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Recent Progress on CORC® Cables and Wires

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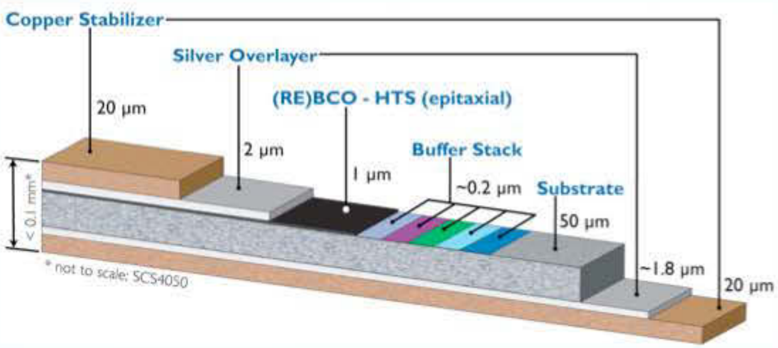
Conductor on Round Core (CORC®) cables

CORC® cable principle based on strain management
Winding many high-temperature superconducting YBCO coated conductors from SuperPower in a helical fashion with the YBCO under compression around a small former to obtain high cable currents



RE-$Ba_2Cu_3O_{7-\delta}$ coated conductor made by SuperPower Inc.

Single tape wound into a CORC® cable

Benefits of CORC® cables and wires
- Very high currents and current densities
- Mechanically very strong
- Very flexible
- High level of conductor transposition

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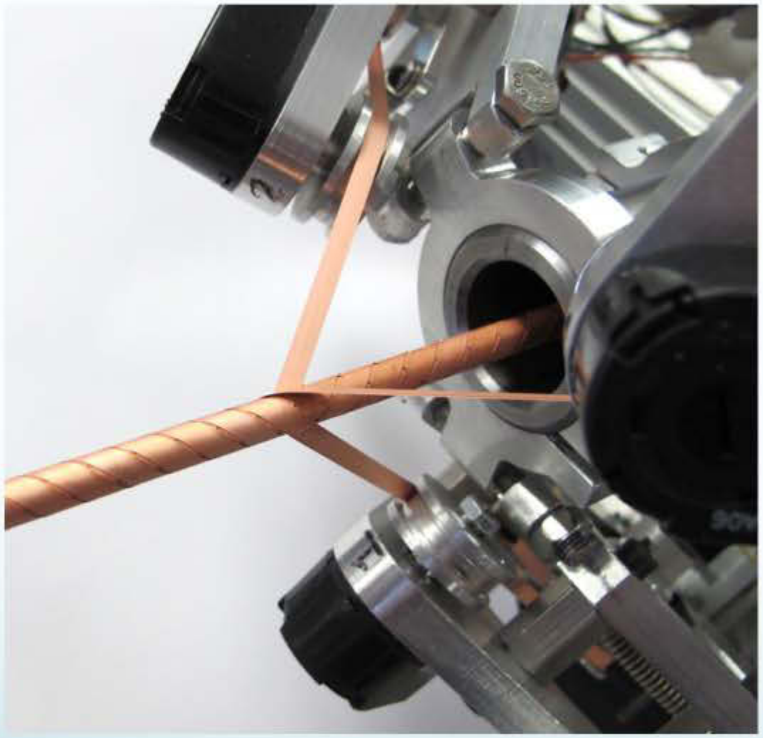
CORC® cable production at ACT

Winding of long CORC® cables with custom cable machine

- Accurate control of cable layout
- Long cable lengths possible (> 100 meters)
- I_c retention after winding 95-100 %



First commercial sale (CERN)

- 12 meter CORC® cable (38 tapes)
- Cable for detector magnets
- Delivered August 2014

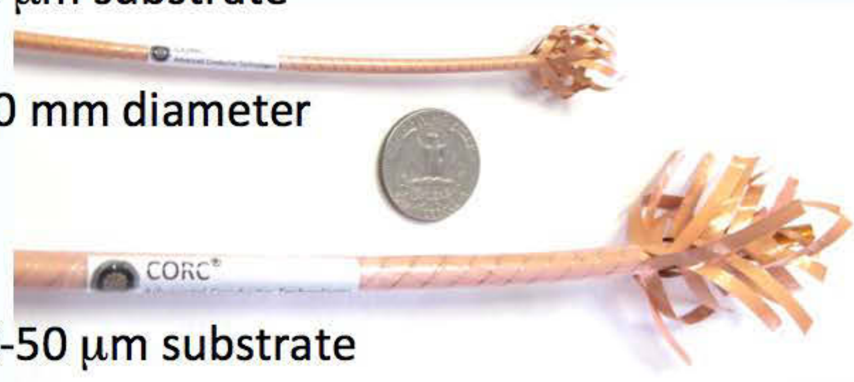
Many commercial orders followed

About 200 meters of CORC® cable and wire total between 2014 and Oct. 2017

CORC® magnet cables and wires

CORC® wires (2.5-4.5 mm diameter)

- Wound from 2-3 mm wide tapes with 30 μm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to < 50 mm diameter

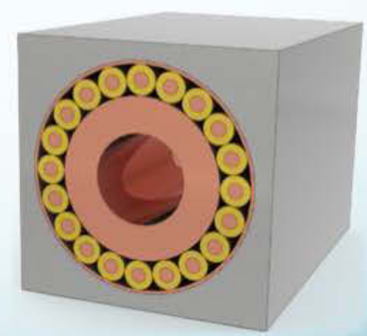


CORC® cable (5-8 mm diameter)

- Wound from 3-4 mm wide tapes with 30-50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to > 100 mm diameter

CORC®-Cable In Conduit Conductor (CICC)

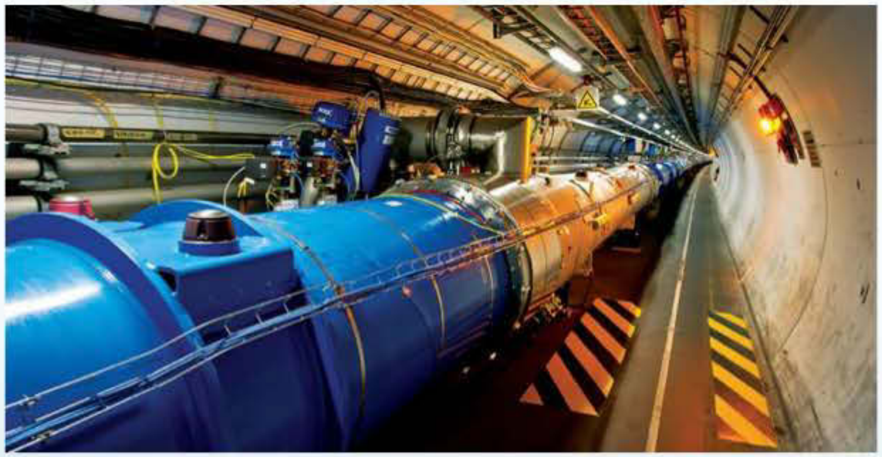
- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 1 meter



CORC® cable development for accelerator magnets

Overall goals

1. High engineering current density J_e (20 T) > 600 A/mm^2
2. Small cable bending diameters 20 – 50 mm
3. Develop CORC® cables and wires for new magnet configurations



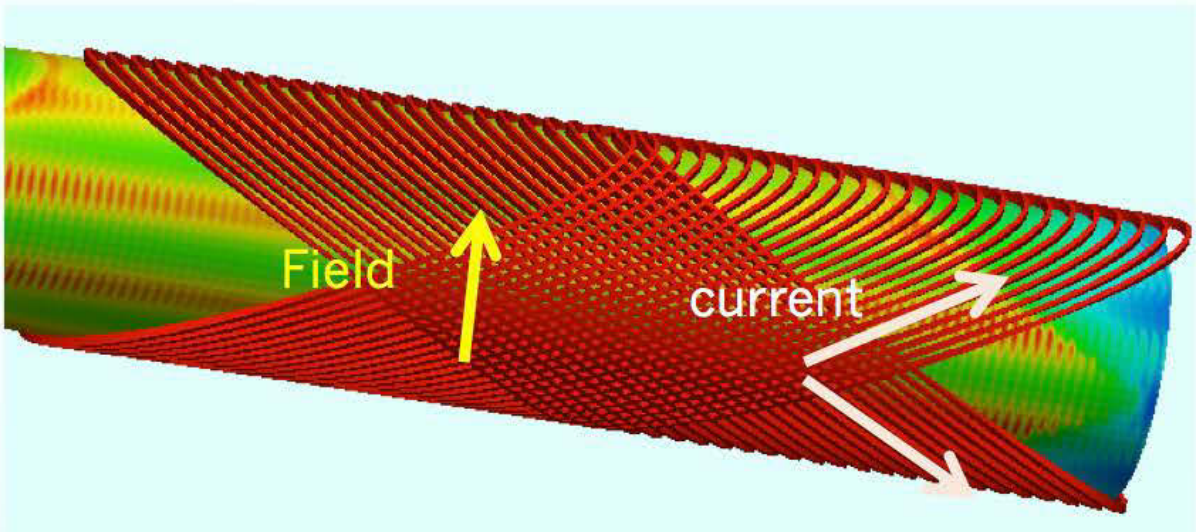
LHC

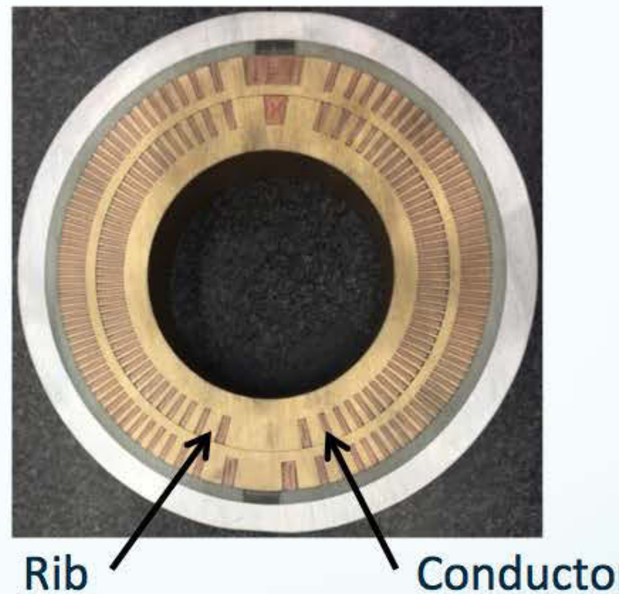
Heidelberg PBT gantry

Canted-Cosine-Theta magnets wound from CORC® wires

Canted-Cosine-Theta magnet program with Berkeley National Laboratory

- Conductor-friendly magnet design resulting in low stresses
- Delivers excellent geometric field quality in straight section and coil ends





CORC® CCT magnet program goals

- Reach 5 T in CORC® CCT insert with 10 T (15 T) LTS CCT outsert
- Develop the CORC® CCT magnet technology in several steps
    - C1: 1 T 4.2 K, self-field, low-J_e CORC® wire
    - C2: 4-5 T 4.2 K, self-field, 2-3 T in 10 T, high-J_e CORC® wire
    - C3: 5 T in 15 T background, advanced CORC® wires (<25 μm substrate)

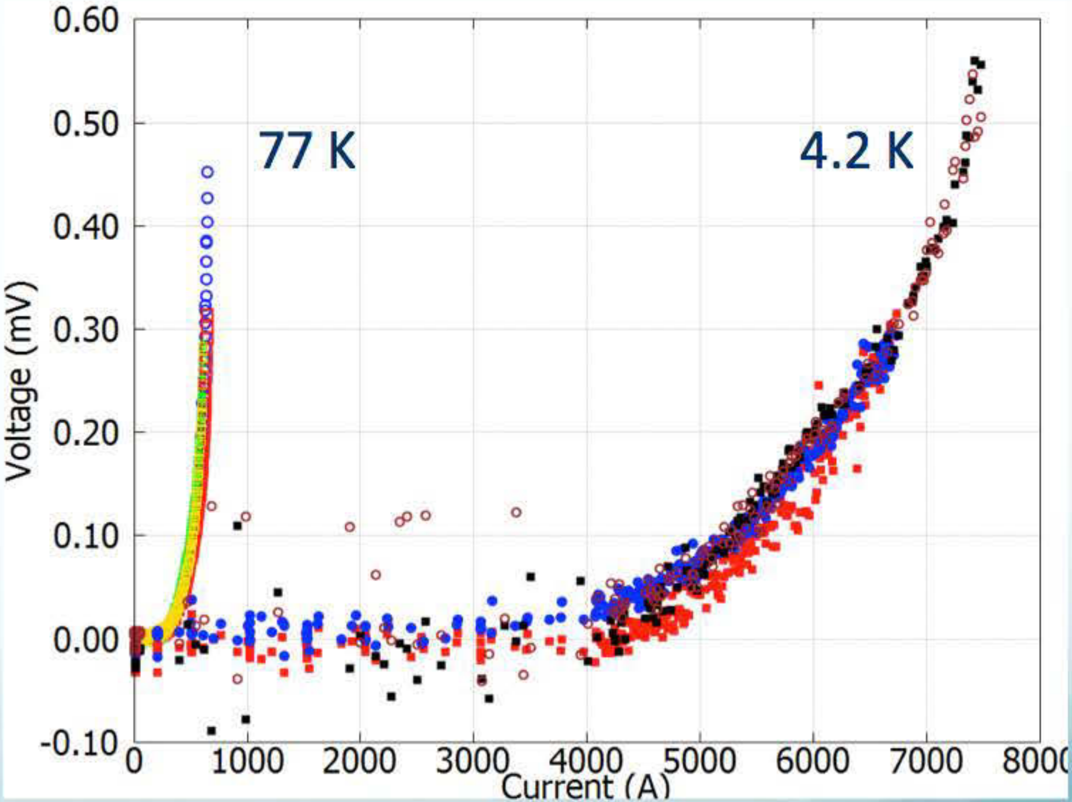
Baby coil C1-0: CORC® wire test for CCT-C1

CCT C1-0: CORC® wire with 16 tapes

- 2 Layers
- 3 Turns per layer
- Inner layer I.D. 70 mm
- Minimum bending diameter 50 mm

CCT C1-0 performance

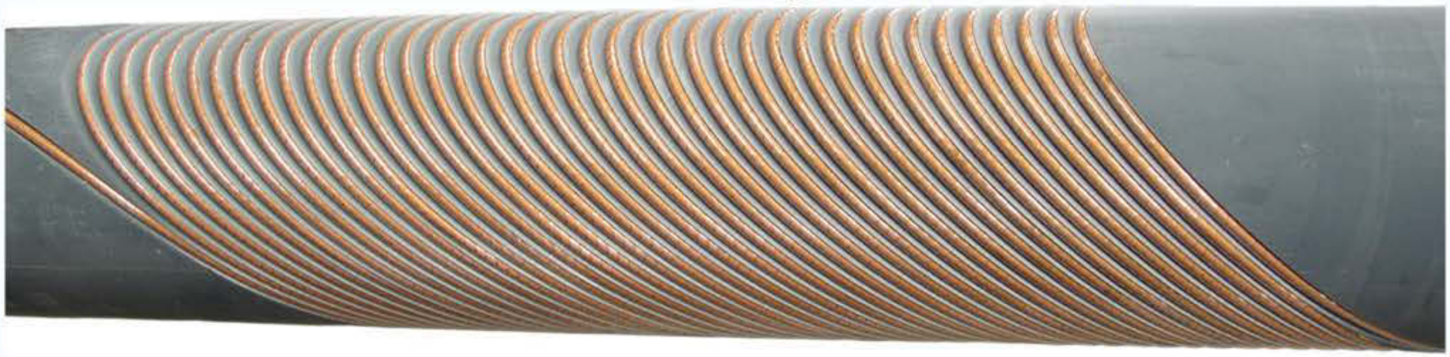
- I_c (77 K) = 646 A (layer A) and 675 A (layer B)
- I_c (4.2 K) = 6,700 A (both layers)



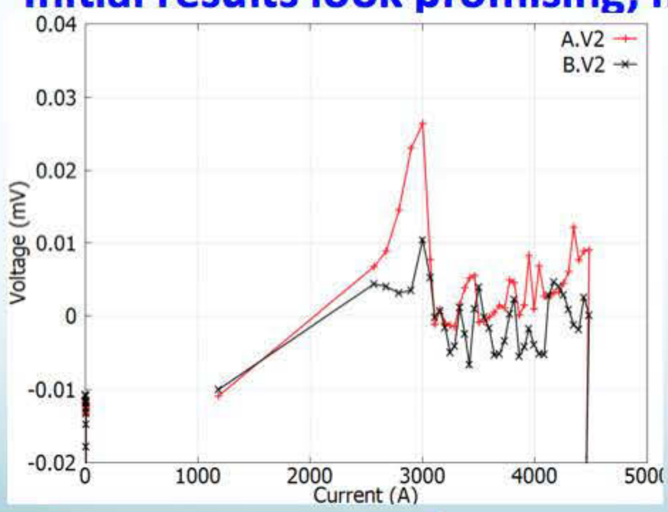
CORC® CCT-C1: 1 T at 4.2 K self-field

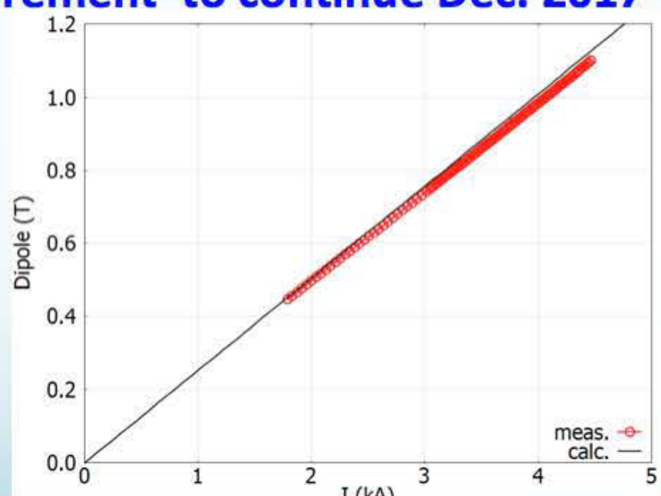
CCT-C1 Magnet wound at LBNL

- 2 Layers, 40 turns per layer
- LBNL ordered 50 m of CORC® wire in 2016
- CORC® wire contains 16 tapes, J_e (20 T) = ~150 A/mm^2



Initial results look promising, measurement to continue Dec. 2017

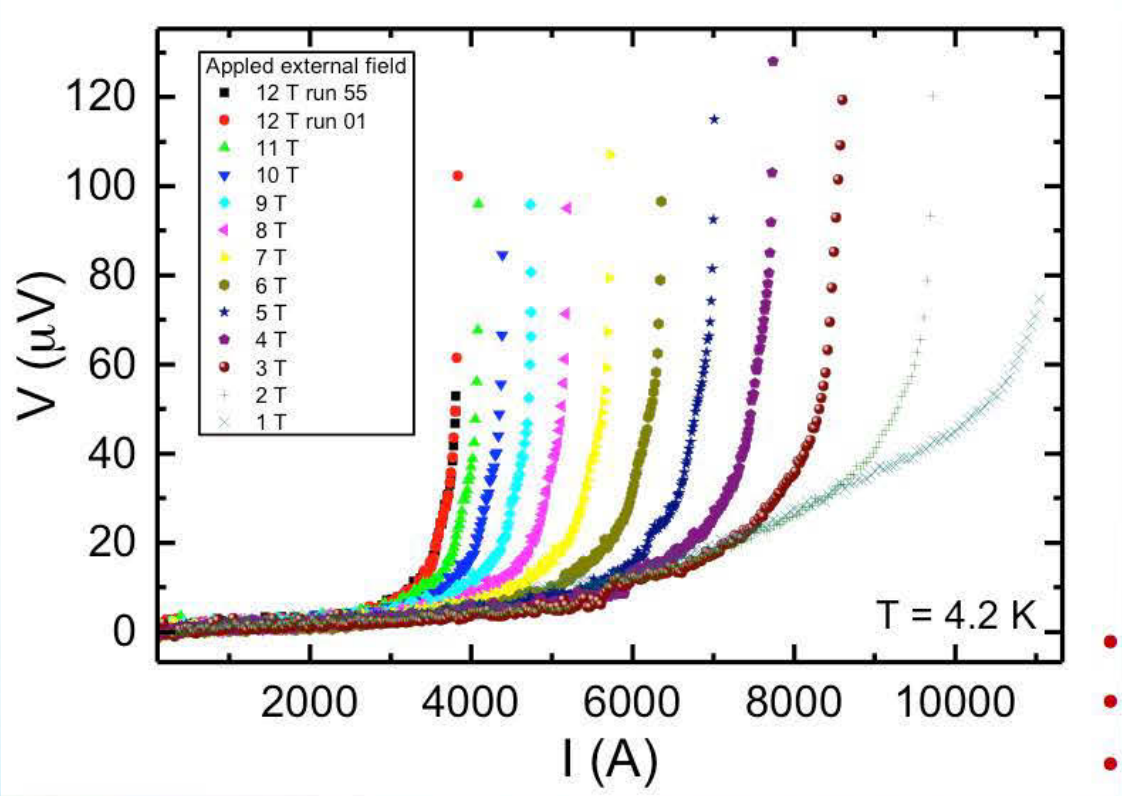




27-Tape CORC® magnet wire for C2

High-J_e CORC® wire layout

- 27 tapes, 2 mm wide, 30 μm substrate
- 3.6 mm diameter
- 5 turns on 60 mm diameter mandrel



- I_c = 3,831 A (4.2 K, 12 T, 1 μV/cm)
- **Projected J_e(20 T) 259 A/mm²**
- **No degradation due to stress cycling**

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UNIVERSITY OF TWENTE. CERN BERKELEY LAB

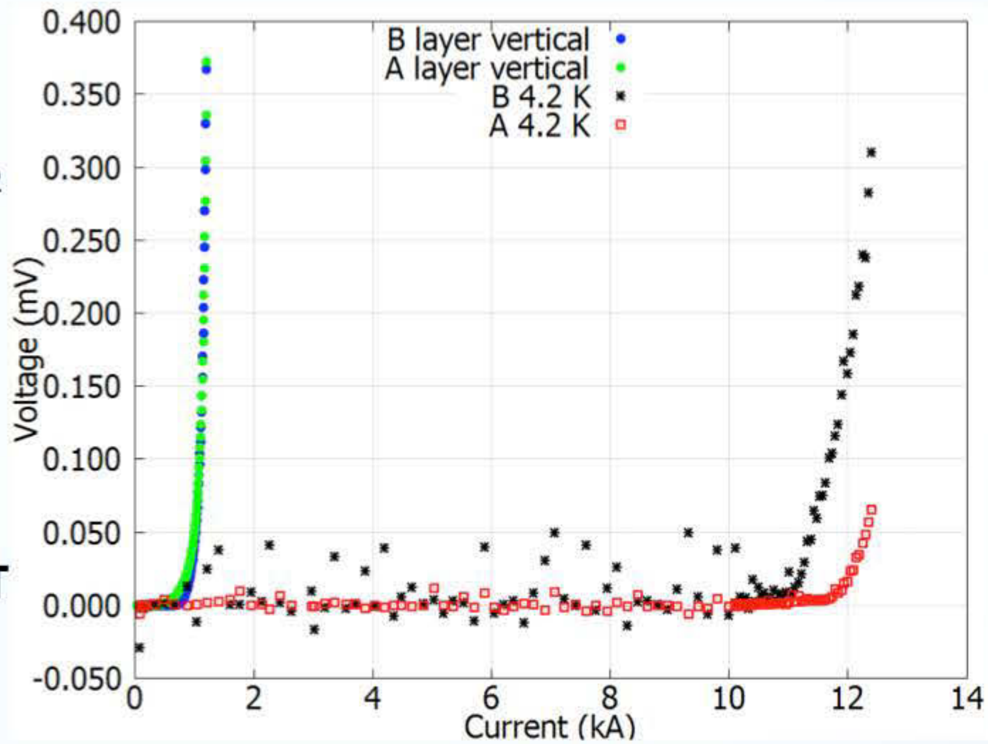
Baby coil C2-0: pretest for CCT-C2 (2-3 T in 10 T)

CCT C2-0: CORC® wire with 29 tapes

- 3-turn per layer
- Inner layer I.D. 85 mm
- CORC® wire J_e (20 T) = ~250-300 A/mm²

CCT C2-0 performance

- I_c (77 K) = 1.092, 1,067 A (layer A, B)
- I_c (4.2 K) = 12,141, 11,078 A (layer A,B)
- Dipole field 0.68 T (4.2 K)
- Peak J_e(4.2 K) = 1,198 A/mm²
- **Expected field of CCT-C2 (40 turns) ~5 T**

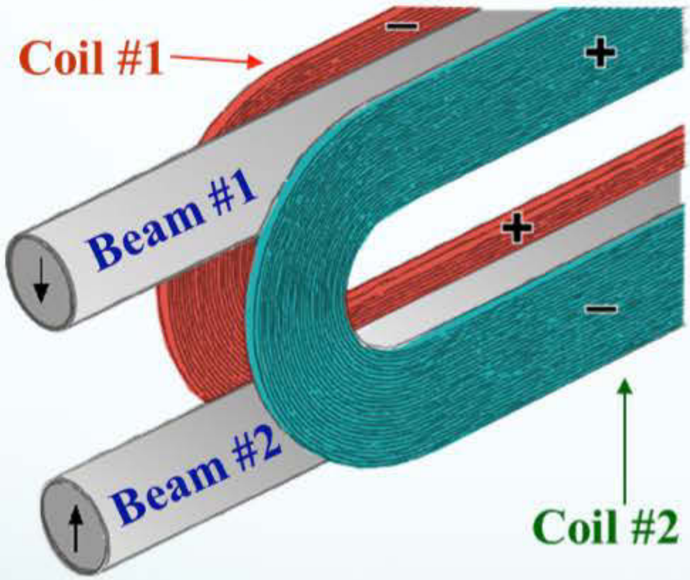


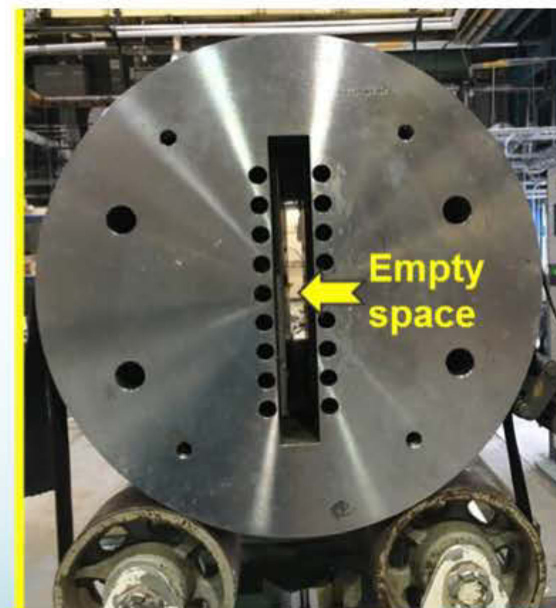
- Coil B burned out at 12,400 A at 4.2 K due to unprotected quench
- CORC® wire has been replaced to finalize testing
- Order for 75 m of high-J_e CORC® wire received from LBNL
- Full-size coil C2 expected to be wound in Q2 2018

Common coil magnet wound from CORC® cables

Common Coil magnet program with Brookhaven National Laboratory

- CORC® cable common coil insert
- Combine with 10 T LTS common coil outsert
- Operating J_e 400-500 A/mm² (15-20 T)
- Operating current 10 kA in series with LTS outsert





Common coil benefits

- Only large bending diameters required
- Allowing CORC® cables to be used
- Allowing use of highest J_e cables

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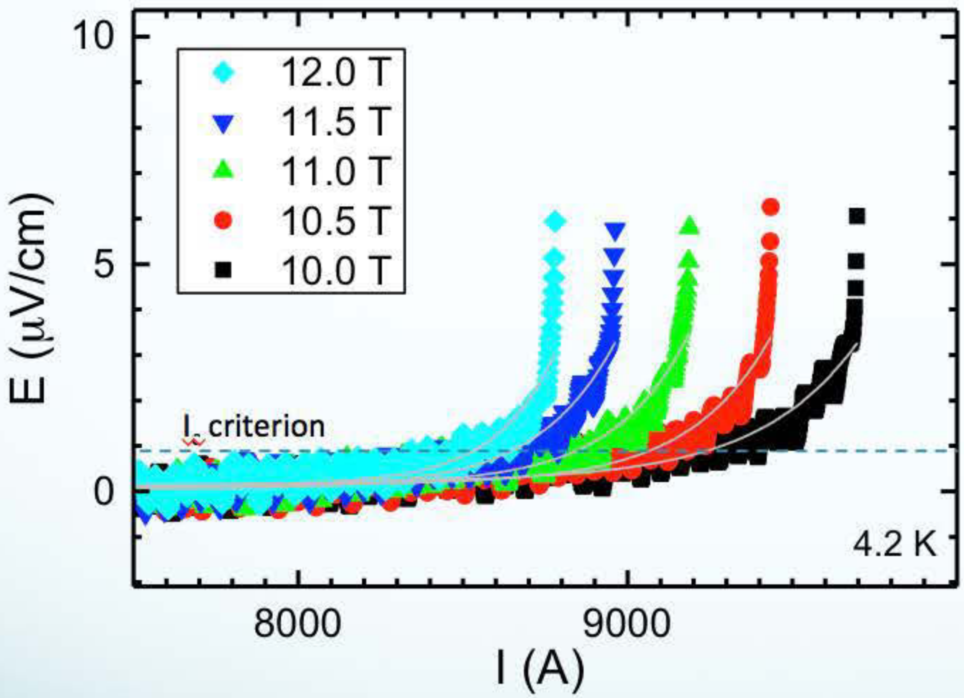
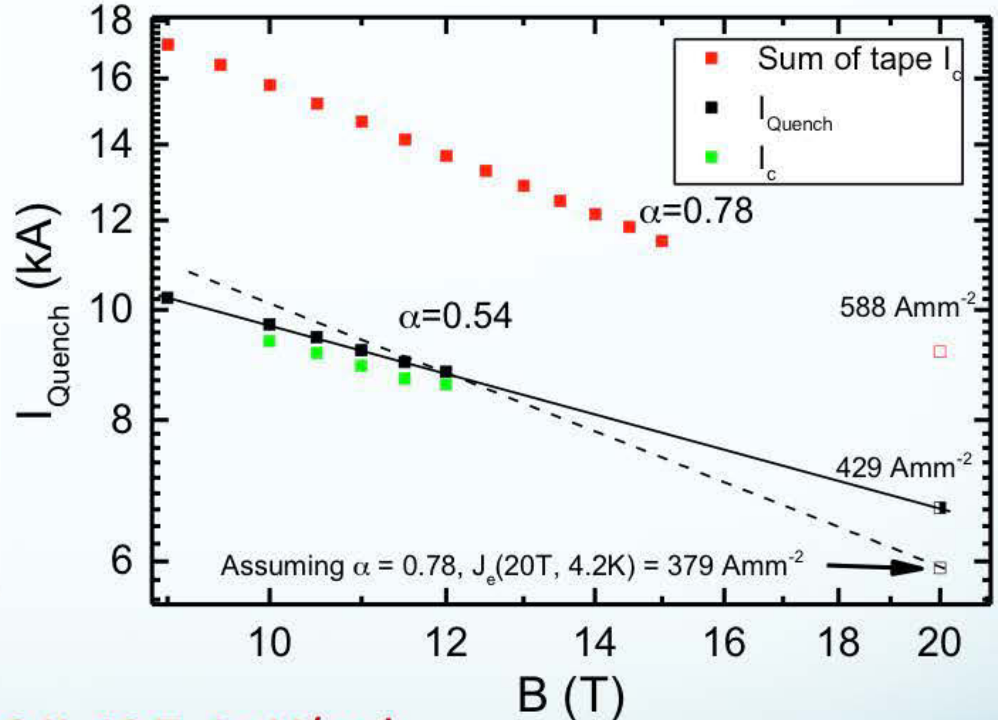
BROOKHAVEN NATIONAL LABORATORY

Record CORC® magnet wire performance

High-J_e CORC® wire layout

- 50 tapes, 2-3 mm wide, 30 μm substrate
- 4.46 mm CORC® wire diameter
- 62 mm hairpin (much tighter bend than in Common Coil)

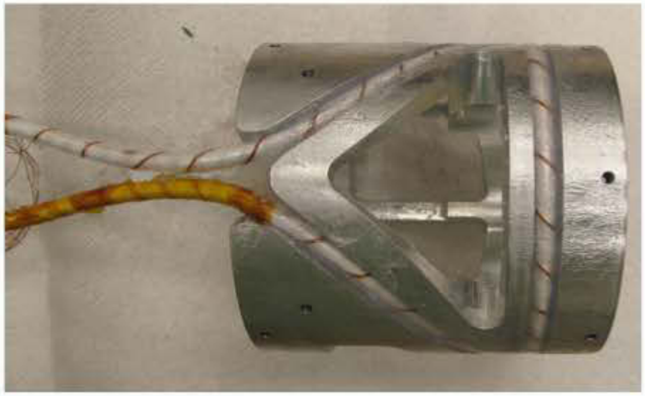




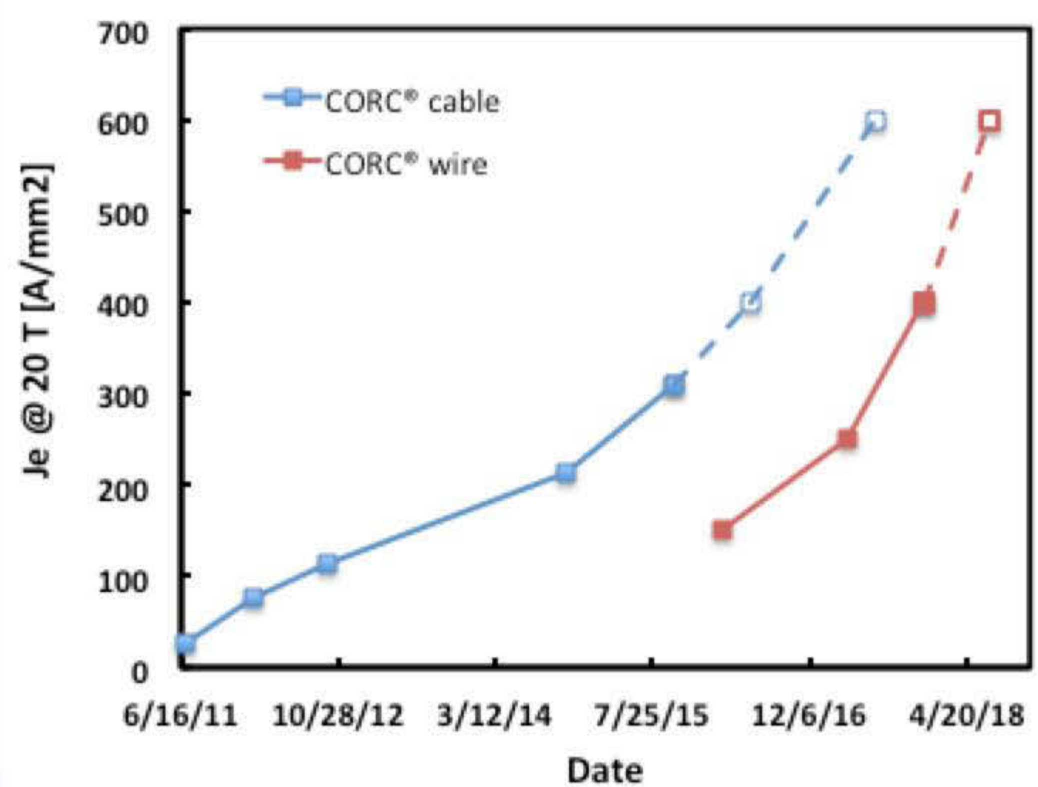
- I_c = 8,591 A (4.2 K, 12 T, 1 μV/cm)
- **Projected J_e(20 T) between 379 and 429 A/mm²**
- I_c retention is 74.5 % of initial tape I_c

CORC® magnet cable and wire performance

CORC® cable tested at 100 mm diameter (2011 – 2015)



CORC® wire tested at 60 mm diameter (2016 –)



Closing in on J_e > 600 A/mm² goal

- Even though test facility at NHMFL taken off-line in 2015
- In-house testing limited to 62 mm bending diameter
- J_e (20 T) now exceeded 400 A/mm² in CORC® wire

CORC® power transmission cables for the US Navy

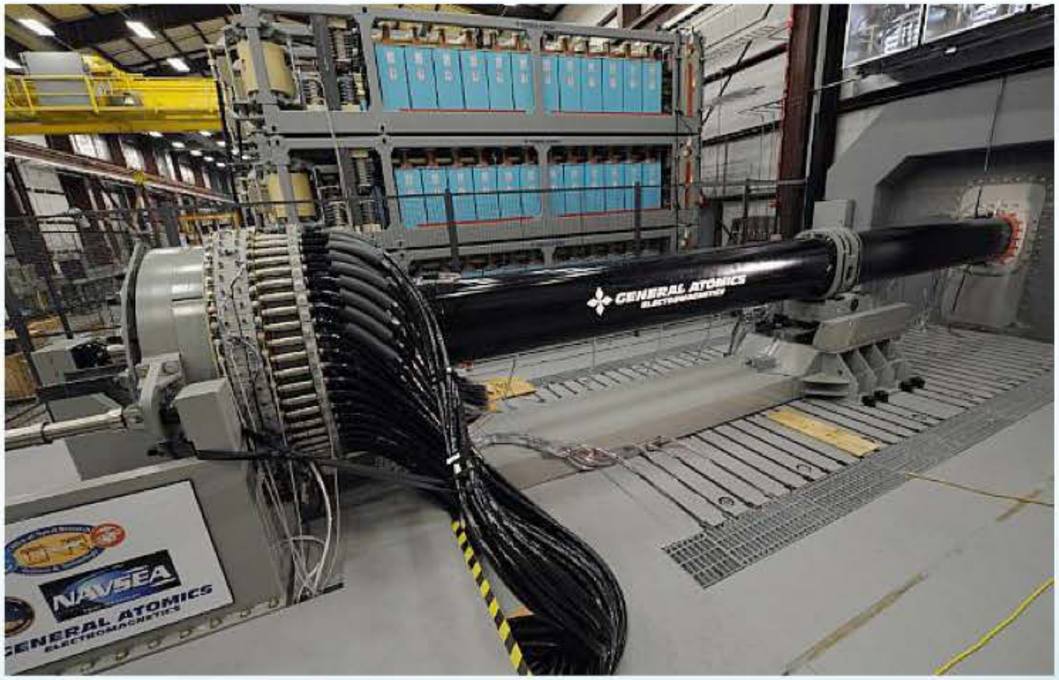
CORC® power cables in collaboration with Center for Advanced Power Systems

- Operation in helium gas at 50 K
- Dc and ac cables
- 3-10 kA per phase
- 1-20 kV operation
- Fault current limiting capabilities

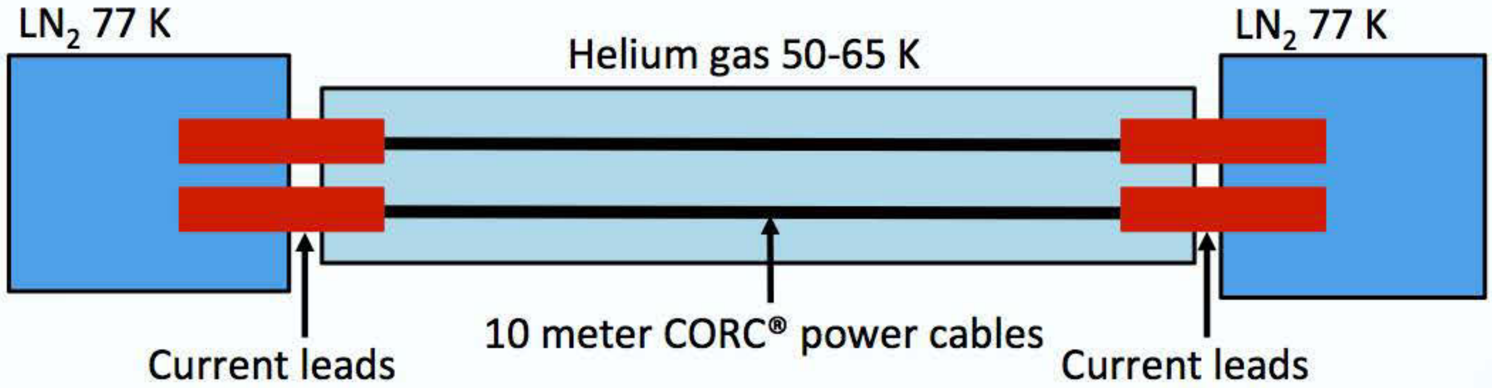
Potential applications

- Navy ships
- Electric aircraft
- Data centers

NAVSEA
WARFARE CENTERS
Philadelphia

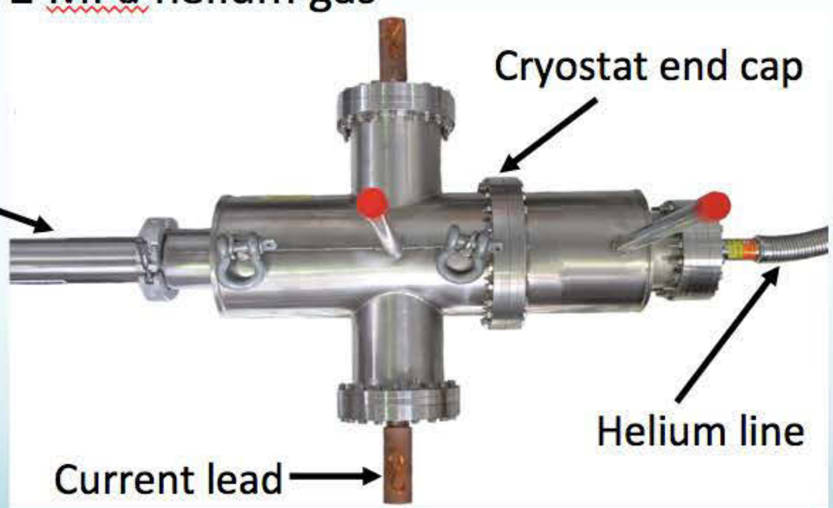


10-Meter 2-Pole CORC® DC Power System



Goal

- 2-Pole dc CORC® power transmission cable
- 10 meter long twisted pair cable layout
- Operating current 4,000 A (50 K)
- Cooled with 2 MPa helium gas



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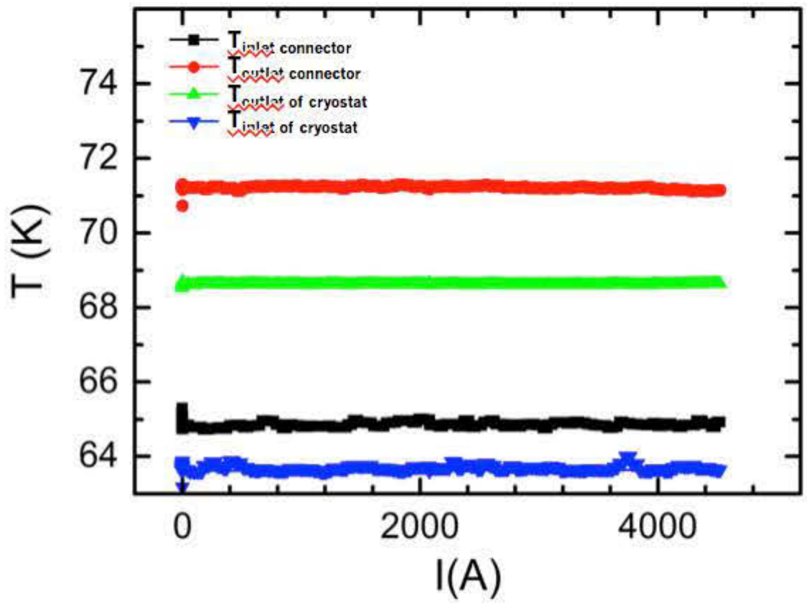
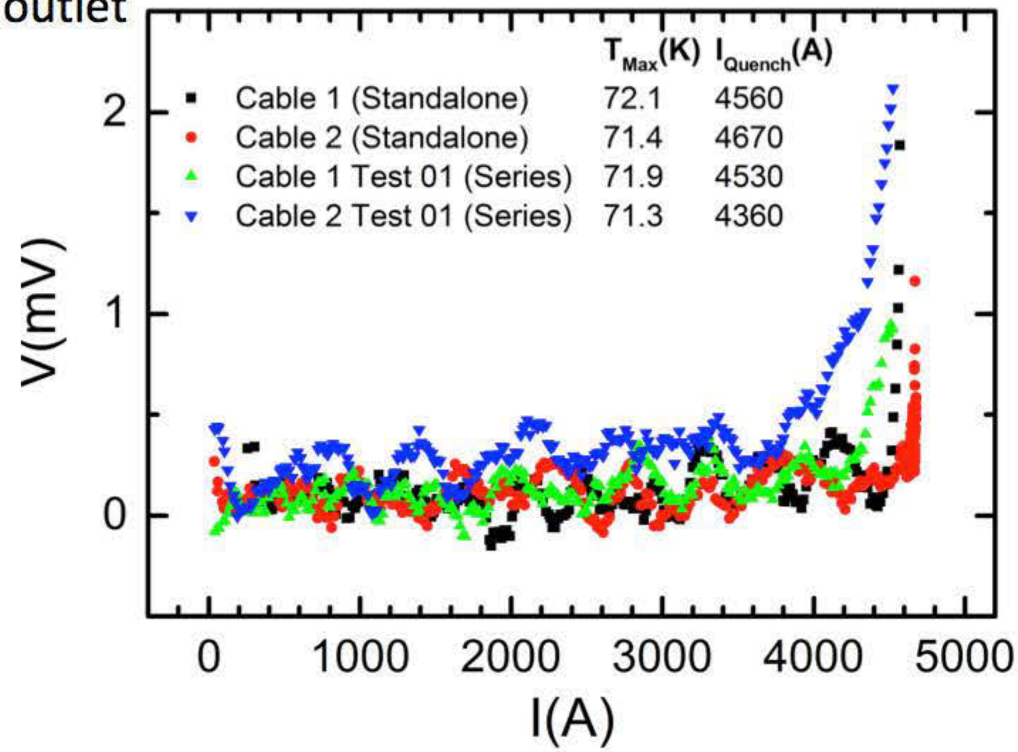
10-Meter 2-Pole CORC® System Test

Test procedure

- Cool-down to 64 K inlet, and 72 K outlet
- Test each phase individually
- Test phases connected in series





- **Individual cable tests I_{quench} (Phase 1) = 4,560 A, I_{quench} (Phase 2) = 4,670 A**
- **Series connected cable tests I_{quench} (Phase 1) = 4,530 A, I_{quench} (Phase 2) = 4,360 A**
- **Results suggest that I_{quench} at 50 K would be > 10,000 A**

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CORC® Power transmission system shipped to Navy

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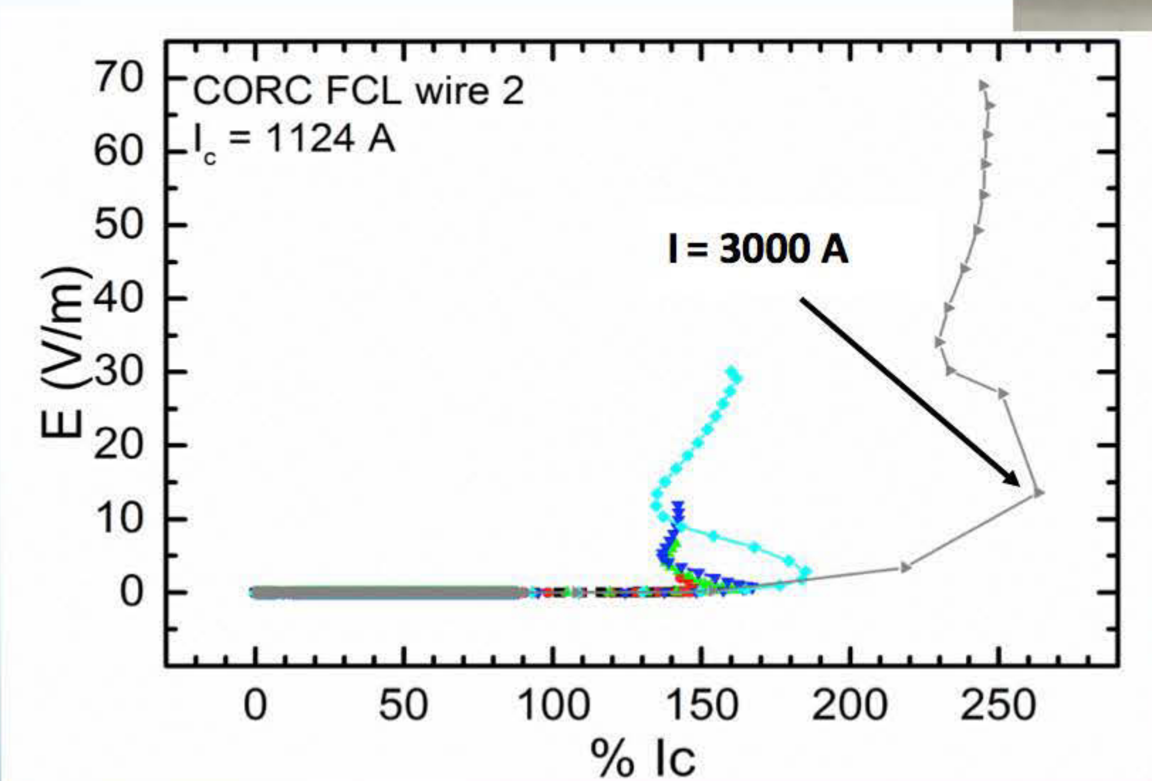
Development of CORC® Fault Current Limiting wires

CORC® FCL wires

- Current sharing between tapes with short twist pitch removes the requirement for tape laminations
- Minimal normal conducting material
- Fast response to overcurrent < 20 ms

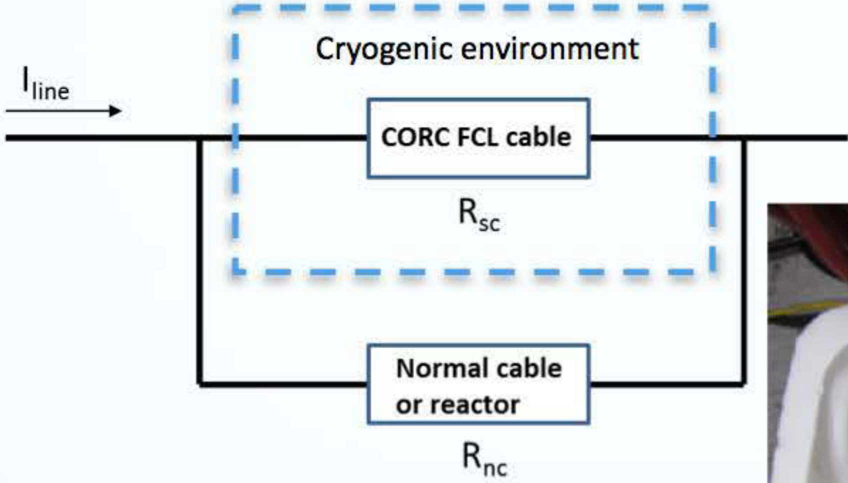


Electric field over CORC® wire 70 V/m after 15 ms!

Data points 1 ms apart

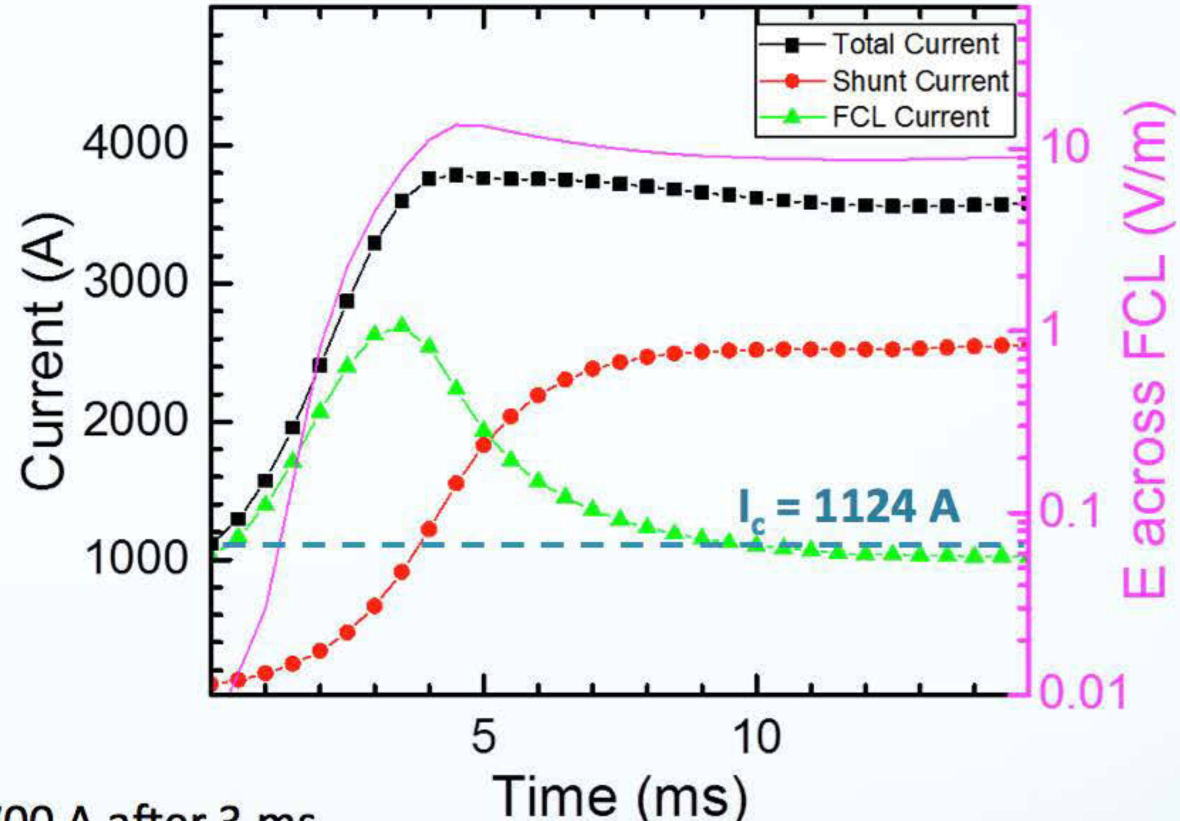
Overcurrent testing of a hybrid CORC® FCL system

CORC® FCL wire in parallel with room temperature shunt



Configuration allows isolation superconducting wire after fault, enabling cool-down to cryogenic temperature

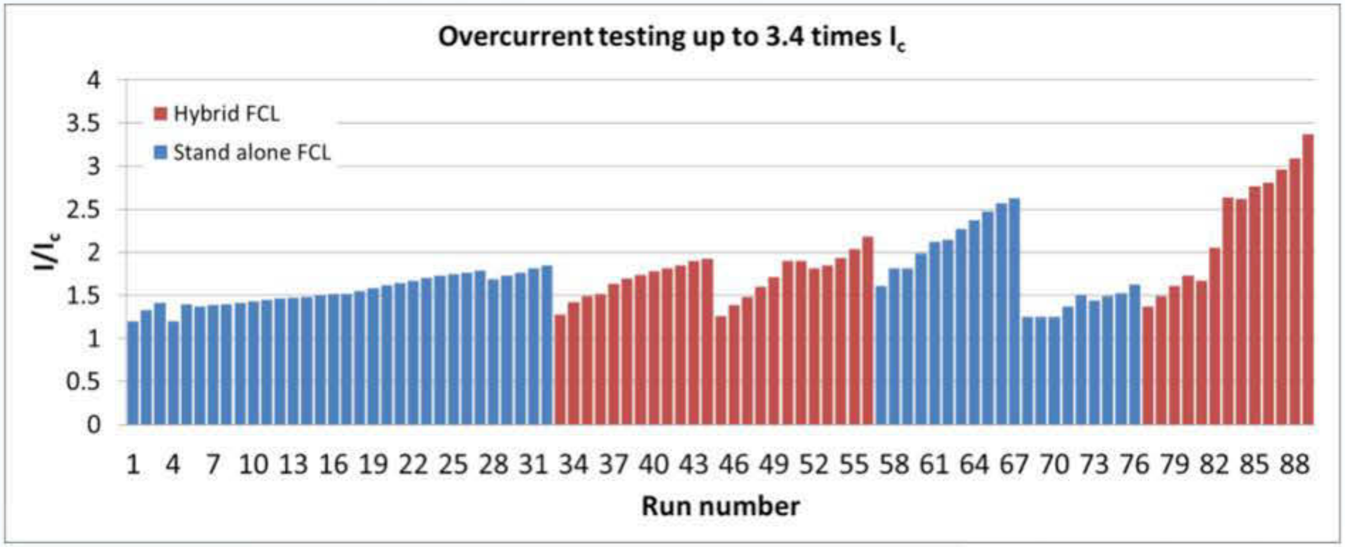
Overcurrent testing of a hybrid CORC® FCL system



Fault overcurrent of 320 % I_c

- Peak current in FCL wire 2,700 A after 3 ms
- FCL voltage 10 V/m after 5 ms
- Current in FCL wire back below I_c after 10 ms, while maintaining 10 V/m over hybrid cable system

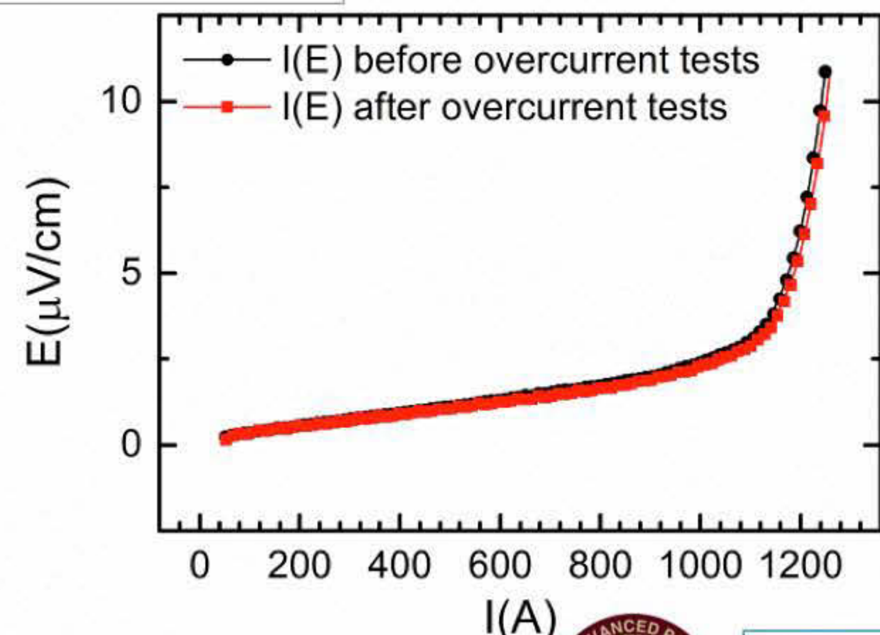
Extensive cycling did not degrade CORC® FCL conductor



Includes

- several non-controlled cool-down cycles (thrown into LN_2 bath)
- full warm-up cycles to room temperature (during 10-20 ms fault)

No degradation after more than 90 faults and several rapid thermal cycles



Summary

CORC® wires and cables have matured into magnet conductors

- High currents have been demonstrated (> 8,000 A (4.2 K, 12 T)
- High current densities have been reached (> 400 A/mm^2 (4.2 K, 20 T)
- CORC® wires are highly flexible (< 50 mm bending diameter)
- Several CORC® magnet programs underway

CORC® cables and wires enable high-current density power transmission

- Helium gas-cooled 2-pole CORC® dc power cable system demonstrated
- Current rating of 10 kA at 50 K
- CORC® wires allow Fault Current Limiting at over 70 V/m