

# Latest development of CORC<sup>®</sup> cables and wires for high-field magnets for compact fusion reactors and particle accelerators

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# CORC<sup>®</sup> cables and wires for high-field magnet applications

## CORC<sup>®</sup> wires (2.5 – 4.5 mm diameter)

- Wound from 2 – 3 mm wide tapes with 25 and 30  $\mu\text{m}$  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<sup>®</sup> cable (5 – 8 mm diameter)

- Wound from 3 – 4 mm wide tapes with 30 – 50  $\mu\text{m}$  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



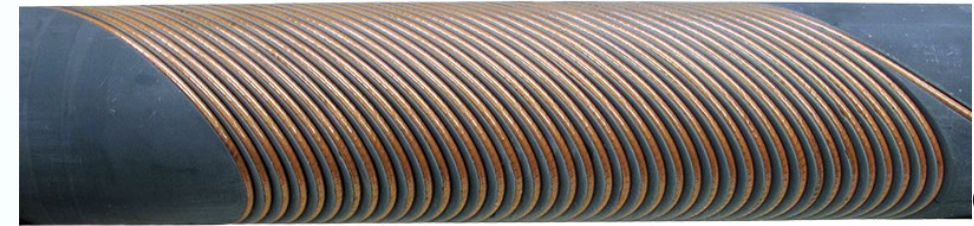
# CORC<sup>®</sup> wire development of CCT magnets developed at LBNL

## 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<sup>®</sup> CCT insert

## Successful demonstration of 1.2 T (CCT-C1)

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



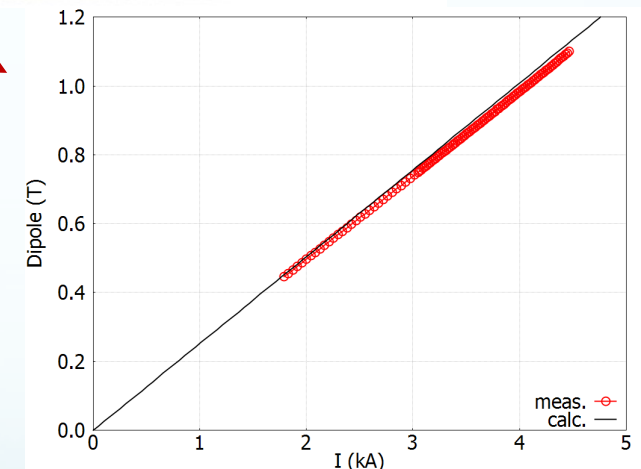
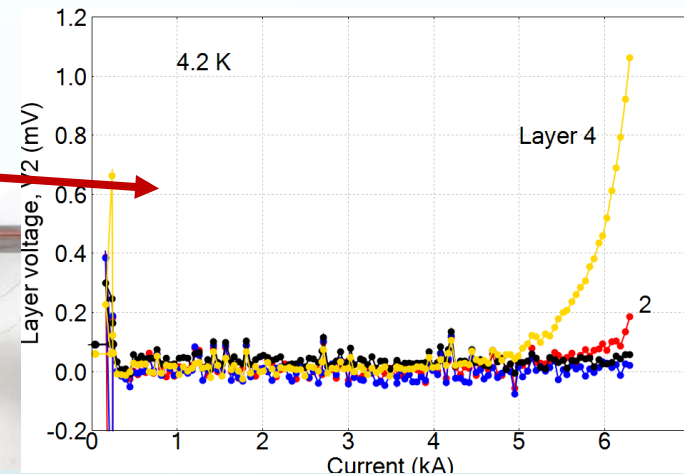
CORC<sup>®</sup> CCT-C1

## Successful demonstration of 2.9 T (CCT-C2)

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



CORC<sup>®</sup> CCT-C2



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

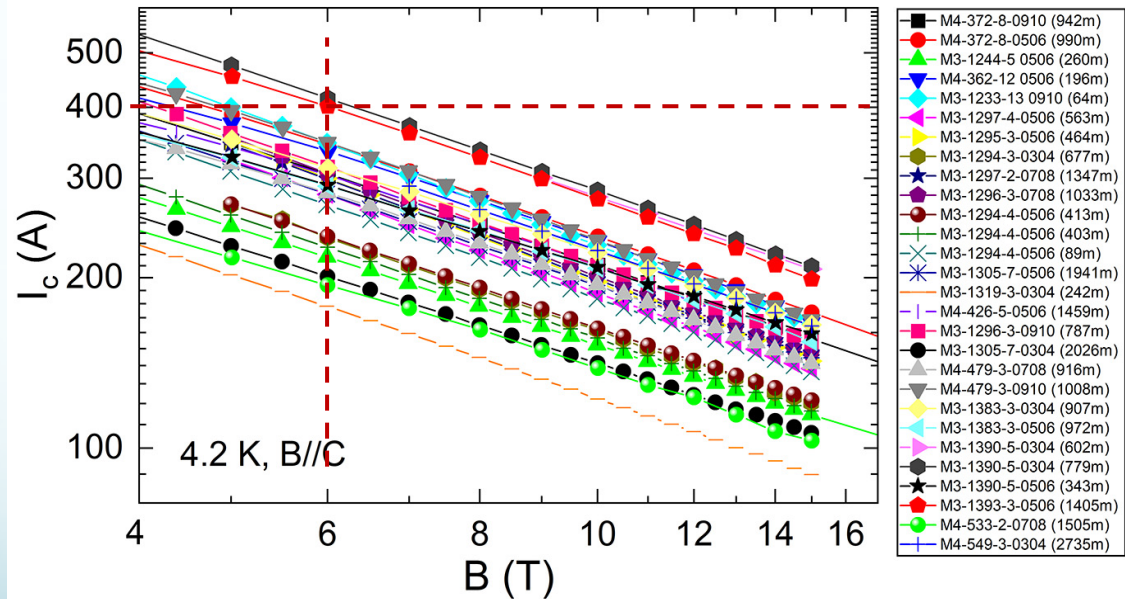


# CORC<sup>®</sup> wire development for magnet CCT-C3 (5 T)

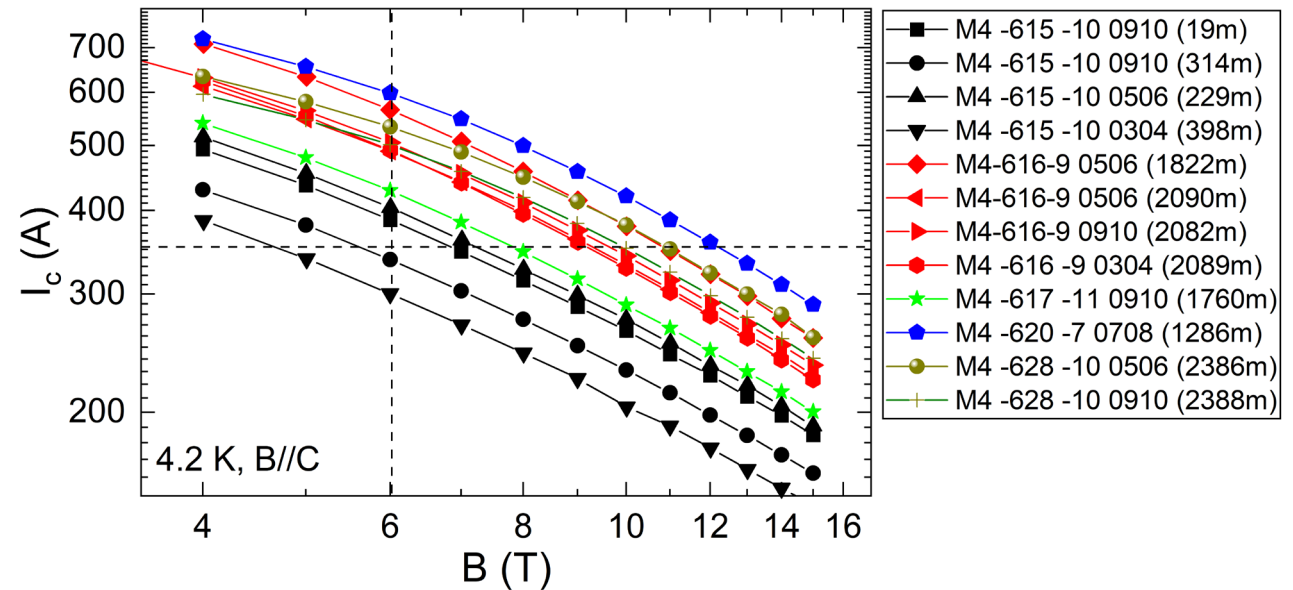
## How to reach 5 T in CCT-C3?

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

Performance of SuperPower SCS2030-AP tape 2016 - 2020



Performance of SuperPower SCS2030-HM tape 2021 - 2022



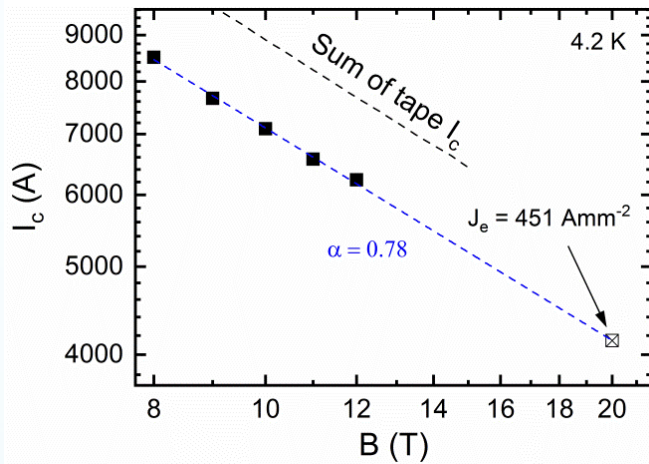
**All 10 km of SuperPower SCS-2030-HM tapes have been received and qualified**



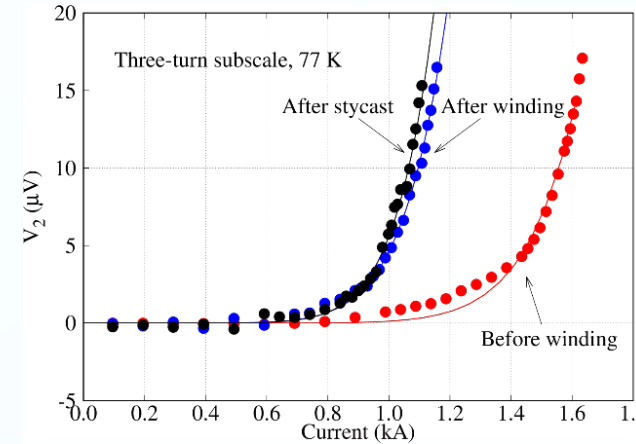
# HM-based CORC<sup>®</sup> wire performance: early-2022 process (P1)

## CORC<sup>®</sup> 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  $J_e(20\text{ T})$  of 450 A/mm<sup>2</sup> (63 mm bending diameter) demonstrated



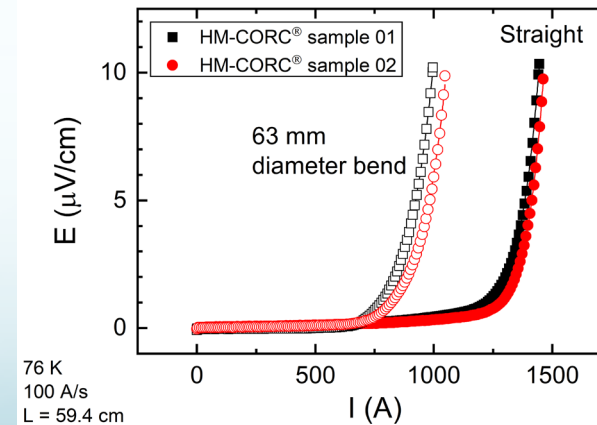
J.D. Weiss, et al., *Supercond. Sci. Technol.* **33**, 044001 (2020)



AP-tape CORC<sup>®</sup>  
CCT mandrel

## CORC<sup>®</sup> wire performance early 2022 (HM tape based)

- Long-length  $J_e(20\text{ T})$  of 400 – 450 A/mm<sup>2</sup> 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**



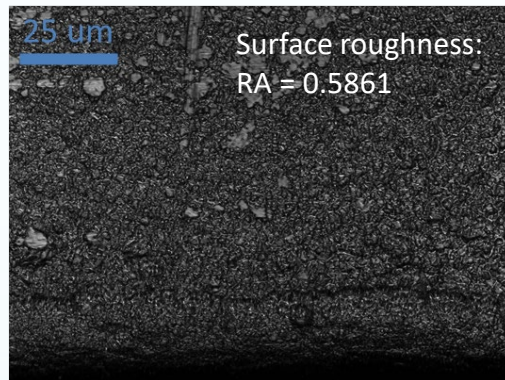
HM-tape CORC<sup>®</sup>  
Hairpin bend



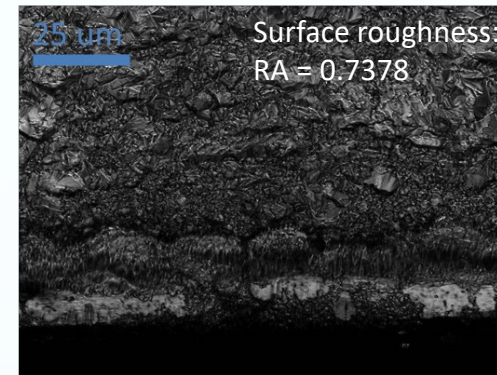
# Cause of loss in CORC<sup>®</sup> wire flexibility

## Cause of loss in bending performance HM-based CORC<sup>®</sup> wires using process P1

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

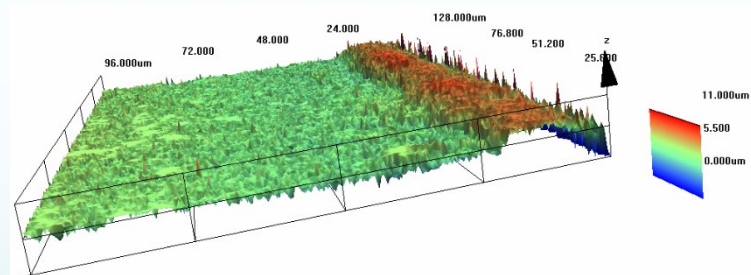


2016 – 2020 SCS-2030-AP tape

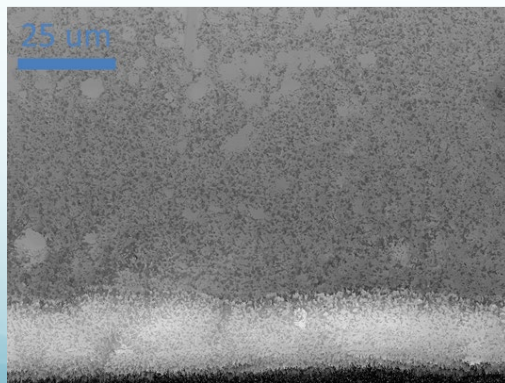
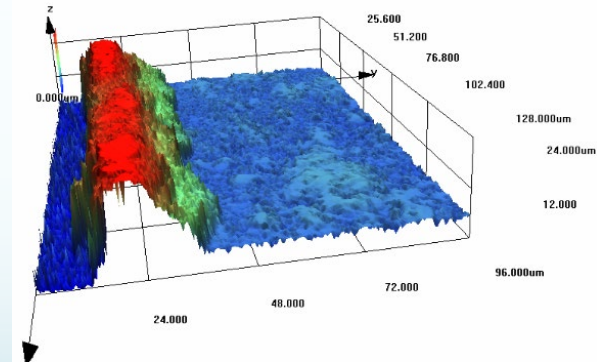


2021 – 2022 SCS-2030-HM tape

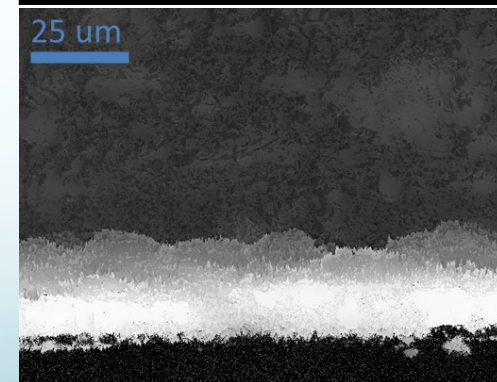
Tape edge



10-20  $\mu\text{m}$  thick,  
Intermittent burr



Height map



Height map



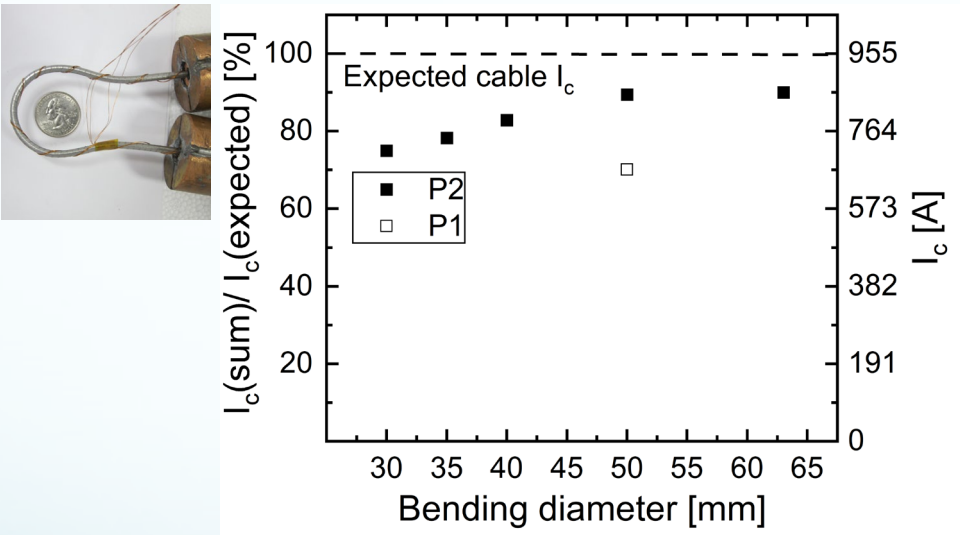
# Next generation CORC<sup>®</sup> wire performance (late 2022)

## Development of new winding and lubrication process (P2)

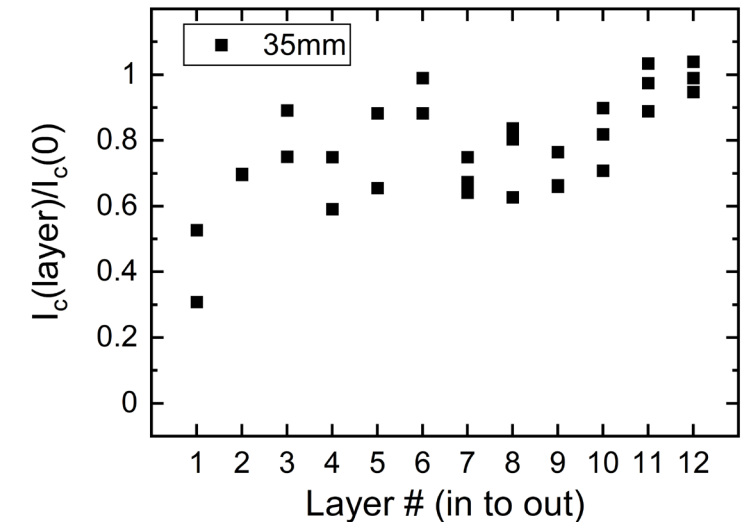
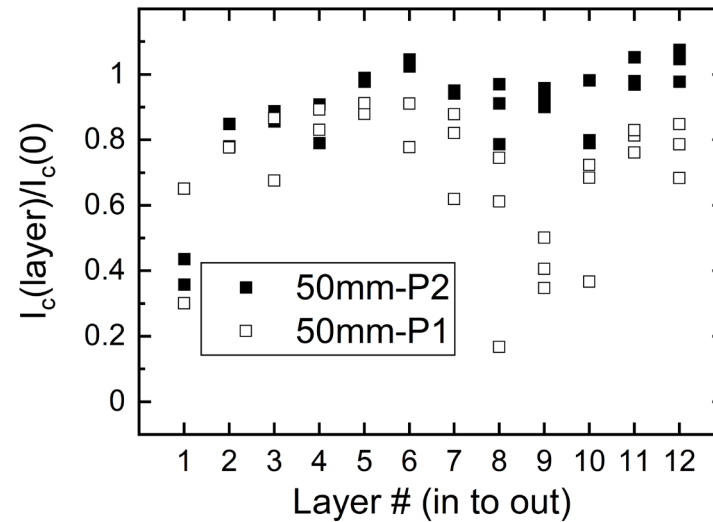
- Should allow CORC<sup>®</sup> wire bending to at least 60 mm diameter with use of “rough” tapes
- Should be applicable to long-length CORC<sup>®</sup> wire production



## Next generation CORC<sup>®</sup> wires bending performance



## Extracted tape $I_c$ after bending



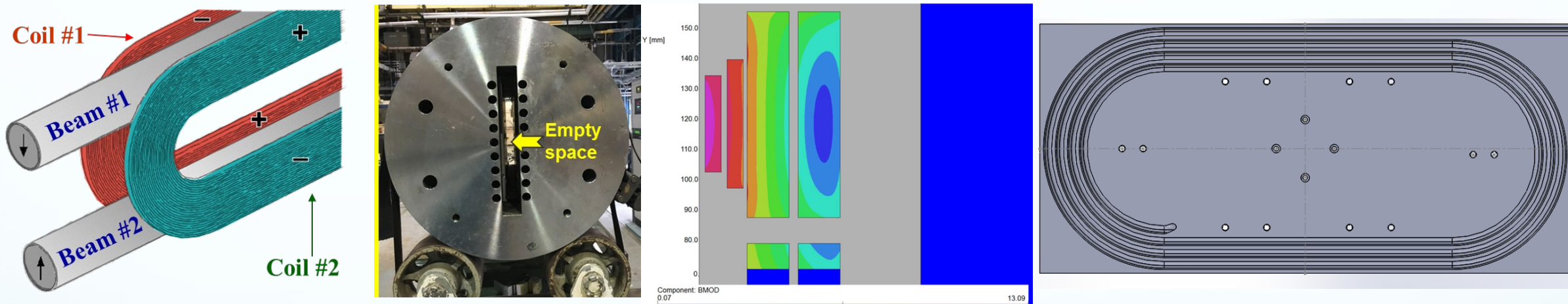
## Next generation 30-tape CORC<sup>®</sup> wire bending

- $I_c$  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<sup>®</sup>-based Common Coil development

## CORC<sup>®</sup> Common Coil program goals

- Develop a low-field CORC<sup>®</sup>-based insert to operate within the 10 T LTS outsert at BNL
- Verify the coil winding procedure and CORC<sup>®</sup> 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<sup>®</sup> cables for the Common Coil inserts (requires bending to 200 mm diameter only)

- CORC<sup>®</sup> cable based on 4 mm wide SuperOx tape for the low-field insert
- 5.5 mm diameter CORC<sup>®</sup> cable (SuperOx): 24 tapes (35  $\mu\text{m}$  substrate): expected  $J_e(20\text{ T})$  350 A/mm<sup>2</sup>
- CORC<sup>®</sup> 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<sup>®</sup> cable (SuperPower): 32 tapes (30  $\mu\text{m}$  substrate): expected  $J_e(20\text{ T})$  500 A/mm<sup>2</sup>





# Development of CORC<sup>®</sup>-compatible Common Coil support structure

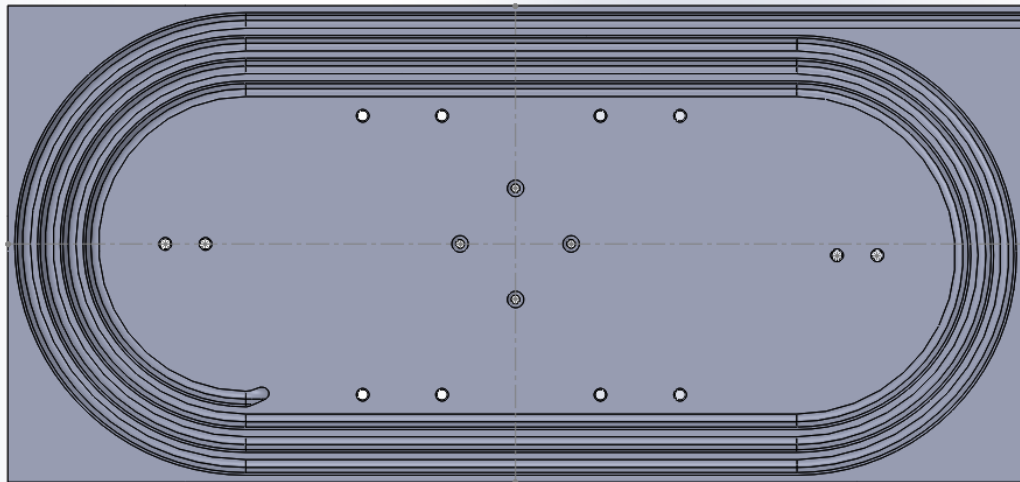
## Common Coil inserts

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

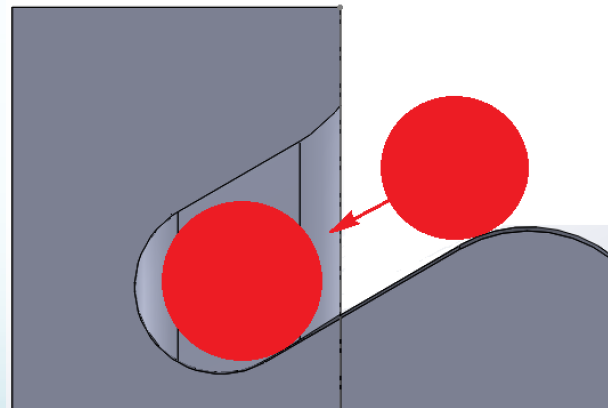
## Coil structure requirements

- Winding the CORC<sup>®</sup> 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)

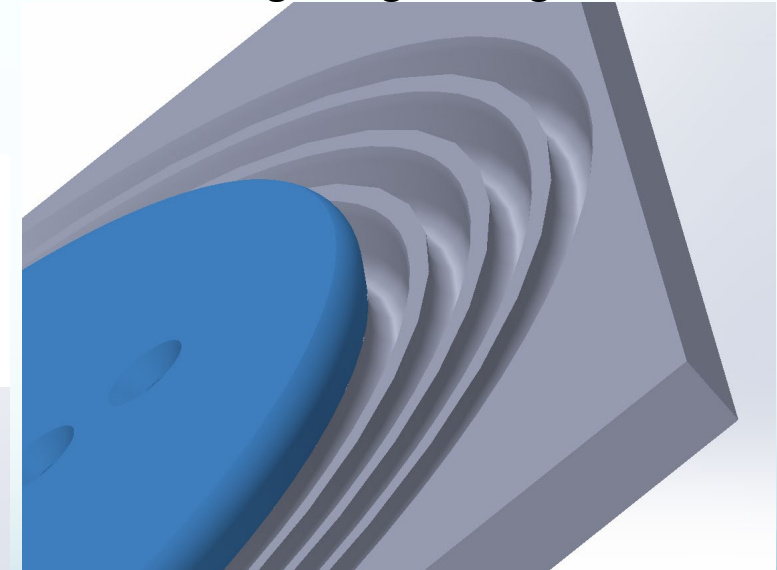
4-turn single CORC<sup>®</sup> pancake



CORC<sup>®</sup> cable sliding into slanted groove



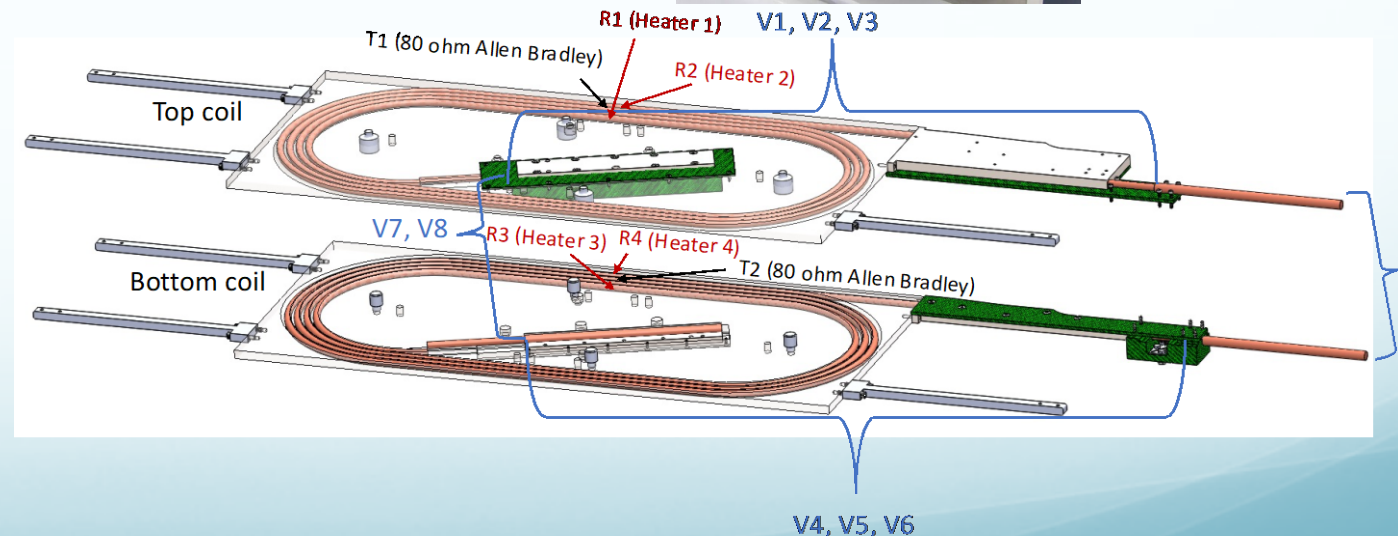
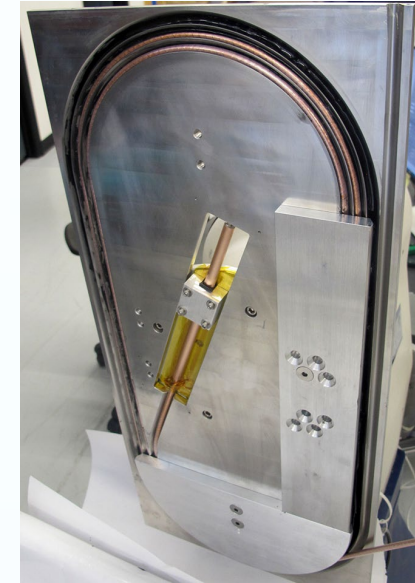
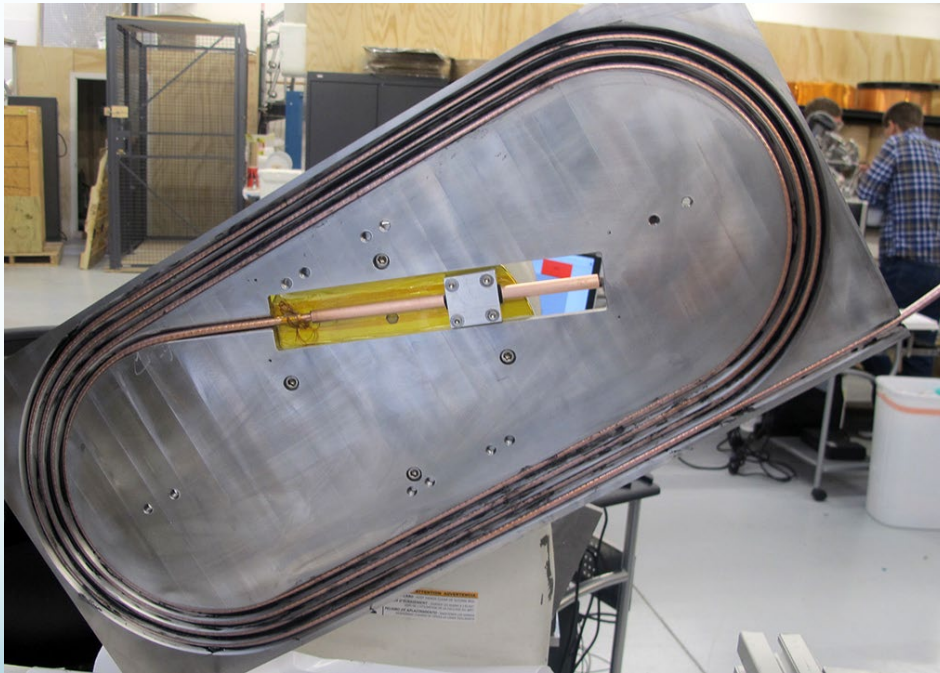
Winding using cable guides



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

## Low-field CORC® Common Coil insert

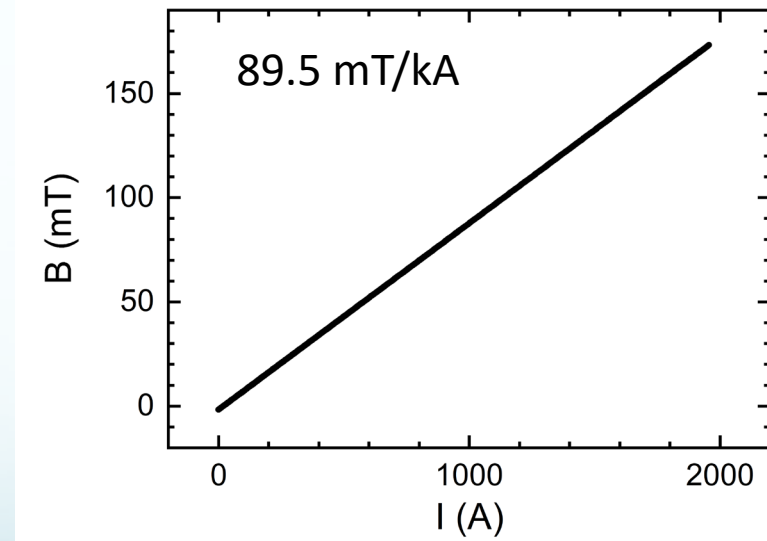
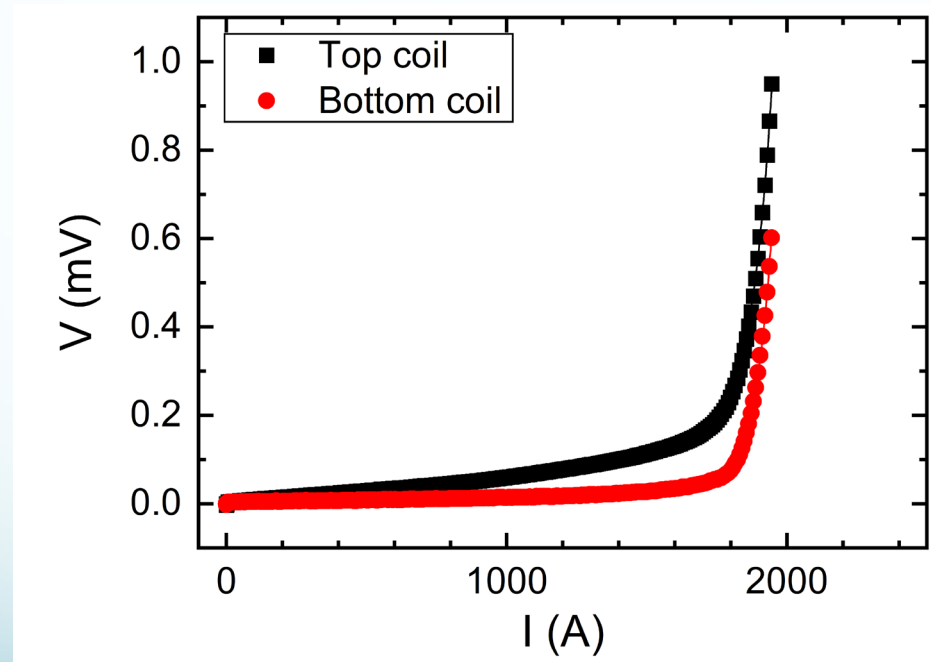
- Wound from 8 meters of CORC® cable
- Stycast epoxy impregnation after winding
- Contains co-wound voltage wires and optical fibers, Hall probe arrays for quench detection



# 76 K test of low-field CORC<sup>®</sup> Common Coil insert at ACT

## Initial performance test in liquid nitrogen at ACT

- Cable transition at 1.9 kA
- Field generated 170 mT



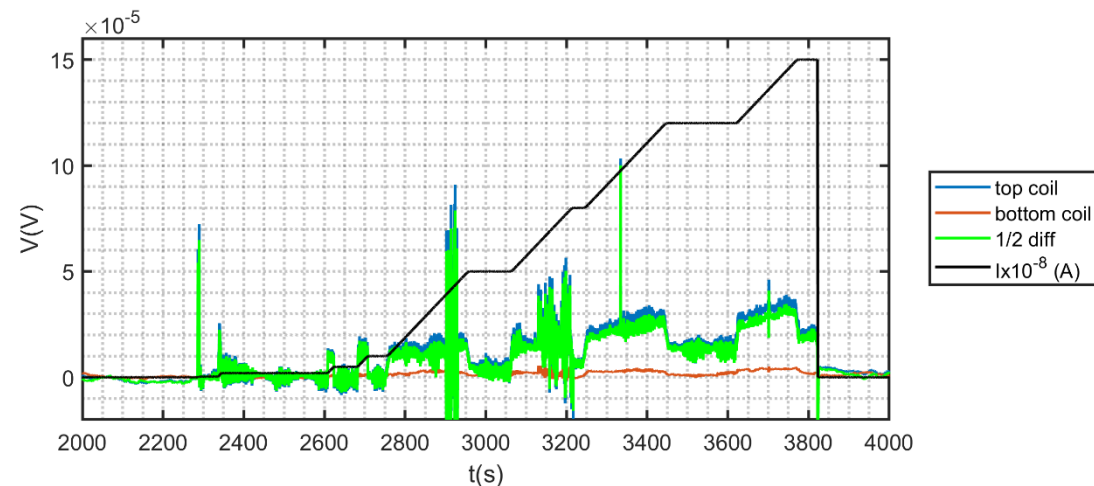
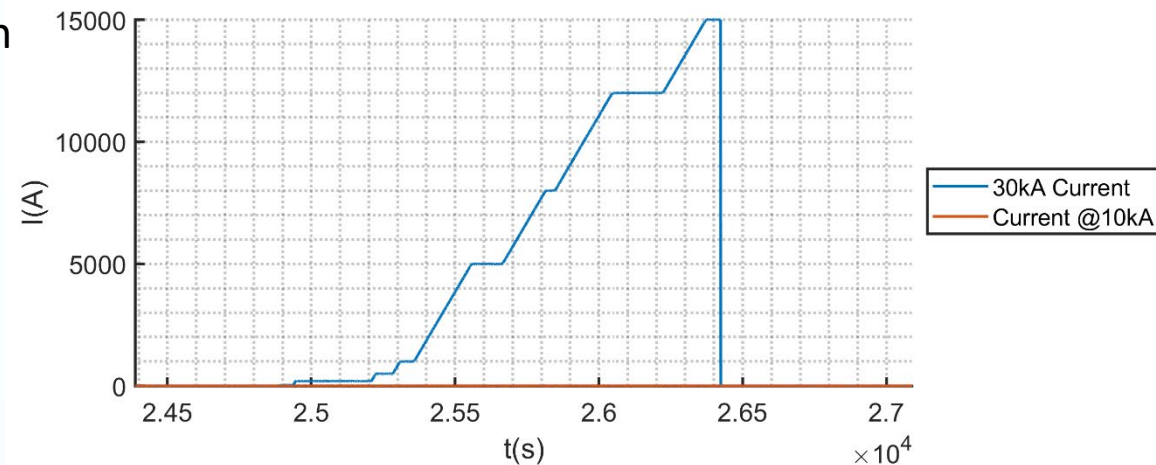
# Initial CORC<sup>®</sup> Insert Test in the Common Coil Outsert

## 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

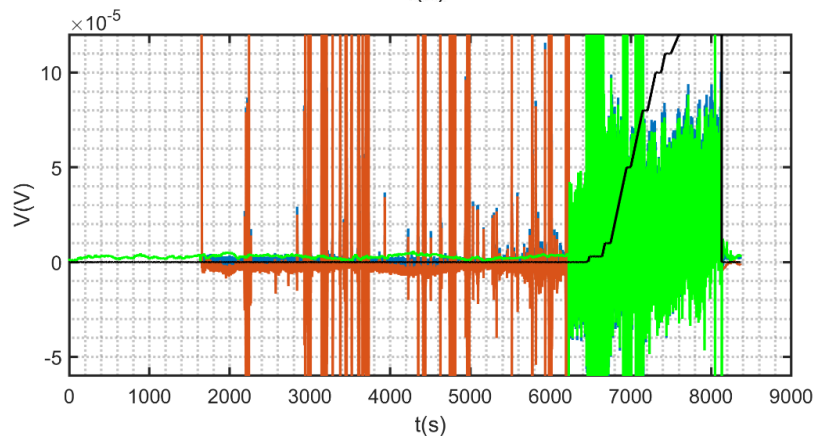
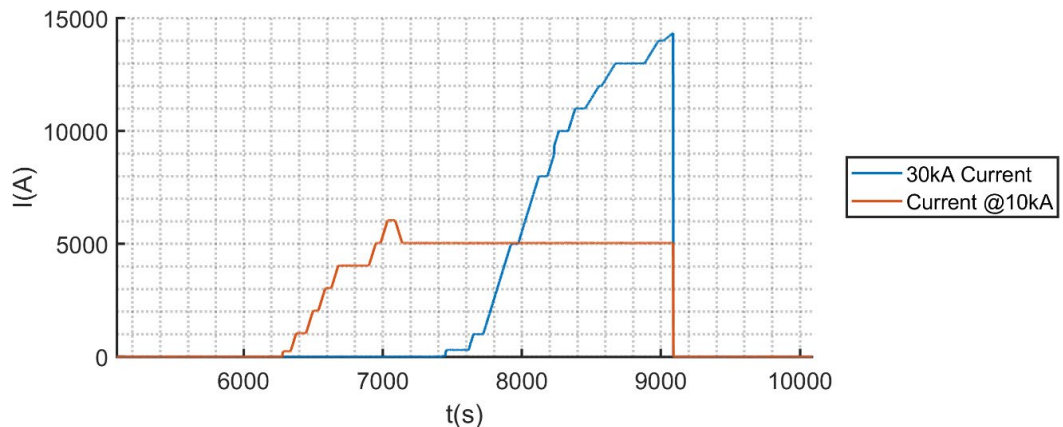


## Self-field test CORC<sup>®</sup> insert to 15 kA (record)

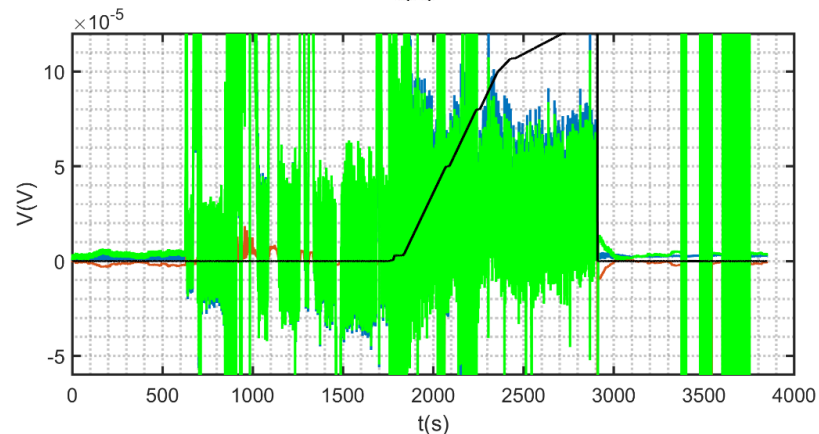
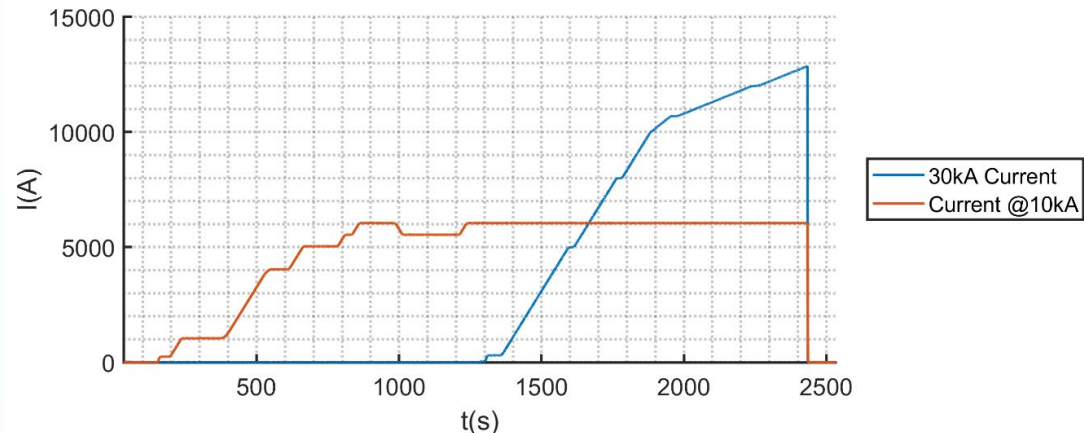


# Initial CORC<sup>®</sup> Insert Test in the Common Coil Outsert

5 T outsert field  
quench trigger at 14.36 kA



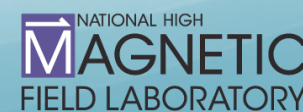
6 T outsert field  
quench trigger at 12.87 kA



Test will resume in May 2023 after outsert lead repair



Advanced Conductor Technologies  
www.advancedconductor.com



# Development of prototype Ohmic Heating coil for compact fusion reactors

## Ohmic Heating coil operating parameters

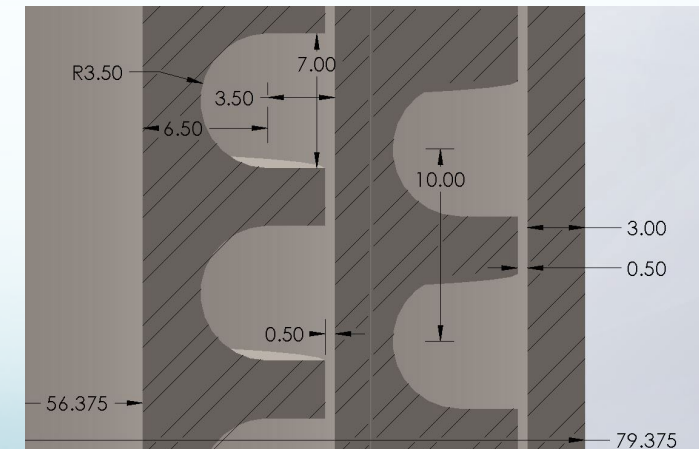
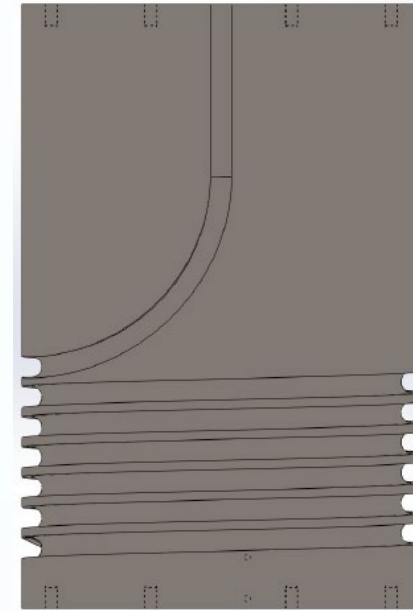
- Peak magnetic field on the conductor of 20 T
- Coil inner diameter 0.2 meters
- Operating current around 20 kA

## 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

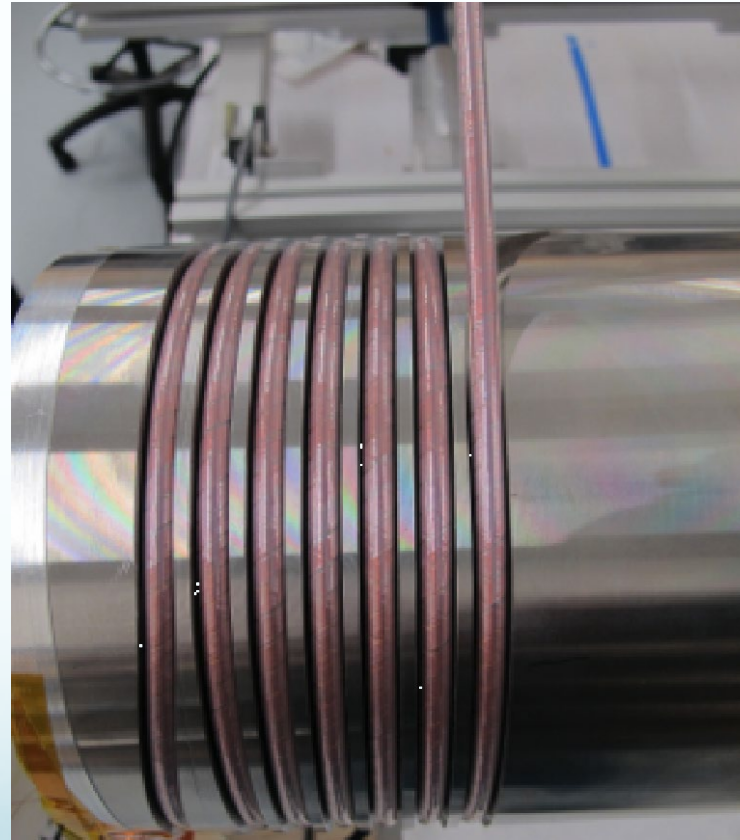
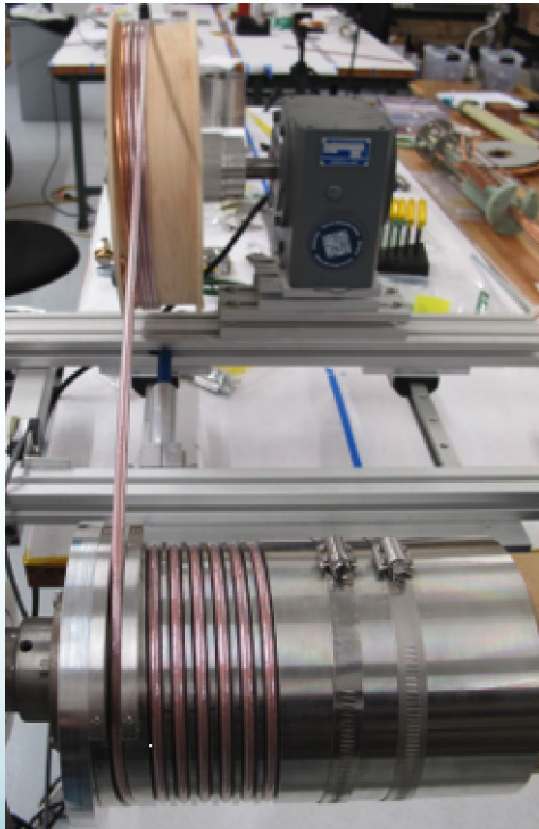
- Will the cable degrade at high cyclic operating loads?
  - Axial tensile loads before the cable hits the wall
  - Transverse compressive loads once hitting the wall
- Can the current be ramped at rates of about 10 kA/s needed to provide the flux swings?
  - Does the current distribution remain homogeneous?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



# Ohmic Heating coil winding at ACT

## Coil parameters

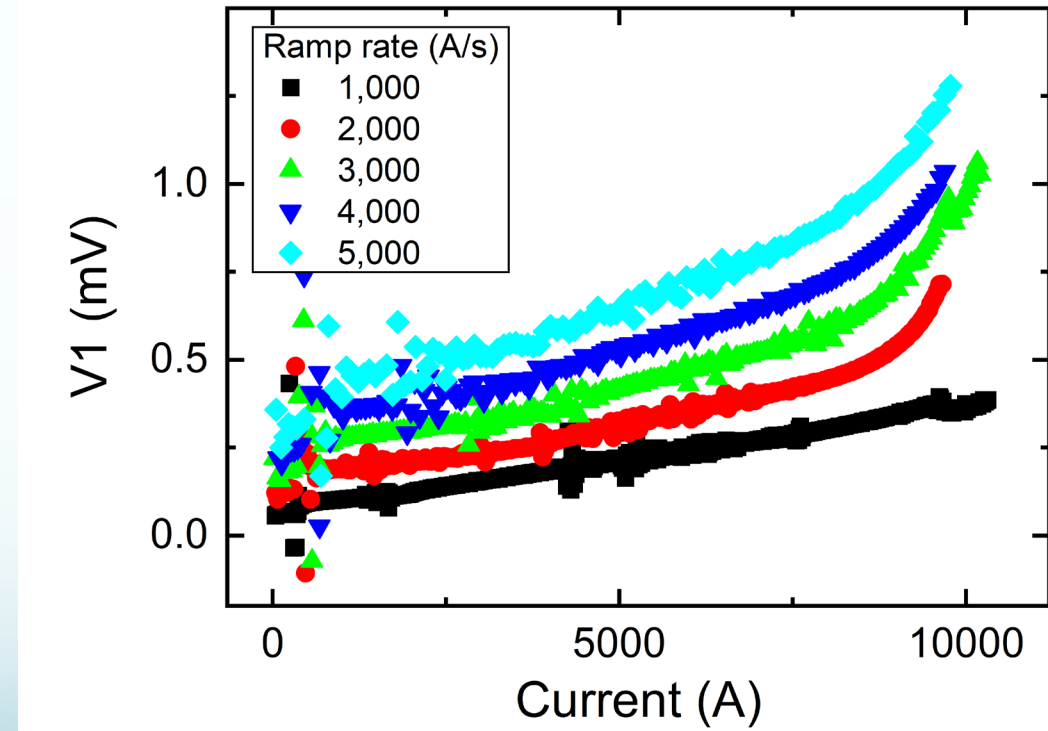
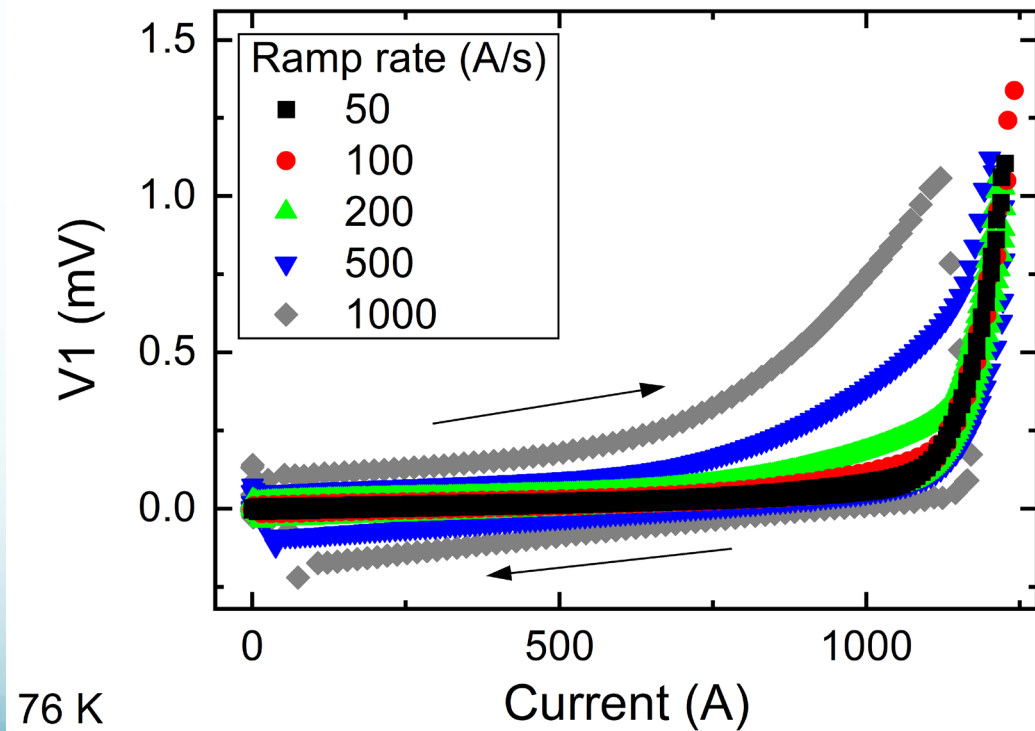
- 2-layers, 6 turns per layer
- About 8 meters of CORC® cable
- Cable wound from 16 tapes



# 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





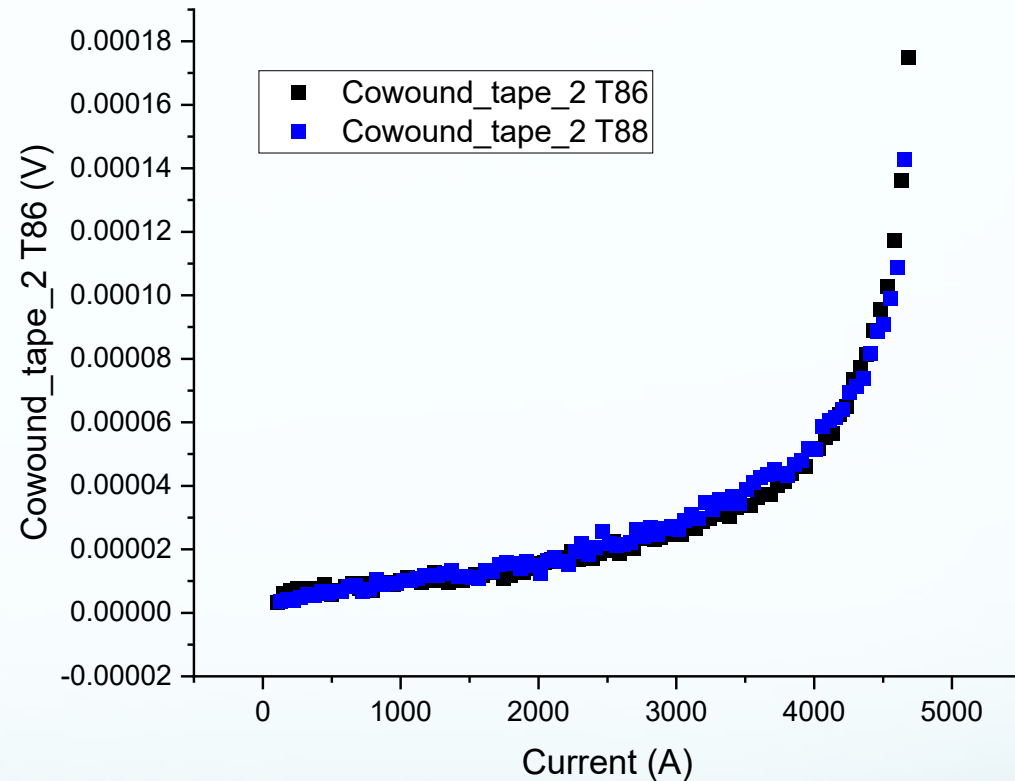
# Testing of Ohmic Heating coil within a 12 T LTS outsert

## 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<sup>2</sup>, JBr hoop stress 185 MPa (110 % of expected critical stress of cable)
- No degradation after 68 stress cycles

## Next steps

- Prepare set of CORC<sup>®</sup> 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<sup>®</sup> 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<sup>®</sup> wires with  $J_e(20\text{ T}) > 400\text{ A/mm}^2$

## CORC<sup>®</sup> Common Coil insert development

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

## CORC<sup>®</sup>-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<sup>®</sup> 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<sup>®</sup> OH coils that operate at higher stresses and at high current ramp rates are planned

