Latest development on CORC® cables and wires for high-field magnet and electric aircraft applications

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

Sven Doenges & Kyle Radcliff
Advanced Conductor Technologies, Boulder, Colorado, USA

Zach Johnson
Type One Energy, Boston, Massachusetts, USA

Emelie Nilsson, Jean-François Rouquette, Jean Rivenc, & Ludovic Ibanez
Airbus UpNext SAS, Toulouse France

Chul Kim, Peter Cheetham & Sastry Pamidi
Center for Advanced Power Systems, Florida State University, Tallahassee, Florida, U.S.A.

Dmytro Abraimov & Lance Cooley
Applied Superconductivity Center, Florida State University, Tallahassee, Florida, U.S.A.

Yifei Zhang & Drew Hazelton
SuperPower. Glennville, New York, U.S.A.

Virginia Phifer
VEIR, Woburn, Massachusetts, U.S.A.

Doan Nguyen & Linh Nguyen
Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

Xiaorong Wang, Reed Teyber & Hugh Higley
Lawrence Berkeley National Laboratory, Berkeley, California, U.S.A.

Mithlesh Kumar, Piyush Yoshi & Ramesh Gupta
Brookhaven National Laboratory, Upton, New York, U.S.A.

ISS 2023, Wellington, New Zealand, November 28th, 2023

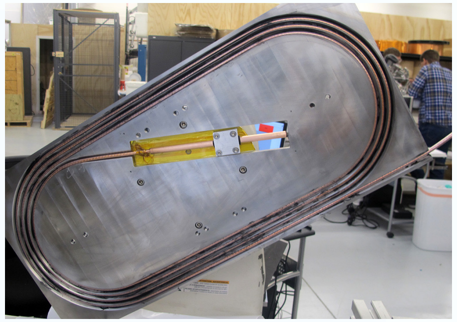
Advanced Conductor Technologies
www.advancedconductor.com

AIRBUS · Los Alamos NATIONAL LABORATORY · BROOKHAVEN NATIONAL LABORATORY · BERKELEY LAB · CENTER FOR ADVANCED POWER SYSTEMS FSU

Outline

Canted-cosine-theta accelerator magnets

- Development of 5 T stand-alone CCT magnet towards 20 T hybrid magnets
- Addressing one of the key shortcomings of CORC® wires: its bending flexibility



Common Coil insert racetrack magnets

- Developing CORC® Common Coil insert magnets and operate them within a 10 T LTS outsert
- Development of novel racetrack winding technology optimized for CORC® cables

High-field CORC® solenoids

- Exploring the impact of current sharing in CORC® wires containing many tape dropouts on the coil performance

Development of CORC® power cables for electric aircraft

- Development of the ac and dc CORC® power busses for Airbus ASCEND
- Initial testing complete

Development of Canted-Cosine-Theta accelerator magnets from CORC® wires

Advanced Conductor Technologies
www.advancedconductor.com

CORC® wire development of CCT magnets developed at LBNL

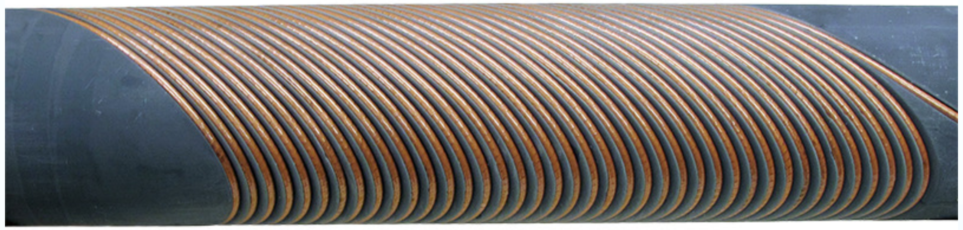
Program goal to reach 20 T dipole field by

- 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

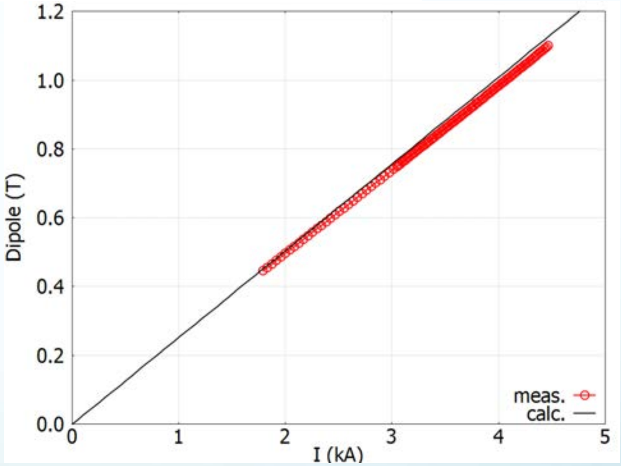
A 1.2-T canted cos ϑ dipole magnet using high-temperature superconducting CORC® wires, X. Wang, et al., *Supercond. Sci. Technol.* **32**, 075002 (2019)

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



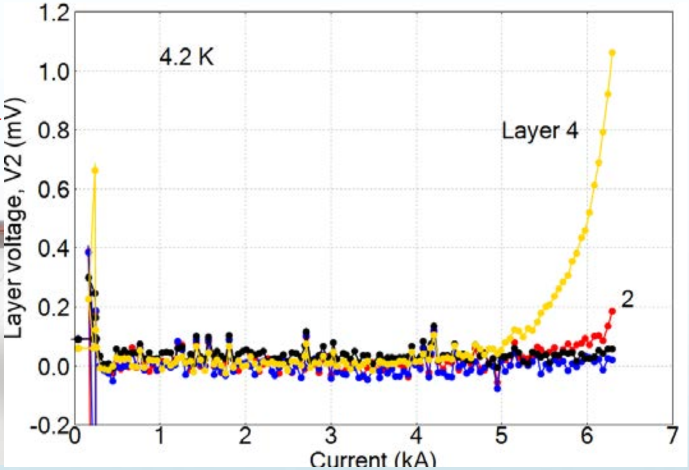
CORC® CCT-C1



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)

Advanced Conductor Technologies
www.advancedconductor.com

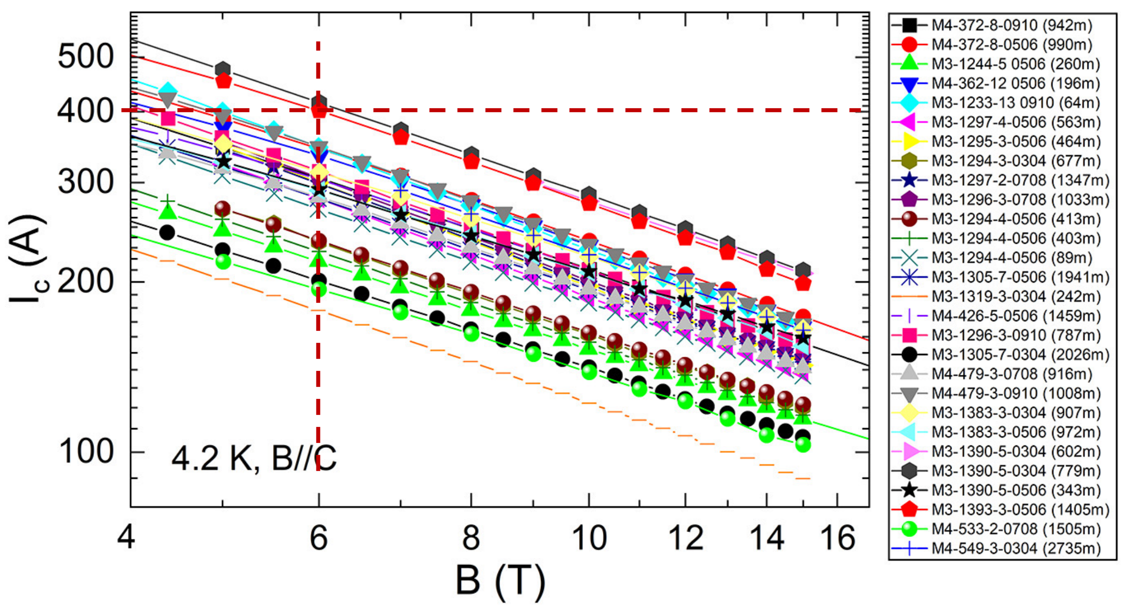
BERKELEY LAB

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

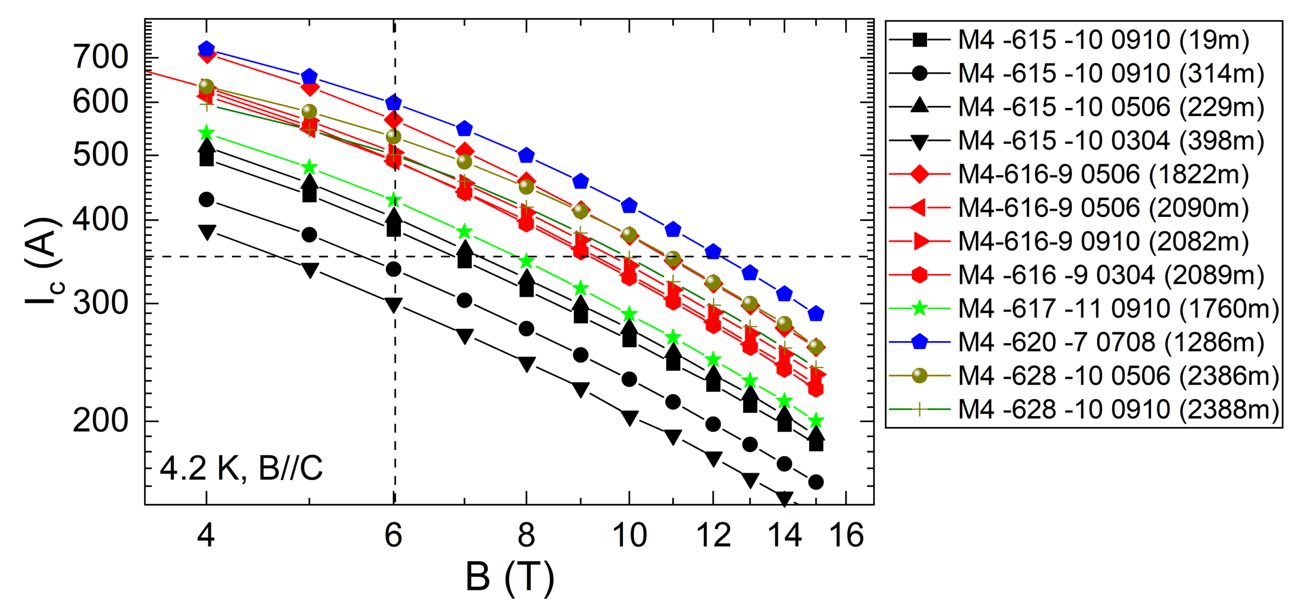
How to reach 5 T in CCT-C3?

- 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 tapes delivered in 2022, but there's a problem:
CORC® wires wound from HM tapes can't be bent!

Advanced Conductor Technologies
www.advancedconductor.com

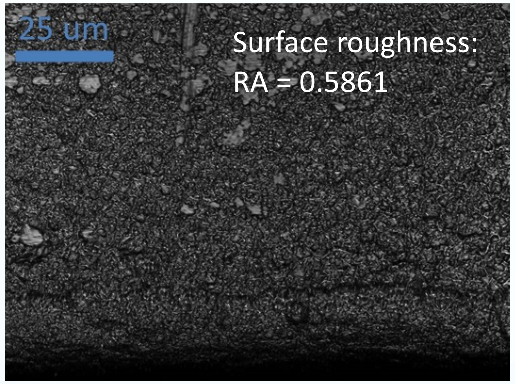
BERKELEY LAB

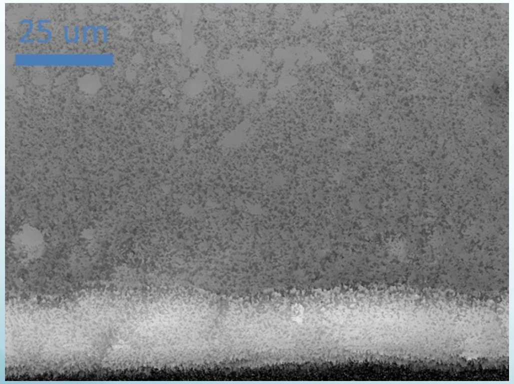
Surface quality of 2021 – 2022 SuperPower tapes

Main differences between SuperPower AP and HM tapes

- Very high surface roughness of HM tapes observed
- Intermittent major slitting bur and course granularity in copper plating in 2021– 2022 tapes (all HM)

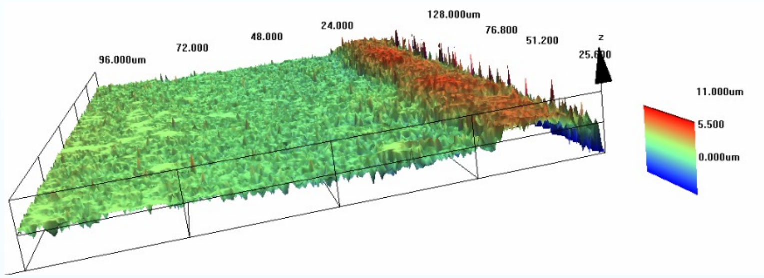
SuperPower SCS-2030-AP tape (2016 – 2020)



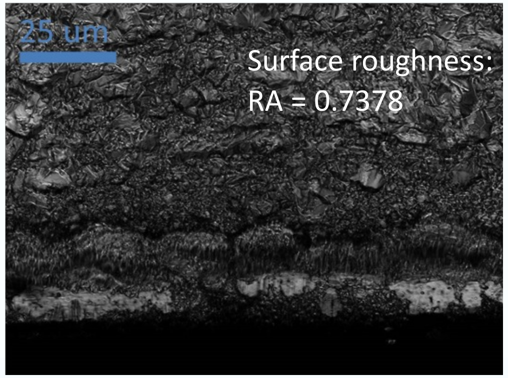


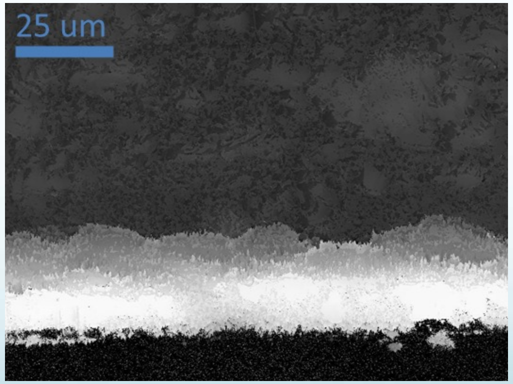
Height map

Tape edge



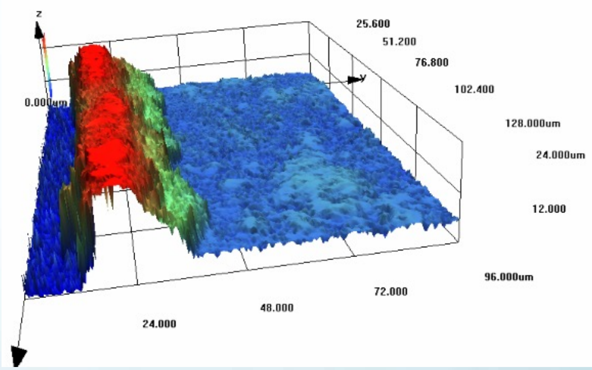
SuperPower SCS-2030-HM tape (2021 – 2022)





Height map

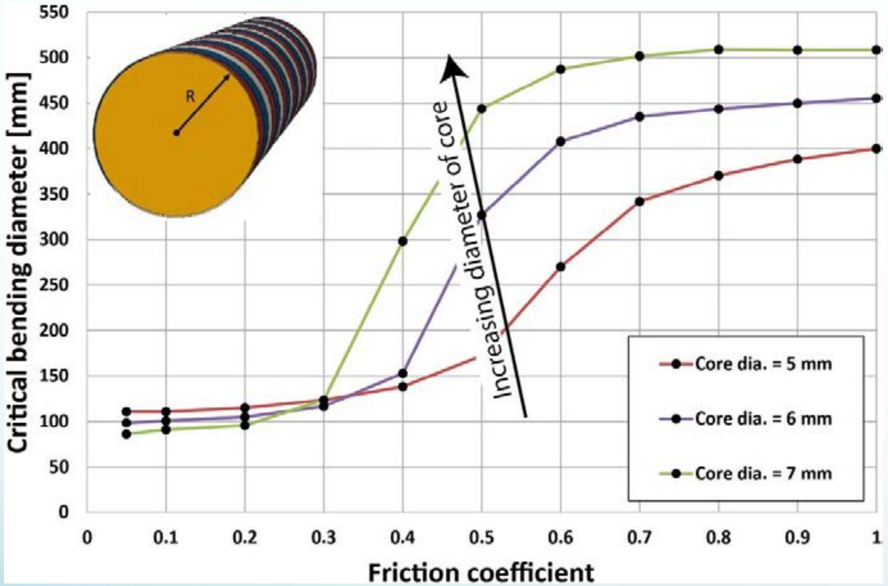
10-20 μm thick,
Intermittent burr

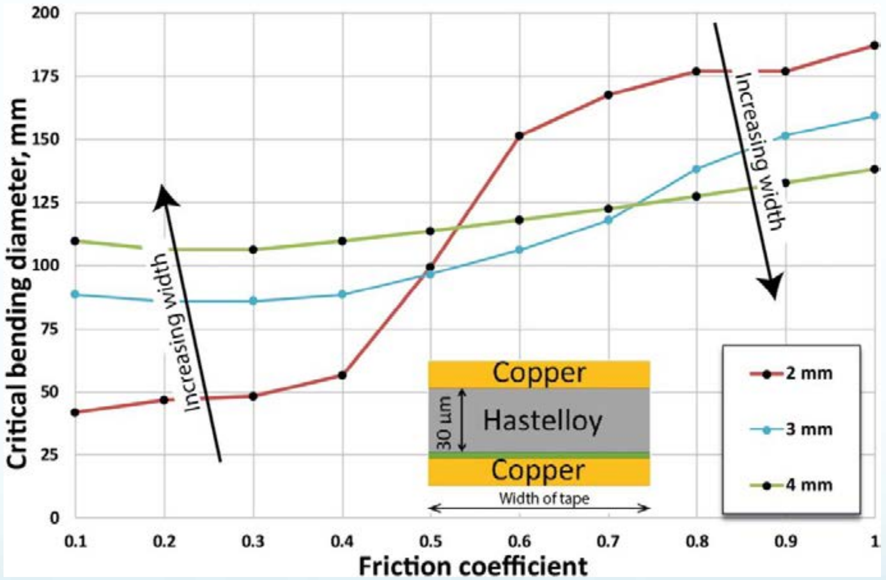


The impact of friction on the bending of CORC® wires

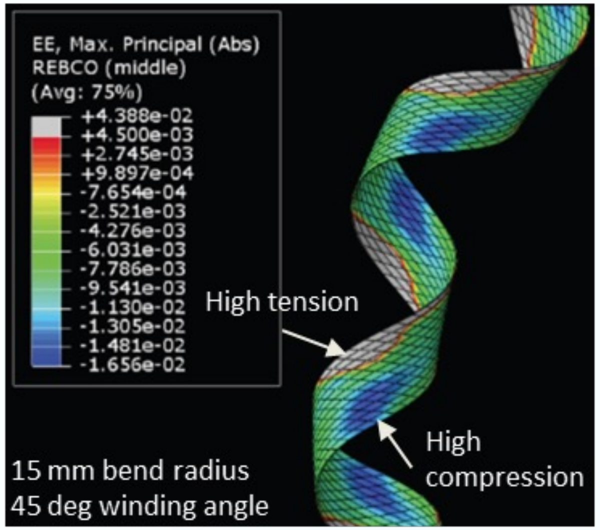
Bendability of CORC® wires due to helical tape wind, but affected by

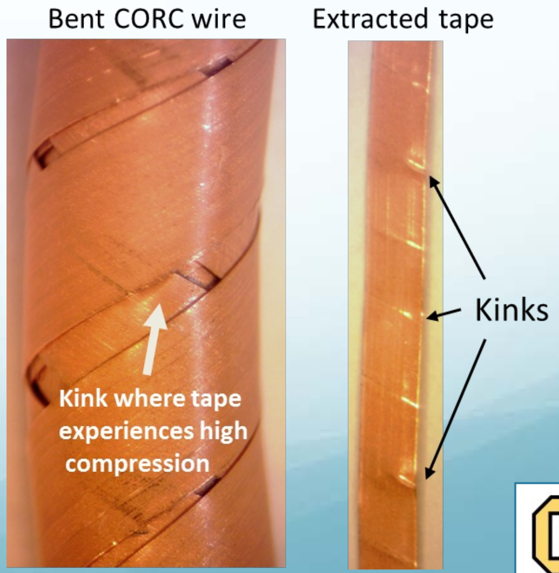
- Tape width and thickness (both of substrate and Cu plating)
- Gap spacing between tapes and number of tape layers
- Core thickness and tape winding angle
- **Friction coefficient: the tapes need to slide!!**





FEM model showing single tape





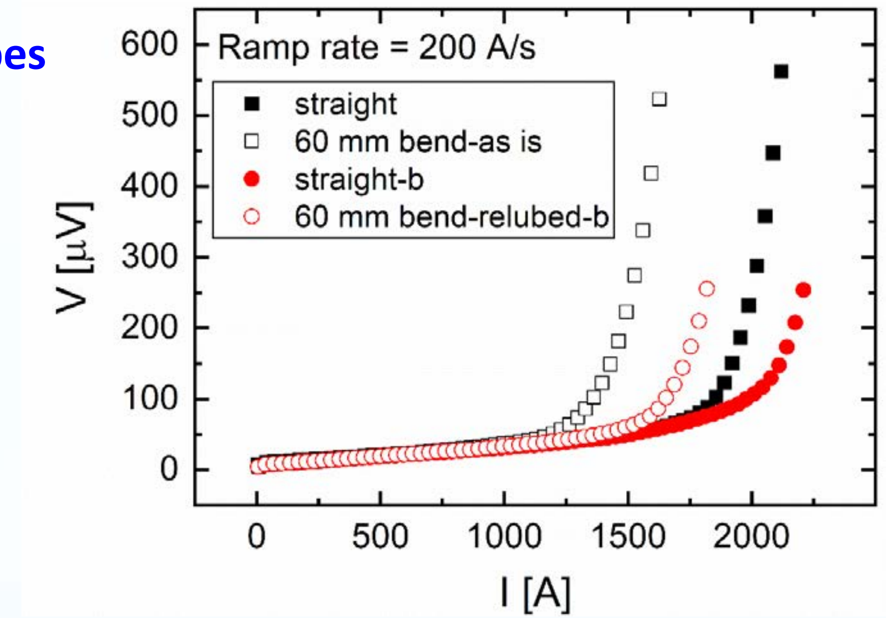
V.A. Anvar, et al., "*Bending of CORC® cables and wires: finite element parametric study and experimental validation*", *Supercond. Sci. Technology* **31**, 115006 (2018)

Problem with CORC® wires for CCT-C3: Loss of bending performance

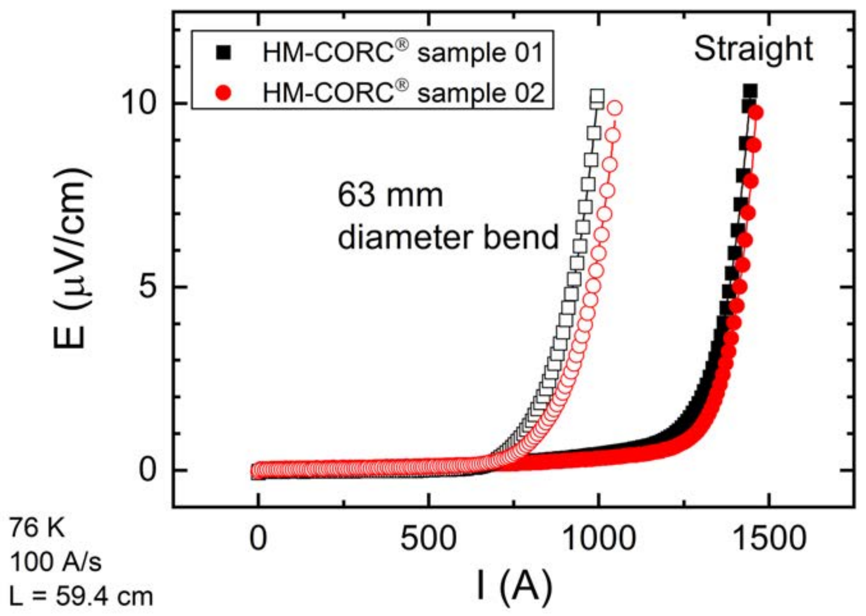
Previous generation of 30-tape CORC® wires, based on "AP" tapes

- Using "conventional winding and lubrication process" (P1)
- Wound into CCT magnet structure with 60 mm bend at poles
- **About 70 – 80 % I_c retention at 60 mm diameter => ok, not great**

AP-tape CORC® wire



HM-tape CORC® wire



CORC® wire performance when wound from HM tapes

- Bending to 60 mm diameter resulted in 35 – 40 % degradation!!!
- **This is unacceptable and won't allow CCT-C3 to reach 5 T**

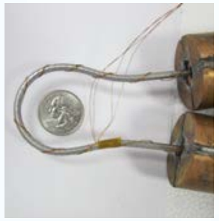
Advanced Conductor Technologies
www.advancedconductor.com

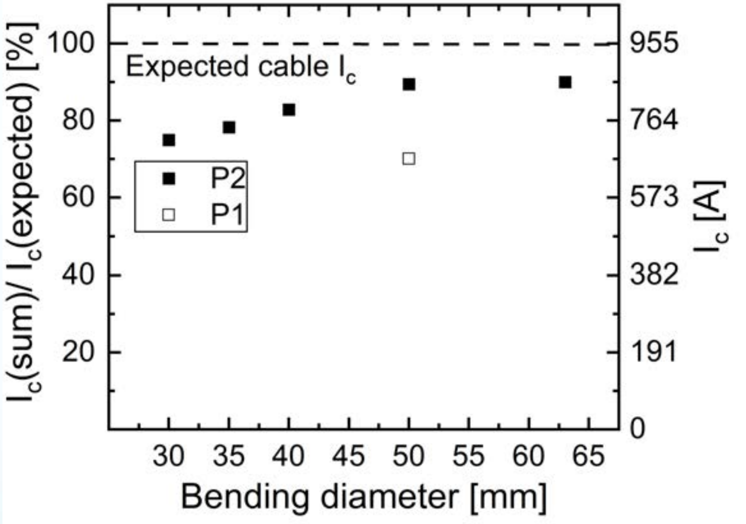
CORC® wires with highly improved bending flexibility

New CORC® wire manufacturing procedure (P2) should

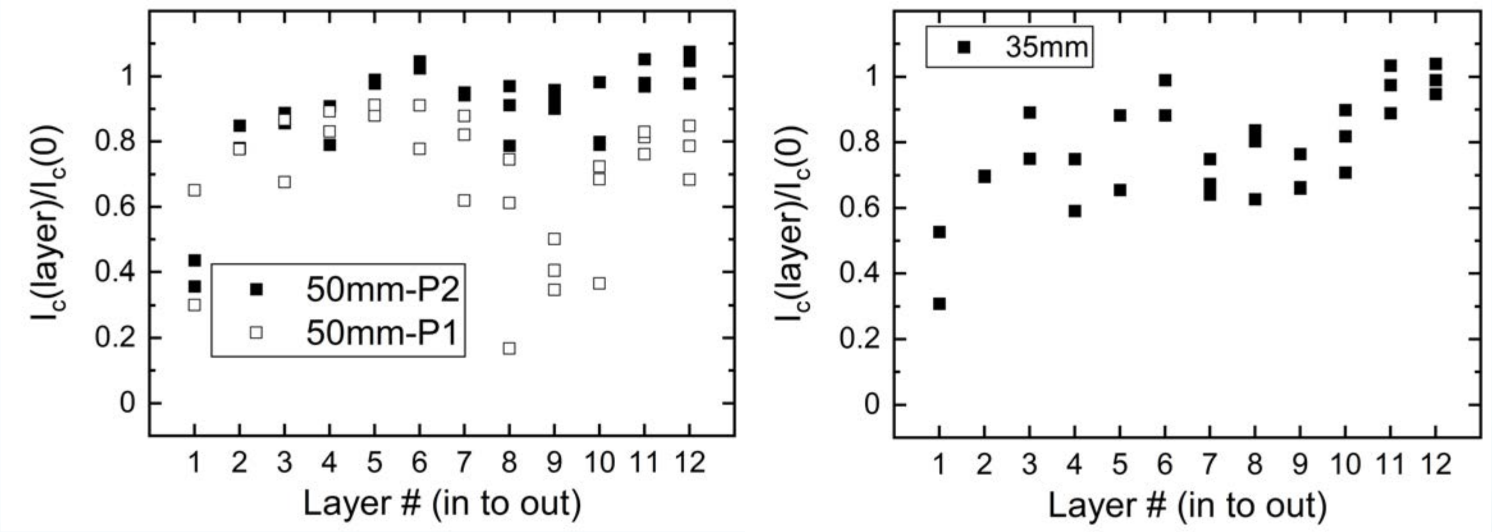
- Recover bending flexibility when using "rough" tapes (such as latest SuperPower tapes)
- Allowing even smaller bending diameters than previous generation CORC® wires

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

Status of magnet CCT-C3 and potential layout CCT-C4

Status CCT-C3 magnet

- 5 out of 6 CORC® wires have been delivered to LBNL in October-November 2023
- Last CORC® wire will be delivered in December
- CCT-C3 magnet will be wound in Q2-2024

Goal of potential CCT-C4 magnet

- Increase the self-field dipole field with respect to CCT-C3
- At the same time, reduce the O.D. from 160 mm to less than 120 mm to be compatible with future 11 T CCT outsert
- Achieve this by reducing the bending diameter at the pole from 60 mm to 40 mm using the 30-tape CORC® wire
- No high conductor pinning required, same CORC® wire layout as CCT-C3

CCT-C4 Option 1

- 4 layers, 70 mm aperture, 118 mm O.D.
- Stand-alone dipole field of 6.2 T
- 3.3 T as insert within a 11 T outsert, resulting in a combined field of 14.3 T

CCT-C4 Option 2

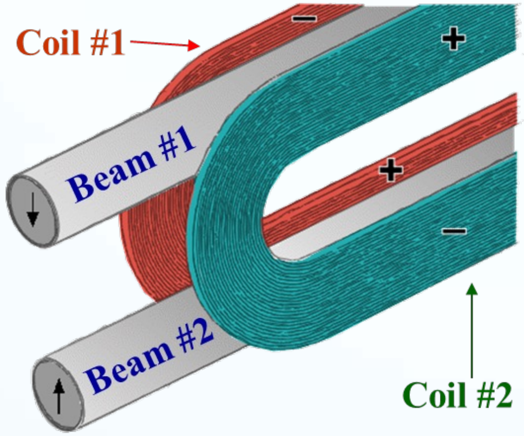
- 6 layers, 45 mm aperture, 117.2 mm O.D.
- Stand-alone dipole field of 7 T
- 4 T as insert within a 11 T outsert, resulting in a combined field of 15 T

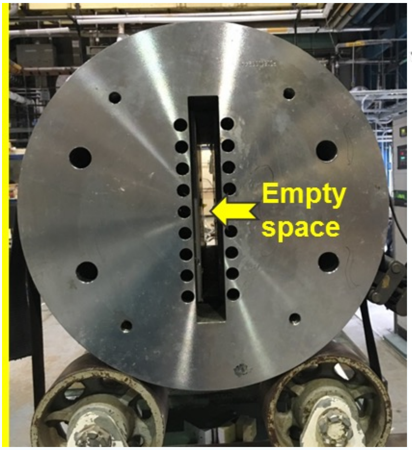
Development of CORC® Common Coil racetrack coils

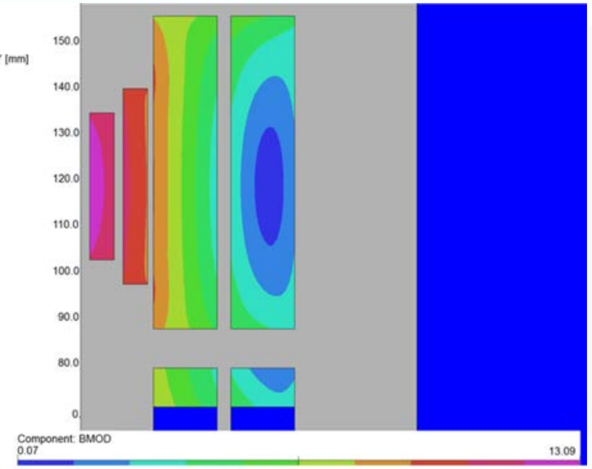
CORC®-based Common Coil development

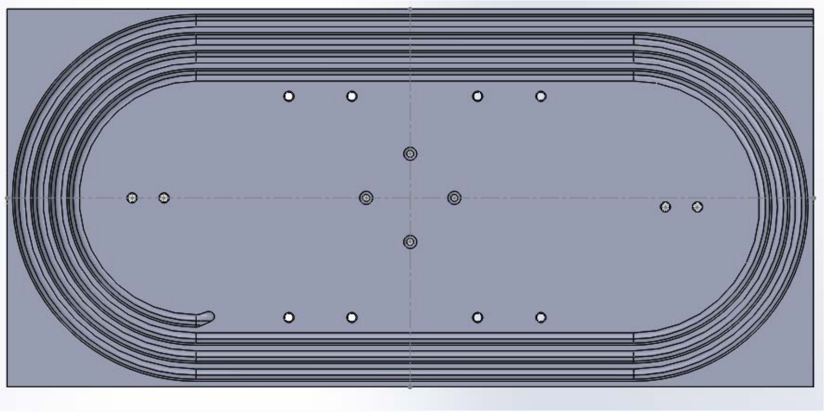
CORC® Common Coil program goals

- 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

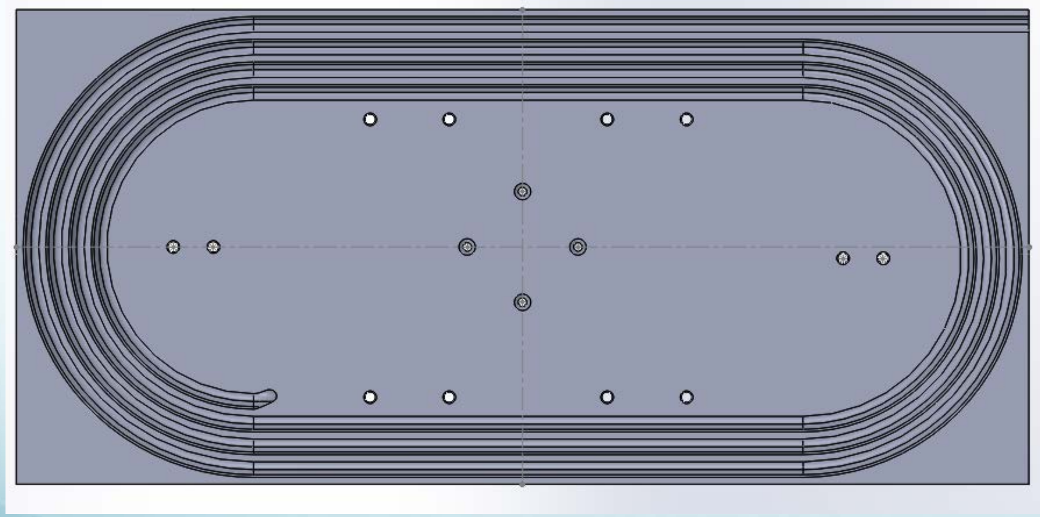
Common Coil inserts

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

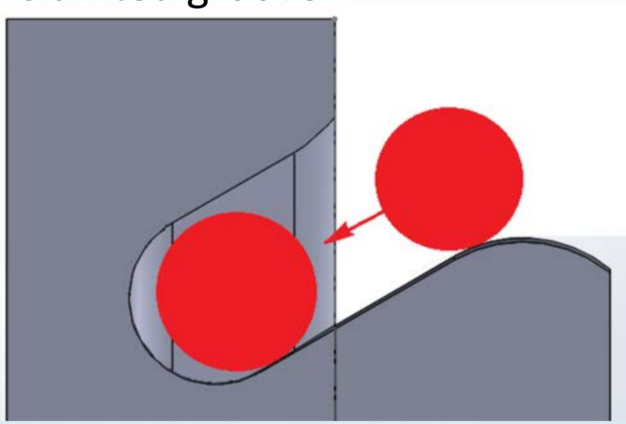
Coil structure requirements

- 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)

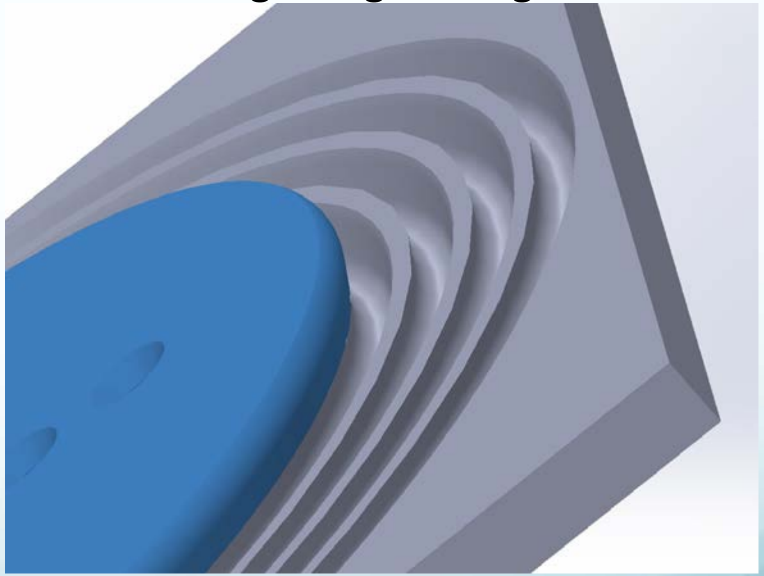
4-turn single CORC® pancake



CORC® cable sliding into slamted groove



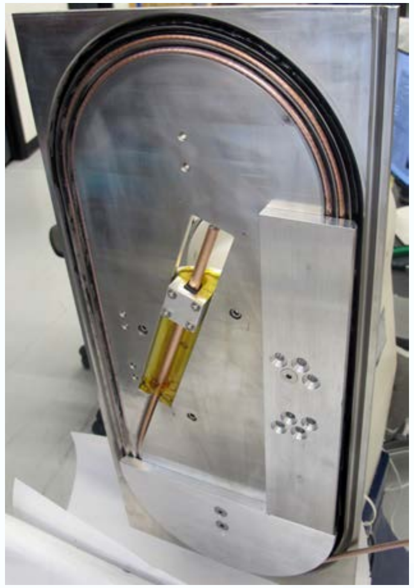
Winding using cable guides

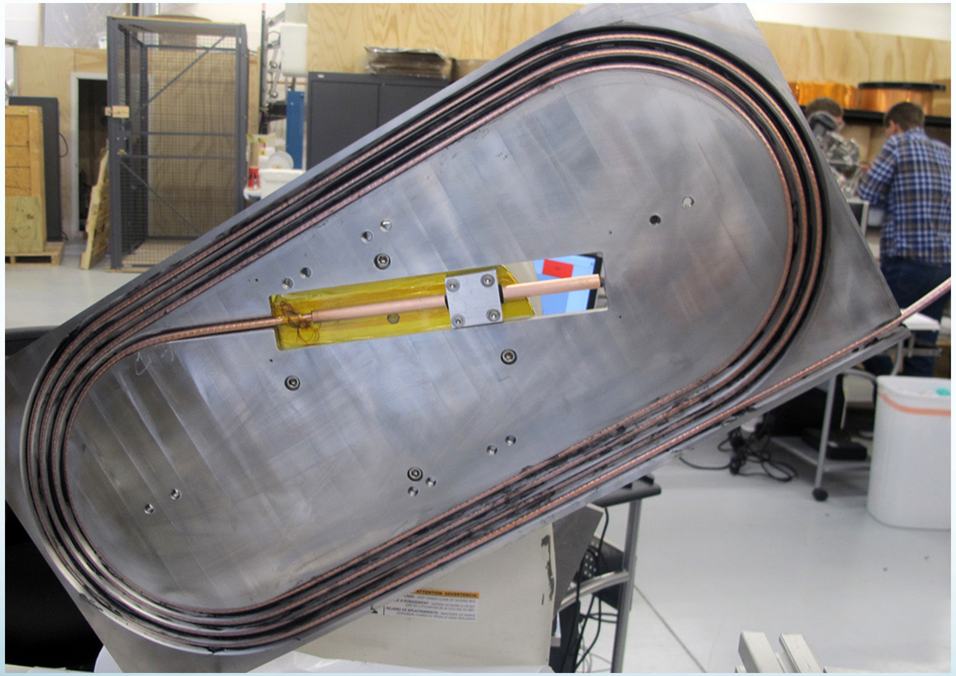


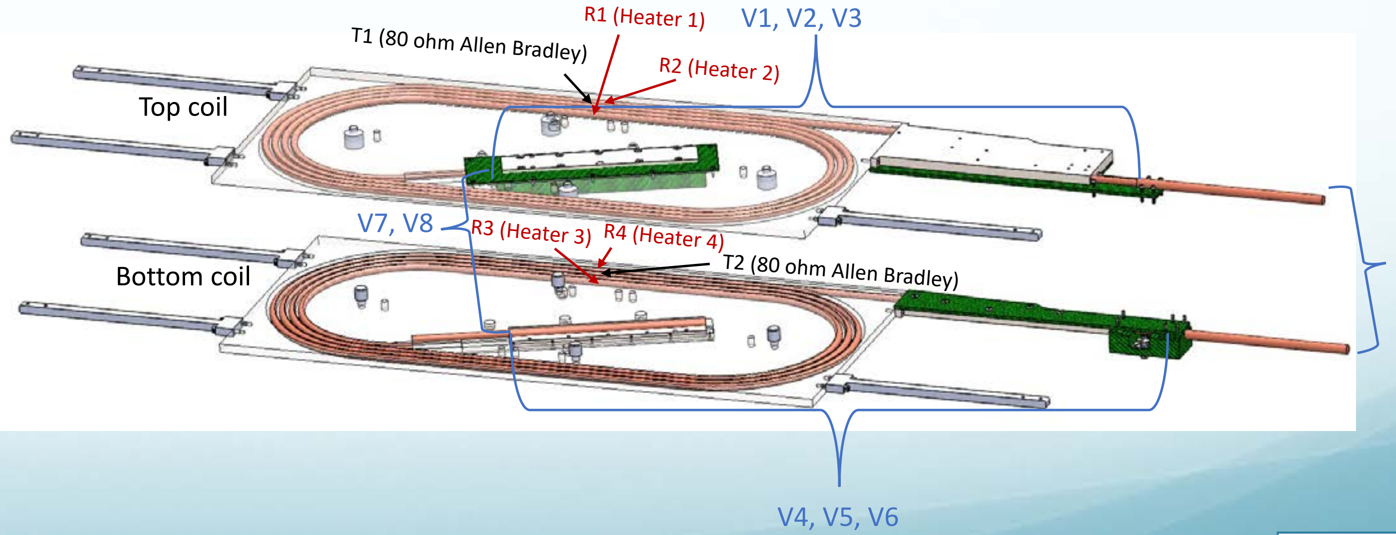
Winding of low-field CORC® Common Coil insert at ACT

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





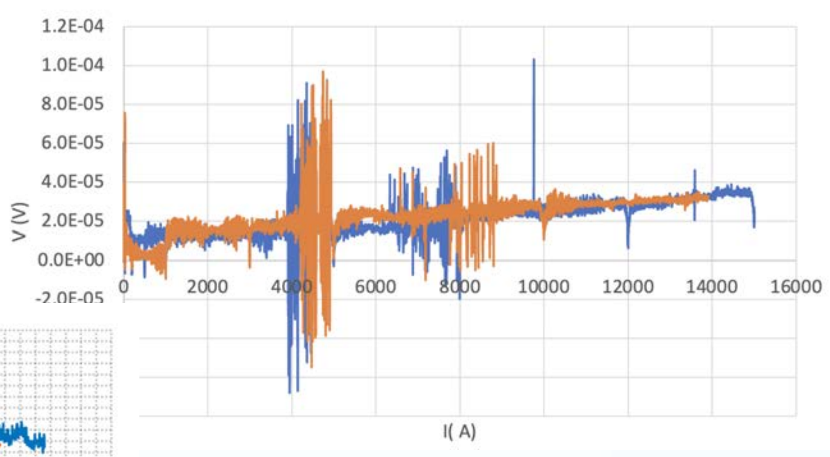


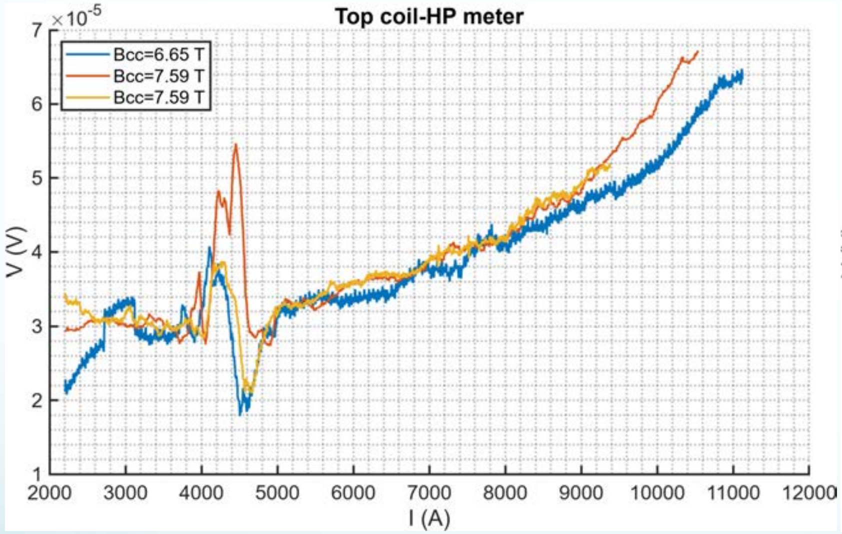
Low-field CORC® Insert Test in the Common Coil Outsert

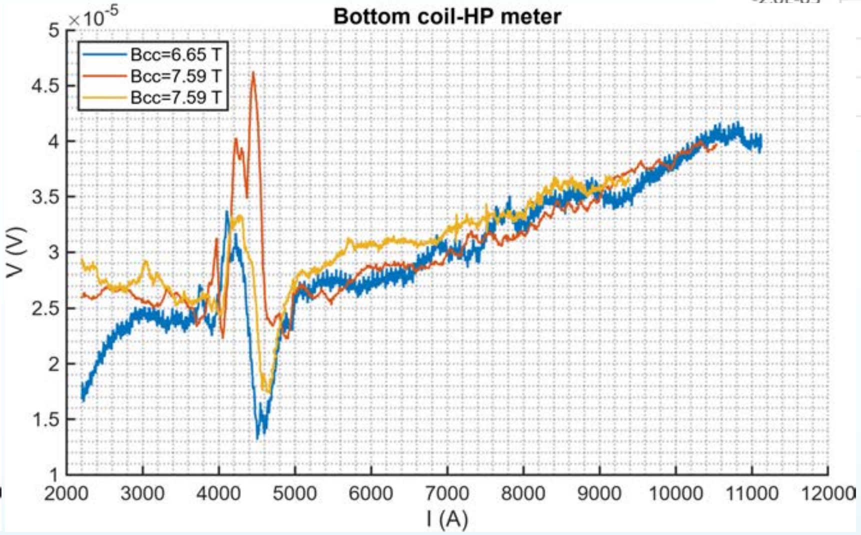
Results

- Now quench when powered to 15 kA in self-field (record current)
- Insert powered to over 10 kA in 7.59 T outsert field, causing the LTS outsert to quench
- No degradation in CORC® insert coil detected

Self-field test to 15 kA







Next steps

- Complete the 3 T CORC® Common Coil insert (December 2023)
- Test the 3 T insert in LTS Common Coil before the end of Q1-2024

Current sharing in CORC® conductors

A solenoid wound from CORC® wire with many tape defects

Program goals

DOE-EERE grant DE-EE0007872

- Explore the effect of significant tape defects on the performance of CORC® wires
- Demonstrate a significant CORC® solenoid at intermediate temperatures and fields

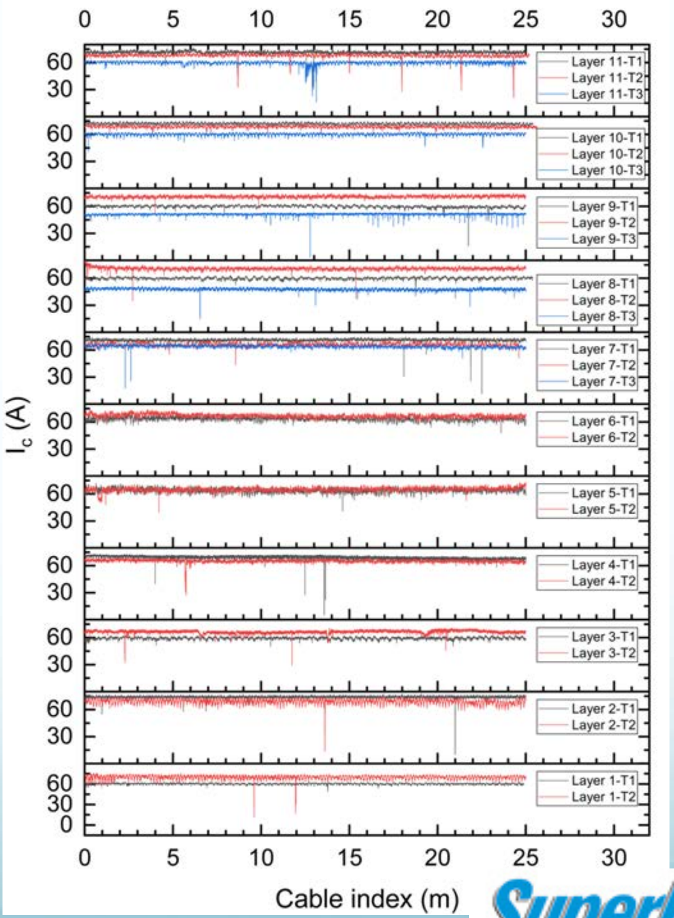
Coil properties

- CORC® wire wound from 27 “VIC” tapes, each containing several sharp dropouts
- 4-layer, 81-turn solenoid with 74 mm ID
- Conduction cooled through copper shells for testing at 20 – 60 K

CORC® wire properties

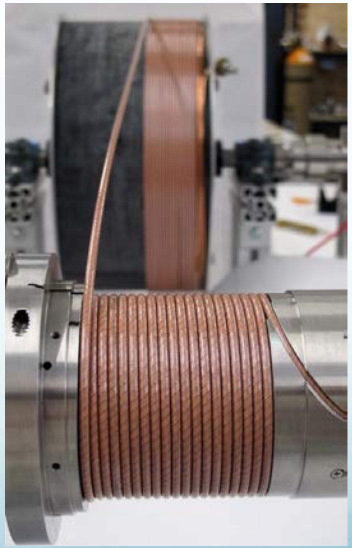
CORC OD (mm)	3.6
# of 2 mm wide tapes	27
Central Transfer function (T/kA)	0.88
Peak Transfer function (T/kA)	1.03
CORC® Length (m)	24.6

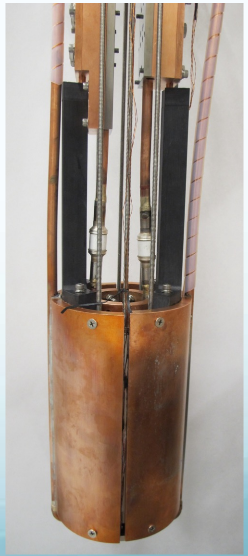
Tapestar of VIC tapes



Coil dimensions

	ID (mm)	OD (mm)	height (mm)	Turns
Layer 1	74.00	81.24	69.35	19
Layer 2	83.24	90.48	73.00	20
Layer 3	92.48	99.72	76.65	21
Layer 4	101.72	108.96	80.30	21.5

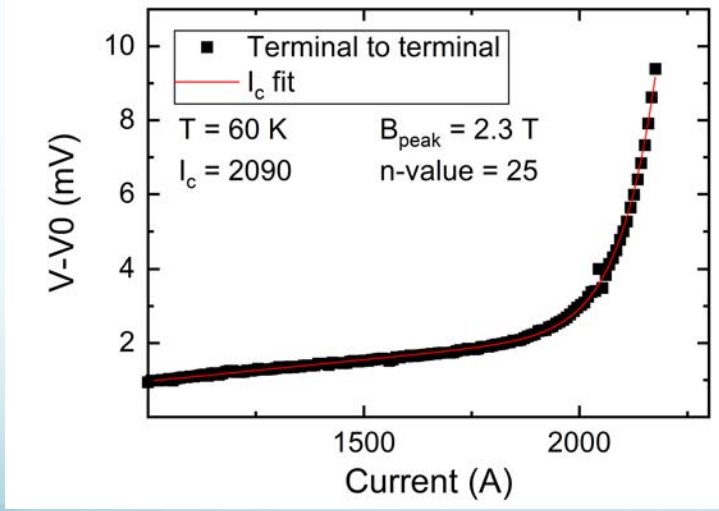


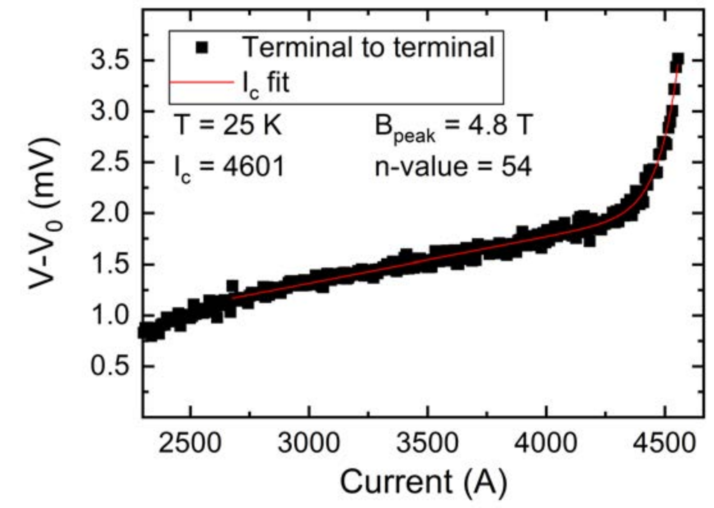


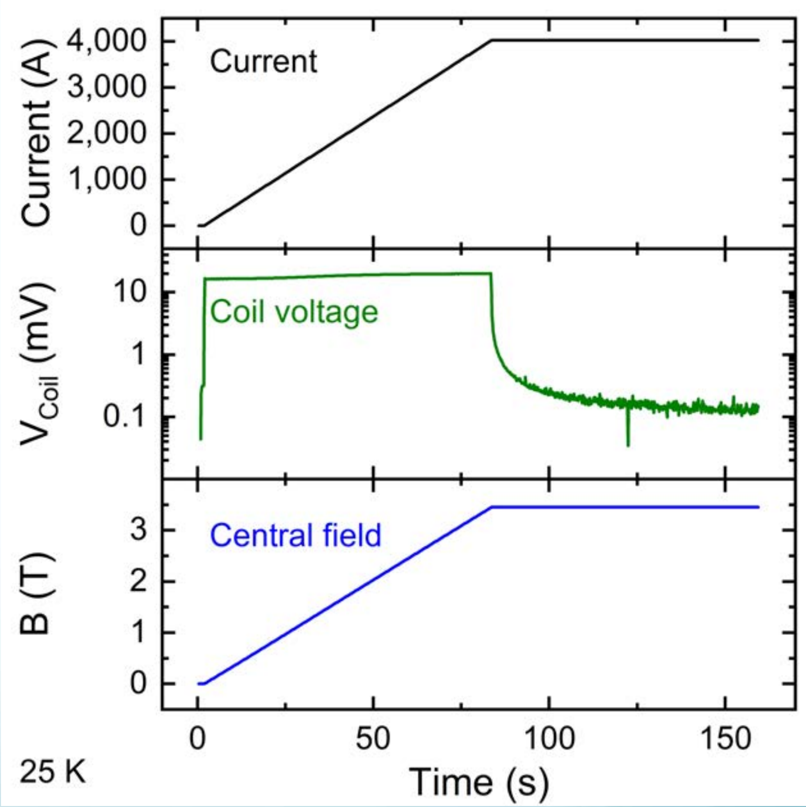
CORC® wires show high tolerance to local tape defect

Results

- Cooling through helium gas cooled copper shells
- Testing at continuous currents of up to 5,000 A
- Peak magnetic field of **2.3 T at 60 K** (2,090 A)
- Peak magnetic field of **4.8 T at 25 K** (4,601 A)
- No effect of tape defects on CORC® wire performance, even during steady-state operation
- **Current sharing in CORC® wires allows significant tape defects!**





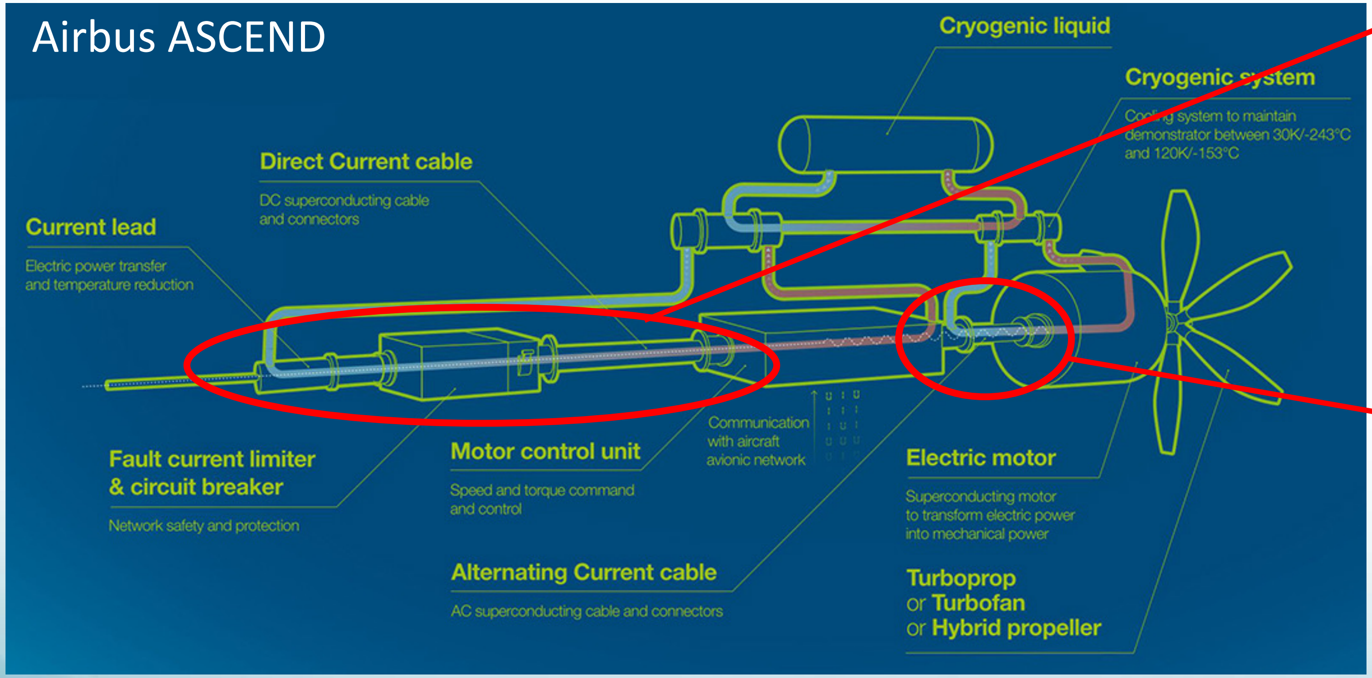


CORC® power cables

Airbus ASCEND: first demonstration of CORC® cables for electric aircraft

Airbus ASCEND (Advanced Superconducting & Cryogenic Experimental powertrain Demonstrator)

- Ground based powertrain demonstrator of the various cold technologies needed for future electric aircraft
- Identify showstoppers: technological, but also economical (size, weight) and visual (elegance)
- Rated at 0.5 MW, cooling with sub-cooled liquid nitrogen
- **Advanced Conductor Technologies received the contract to deliver the dc and ac busses for ASCEND**



Dc bus ASCEND

- 2-Pole twisted pair, 10 meter in length
- Operating current 1.7 kA
- Operating voltage 300 V (2 kV fault)
- Fault Current Limiting abilities
- Current leads to room temperature
- Interface to motor control unit (~100 K)

Ac bus ASCEND

- 3-Phase (3 monopoles), 2 meter in length
- Operating current 1.66 kA rms
- Operating voltage 300 V
- 500 Hz
- Interface to MCU and motor (30 K)

Advanced Conductor Technologies
www.advancedconductor.com

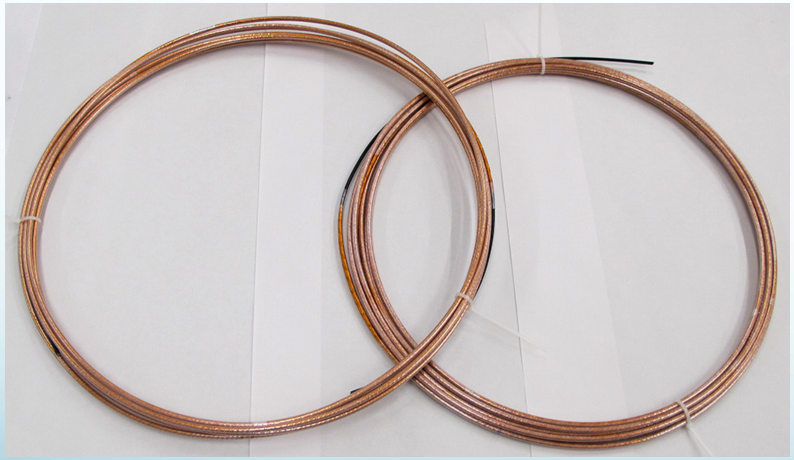
AIRBUS

Airbus ASCEND: CORC® ac and dc bus development

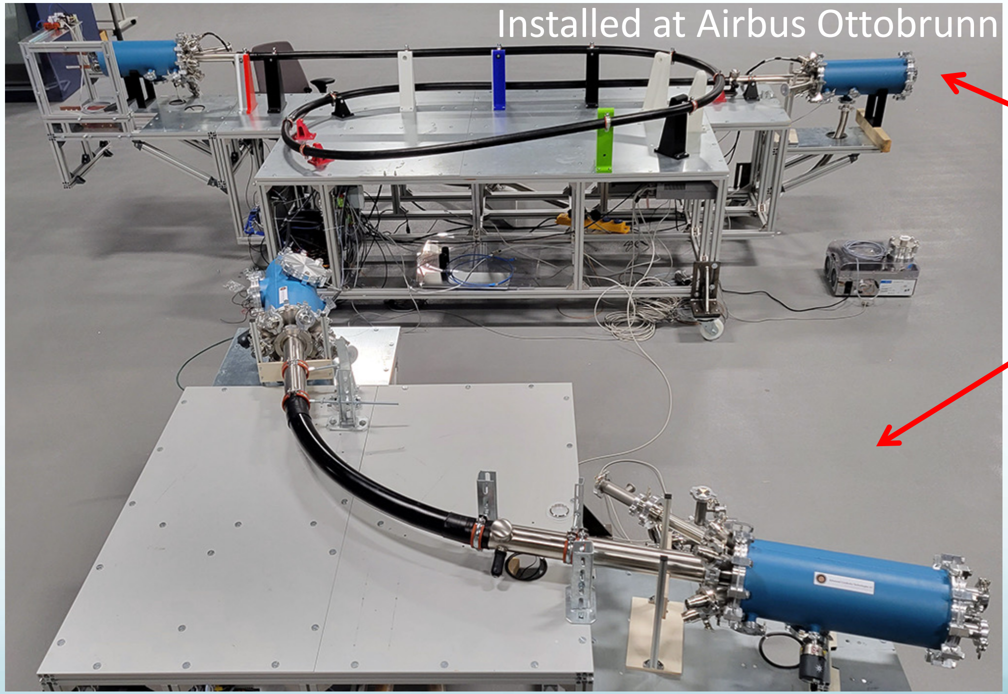
CORC® ac and dc bus status

- All hardware completed November 2022
- Qualification testing at ACT completed December 2022
- Ac and dc busses with connecting devices delivered to Airbus in January 2023
- Assembled at Airbus Ottobrunn April-May 2023
- ASCEND is currently being energized

Two 10-meter long CORC® cables for the dc bus



ASCEND CORC® dc bus ready for testing at ACT



Installed at Airbus Ottobrunn

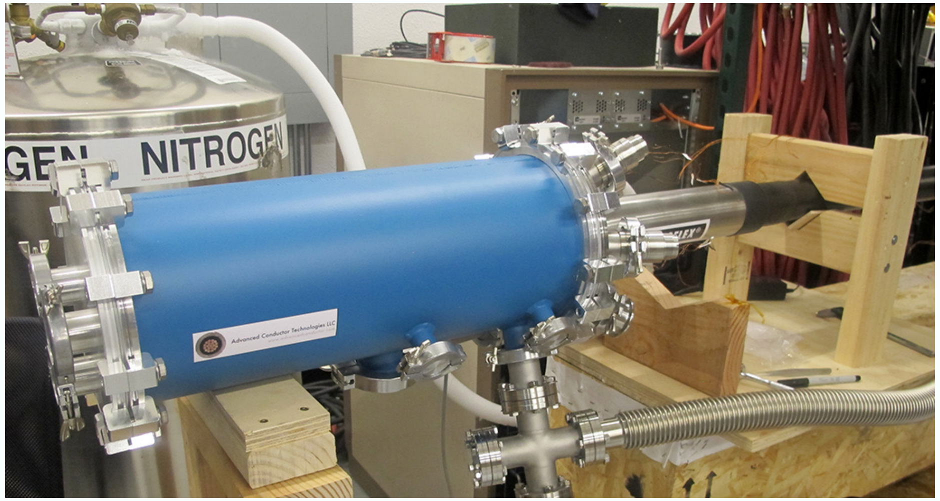
CORC® dc bus

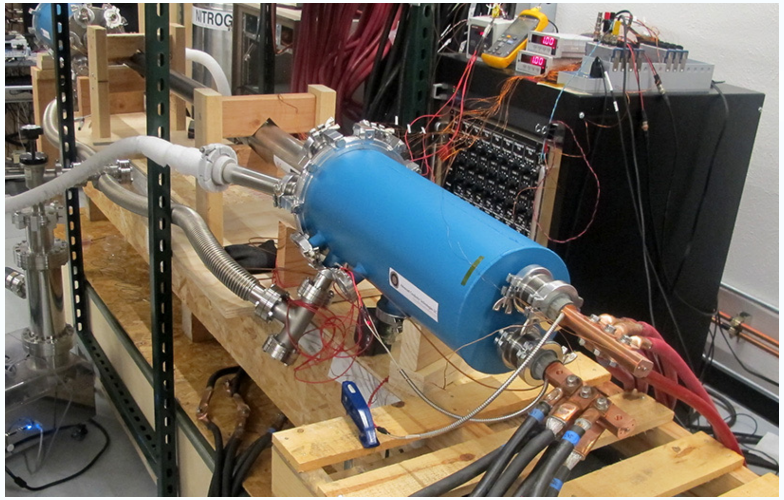
CORC® ac bus

Airbus ASCEND: CORC® dc bus qualification at ACT

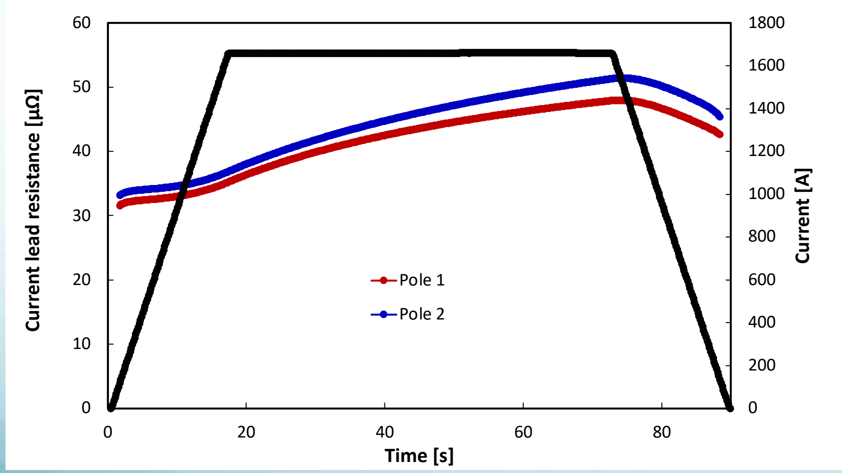
Dc bus qualification

- Cooled with LN_2 from pressurized dewar (80 K)
- Cooldown in 3 hours
- Dc CORC® power cables energized to 1,700 A
- Voltage over current leads measured for short duration

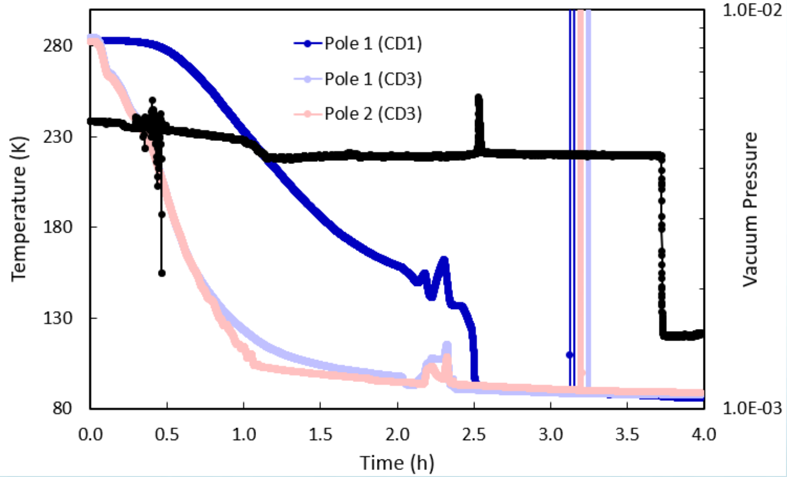




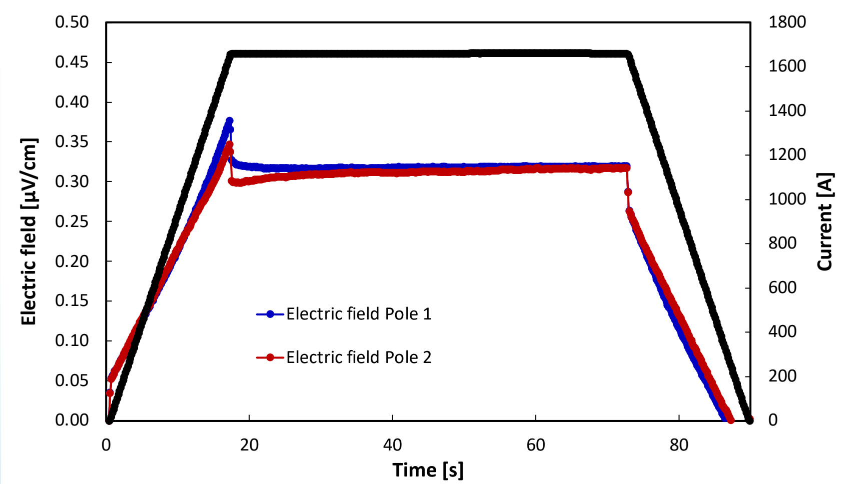
Current lead resistance



Temperature of connecting devices



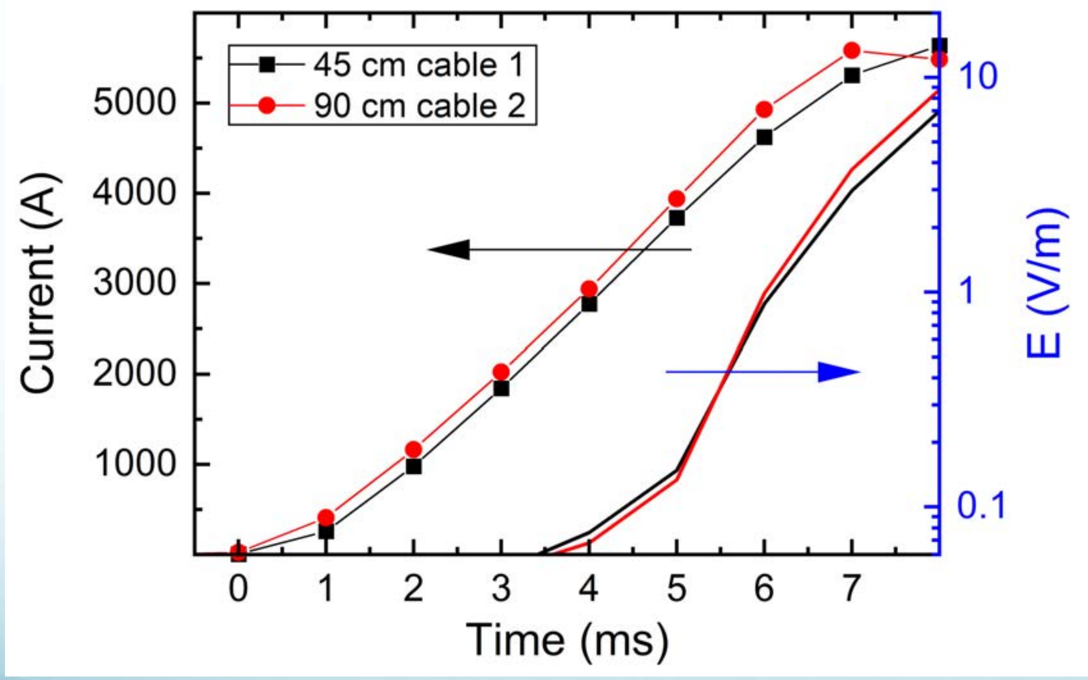
CORC® cable voltage



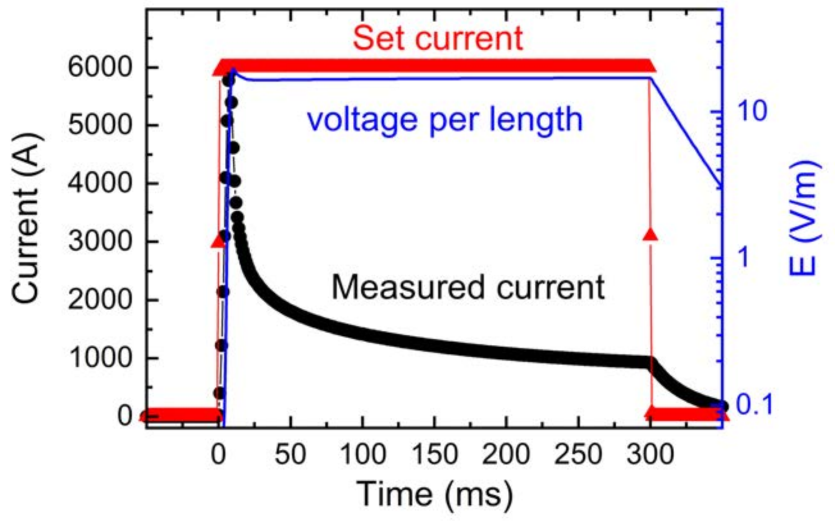
Testing of CORC® dc bus FCL functionality for ASCEND

Short sample CORC® FCL cable tests at ACT

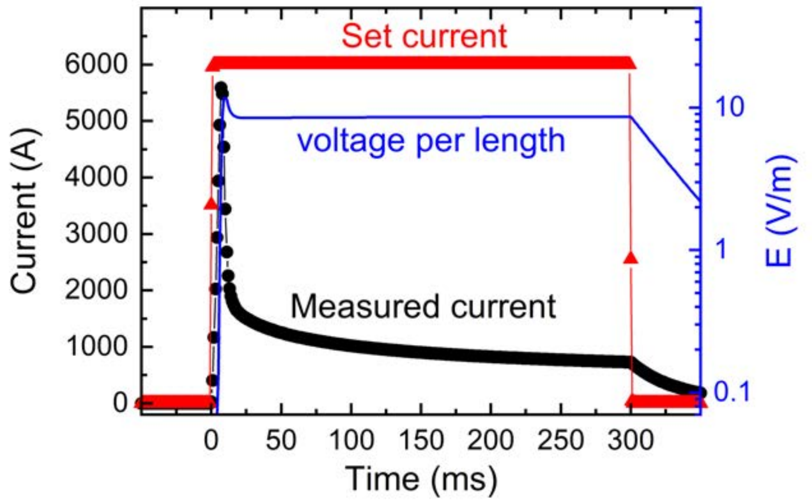
- Single-pole CORC® cable critical current 2.8 kA at 76 K
- Electric field > 7.5 V/m within 5 ms after 6 kA fault starts
- Current limited to less than 2 kA within 7 ms
- No damage to cable even after 300 ms of fault current



0.45 meter CORC® cable



0.9 meter CORC® cable



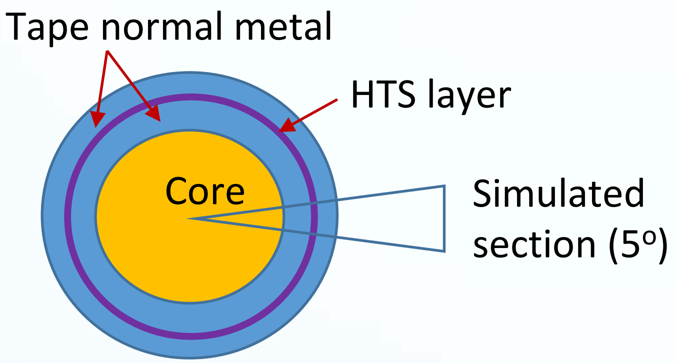
Advanced Conductor Technologies
www.advancedconductor.com

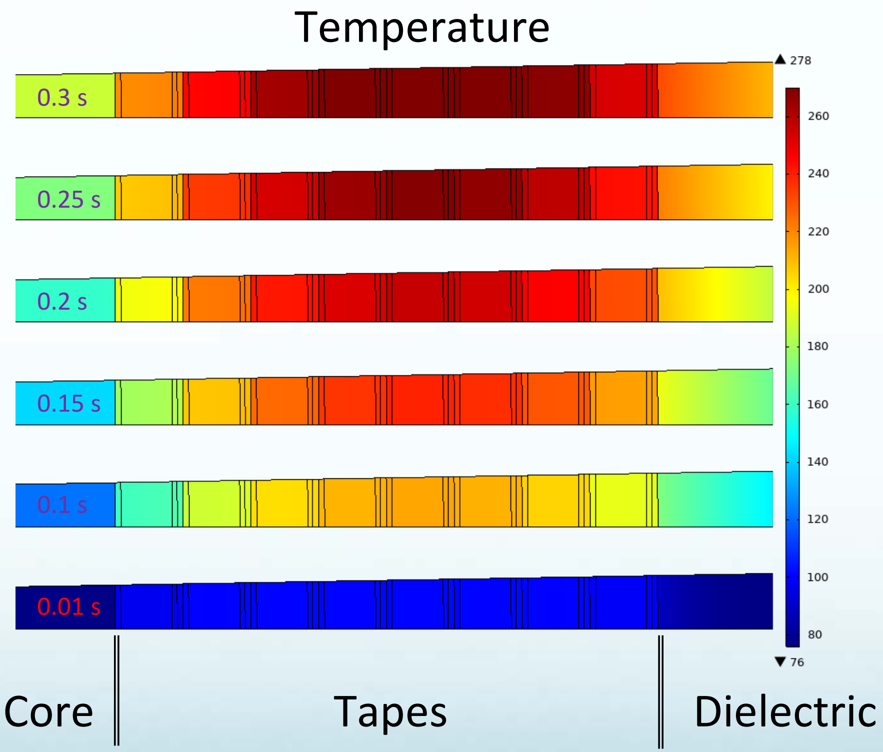
AIRBUS

CORC® FCL cable modeling

Modeling details

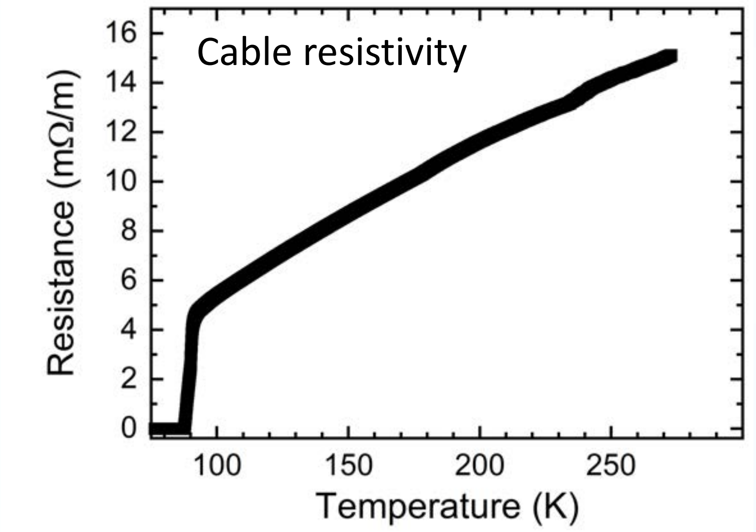
- Simulation is limited to 5° section due to symmetry
- Includes cooling to liquid nitrogen
- Case of a 0.45-meter CORC® FCL cable at 6 kA fault

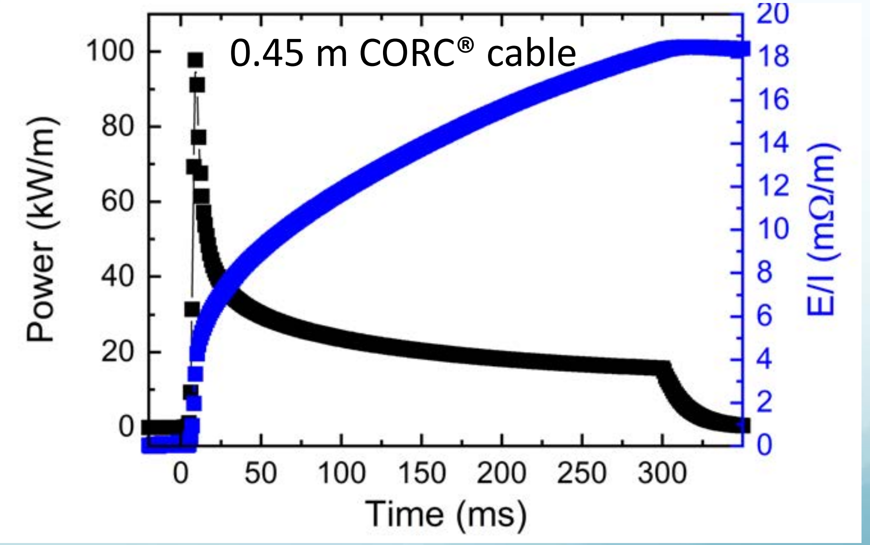




Model results

- Peak temperature of 278 K after 300 ms
- Confirmed by cable resistance measurements





Advanced Conductor Technologies
www.advancedconductor.com

Los Alamos NATIONAL LABORATORY

Summary

Development of Canted-Cosine-Theta accelerator magnets is now on track to deliver 5 T in 2024

- All CORC® wires for the 5 T CCT magnet will be delivered to LBNL before the end of 2023
- The CORC® wire flexibility has been vastly improved by optimizing the winding process
- **CORC® wires are now compatible with "rough" tapes and now allow bending to less than 40 mm diameter**
- The potential next CORC®-based CCT magnet is aimed to generate 15 T within an 11 T LTS outsert

The first CORC® Common Coil insert magnet has been successfully tested

- A new technique to wind CORC® cables into pancake coils has been developed
- The CORC® Common Coil insert was operated degradation-free at over 10 kA within a 7.59 T background field
- A high-field CORC® Common Coil insert will be completed in December 2023 and tested in Q1-2024

CORC® wires have proven to be defect-tolerant

- Current sharing in CORC® wires allows for significant tape dropouts without loss of performance
- A 81-turn CORC® solenoid containing many tape dropouts generated a field of 4.8 T at 25 K

CORC® cables offer a highly attractive solution for electric aircraft

- The 0.5 MW dc and ac busses of the Airbus ASCEND demonstrator are based on CORC® cables
- The CORC® dc and ac busses for ASCEND were qualified and delivered in early 2023
- Results of the ASCEND demonstrator commissioning are expected soon