Latest development of CORC® wires, cables, and cable-in-conduit-conductors and their implementation into prototype accelerator and fusion magnets

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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 < 60 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

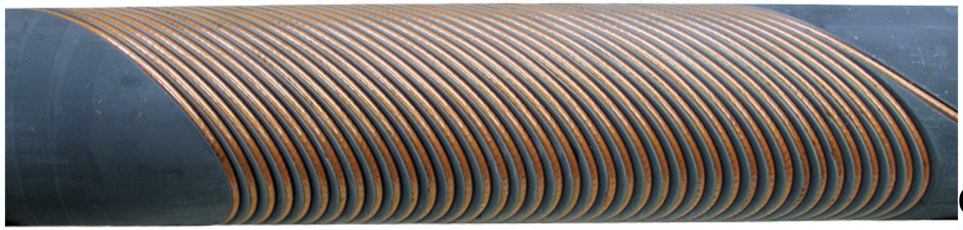
- Allowing high-current, high field coils to be wound without epoxy impregnation
- Withstanding high cyclic operating stresses at 20 kA and 20 T

CORC® wire development of CCT magnets developed at LBNL

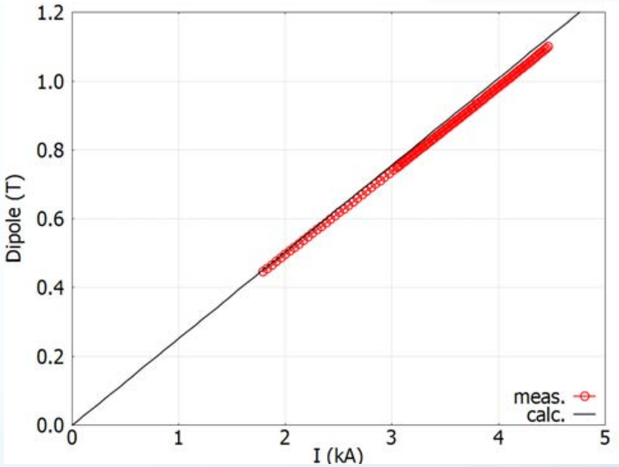
Program goal to reach 20 T dipole field by
- Demonstrating stand-alone CCT magnets at 1 T, 3 T, 5 T and 8 – 10 T
- Combining a 12 – 15 T LTS CCT outsert with a 5 – 8 T CORC® CCT insert

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

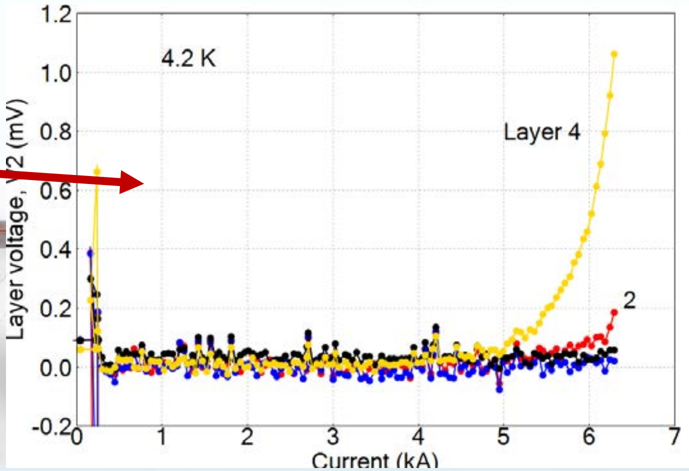


CORC® CCT-C1



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



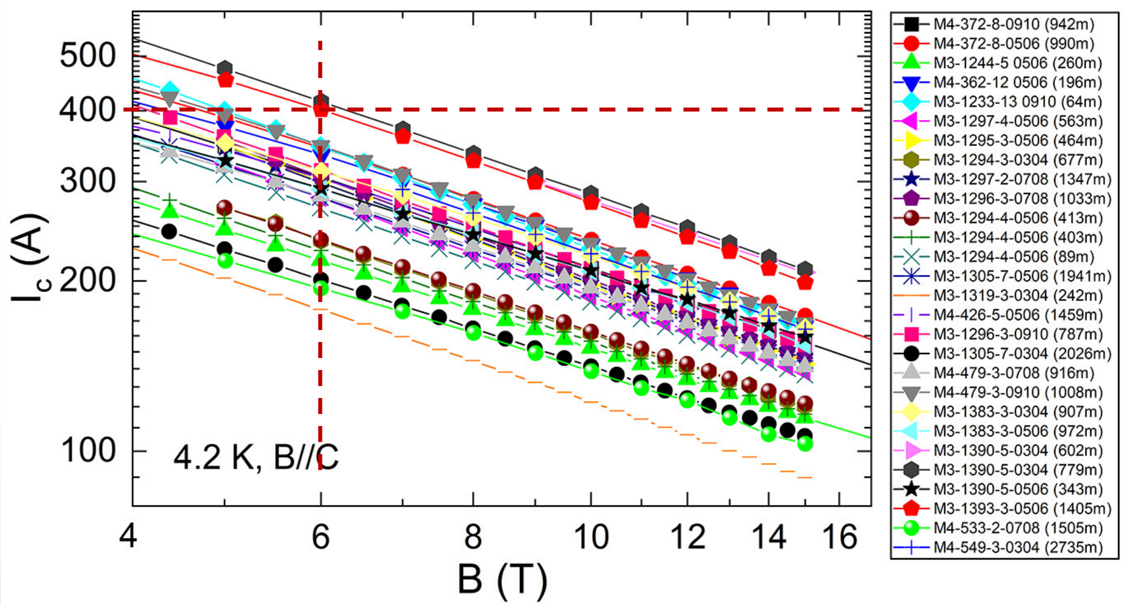
Development and performance of a 2.9 Tesla dipole magnet using high-temperature superconducting CORC® wires, X. Wang, et al., *Supercond. Sci. Technol.* **34**, 015012 (2021)

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

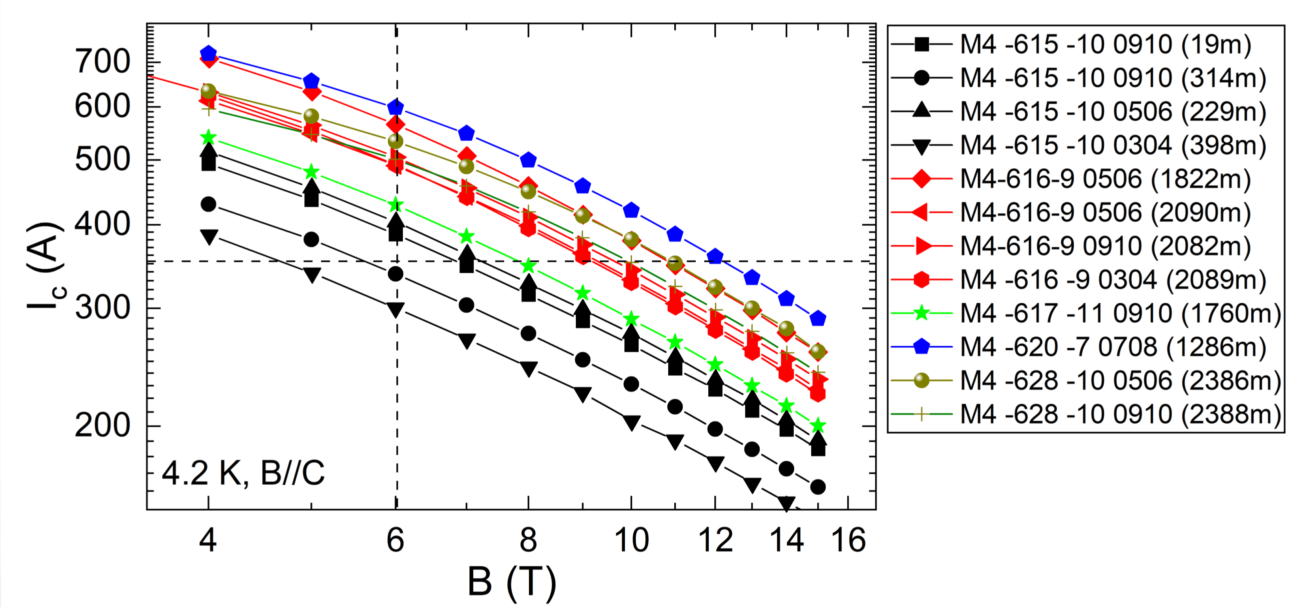
How to reach 5 T in CCT-C3?

- 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

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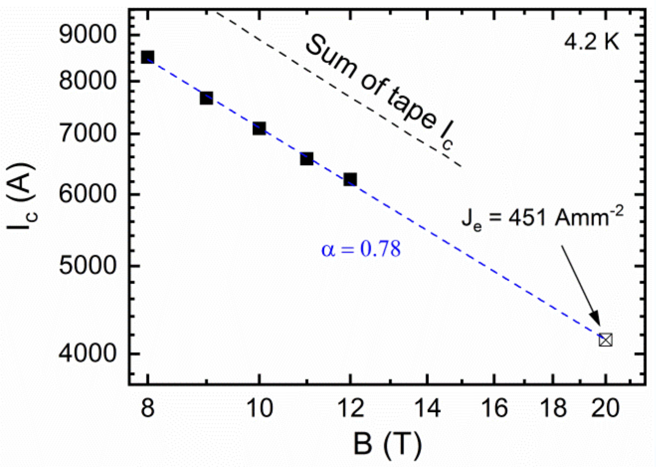
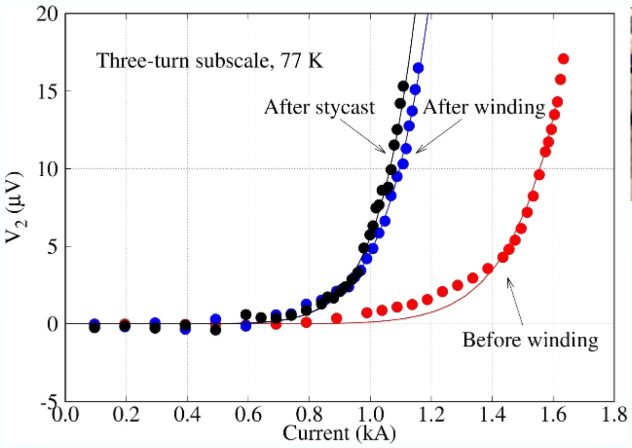
HM-based CORC® wire performance: early-2022 process (P1)

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



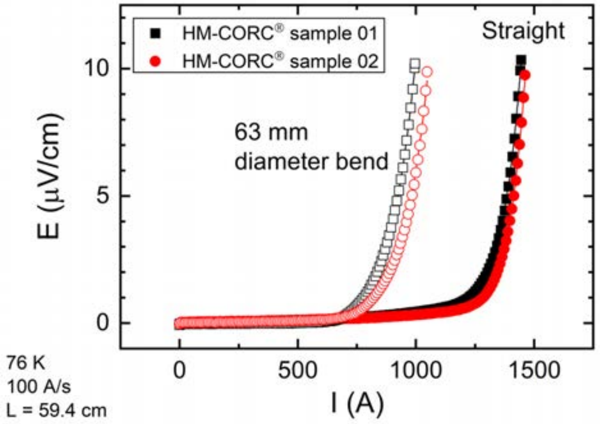
J.D. Weiss, et al., *Supercond. Sci. Technol.* **33**, 044001 (2020)



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 early 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

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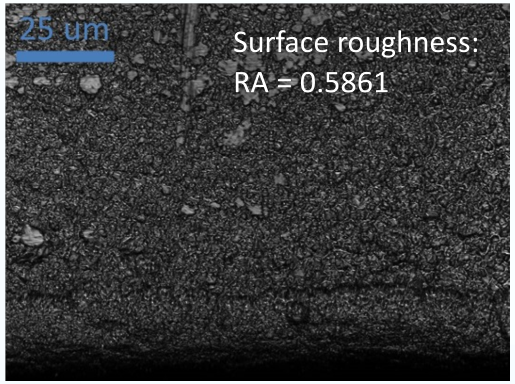
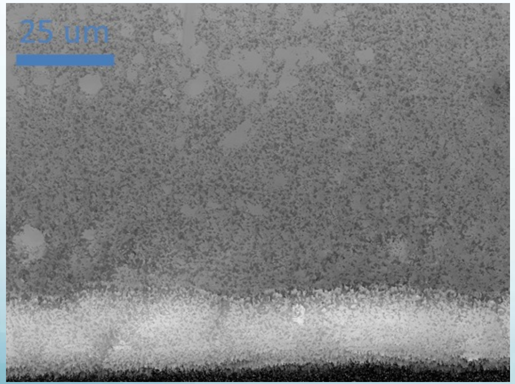
Cause of loss in CORC® wire flexibility

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

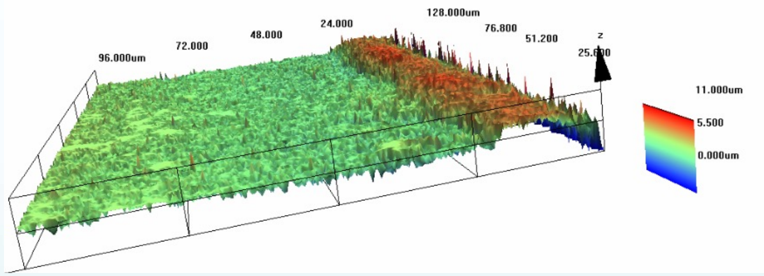


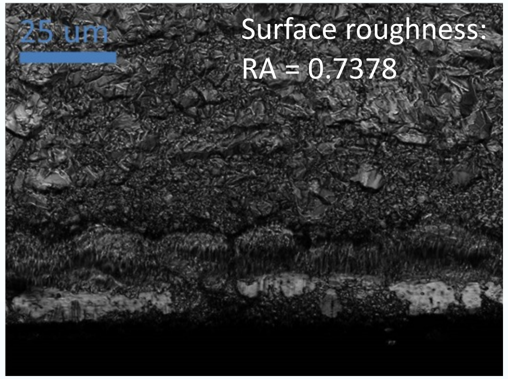
2016 – 2020 SCS-2030-AP tape



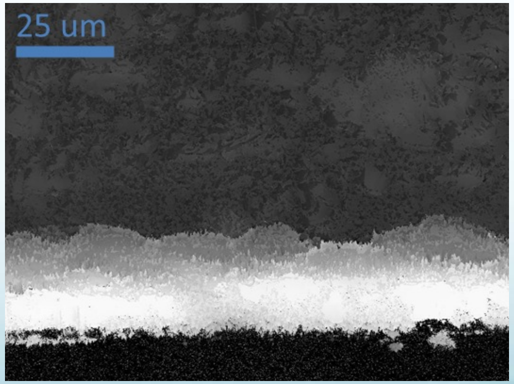
Height map

Tape edge



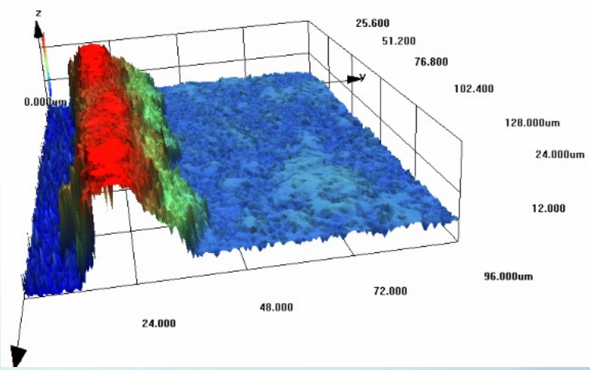


2021 – 2022 SCS-2030-HM tape



Height map

10-20 μm thick,
Intermittent burr

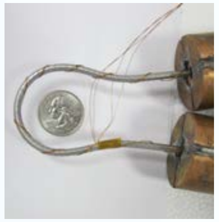


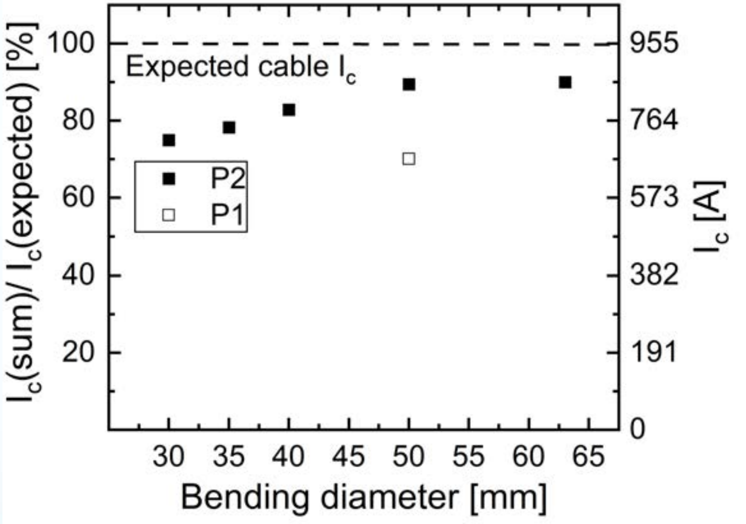
Next generation CORC® wire performance (late 2022)

Development of new winding and lubrication process (P2)

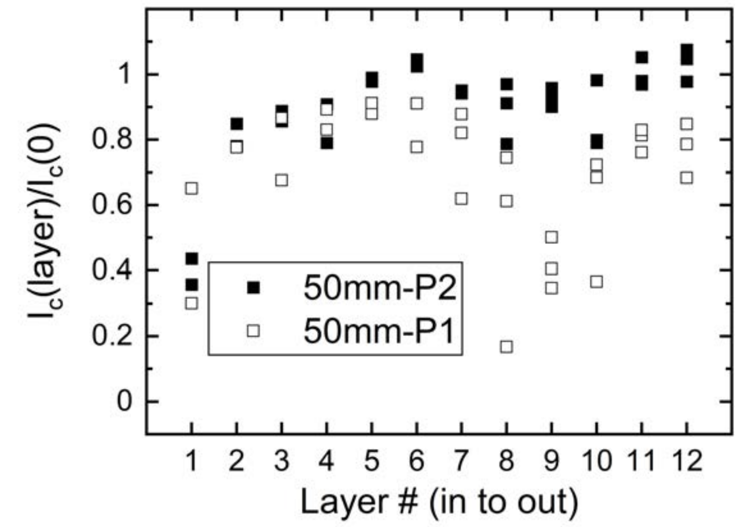
- Should allow CORC® wire bending to at least 60 mm diameter with use of “rough” tapes
- Should be applicable to long-length CORC® wire production

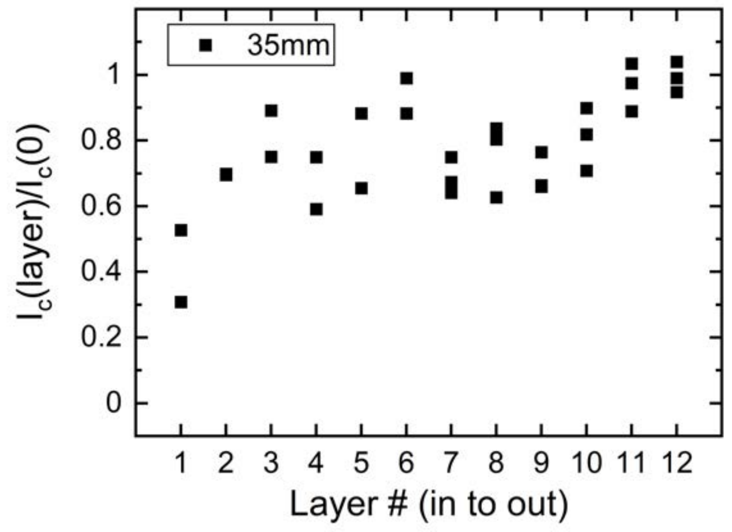
Next generation CORC® wires bending performance





Extracted tape I_c after bending





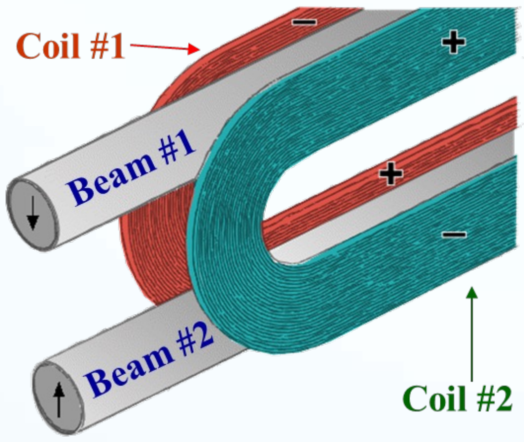
Next generation 30-tape CORC® wire bending

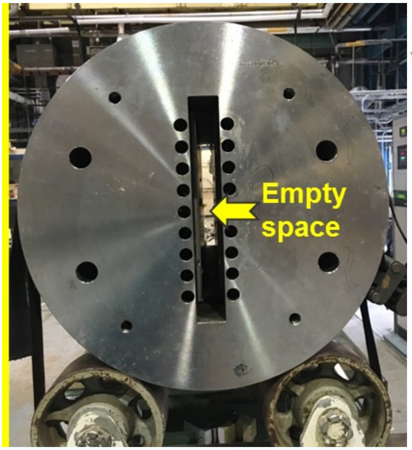
- I_c retention **90 % at 50 mm diameter bend** and around **80 % at 35 mm diameter bend**
- Should provide CCT-C3 with much larger margin in I_c than the 70 % used in its design

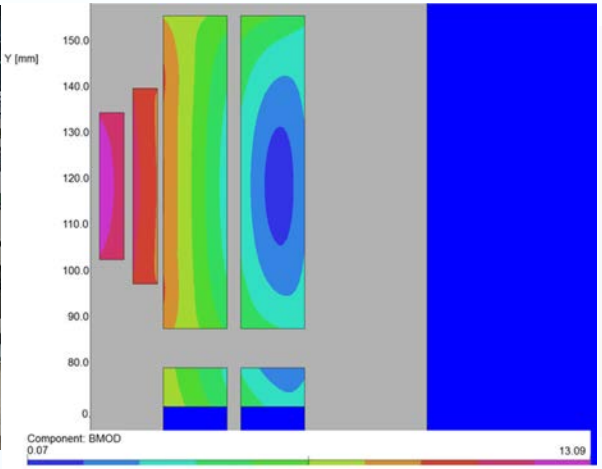
CORC®-based Common Coil development

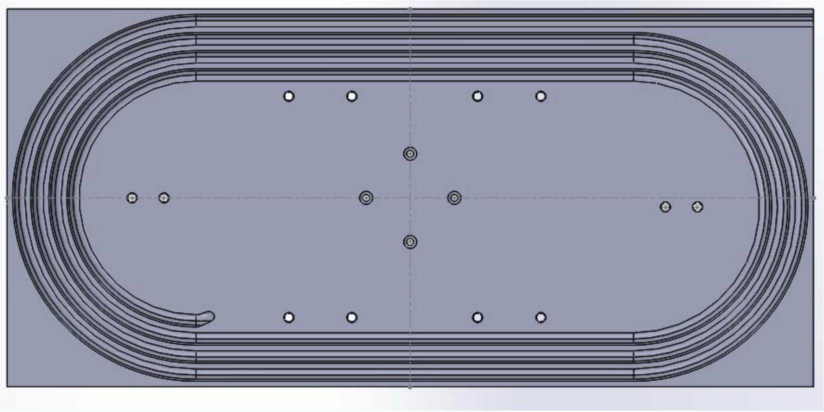
CORC® Common Coil program goals

- 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

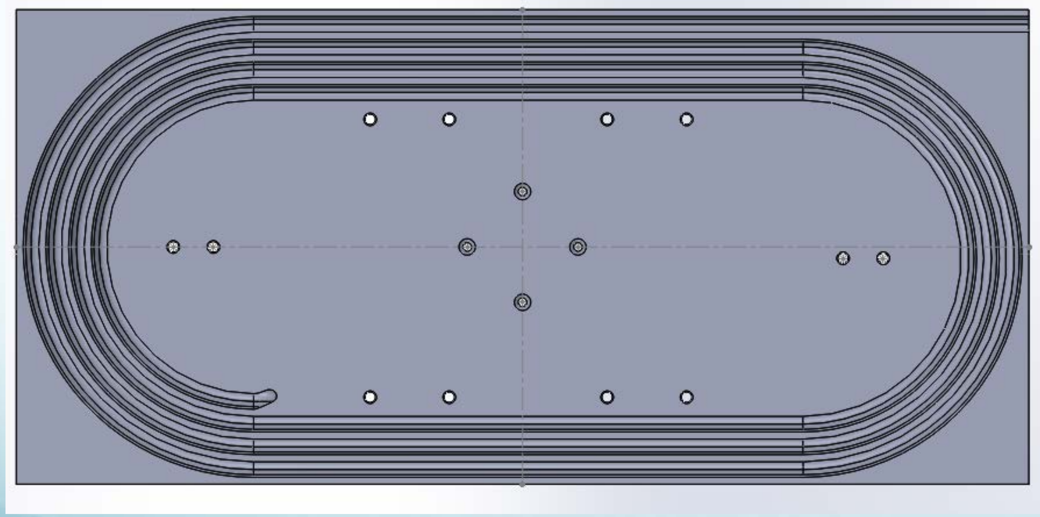
Common Coil inserts

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

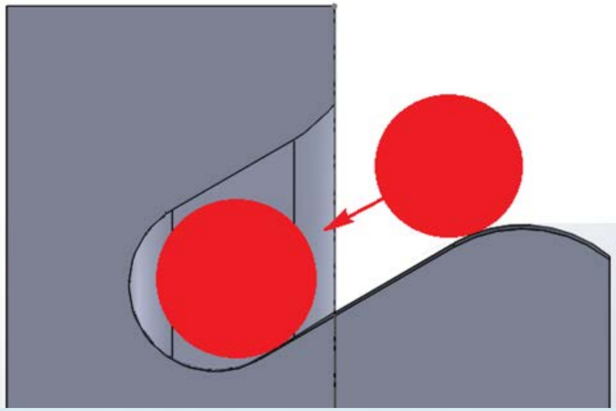
Coil structure requirements

- 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)

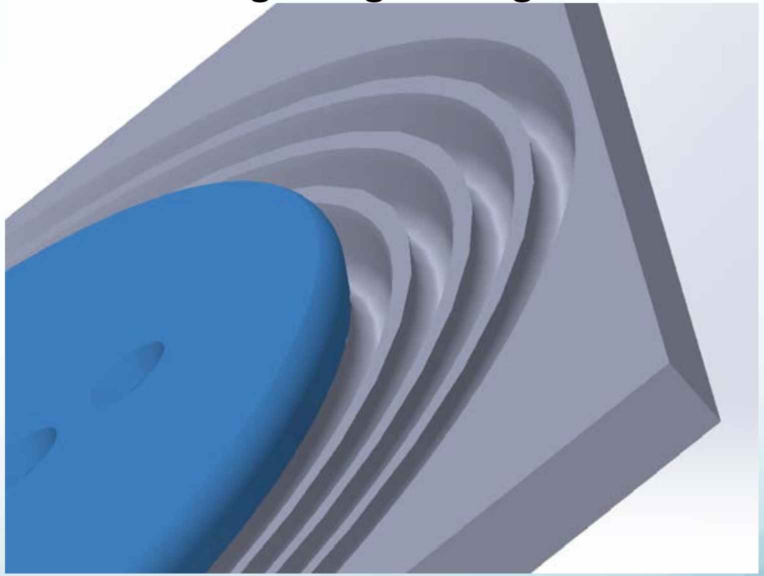
4-turn single CORC® pancake



CORC® cable sliding into slamted groove



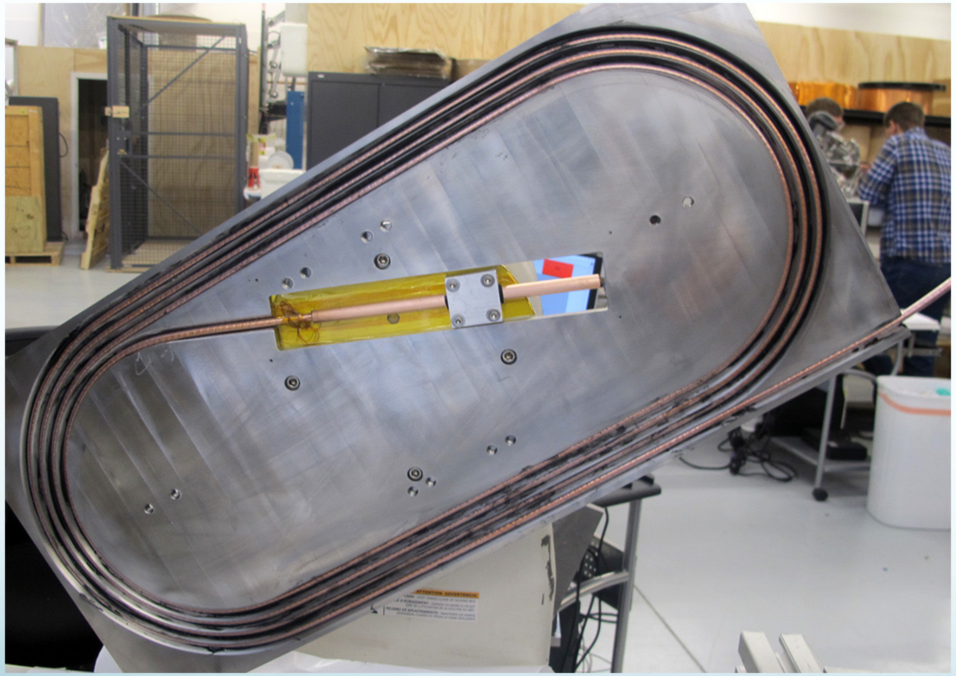
Winding using cable guides

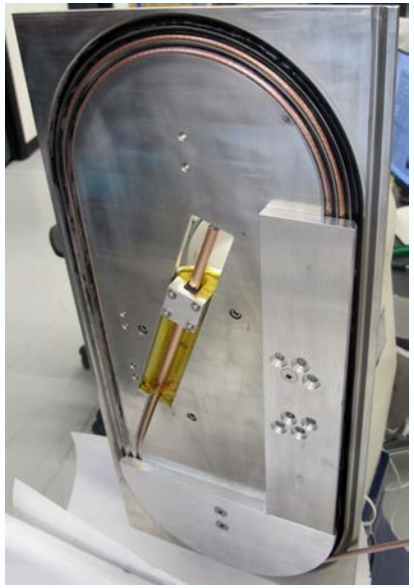


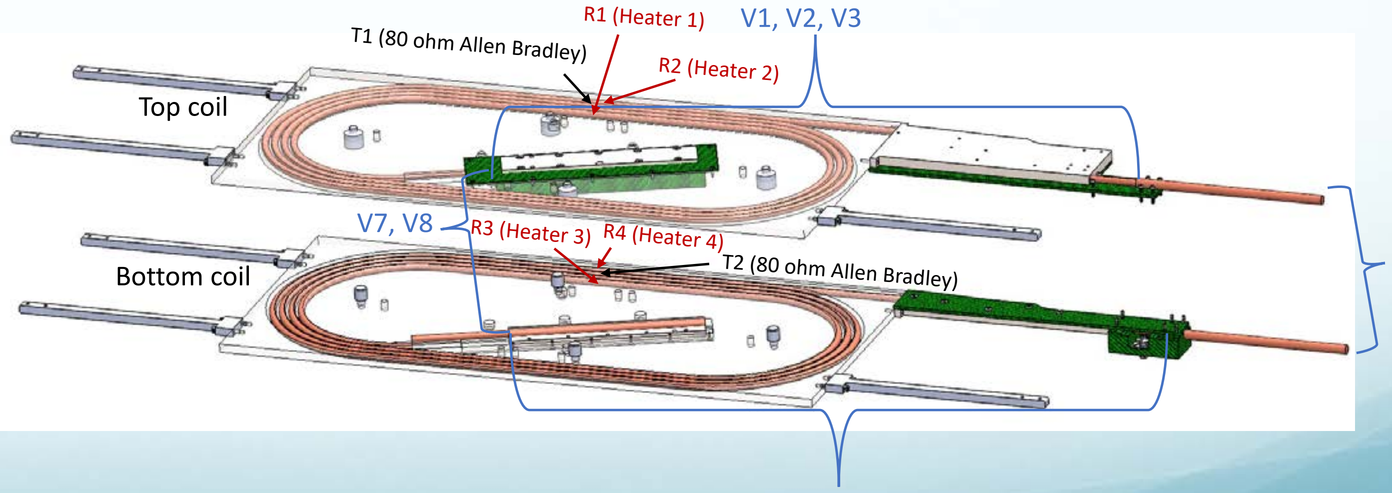
Winding of low-field CORC® Common Coil insert at ACT

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



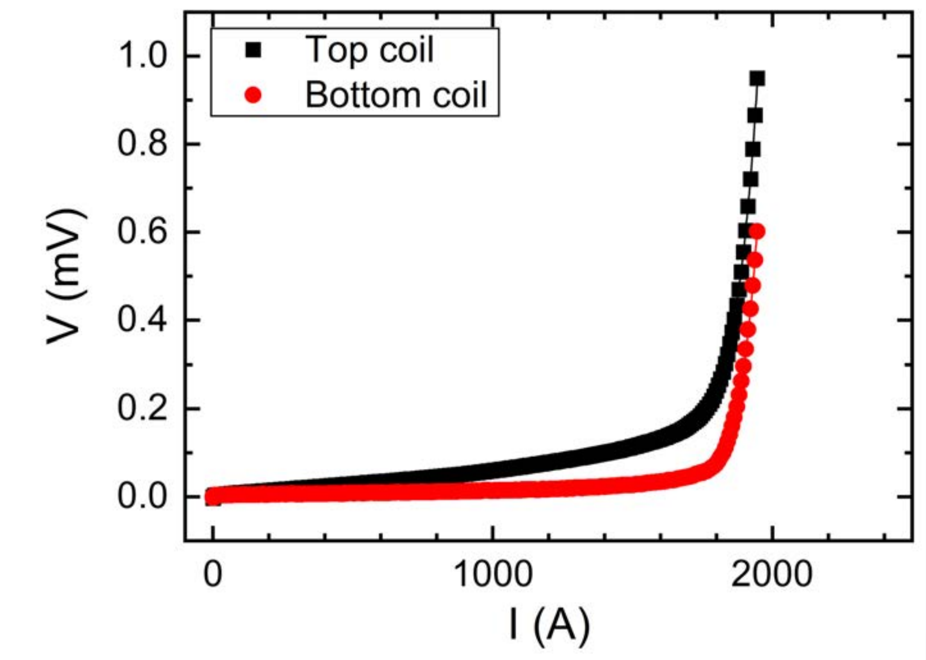


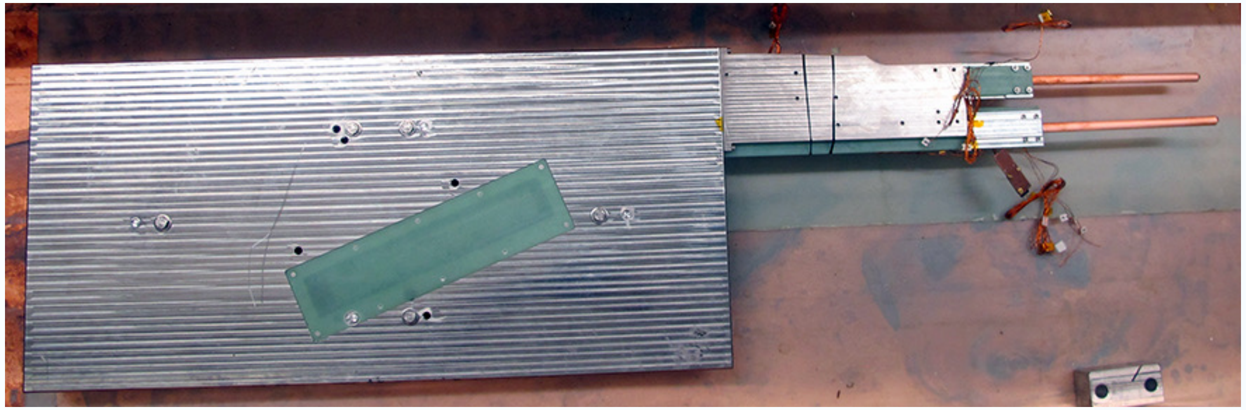


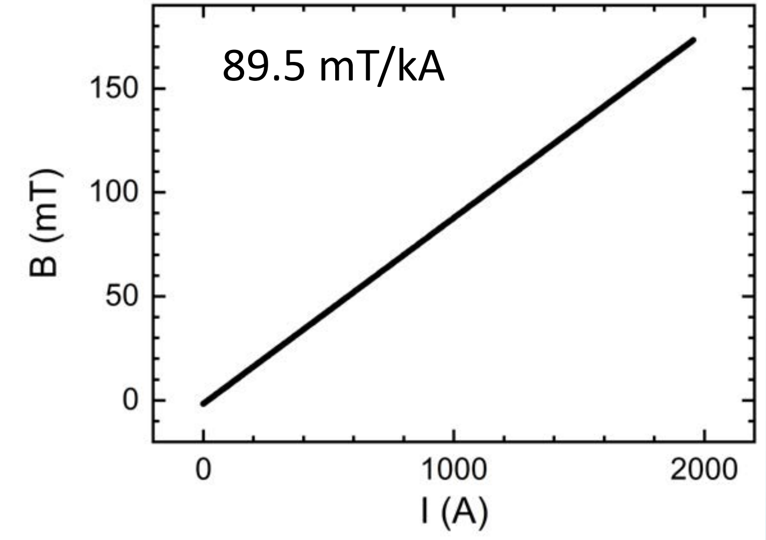
76 K test of low-field CORC® Common Coil insert at ACT

Initial performance test in liquid nitrogen at ACT

- Cable transition at 1.9 kA
- Field generated 170 mT







Common Coil installation

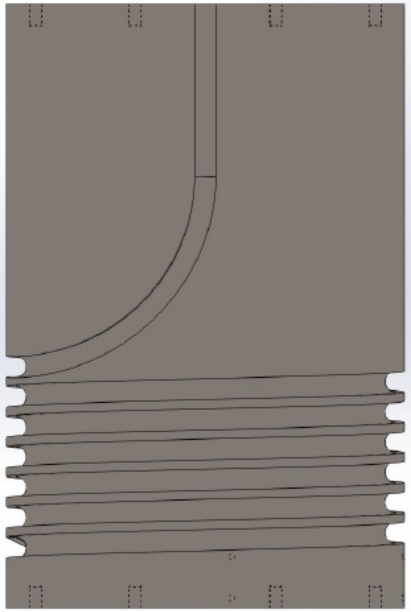
- Low-field Common Coil insert installed at BNL in their LTS outsert August 2022
- Coil test scheduled for December 2022

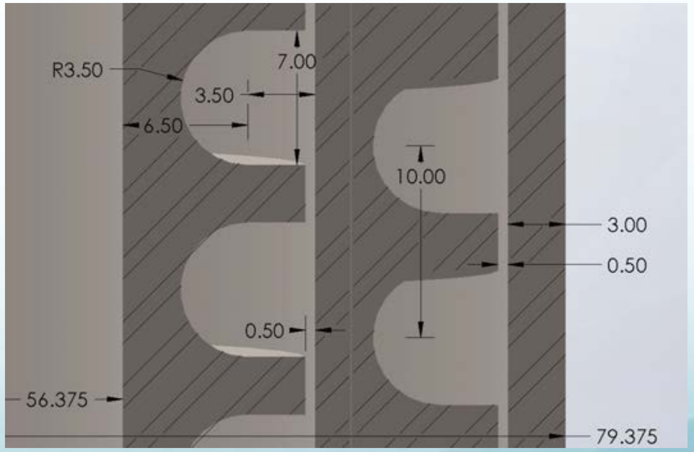
Development of prototype Ohmic Heating coil for compact fusion reactors

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

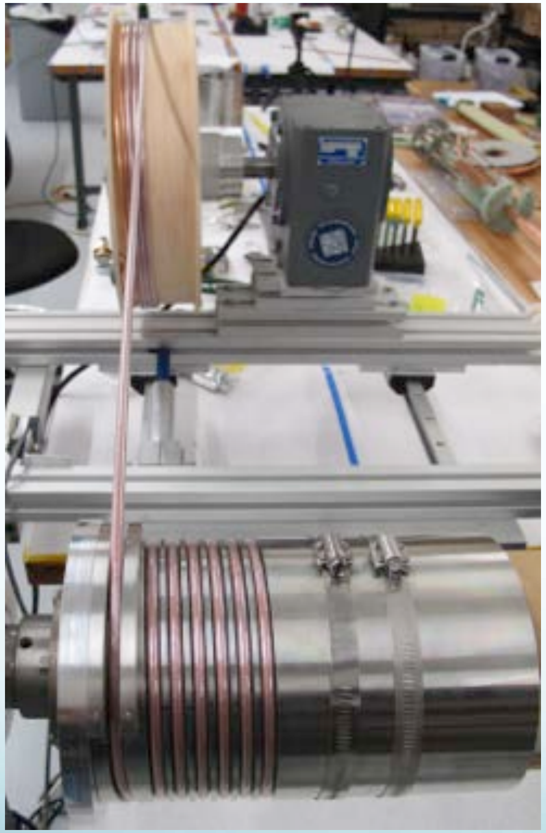
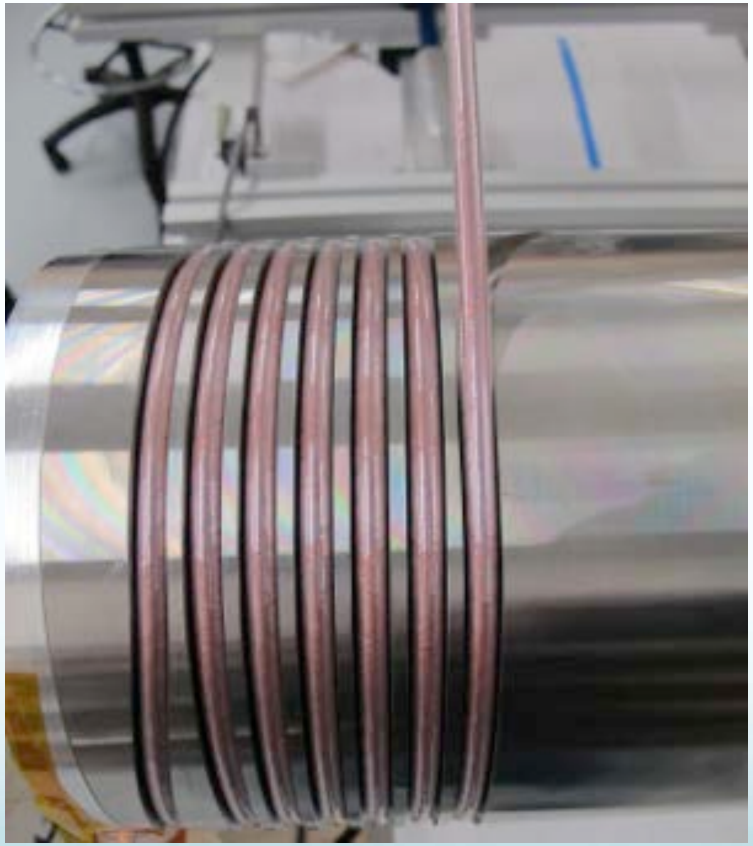
Questions to answer
- Will the cable degrade at high cyclic operating loads?
    - Axial tensile loads before the cable hits the wall
    - Transverse compressive loads once hitting the wall
- Can the current be ramped at rates of about 10 kA/s needed to provide the flux swings?
    - Does the current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





Ohmic Heating coil winding at ACT

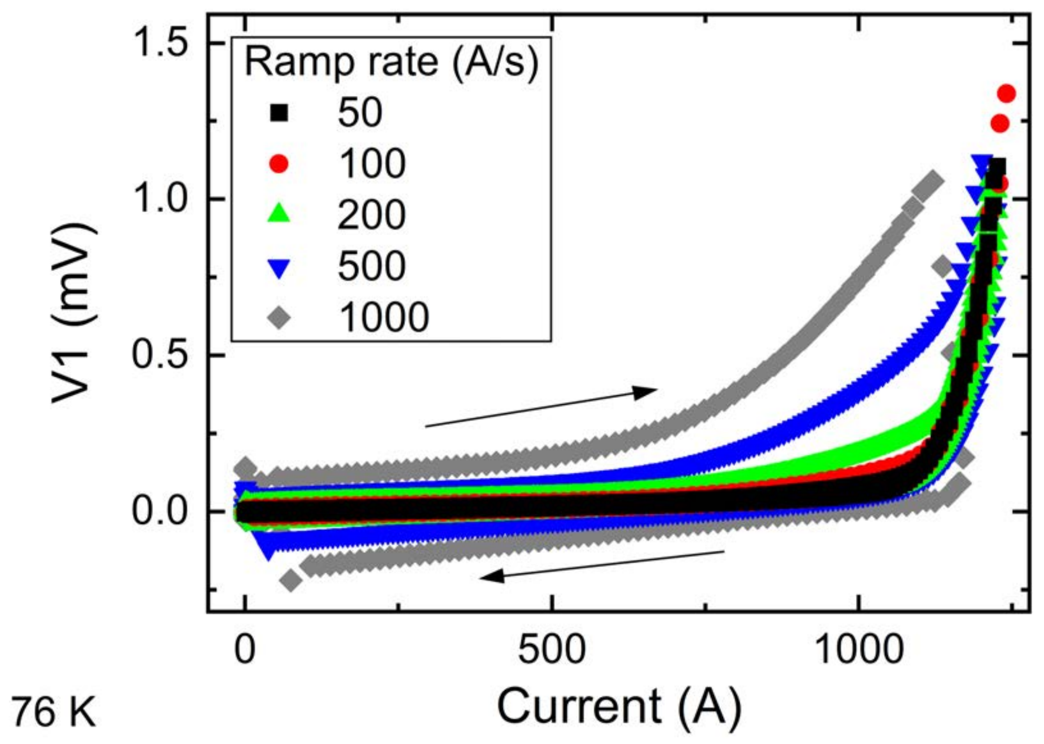
Coil parameters
- 2-layers, 6 turns per layer
- About 8 meters of CORC® cable
- Cable wound from 16 tapes

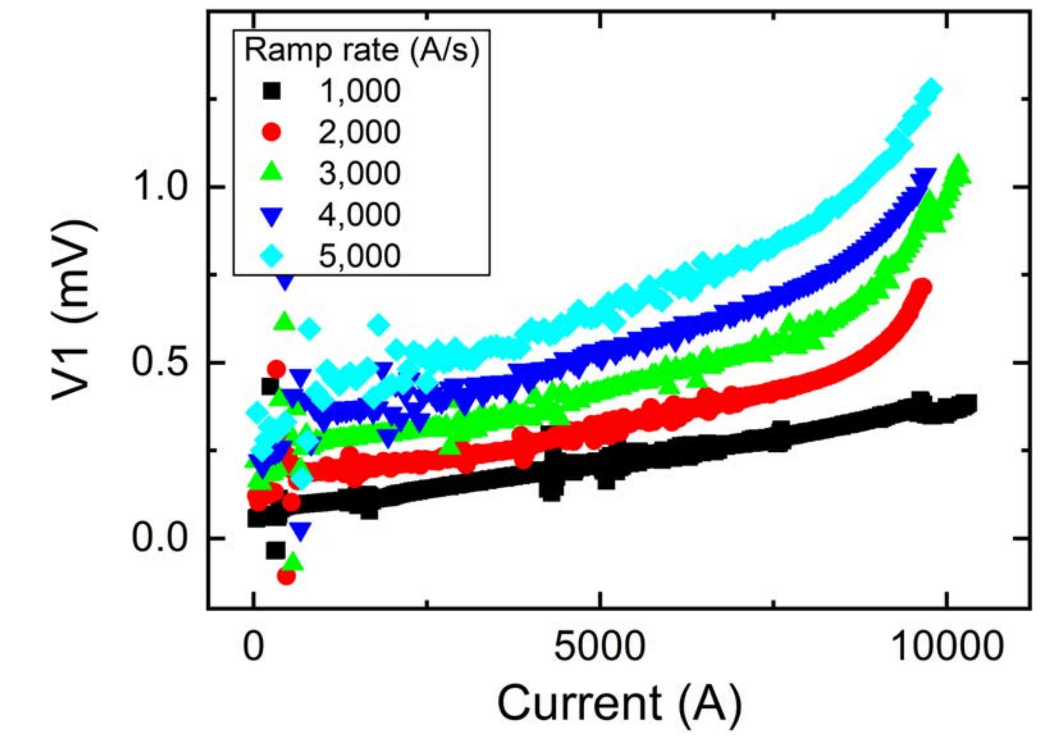




Testing of Ohmic Heating coil at high current ramp rates at ACT

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





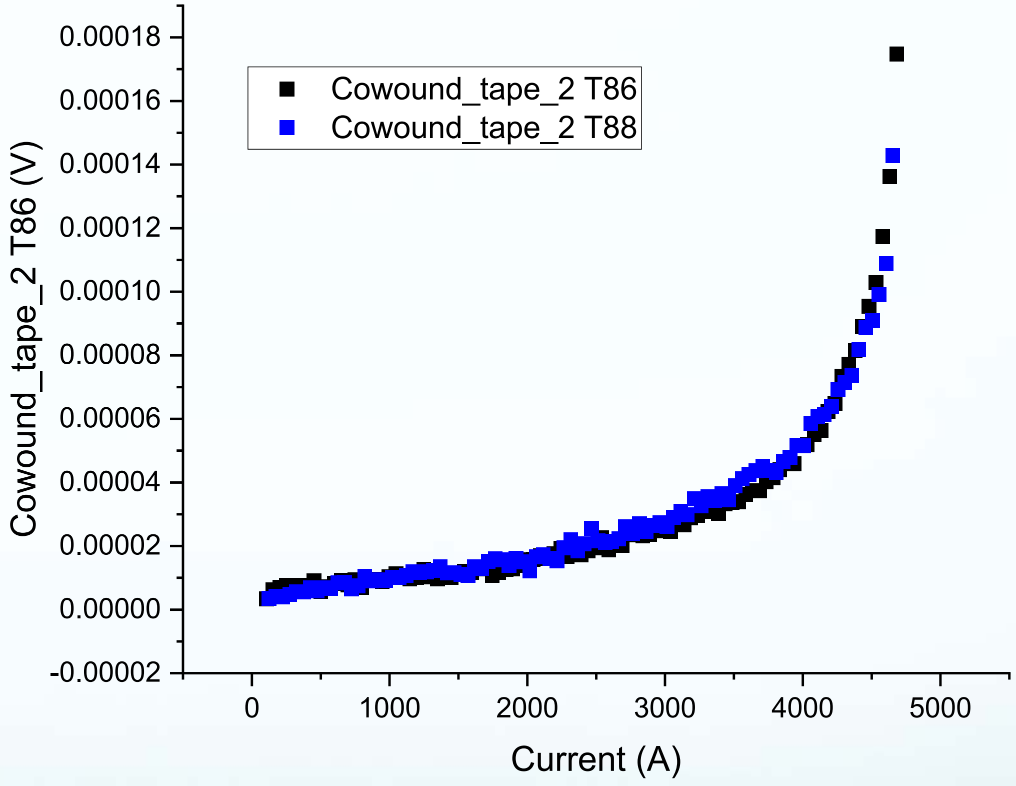
Testing of Ohmic Heating coil within a 14 T LTS outsert

Testing details

- Test in 14 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)



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 installed into the 10 T outsert at BNL
- The high-field CORC® Common Coil insert is scheduled for winding and testing in early 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