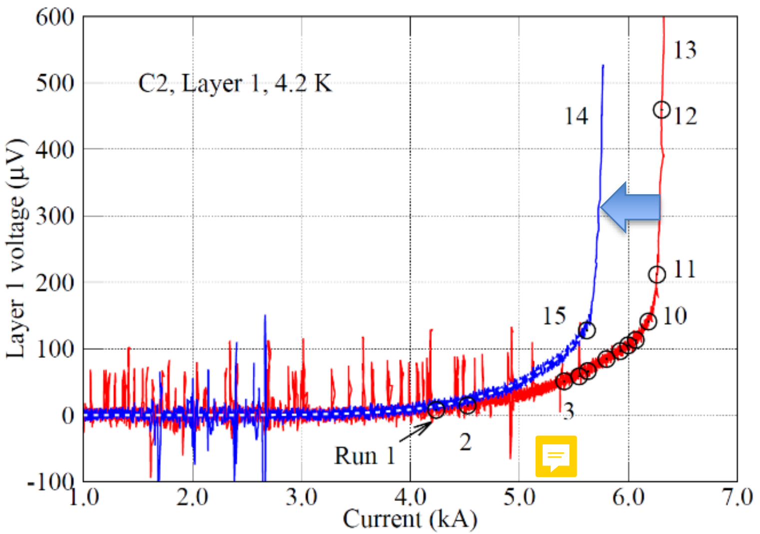
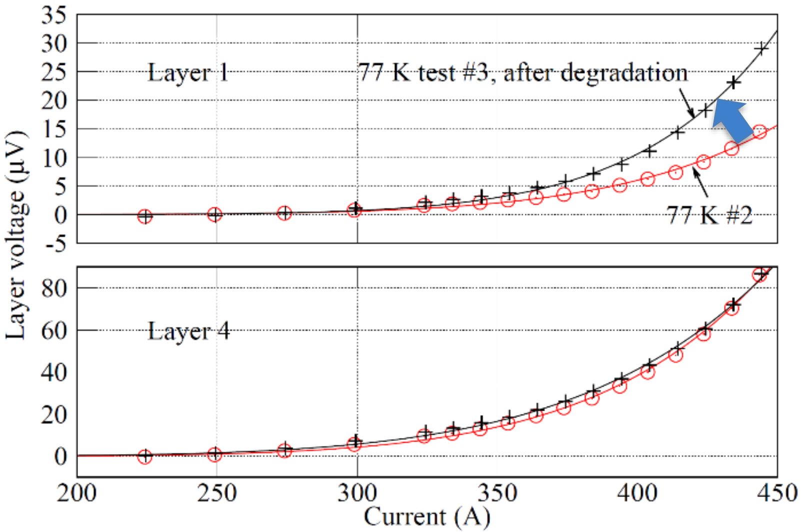
Layer 1 conductor degraded during the thermal runaway at a J_e of 550 A/mm² at 4.2 K



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

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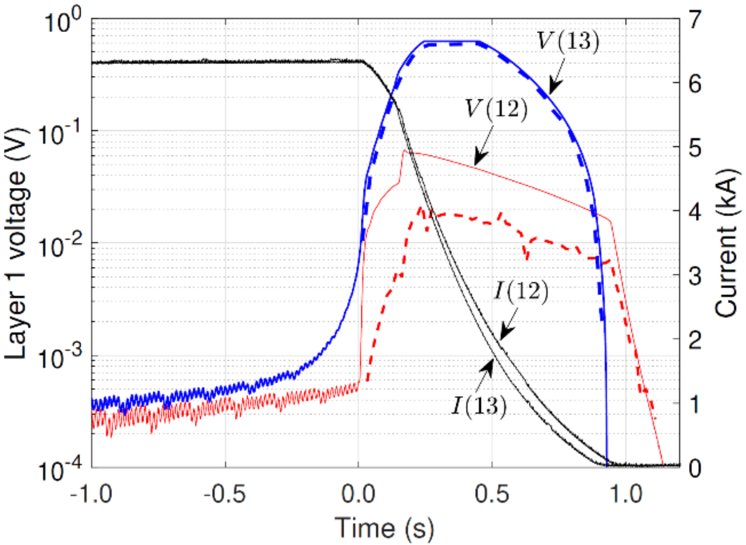
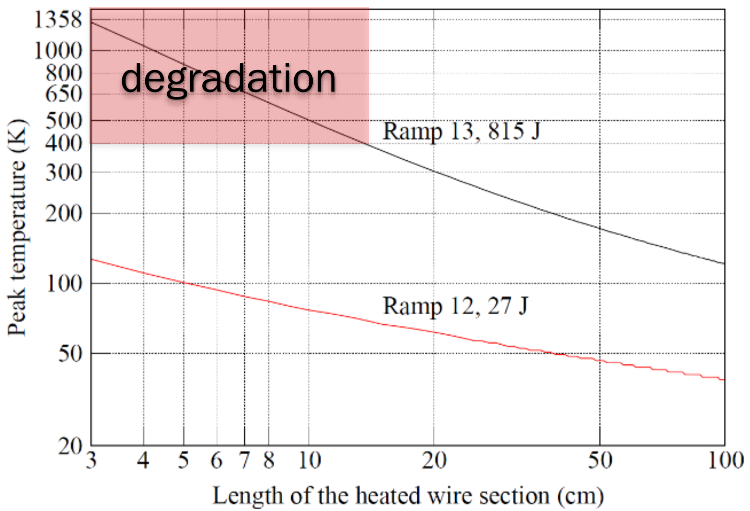
Joule heating during thermal runaway possibly degraded the conductor: try to avoid thermal runaway

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

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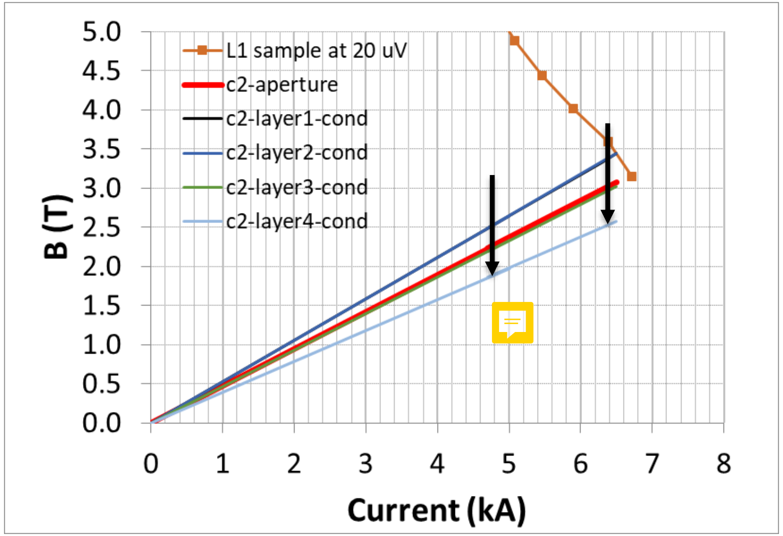
In addition to a 2.9 T field, C2 also generated several open questions. We will address them with next magnets



- Why did Layer 1 started transitioning at 4.8 kA, 73% of the short-sample prediction?
  - Expected or conductor degradation?
- What caused the low performance of Layer 4?
  - Mix of tapes of different I_c values?
- Where is the heat/voltage generated?
  - Distributed sensing?
- How can we improve for the next magnet?

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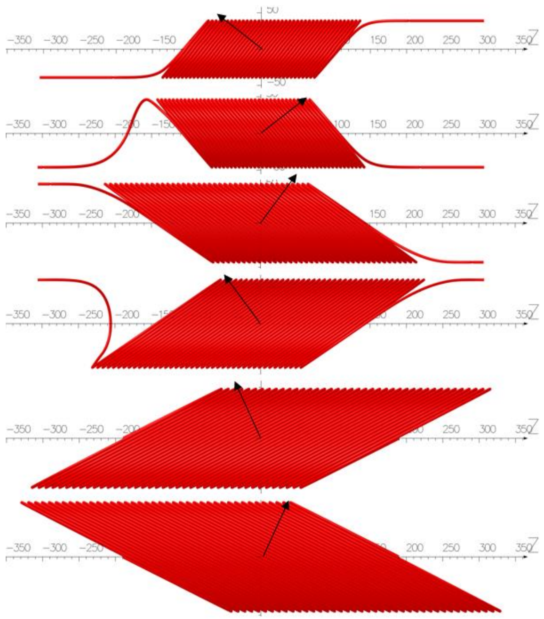
C3: generate 5 T, push for higher conductor performance, and start probing the impact of electromagnetic stresses on conductors



- 2020 – 2023
- 65 mm ID, 160 mm OD, 0.9 m long
- 5 T designed dipole field at 4.2 K at 7 kA

- Aluminum bronze machined mandrels
- Use Stycast to mechanically couple all layers

- Magnet will use 181 m long 30-tape CORC® wire
  - *10 km* of 2 mm wide tapes with 30 μm thick substrate
  - 30 mm minimum bending radius

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Ongoing conductor procurement becomes one of the growing pains

- We ordered commercial REBCO tapes with a specification on the minimum I_c: 350 A at 4.2 K, 6 T
- Non-trivial to meet the specification, even though earlier commercial tapes demonstrated the specified performance
- An excellent opportunity for us to step up to the challenges and grow
- Highlights the strong impact of conductor vendors in REBCO magnet technology development. How can we better help each other?

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Summary

- The US MDP is developing REBCO magnet technology to enable 20+ T dipole magnetic fields
  - Critical component of a *long-range* R&D program supported by DOE Office of Science
- We started working with CORC® wires with a constant need of higher current, 10 – 20 kA, at a smaller bending radius, 10 – 15 mm, at 4.2 K
  - *Higher tape* I_c
  - *Thinner and narrower tapes*: substrate thickness of 20 – 25 μm
- Making magnets with incrementally higher fields is critical to the technology development, and eventually market cultivation
  - Most effective for magnet builders and conductor manufacturers to *work together*

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Backup

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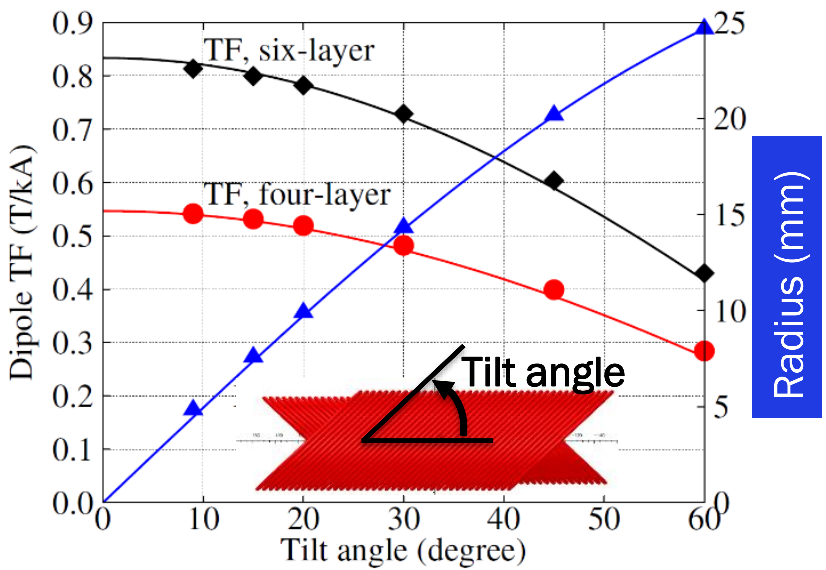
More flexible high-current REBCO wires are critical to demonstrate higher dipole fields



CO reference

- Thinner tapes are the key
  - They allow smaller CORC® bending radii and tilt angles → higher dipole fields
  - 30 μm substrate → 25 μm corresponds to 25% increase in J_e
- Increase pinning performance at 4.2 K
- The resulting tapes will have strong technology and market impact
  - *Need to develop them now*

Questions & Answers for Application Speakers

Application: Accelerator& Power Applications
Organization: LBNL Name: X. Wang

Question	Answer
What are the biggest benefits of using super-conducting technology in your application? *(e.g. Efficiency, Weight, Size)*	We develop high-field magnets for accelerator and fusion applications. The benefit is higher fields in compact magnets without significant resistive heating or energy consumption.
What are the factors that prevent your application from moving to the commercial phase? *(e.g. Cost, Reliability, Productivity, Performance, Related Laws, Standardization, Infrastructure)*	We are still learning how to make magnets and magnet conductors. The magnet performance is yet to be demonstrated and understood.
What do you require from the coated conductors in your application? *(e.g. Low Cost, High Ic@T & B, Low AC loss, Long Piece Length, Reliability, Applicability for Coiling, Mass Production Ability)*	**1st** Engaged conductor partner as part of the magnet development that can quickly respond to magnet needs, assuming an equally responsive counterpart on the magnet side **2nd** Keep pushing the conductor geometry and performance: robust thinner and narrower tapes with higher I_c @ T and B **3rd** Consistent and reproducible geometry and performance of raw tapes and resulting magnet conductors/cables

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Questions & Answers for Application Speakers

Application: Accelerator& Power Applications
Organization: LBNL **Name: X. Wang**

Question	Answer
What do you require from the other fundamental technologies in your application? *(e.g. Superconducting Joint, Persistent Current Switch, Light Weight Cooling System with High Efficiency)*	• Flexible multi-tape cables; cable of cables • Low-resistance joint • Impregnation technique without degrading conductors and then with high radiation tolerance • Distributed sensing of temperature and perhaps strain and magnetic field • Characterize performance of 10 – 100 m long multi-tape cables: geometry, transport current, local weak spots in tapes • Technology enabling the conduction-cooled operation of magnets with an operating current of the order of 10 kA, e.g., cryocoolers, current leads