Latest development of CORC® cables and wires for high-field magnets for compact fusion reactors and particle accelerators

Danko van der Laan & Jeremy Weiss
Advanced Conductor Technologies & University of Colorado, Boulder, Colorado, USA

Kyle Radcliff
Advanced Conductor Technologies, Boulder, Colorado, USA

Zack Johnson
University of Colorado, Boulder, Colorado, USA

D. Abraimov, Ulf Trociewitz, Daniel Davis & David Larbalestier
Applied Superconductivity Center, National High Magnetic Field Laboratory, Tallahassee, Florida, USA

X. Wang, H. Higley & S. O. Prestemon
Lawrence Berkeley National Laboratory

Yuhu Zhai
Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA

Mithlesh Kumar, Ramesh Gupta & Piyush Joshi
Brookhaven National Laboratory, Upton, New York, USA

Advanced Conductor Technologies
www.advancedconductor.com

CCA23, Houston TX, April 5th, 2023

PPPL | BROOKHAVEN NATIONAL LABORATORY | NATIONAL HIGH MAGNETIC FIELD LABORATORY | BERKELEY LAB

CORC® cables and wires for high-field magnet applications

CORC® wires (2.5 – 4.5 mm diameter)
- Wound from 2 – 3 mm wide tapes with 25 and 30 μm substrate
- Typically, no more than about 30 tapes
- Flexible with bending down to < 40 mm diameter

Canted-cosine theta accelerator magnets
- Ultimate goal to reach a dipole field of 20 T
- Eventually allowing operation at 20 K

CORC® cable (5 – 8 mm diameter)
- Wound from 3 – 4 mm wide tapes with 30 – 50 μm substrate
- Typically, no more than about 50 tapes
- Flexible with bending down to > 100 mm diameter

Common Coil accelerator magnets
- Operated in series with LTS outsert
- Ultimate goal to reach a dipole field of 20 T

Ohmic Heating coils for compact fusion machines
- Allowing high-current, high field coils to be wound without epoxy impregnation
- Withstanding high cyclic operating stresses at 20 kA and 20 T

CORC® wire development of CCT magnets developed at LBNL

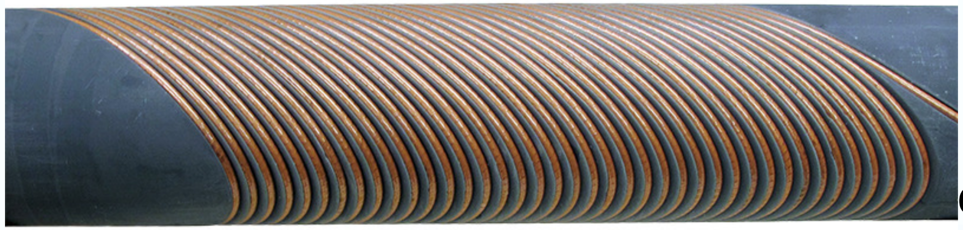
Program goal to reach 20 T dipole field by

- Demonstrating stand-alone CCT magnets at 1 T, 3 T, 5 T and 8 – 10 T
- Combining a 12 – 15 T LTS CCT outsert with a 5 – 8 T CORC® CCT insert

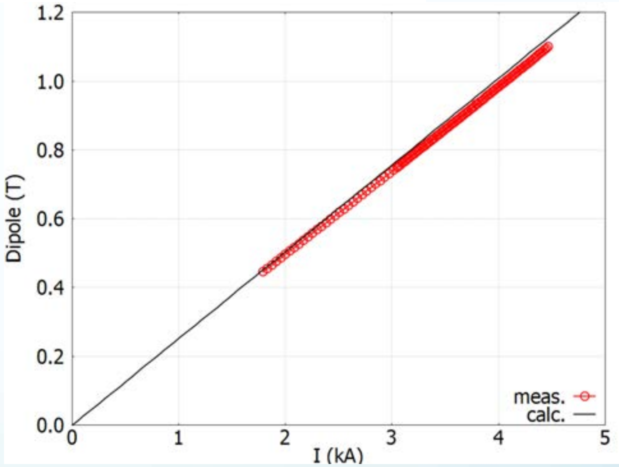
A 1.2-T canted cos ϑ dipole magnet using high-temperature superconducting CORC® wires, X. Wang, et al., *Supercond. Sci. Technol.* **32**, 075002 (2019)

Successful demonstration of 1.2 T (CCT-C1)

- First 2-layer coil wound from low-J_e 16-tape CORC® wire to learn the magnet winding procedures
- Generated 1.2 T at 4.5 kA



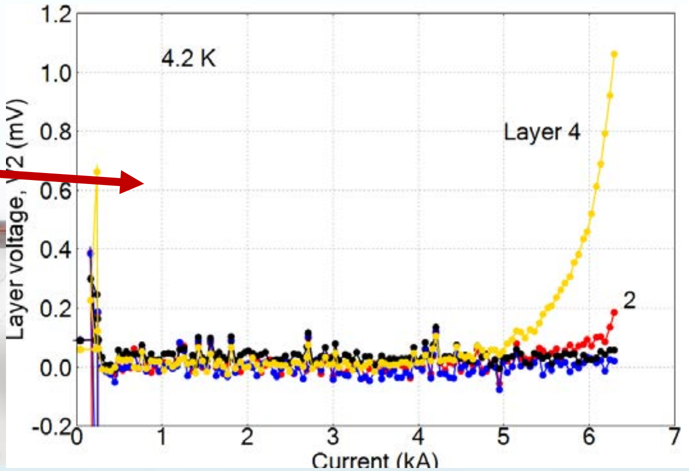
CORC® CCT-C1



Successful demonstration of 2.9 T (CCT-C2)

- 4-Layer coil wound from medium-J_e 30-tape CORC® wire resulting in significant stresses
- Generated 2.9 T at 6.5 kA

CORC® CCT-C2



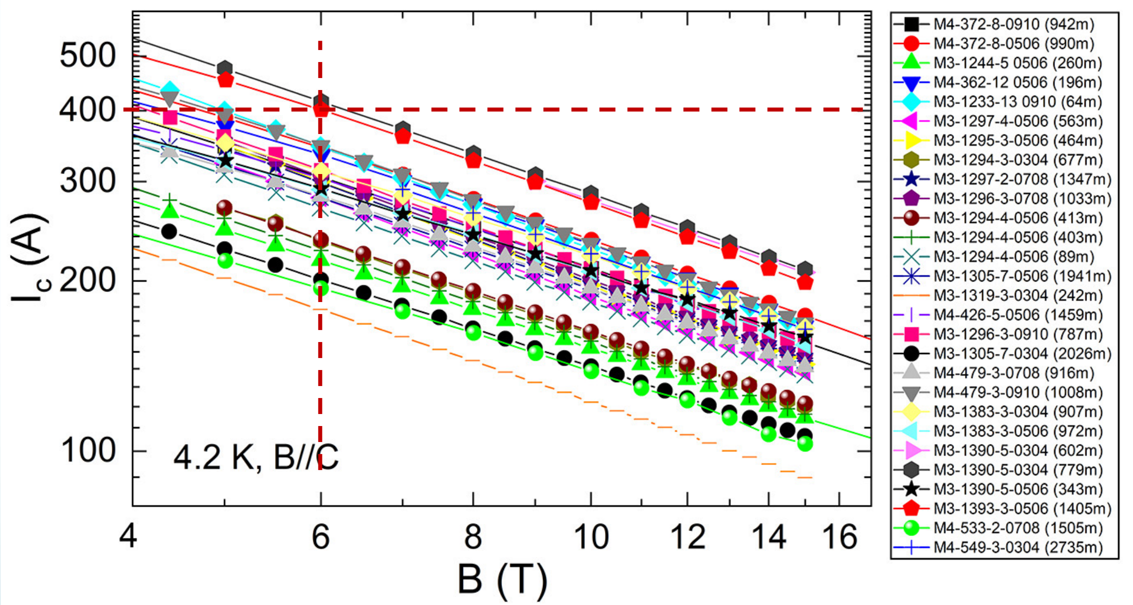
Development and performance of a 2.9 Tesla dipole magnet using high-temperature superconducting CORC® wires, X. Wang, et al., *Supercond. Sci. Technol.* **34**, 015012 (2021)

CORC® wire development for magnet CCT-C3 (5 T)

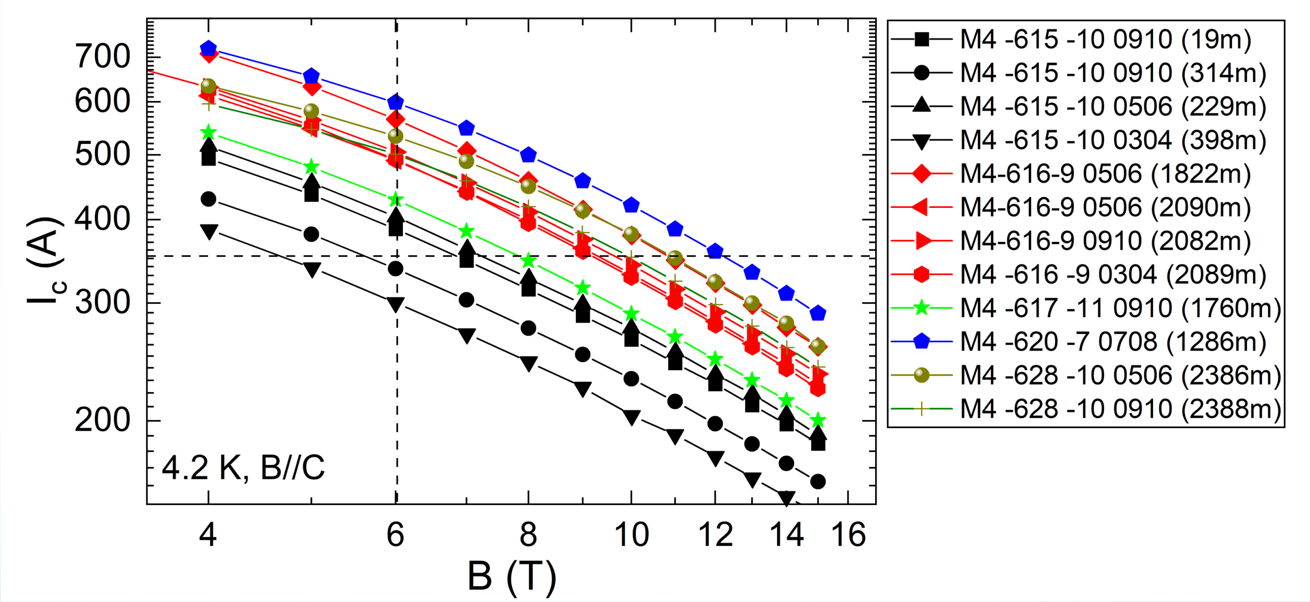
How to reach 5 T in CCT-C3?

- Magnet containing 6 layers with 40 turns each, requiring 145 meters of CORC® wire
- Develop high-J_e CORC® wire from 30 tapes using SuperPower's new "HM" formulation
- Order placed for 10 km of SCS-2030 HM tape with minimum I_c(4 K, 6 T) of 400 A

Performance of SuperPower SCS2030-AP tape 2016 - 2020



Performance of SuperPower SCS2030-HM tape 2021 - 2022



All 10 km of SuperPower SCS-2030-HM tapes have been received and qualified

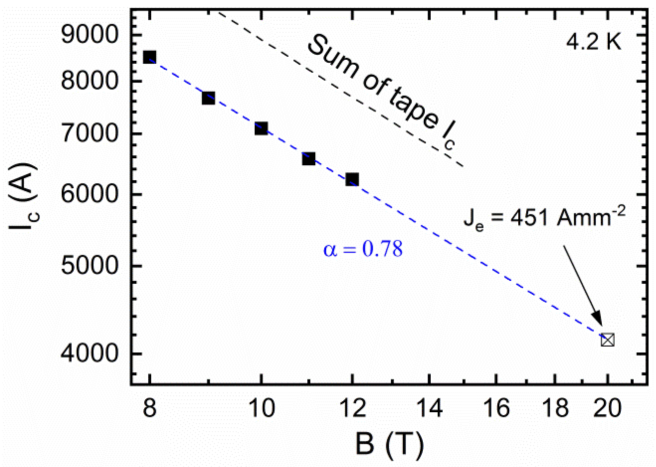
Advanced Conductor Technologies
www.advancedconductor.com

PPPL · BROOKHAVEN NATIONAL LABORATORY · NATIONAL HIGH MAGNETIC FIELD LABORATORY · BERKELEY LAB

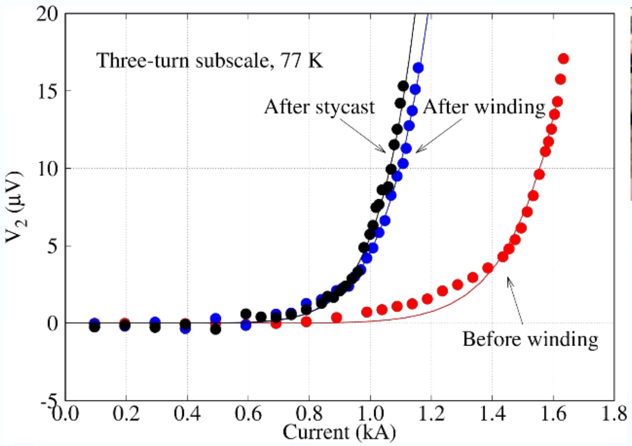
HM-based CORC® wire performance: early-2022 process (P1)

CORC® wire performance pre-2022 (AP tapes based)

- Bending to 60 mm diameter (as required for CCT-C2 and CCT-C3) resulted in 20 – 30 % degradation
- Short-sample J_e(20 T) of 450 A/mm^2 (63 mm bending diameter) demonstrated



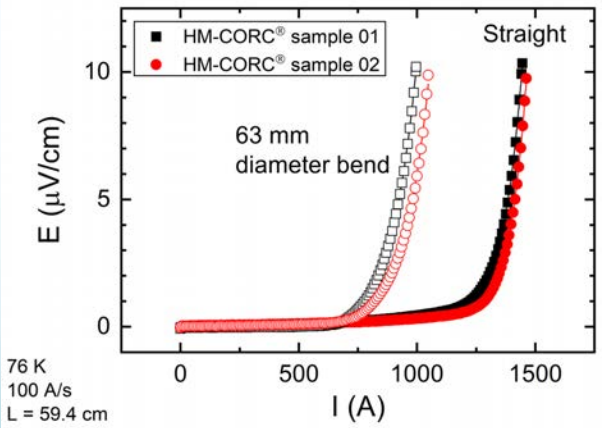
J.D. Weiss, et al., *Supercond. Sci. Technol.* **33**, 044001 (2020)



AP-tape CORC®
CCT mandrel

CORC® wire performance early 2022 (HM tape based)

- Long-length J_e(20 T) of 400 – 450 A/mm^2 at 20 T (70 % I_c retention at 63 mm bending diameter) expected
- J_e confirmation Q2 2023 (liquid helium pending)
- Bending to 60 mm diameter resulted in 35 – 40 % degradation!!!
- This is unacceptable and won't allow CCT-C3 to reach 5 T

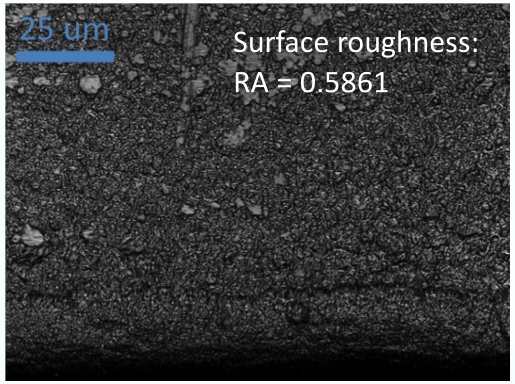


HM-tape CORC®
Hairpin bend

Cause of loss in CORC® wire flexibility

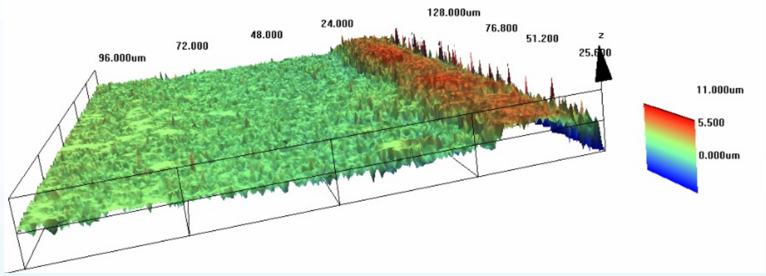
Cause of loss in bending performance HM-based CORC® wires using process P1

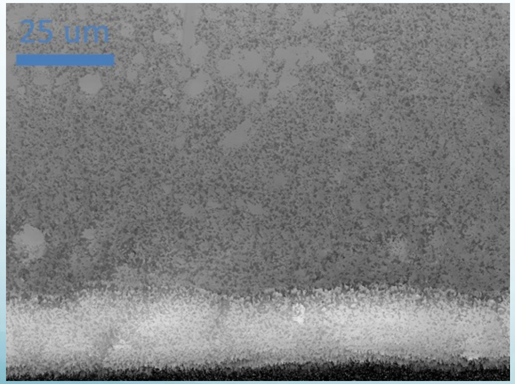
- Very high surface roughness of HM tapes observed
- Intermittent major slitting bur and course granularity in copper plating
- Higher friction between tapes in CORC® wires prevents tape sliding during bending



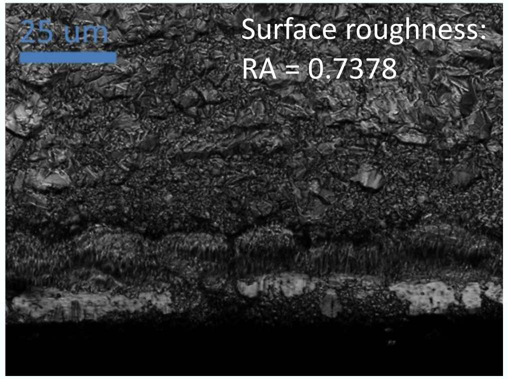
2016 – 2020 SCS-2030-AP tape

Tape edge



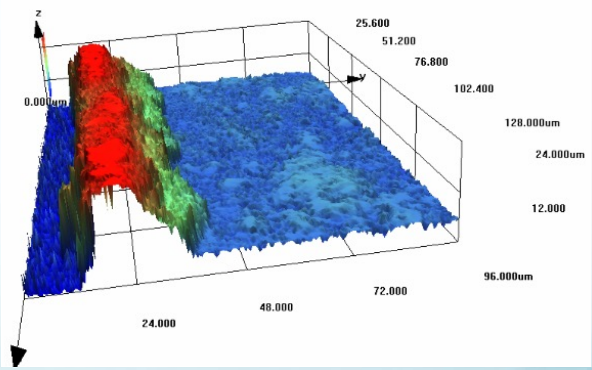


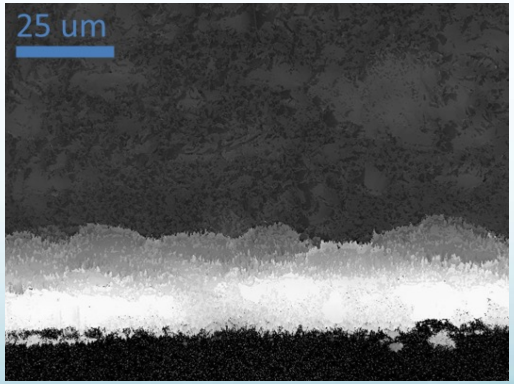
Height map



2021 – 2022 SCS-2030-HM tape

10-20 μm thick,
Intermittent burr





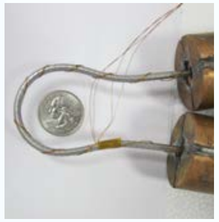
Height map

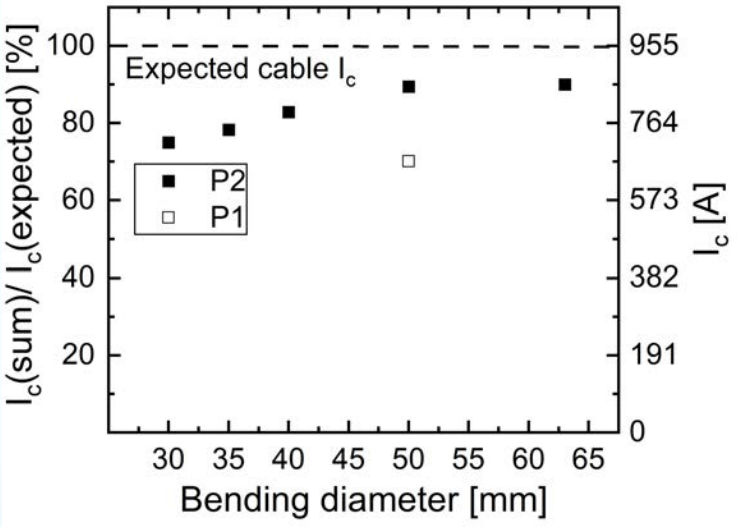
Next generation CORC® wire performance (late 2022)

Development of new winding and lubrication process (P2)

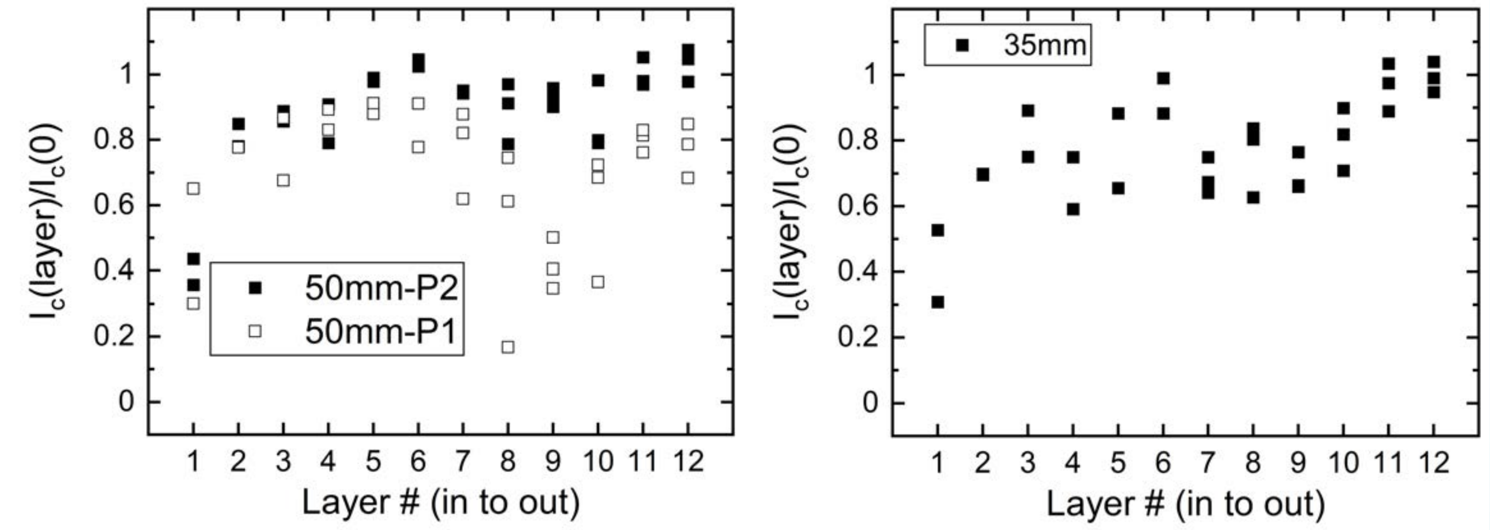
- Should allow CORC® wire bending to at least 60 mm diameter with use of "rough" tapes
- Should be applicable to long-length CORC® wire production

Next generation CORC® wires bending performance





Extracted tape I_c after bending



Next generation 30-tape CORC® wire bending

- I_c retention **90 % at 50 mm diameter bend** and around **80 % at 35 mm diameter bend**
- Should provide CCT-C3 with much larger margin in I_c than the 70 % used in its design

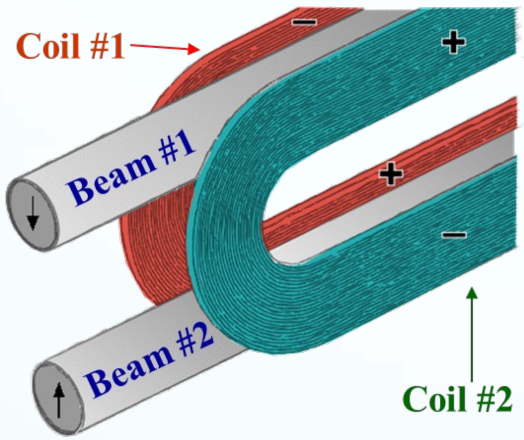
Advanced Conductor Technologies
www.advancedconductor.com

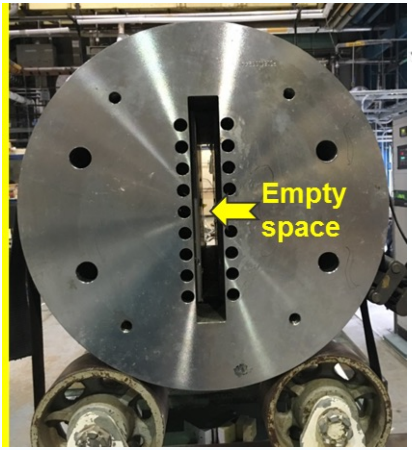
PPPL BROOKHAVEN NATIONAL LABORATORY NATIONAL HIGH MAGNETIC FIELD LABORATORY BERKELEY LAB

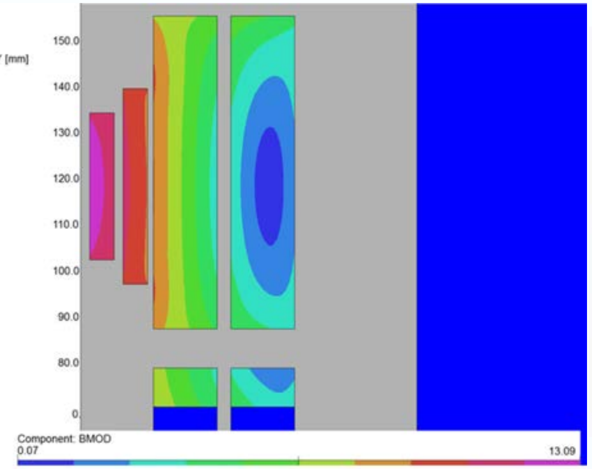
CORC®-based Common Coil development

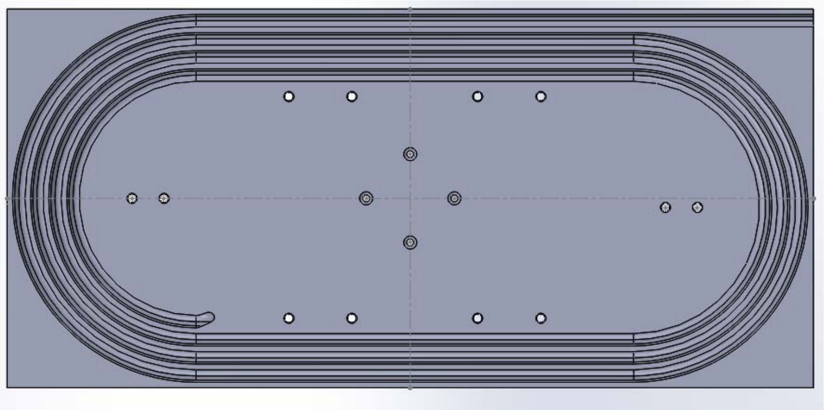
CORC® Common Coil program goals

- Develop a low-field CORC®-based insert to operate within the 10 T LTS outsert at BNL
- Verify the coil winding procedure and CORC® cable support and perform initial quench studies
- Develop a 3 T insert to generate a combined field of 13 T when operated in series with the outsert









CORC® cables for the Common Coil inserts (requires bending to 200 mm diameter only)

- CORC® cable based on 4 mm wide SuperOx tape for the low-field insert
- 5.5 mm diameter CORC® cable (SuperOx): 24 tapes (35 μm substrate): expected J_e(20 T) 350 A/mm^2
- CORC® cable based on 4 mm wide SuperPower tape for the 3 T insert operating at 10.8 kA (13 T peak)
- 5.0 mm diameter CORC® cable (SuperPower): 32 tapes (30 μm substrate): expected J_e(20 T) 500 A/mm^2

Development of CORC®-compatible Common Coil support structure

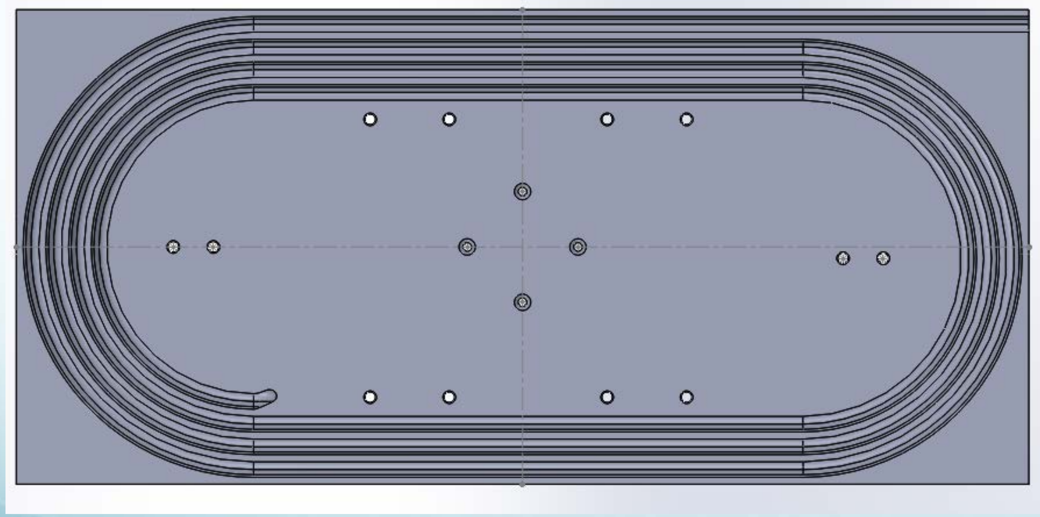
Common Coil inserts

- Low-field insert: two opposing single pancakes of 4 windings each
- 13 T insert: two opposing double pancakes of 6 and 8 winding each

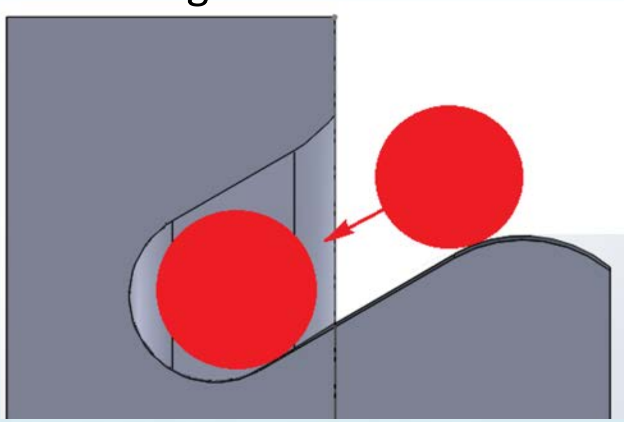
Coil structure requirements

- Winding the CORC® cable under tension without the need to “push” cable for placement
- Support against 13 T x 10.8 kA = 140 kN/m transverse load (into the plate)

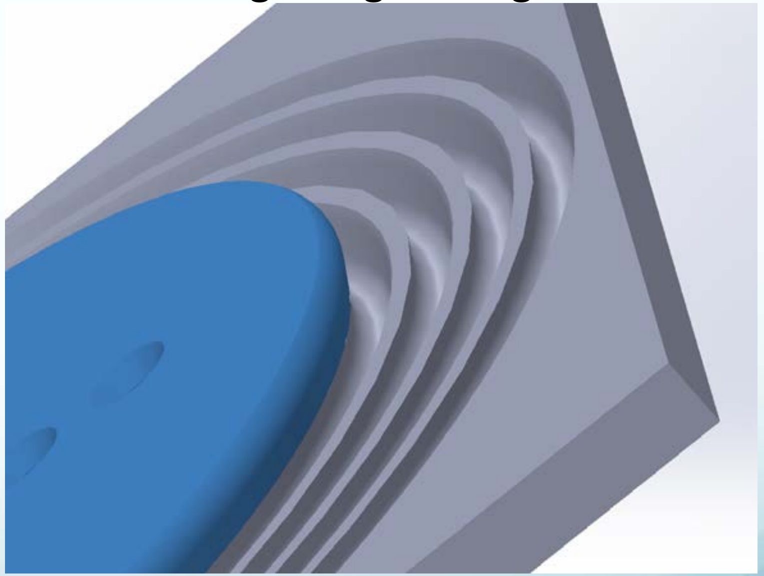
4-turn single CORC® pancake



CORC® cable sliding into slamted groove



Winding using cable guides



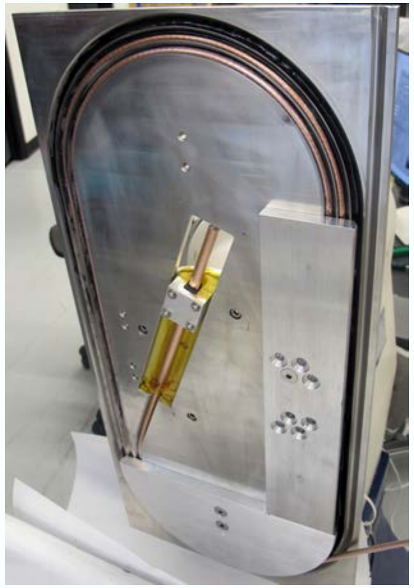
Advanced Conductor Technologies
www.advancedconductor.com

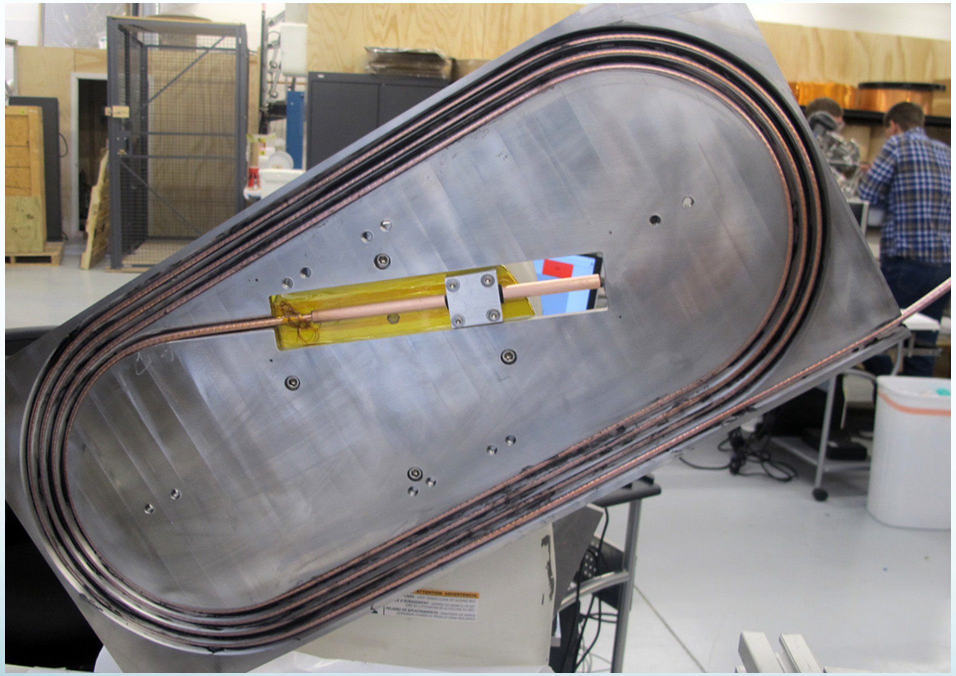
PPPL BROOKHAVEN NATIONAL LABORATORY NATIONAL HIGH MAGNETIC FIELD LABORATORY BERKELEY LAB

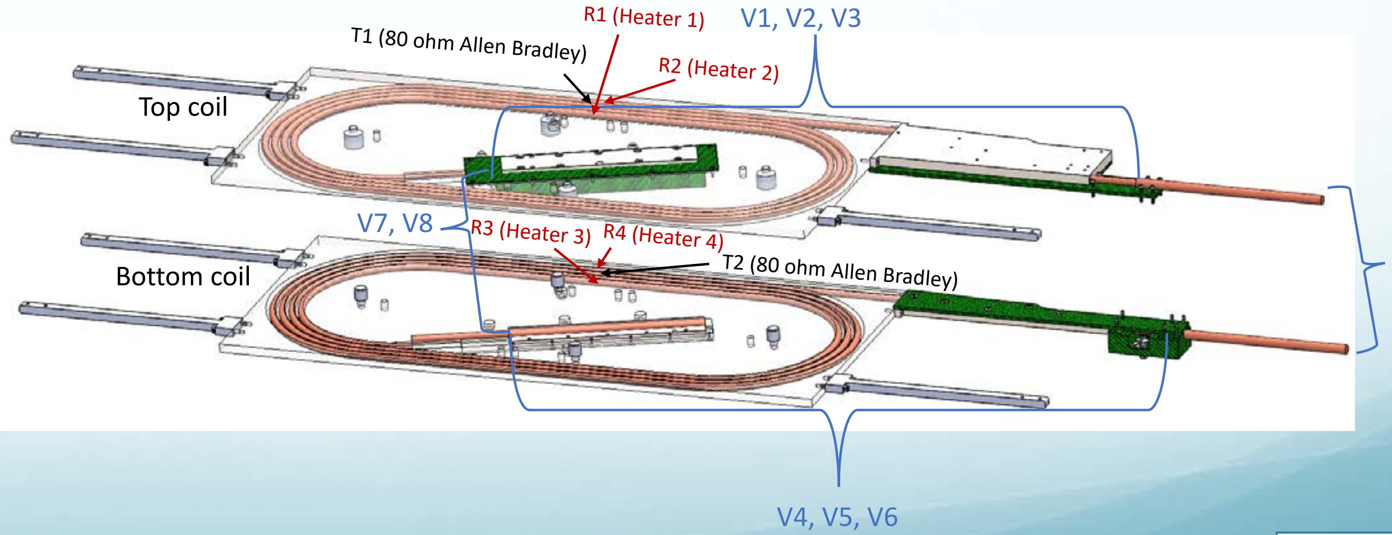
Winding of low-field CORC® Common Coil insert at ACT

Low-field CORC® Common Coil insert

- Wound from 8 meters of CORC® cable
- Stycast epoxy impregnation after winding
- Contains co-wound voltage wires and optical fibers, Hall probe arrays for quench detection



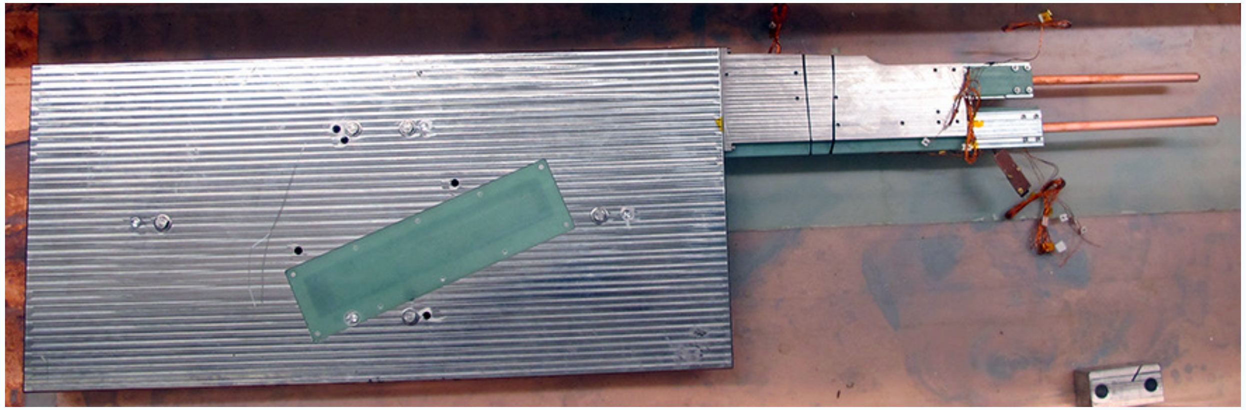


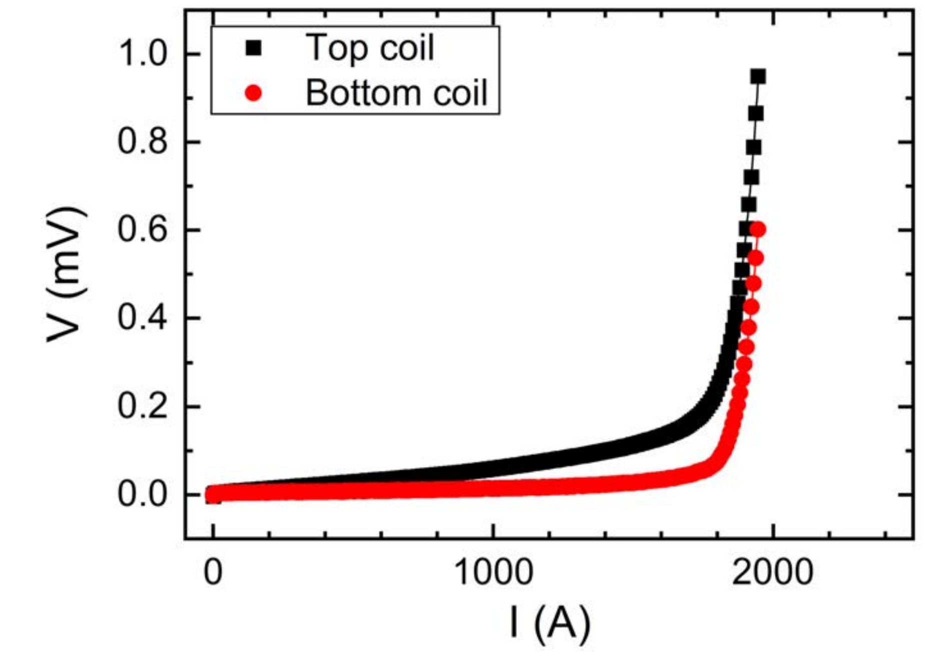


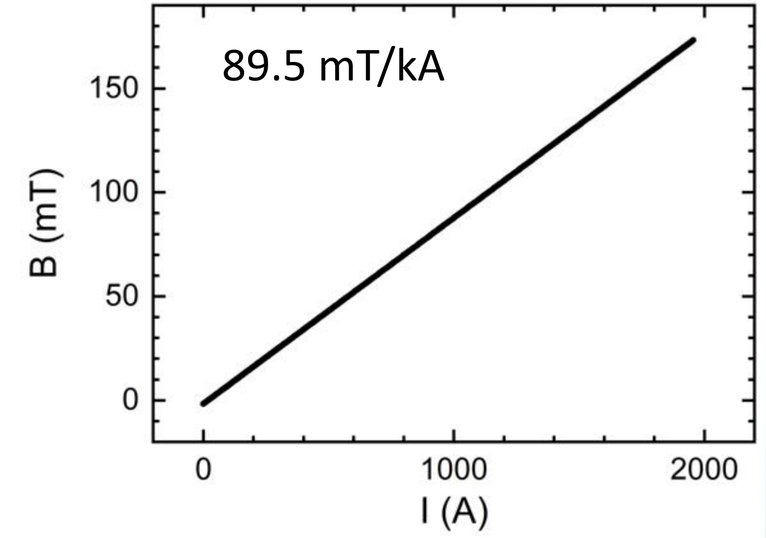
76 K test of low-field CORC® Common Coil insert at ACT

Initial performance test in liquid nitrogen at ACT

- Cable transition at 1.9 kA
- Field generated 170 mT





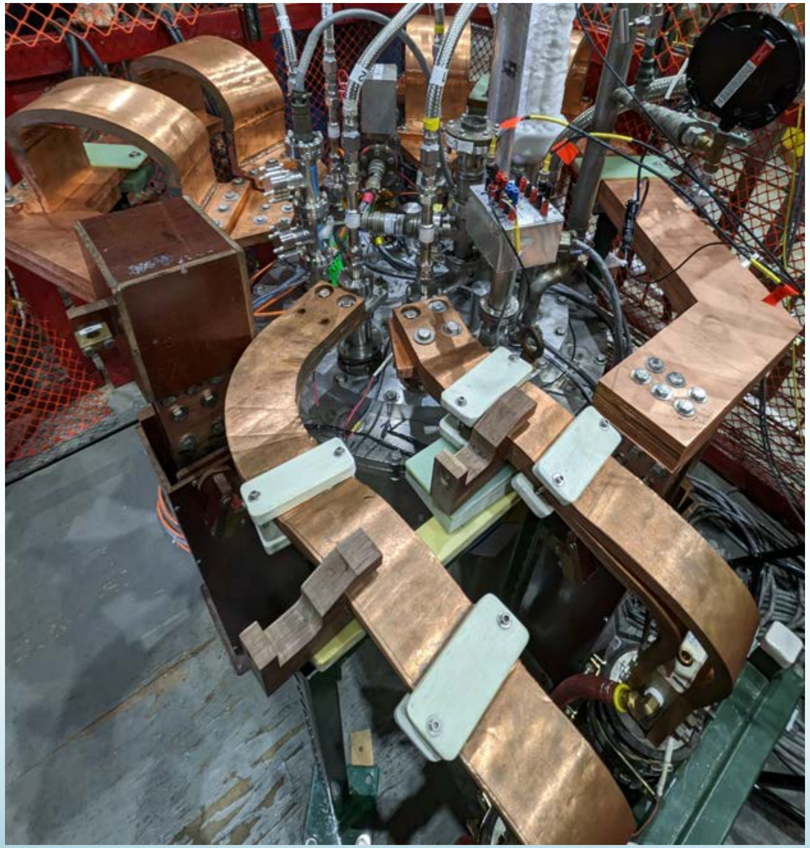


Advanced Conductor Technologies
www.advancedconductor.com

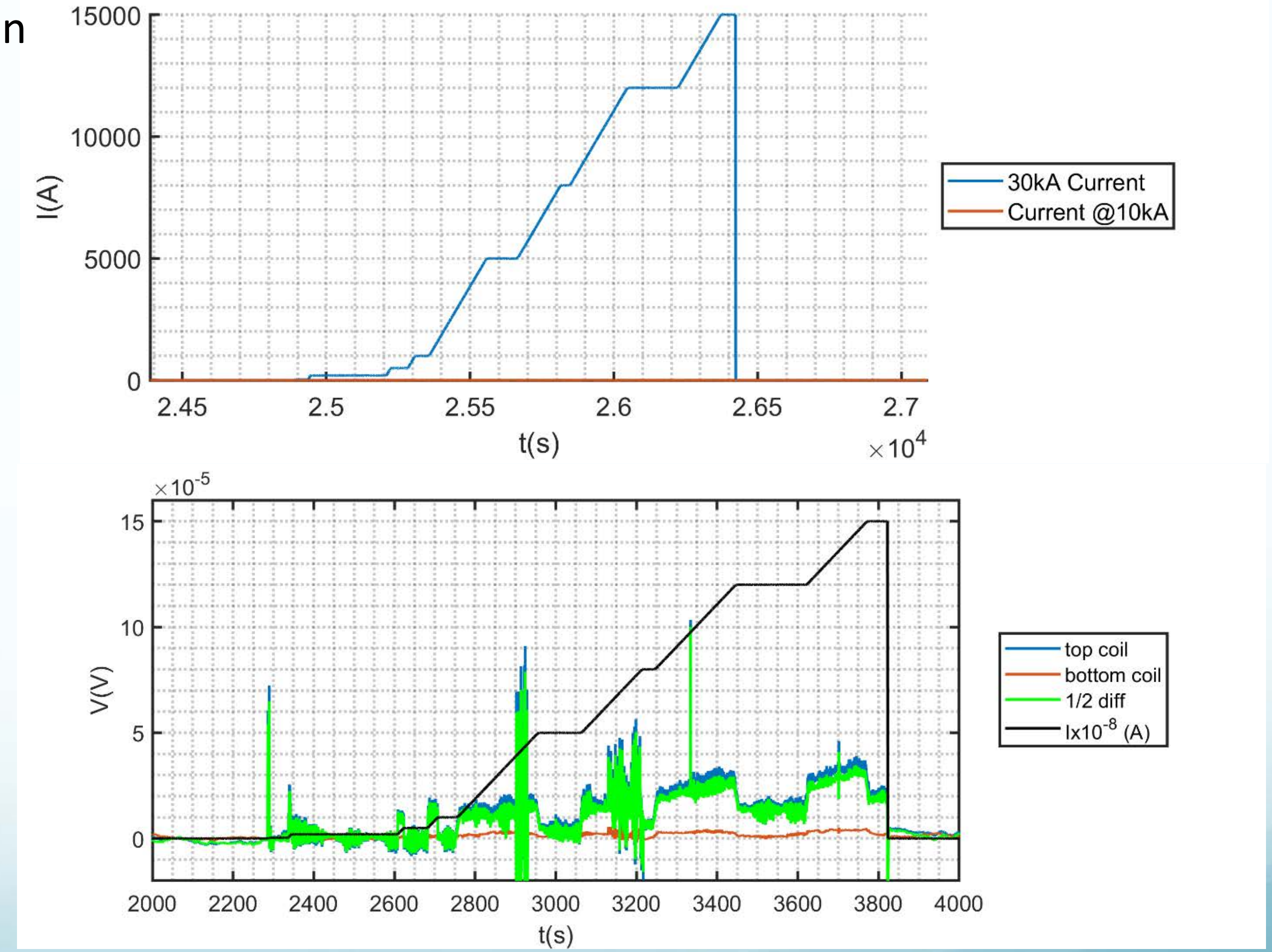
Initial CORC® Insert Test in the Common Coil Outsert

Current lead problem with Common Coil outsert

- Heating at current lead connection caused LTS quenches
- Testing at 0 T outsert field, or up to 6 T for short duration

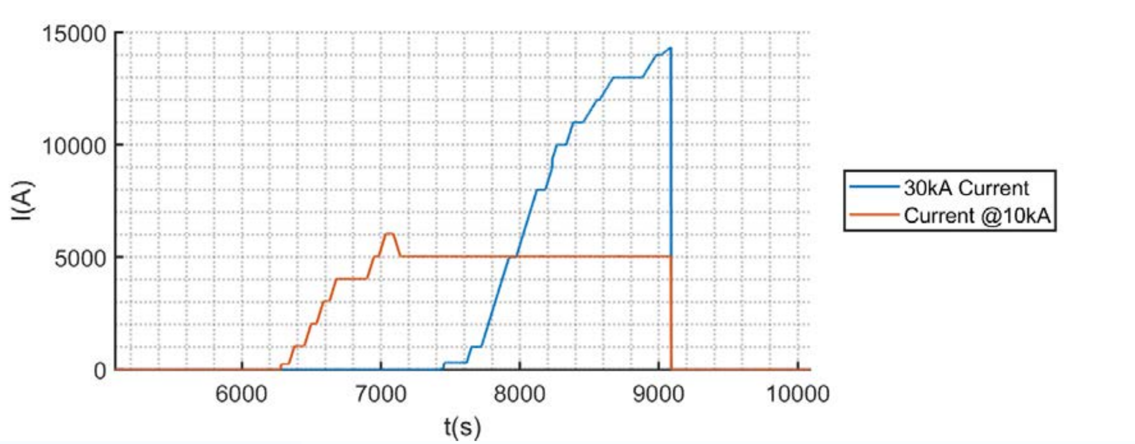


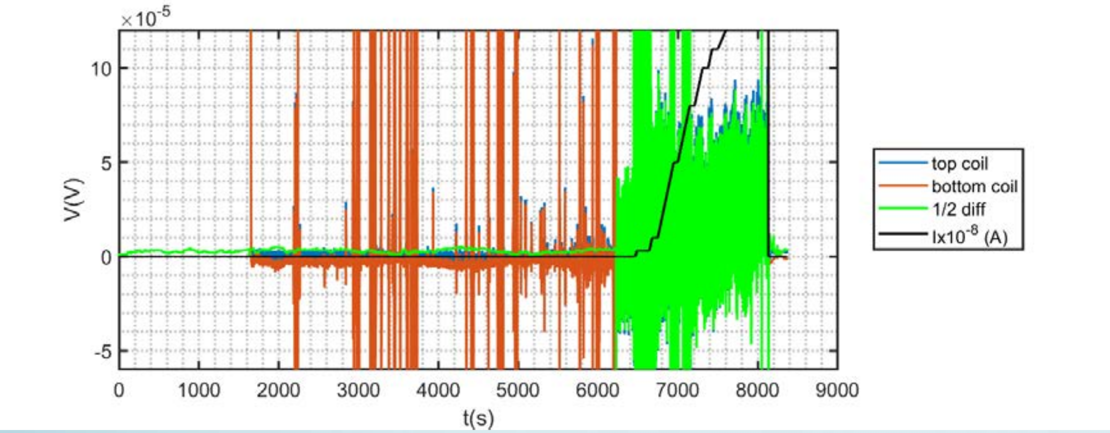
Self-field test CORC® insert to 15 kA (record)



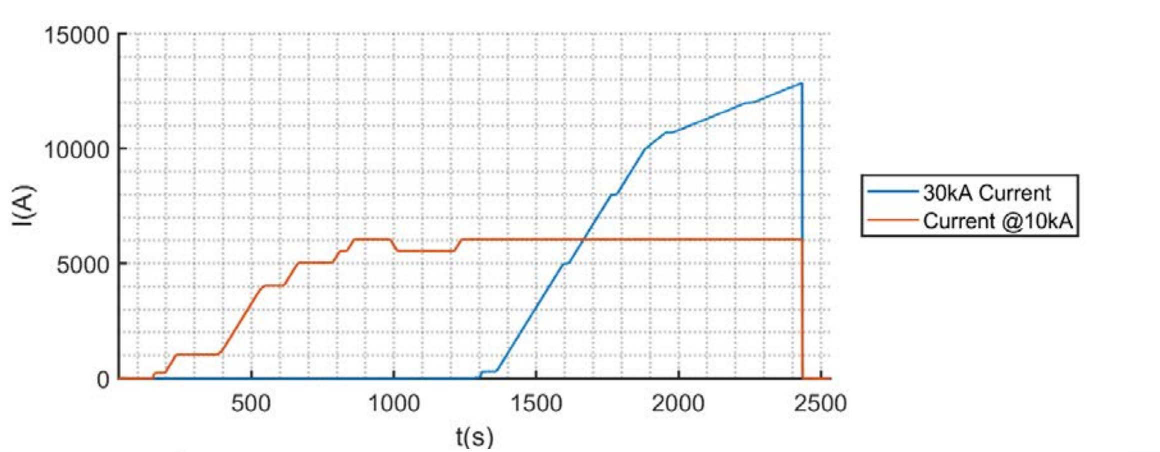
Initial CORC® Insert Test in the Common Coil Outsert

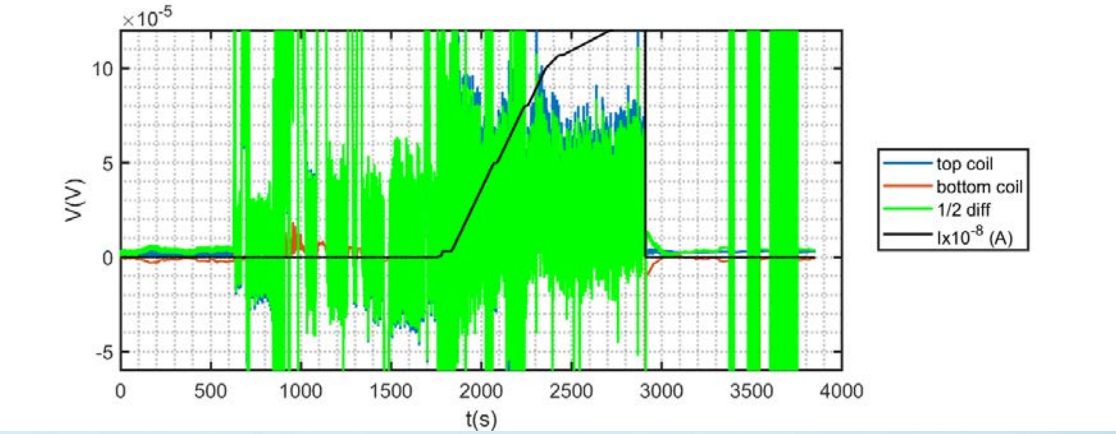
5 T outsert field
quench trigger at 14.36 kA





6 T outsert field
quench trigger at 12.87 kA





Test will resume in May 2023 after outsert lead repair

Development of prototype Ohmic Heating coil for compact fusion reactors

Ohmic Heating coil operating parameters

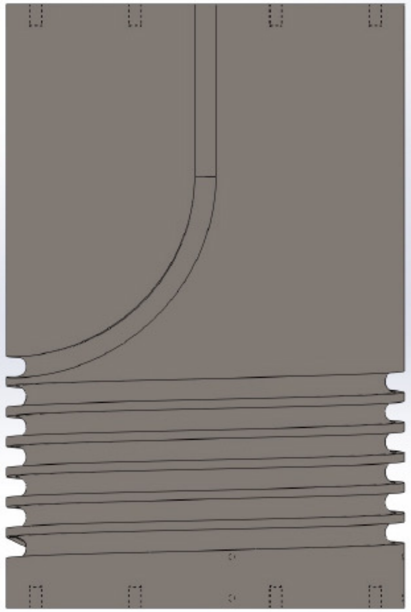
- Peak magnetic field on the conductor of 20 T
- Coil inner diameter 0.2 meters
- Operating current around 20 kA

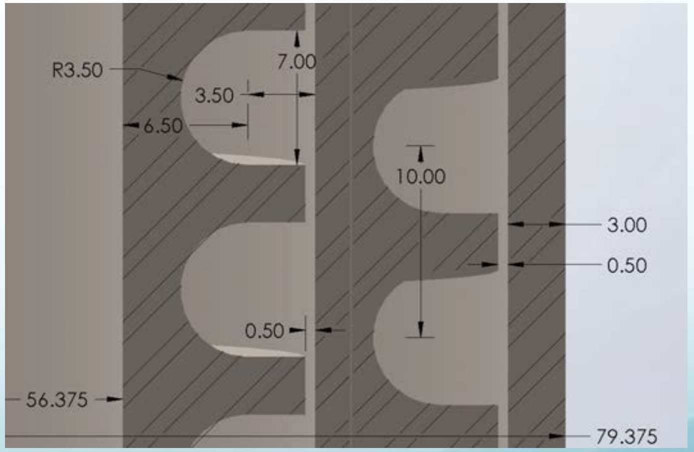
Coil winding approach

- Avoid epoxy impregnation
- Inner diameter makes winding a jacketed conductor impractical
- Instead, winding the cable directly into grooved mandrels
- Support provided by mandrels
- 1 mm spacing between cable and mandrel

Questions to answer

- Will the cable degrade at high cyclic operating loads?
    - Axial tensile loads before the cable hits the wall
    - Transverse compressive loads once hitting the wall
- Can the current be ramped at rates of about 10 kA/s needed to provide the flux swings?
    - Does the current distribution remain homogeneous?
    - Will ramping losses overwhelm the cooling?

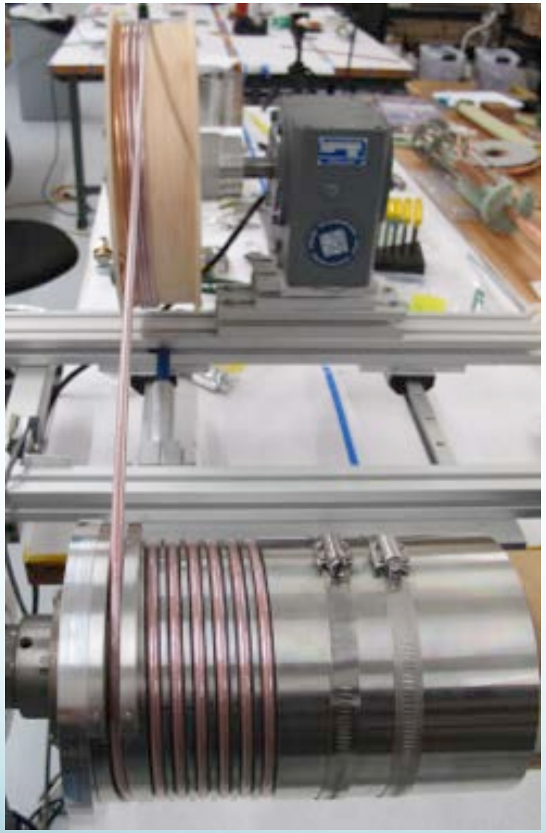


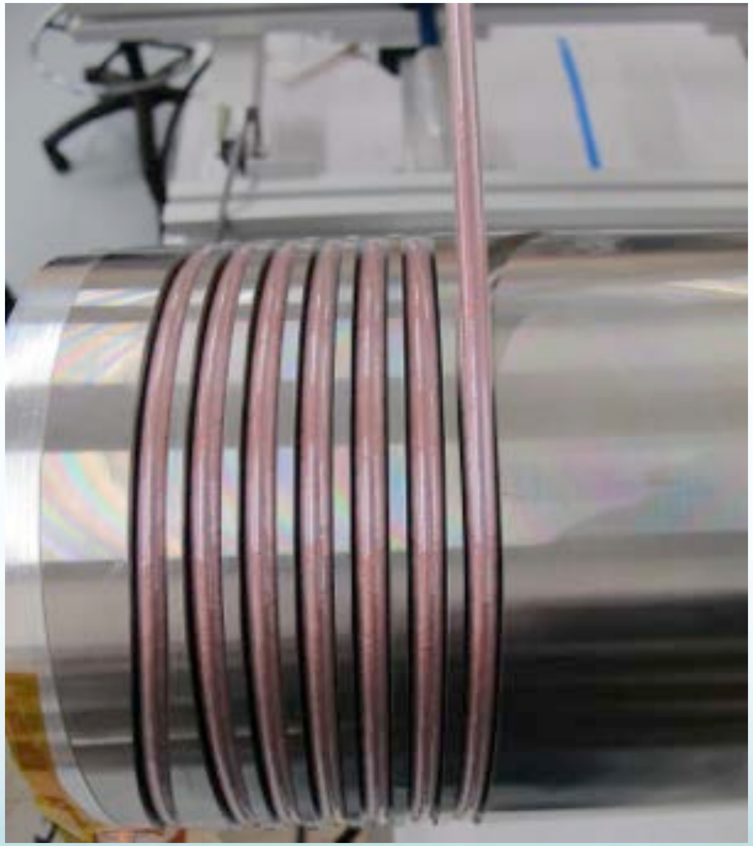


Ohmic Heating coil winding at ACT

Coil parameters

- 2-layers, 6 turns per layer
- About 8 meters of CORC® cable
- Cable wound from 16 tapes

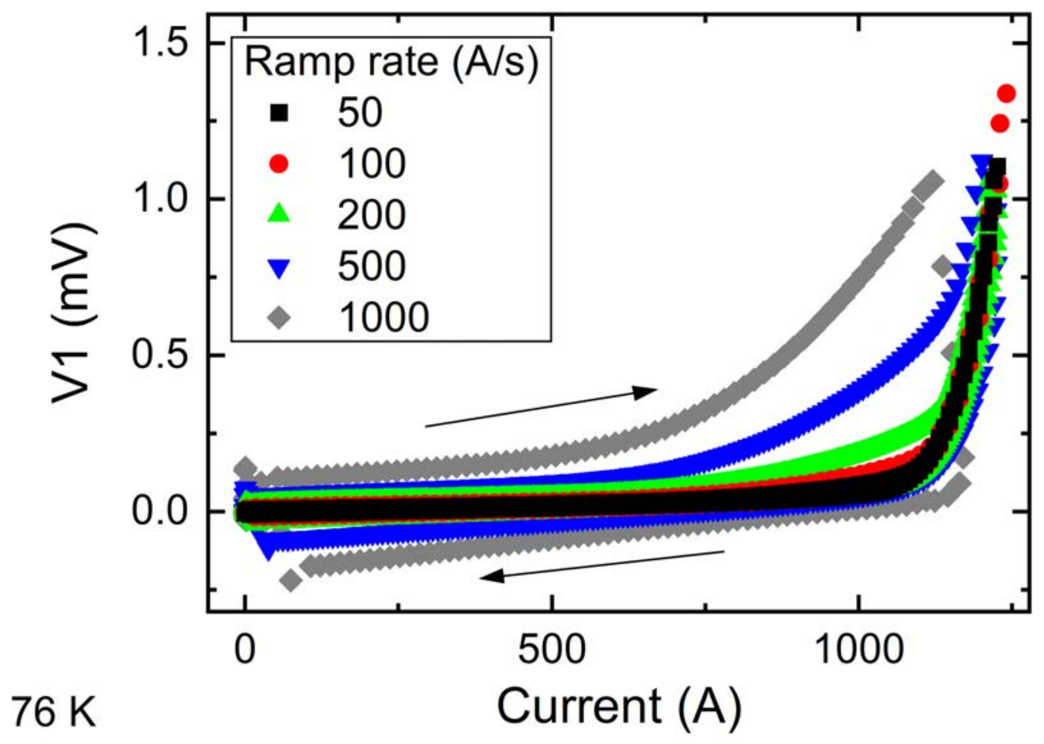


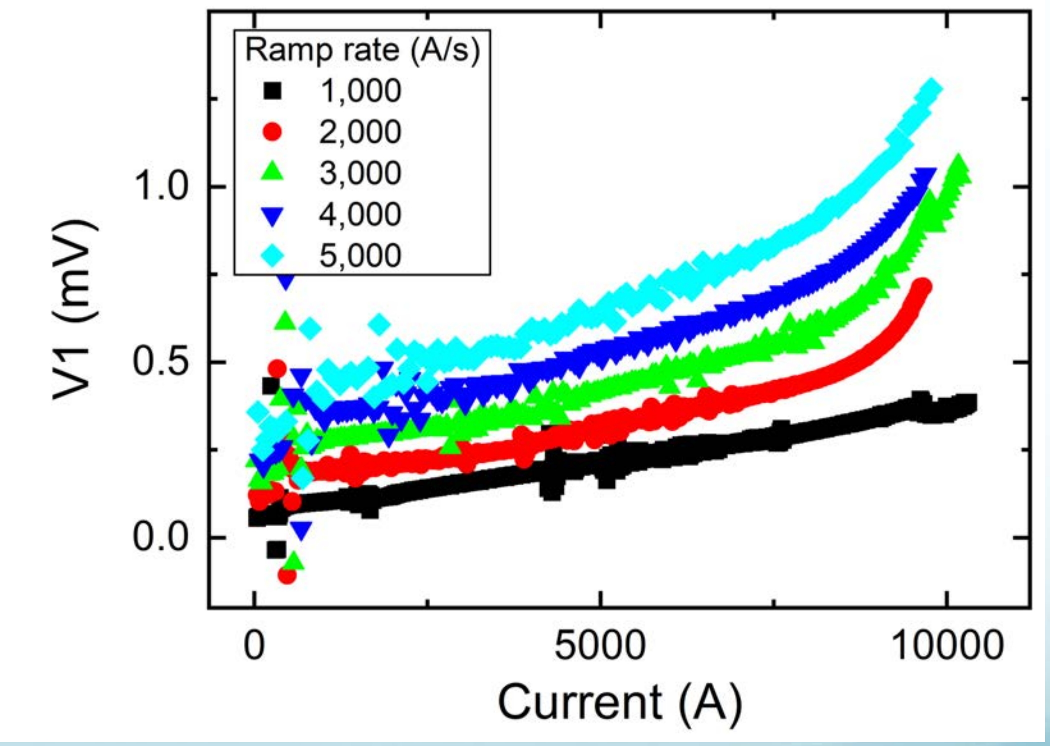


Testing of Ohmic Heating coil at high current ramp rates at ACT

Testing details

- Test stand-alone at ACT
- Coil operated in liquid nitrogen and in liquid helium
- Current ramp rates up to 5 kA/s to 10 kA at 4 K
- Current distribution stayed mostly homogeneous





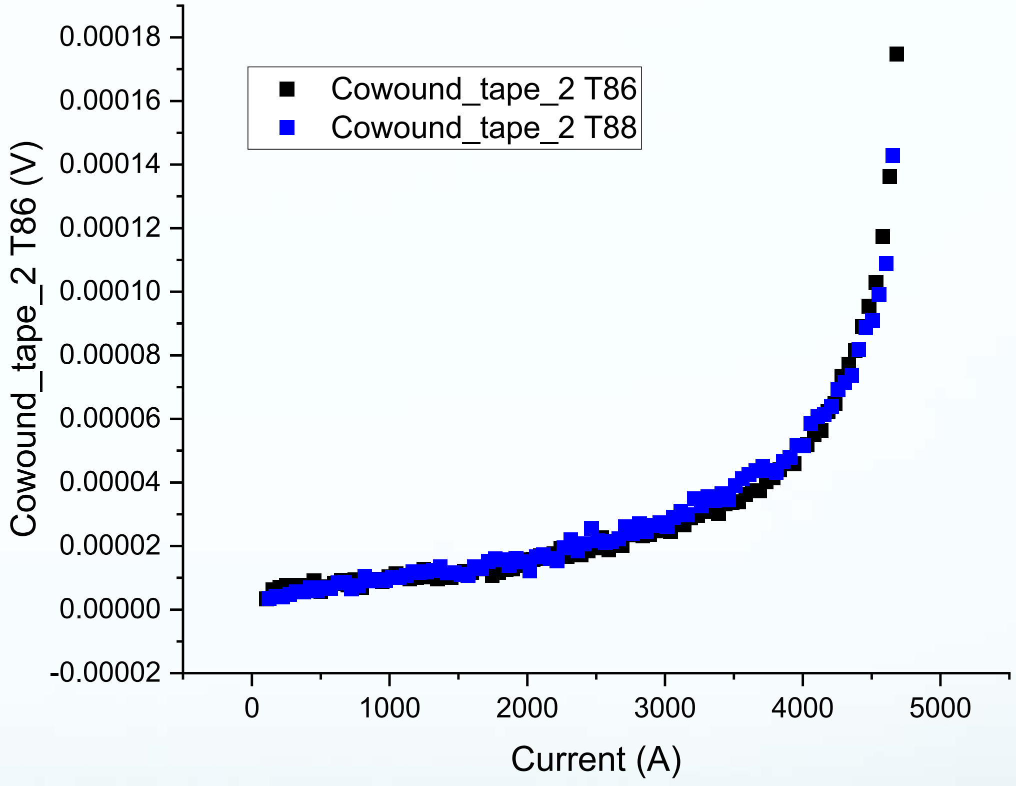
Advanced Conductor Technologies
www.advancedconductor.com

PPPL BROOKHAVEN NATIONAL LABORATORY NATIONAL HIGH MAGNETIC FIELD LABORATORY BERKELEY LAB

Testing of Ohmic Heating coil within a 12 T LTS outsert

Testing details

- Test in 12 T 160 mm bore outsert at ASC-NHMFL
- Repeated current ramping into transition at 4.6 kA in 12 T background field
- J_e 200 A/mm^2, JBr hoop stress 185 MPa (110 % of expected critical stress of cable
- No degradation after 68 stress cycles



Next steps

- Prepare set of CORC® OH coils with higher current and current density to allow higher JBr stresses of 200 to 500 Mpa
- Explore the effect of larger spacing between cable and support, requiring larger levels of axial elongation of the cable (1 – 2 % axial strain)

Advanced Conductor Technologies
www.advancedconductor.com

PPPL
BROOKHAVEN NATIONAL LABORATORY
NATIONAL HIGH MAGNETIC FIELD LABORATORY
BERKELEY LAB

Summary

Next generator of CORC® wires allow for much smaller bending diameters

- New winding and lubrication process is compatible with high-surface-roughness REBCO tapes
- Bending to below 50 mm diameter at 90 % I_c retention
- Bending to below 35 mm diameter at almost 80 % I_c retention
- SuperPower HM tapes now allow for long-length CORC® wires with J_e(20 T) > 400 A/mm^2

CORC® Common Coil insert development

- Allowing the use of CORC® cables that are less flexible than CORC® wires
- Coil support and winding technology compatible with CORC® have been developed
- Low-field CORC® Common Coil insert has been wound and initial tests performed in the outsert at BNL
- The high-field CORC® Common Coil insert is scheduled for winding and testing in Q2 2023

CORC®-based Ohmic Heating coils

- New coil concept for Ohmic Heating coils has been developed that avoids epoxy impregnation and won't require winding of jacketed conductors to small diameters
- The coil concept has been proven, where the dry-wound CORC® cable didn't degrade after 68 cycles to 185 MPa by operating the coil at 4.6 kA in 12 T background field
- A range of CORC® OH coils that operate at higher stresses and at high current ramp rates are planned