Development of REBCO dipole magnets at LBNL

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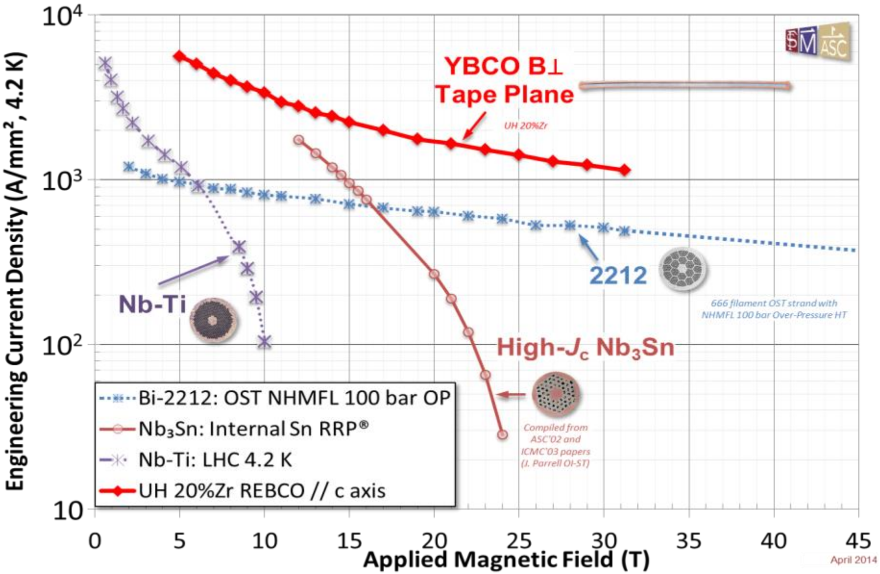
REBCO conductors can enable future dipole magnets beyond 16 T



REBCO magnet R&D is a key component of the US MDP

Peter Lee, ASC/NHMFL/FSU. REBCO data courtesy of Venkat Selvamanickam at Univ. Houston [A. Xu *et al.*, Scientific Reports, Article number 6853, 2017]

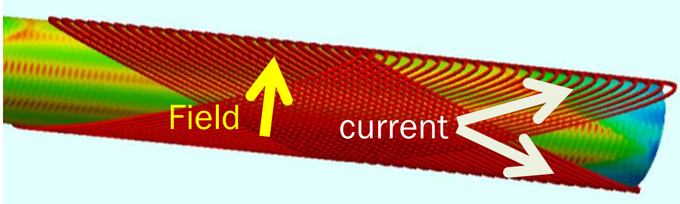
We focus on canted cosθ dipole magnets using round REBCO CORC® wires

- CORC® wires (2.5-4.5 mm diameter)
    - Wound from 2-3 mm wide tapes with 30 µm substrate
    - Highly flexible with bending down to <50 mm diameter

  [J. D. Weiss *et al.*, SuST, 014002, 2017 and references therein]

Advanced Conductor Technologies LLC
www.advancedconductor.com

- Canted cosθ (CCT) accelerator magnets
    - Low conductor stresses
    - Excellent geometric field quality



[D. Meyer and R. Flasck, Nuclear Instruments and Methods, vol. 80, no. 2, pp. 339–341, 1970; S. Caspi *et al.*, IEEE TAS, 4001804, 2014, and references therein]

A phased program to address the driving questions

- How to make CCT magnets using CORC® wires?
- What's the magnet performance?
- What issues limit the magnet performance? How to address them?

- Subscale coil approach with increased complexity

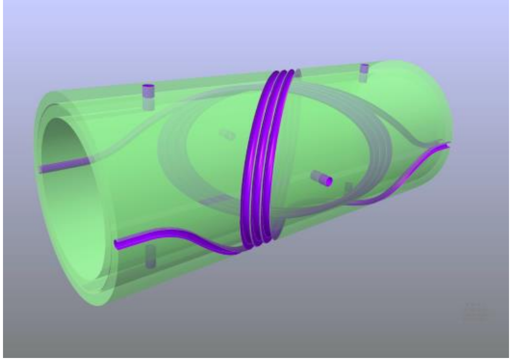
Few-turn mini coil

Multi-turn coil

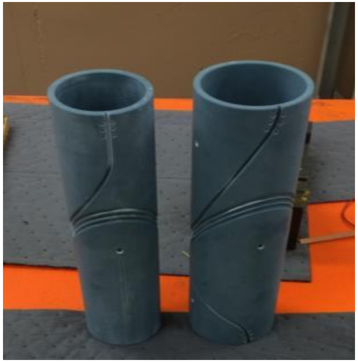
- Stand-alone test to be followed by in-field test
- Close collaboration with the community through the U.S. MDP

Simple geometry and printed mandrels facilitate the coil development

CAD model of a 2-layer assembled coil



Printed mandrels using Accura® Bluestone



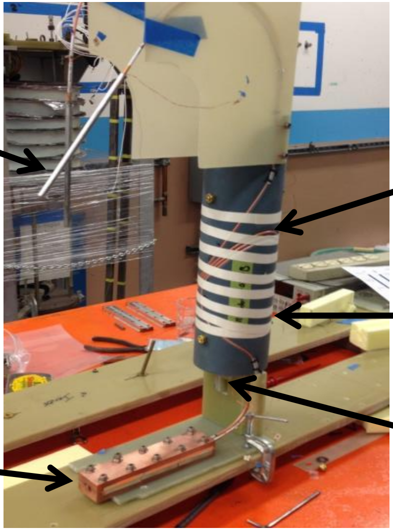
- The wire minimum bending radius drives the coil design

Two magnets (3-turn) are successfully made and tested using CORC® wires

3-turn CCT magnets	C0a	C0b
Wire OD (mm)	3.09	3.63
Number of tapes in the wire	16	29
Expected J_e at 76 K, sf (A/mm^2)	140	234
Expected J_e at 4.2 K, 20 T (A/mm^2)	207	346
Minimum bending radius (mm)	25	30

Each 2-layer coil used about 5 m long wires

We gained very useful experience on coil winding, assembly and test



Lead end terminal

Return-end praying-hand joint

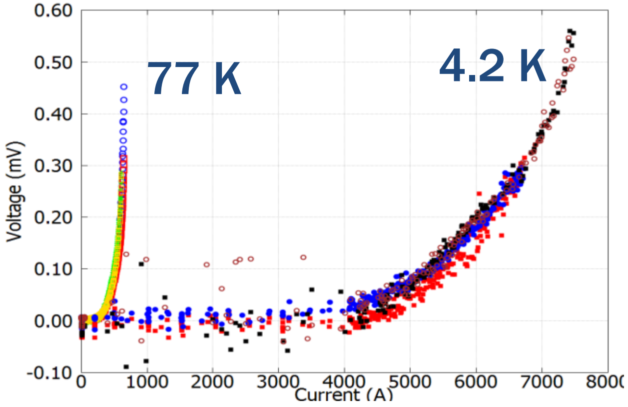
3 turns of CORC® wire

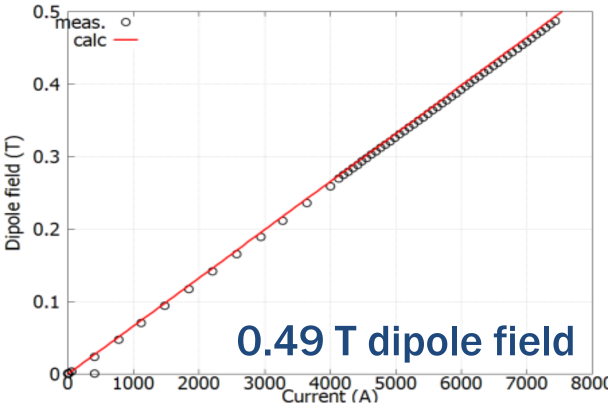
Outer layer (inner layer inside)

Hall sensor assembly

Successful tests suggest the CORC® CCT is a viable concept – C0a magnet with 16-tape wire

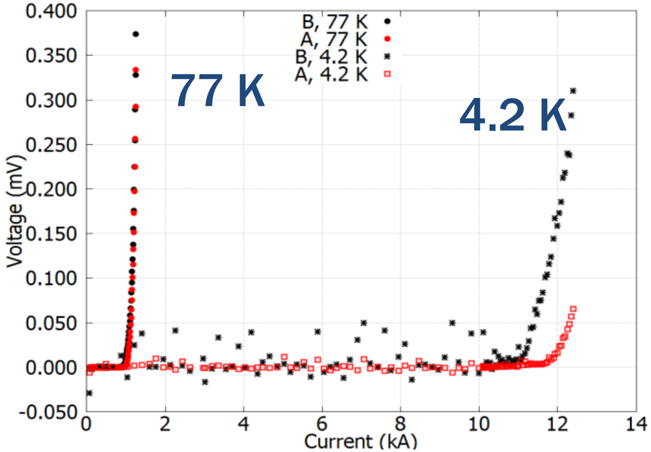
- Reached 645 A at 77 K and 7480 A at 4.2 K. Peak J_e = 997 A/mm^2 at 4.2 K, self-field





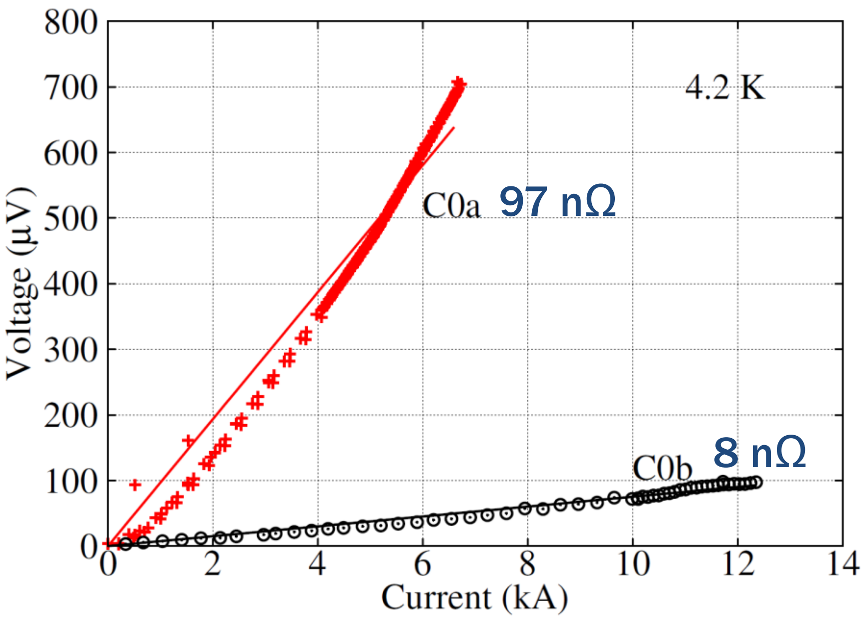
0.49 T dipole field

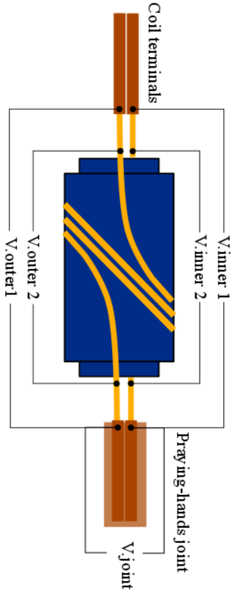
Successful tests suggest the CORC® CCT is a viable concept – C0b magnet with 29-tape wire



Current-carrying capacity x 11 from 77 K to 4.2 K.
Peak J_e 1198 A/mm^2 and a dipole field of 0.68 T

The lowest resistance of the praying-hand joint reached 8 nΩ at 4.2 K





- Soldering the wires can further reduce the joint resistance

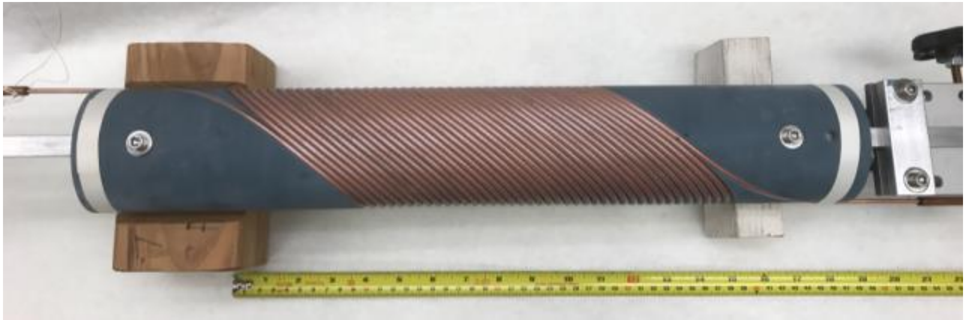
With the experience from the 3-turn CO magnet, we made a 40-turn dipole magnet

Hugh Higley (left) and Andy Lin (right) winding a mockup coil

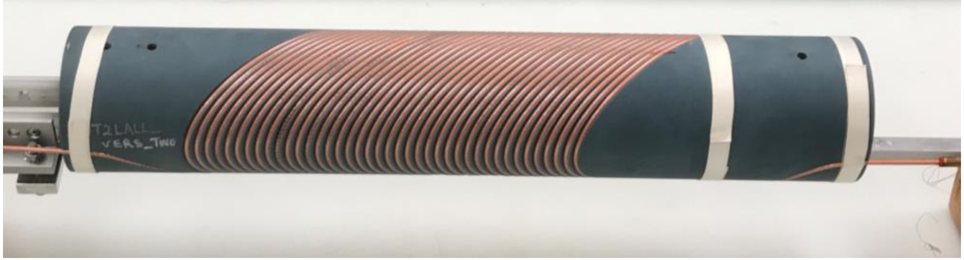
Inner and outer layers of C1 before assembly

- Commercial CORC® wire from ACT: 160812-Berkeley-204 (inner layer), 160823-Berkeley-250 (outer layer)
- Mandrels are made of Accura® Bluestone that have been 3D-printed

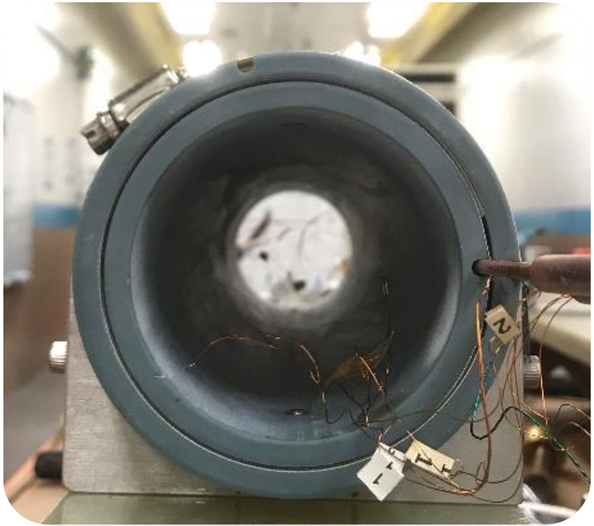
Inner



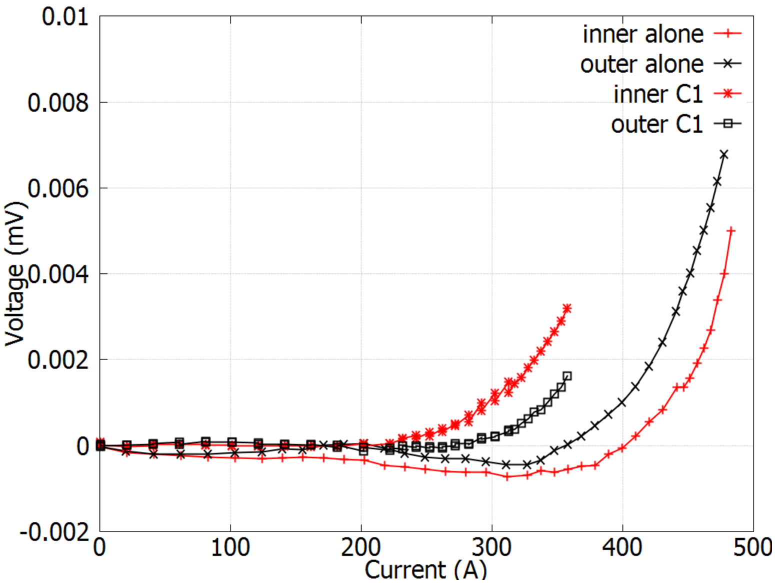
Outer



Assembled C1 magnet before test



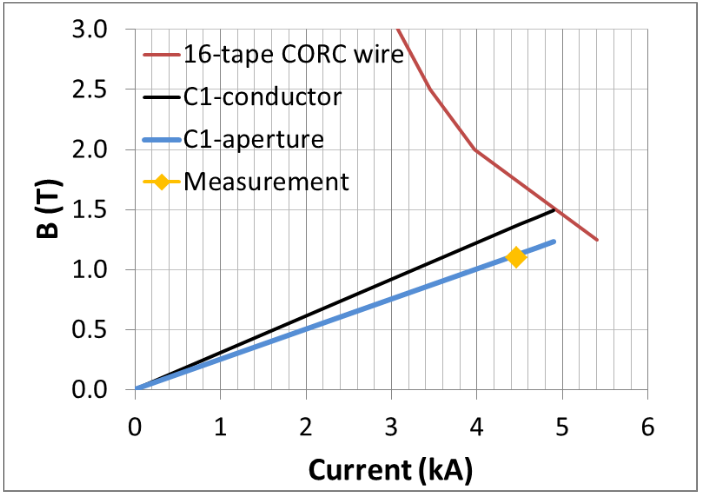
Performance at 77 K was good as we can hope



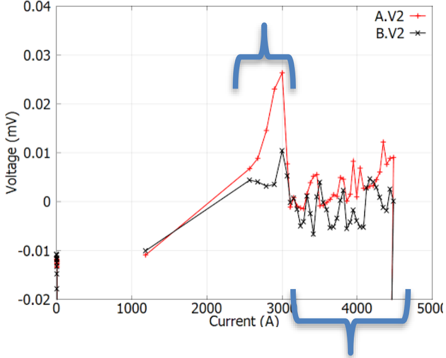
- **Increased field on the conductor after assembling both layers increased the voltage across each layer**

The magnet worked well at 4.2 K

- **C1 reached 1.1 T at 4.2 K, 92% of the expected performance (with the inner layer voltage increase from 0 to 10 μV)**



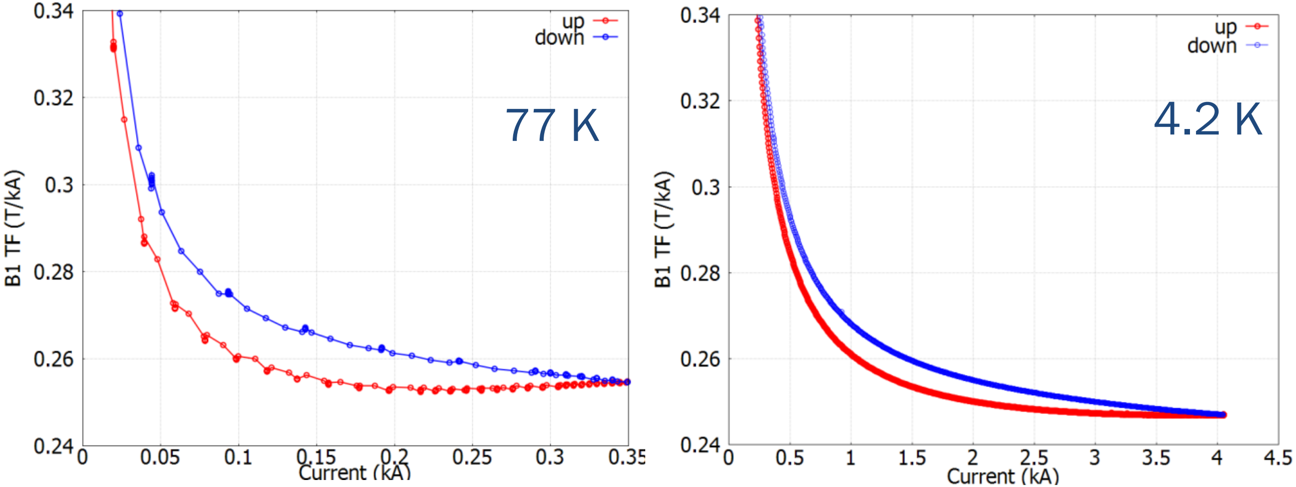
Inductive pickup due to fast current ramping



Resistive voltage rise (red) in the inner layer due to higher field on the conductor

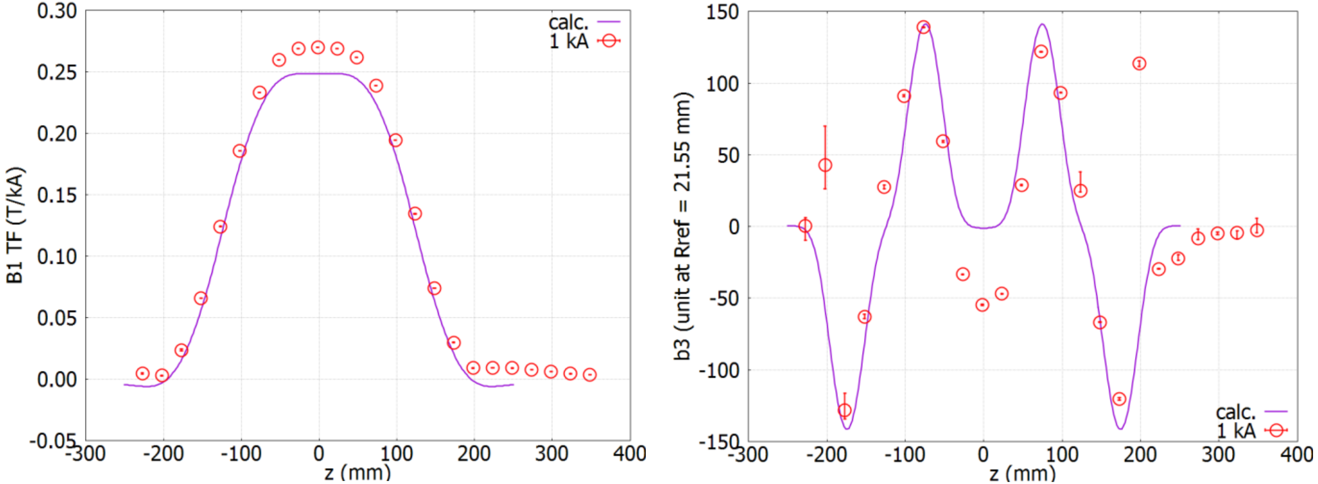
Stronger hysteresis at 77 K than at 4.2 K, self-field

- Measurement at the magnet center with a 100 mm long rotating coil developed by Joe DiMarco at FNAL
- Stronger hysteresis at 77 K than at 4.2 K
  - Maximum hysteresis between up and down ramps is about 4% of the nominal transfer function at 77 K and 2% at 4.2 K



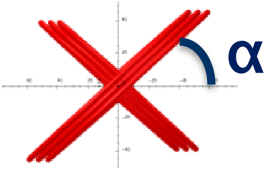
Field profile at 1 kA generally follows the expectation

- **Measurement at the magnet center with a 100 mm long rotating coil developed by Joe DiMarco at FNAL**

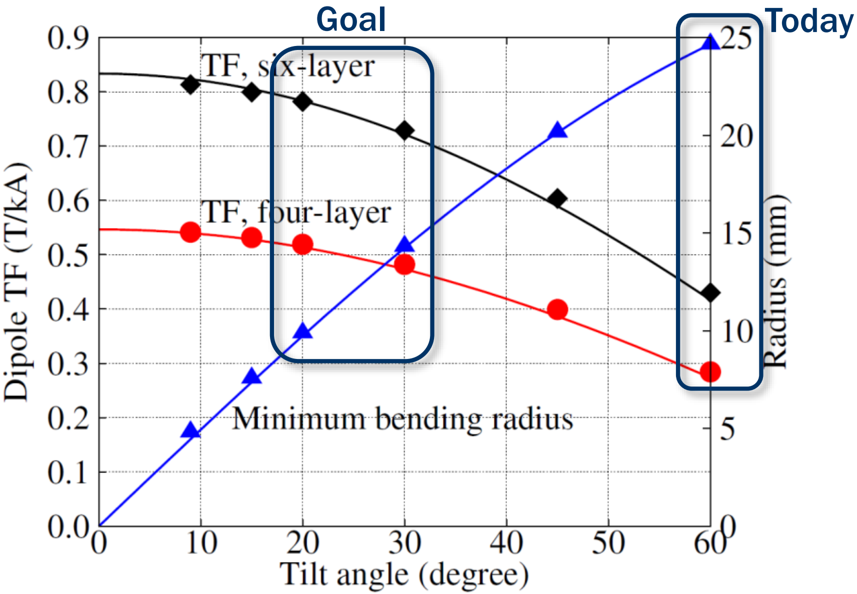


- **We are investigating the deviation from the expected values at the magnet center (possibly due to the persistent-current effects)**

Improving J_e at small bending radii is the focus for further optimization of CORC® wires



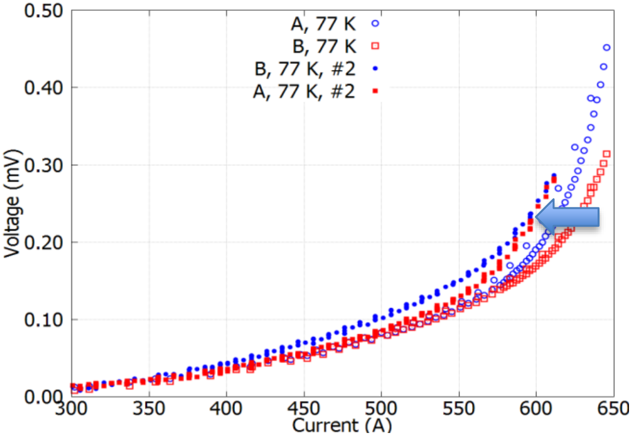
- **Transfer function (TF) ∝ cos(α)**
- **Minimum bending radius (R_{min}) ∝ sin(α)**



- **Proposed R_{min} target: 10 – 15 mm (25 mm today)**
- **Minimum target J_e: 540 A/mm^2 at 21 T, 4.2 K, 15 mm R_{min}**

High J_e conductors require effective quench detection

- Over heating caused issues
  - 5% - 10% current degradation in C0a due to overheating at 4.2 K test
  - C0b burn up at 12.4 kA



- Will study new detection schemes with future magnet tests, e.g., the acoustic approach and the fiber-optic approach
  - [M. Marchevsky and S. A. Gourlay, Acoustic thermometry for detecting quenches in superconducting coils and conductor stacks, Appl. Phys. Lett. 110, 2017]
  - [Scurti F, Ishmael S, Flanagan G and Schwartz J 2016 Superconductor Science and Technology 29 03LT01]

Summary

- The MDP REBCO program is developing magnet technology to exploit the unprecedented conductor performance
    - Demonstrate applications in the next 5 years to create industrial competition and drive cost down
- We successfully developed the first CORC® CCT dipole magnets
    - Demonstrated viability of the concept – no showstoppers foreseen
    - Identified further optimization goals and issues to be addressed

U.S. MAGNET
DEVELOPMENT
PROGRAM