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# High-temperature superconducting CORC® magnet cable and wire development and their application

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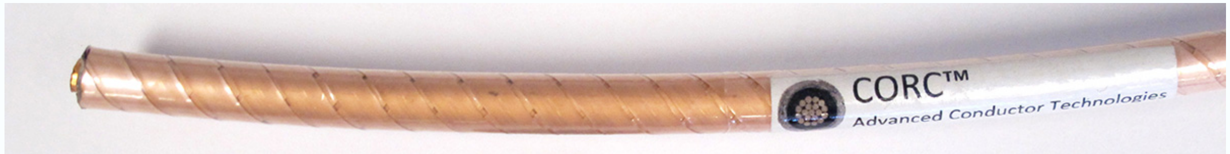
# Outline

1. Introduction of CORC® cables, wires and CICC
2. Current status of CORC® cables
3. CORC® cables used in Common Coils
4. Current status of CORC® wires
5. Magnet programs using CORC® wires
6. CORC®-CICC test in Sultan
7. Summary

# CORC® magnet cables and wires




### 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® 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

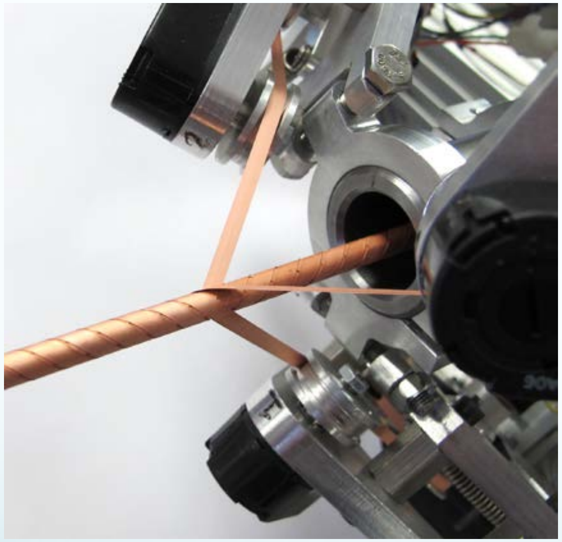
### CORC®-Cable In Conduit Conductor (CICC)

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

# “Current” (2015) CORC® cable performance

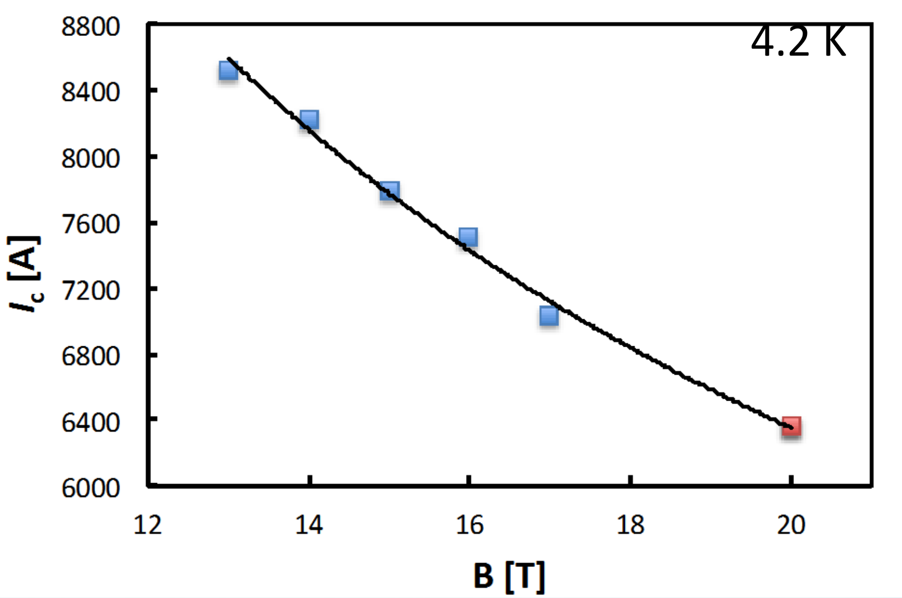
### Winding CORC® cables

- Accurate control of cable layout
- Long cable lengths possible
- $I_c$ retention after winding 95-100 %
- 120 meters wound in 2016, of which 70 meter for commercial orders



### CORC® cable (measured 2015)

- 50 tapes with 30 μm substrate
- 3 mm wide tape $I_c$ (77 K) = 108 A
- Lift factor $I_c$(4.2K, 20T)/$I_c$(77K, s.f.) = 1.72
- Bent to 100 mm diameter



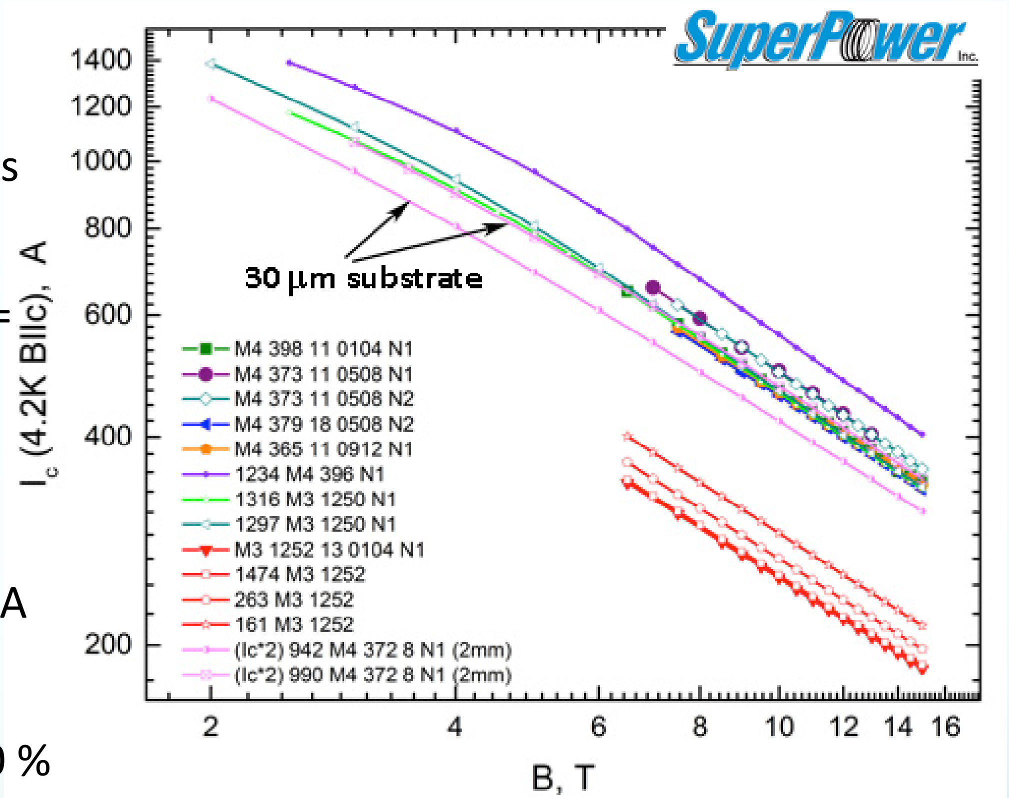

Extrapolated $I_c$ (4.2 K, 20 T) = 6,354 A

**Extrapolated $J_e$ (4.2 K, 20 T) = 309 A/mm²**

# Current CORC® cable performance (untested!)

### Performance of commercial tapes

- Purchased 8,300 meters from SuperPower in 2016
- Tapes with 30 and 50 μm substrates




### Record 2016 samples

- Lift factor $I_c$(4.2K, 20T)/$I_c$(77K, s.f.) = **2.65**
- Typical lift factor (20 T) = 1.9
- $I_c$ (77 K) = 167 A (4 mm, 50 μm)
- $I_c$ (77 K) = 82 A (2 mm, 30 μm)
- Typical $I_c$ (4 mm) 150 A, (2 mm) 68 A

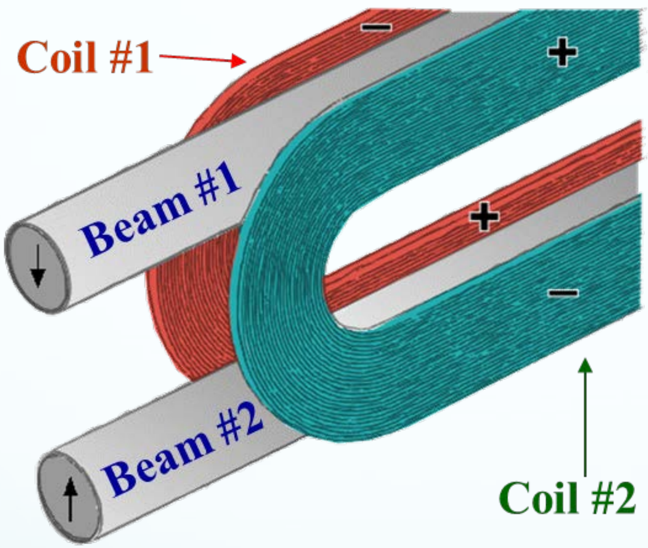
### CORC® cable Oct. 2015 $J_e$(20 T)

- All estimates with $I_c$ retention of 70 %
- Typical $I_c$ and lift factor: $J_e$(20 T) = 375 A/mm$^2$
- Highest $I_c$ and lift factor: $J_e$(20 T) = 560 A/mm$^2$
- At 90 % $I_c$ retention: $J_e$(20 T) = 480-720 A/mm$^2$

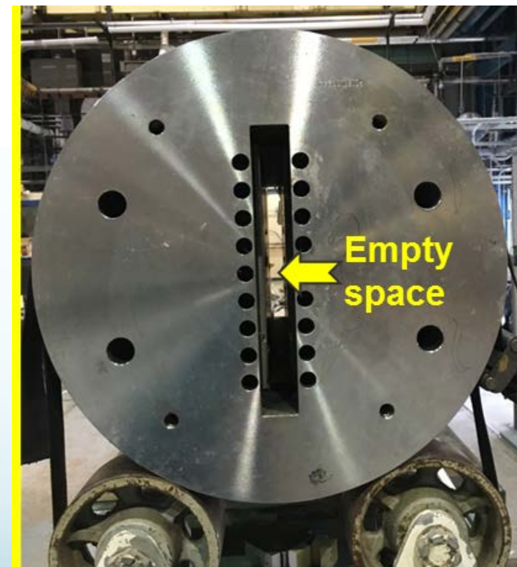
# Common coil magnet from CORC® cables

**Common coil SBIR Phase I program with Brookhaven National Laboratory**

- CORC® cable common coil insert
- Combine with 10 T LTS common coil outsert







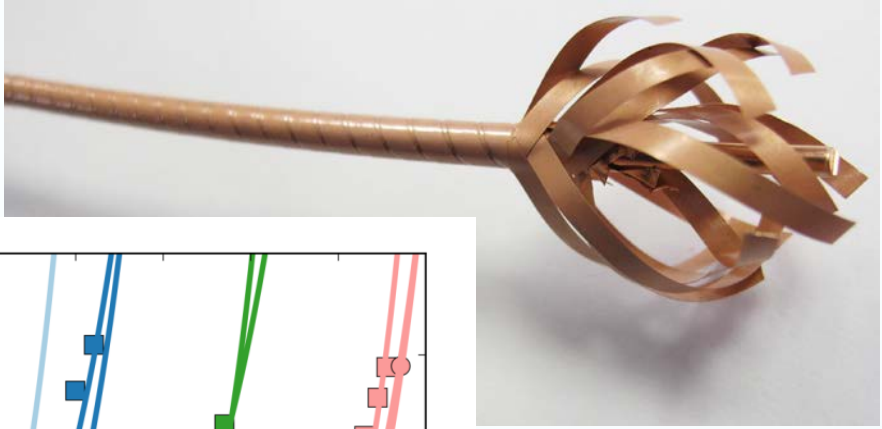

**Common coil benefits**

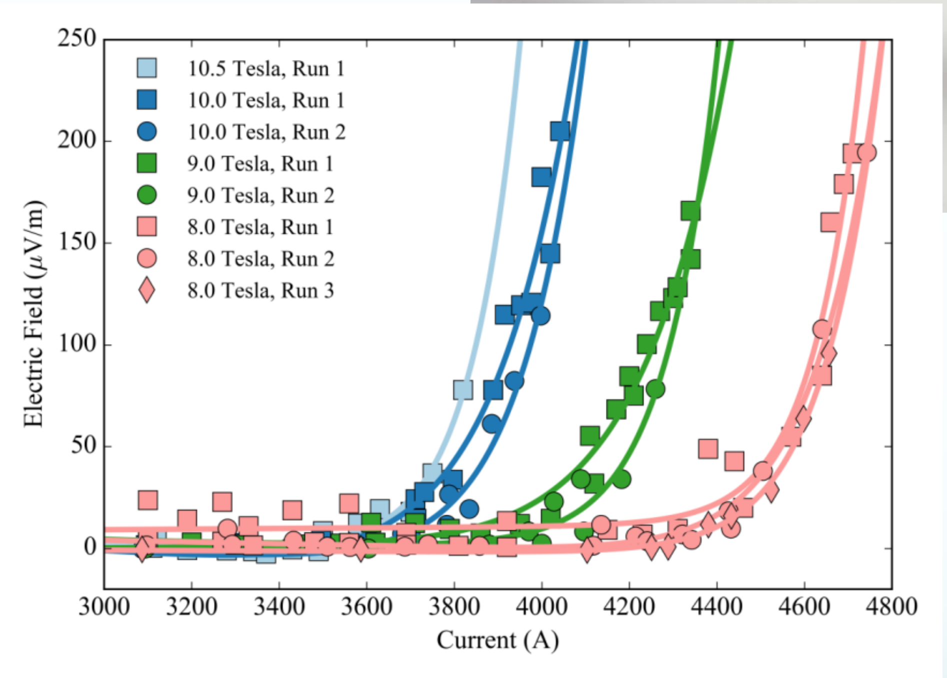
- Only large bending diameters required
- Allowing CORC® cables to be used
- Taking advantage of higher cost/performance ratio

# CORC® magnet wire performance (early 2017)

**High-$J_e$ CORC® wire layout**

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






- **$I_c$ = 3,951 A (4.2 K, 10 T, 1 μV/cm)**
- **Projected $J_e$(20 T) 250 A/mm²**

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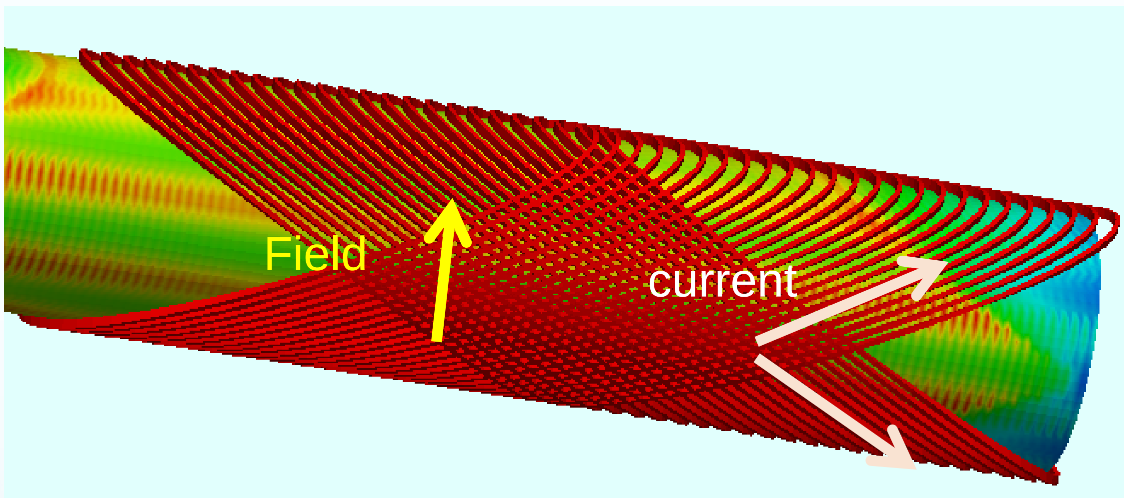
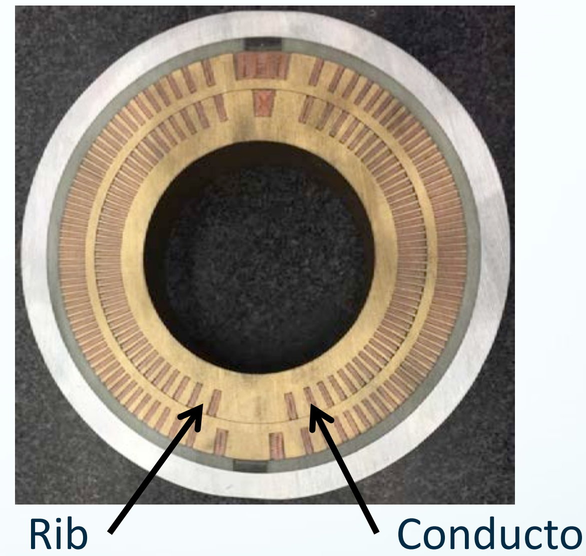
# Canted-Cosine-Theta magnets wound from CORC® wires

### 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, C2, C3)

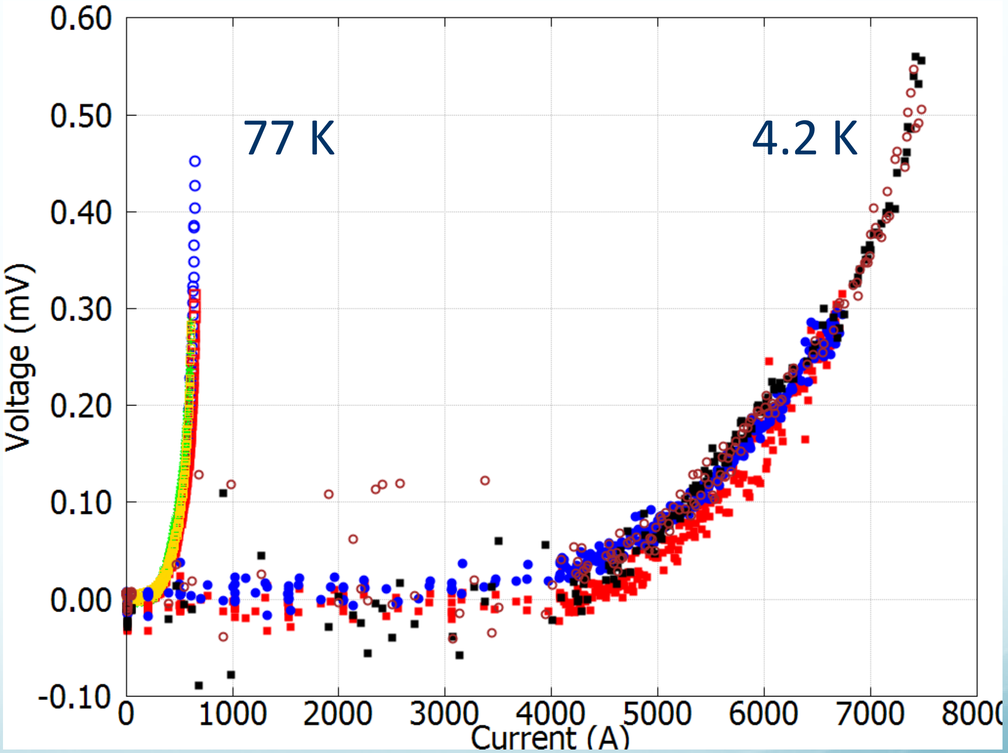
# Model coil C1-0: CORC® wire test for CCT-C1


**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)

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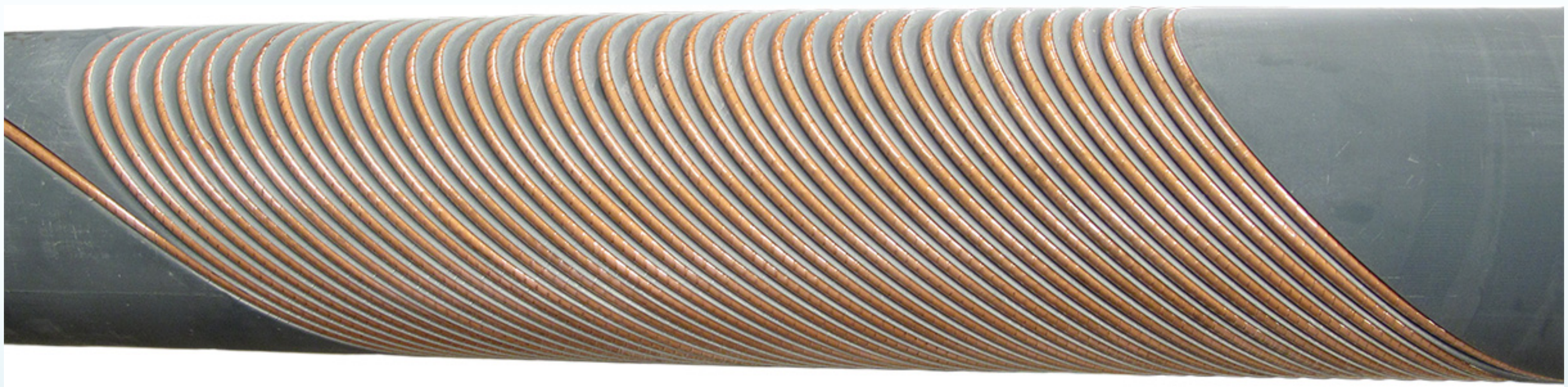
# CORC® CCT-C1

**CCT C1 Magnet wound at LBNL**

- 2 Layers
- 40 Turns per layer
- Total CORC® wire length about 40 m

**Test at 4.2 K scheduled for September 2017**



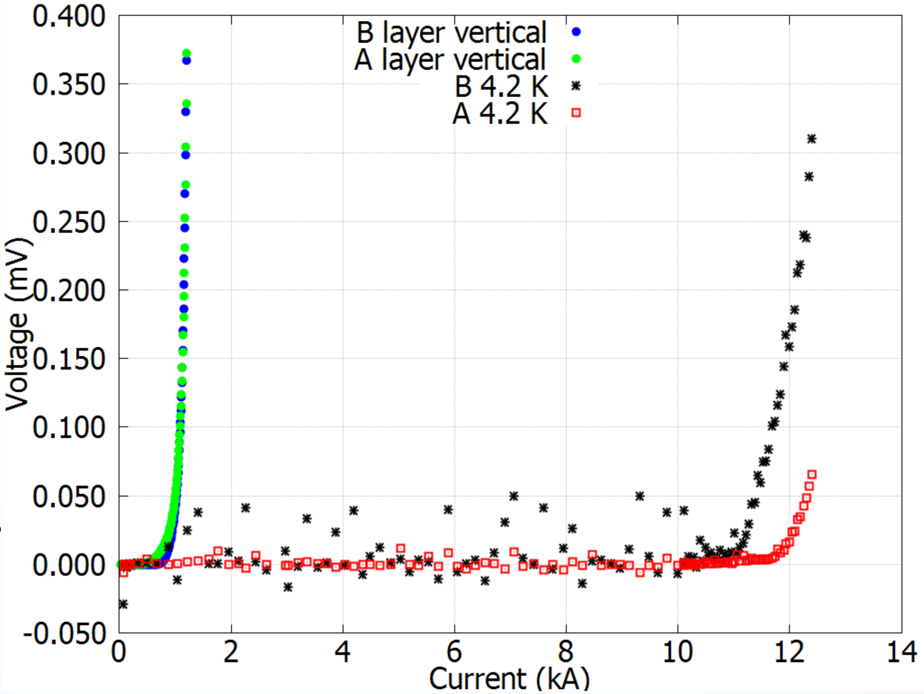
# Model coil C2-0: CORC® wire test for CCT-C2

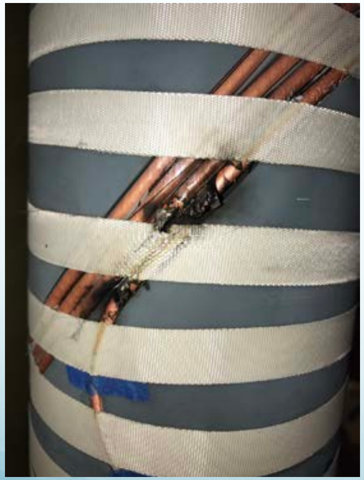
**CCT C2-0: CORC® wire with 29 tapes**

- 3-turn per layer
- Inner layer I.D. 85 mm
- Minimum bending diameter 60 mm

**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/mm$^2$
- **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 is being replaced to finalize testing**

**Full-size coil C2 expected to be wound in Q2 2018**

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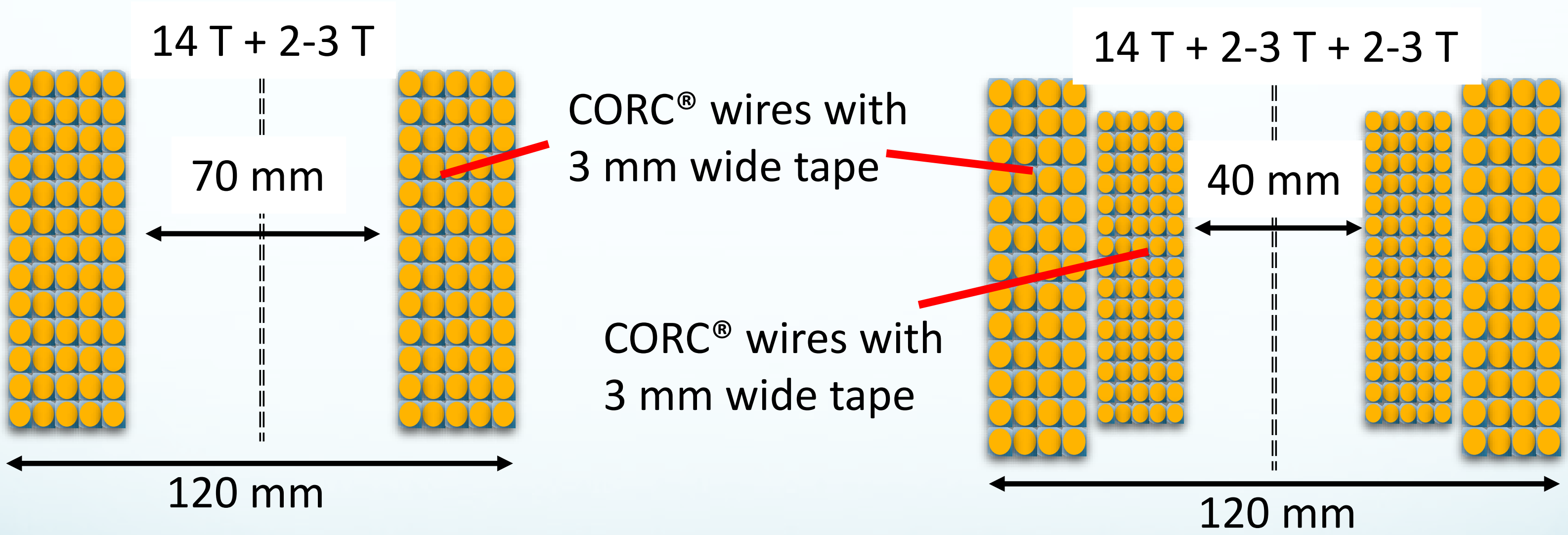
# CORC® wires in high-field insert solenoid

**Final deliverable Phase II SBIR with ASC-NHMFL**

- Develop high-field insert solenoid wound from CORC® wires
- Test insert magnet at 14 T background field at ASC-NHMFL
- Aim for added field of at least 2-3 T, maybe 5 T depending on tape performance

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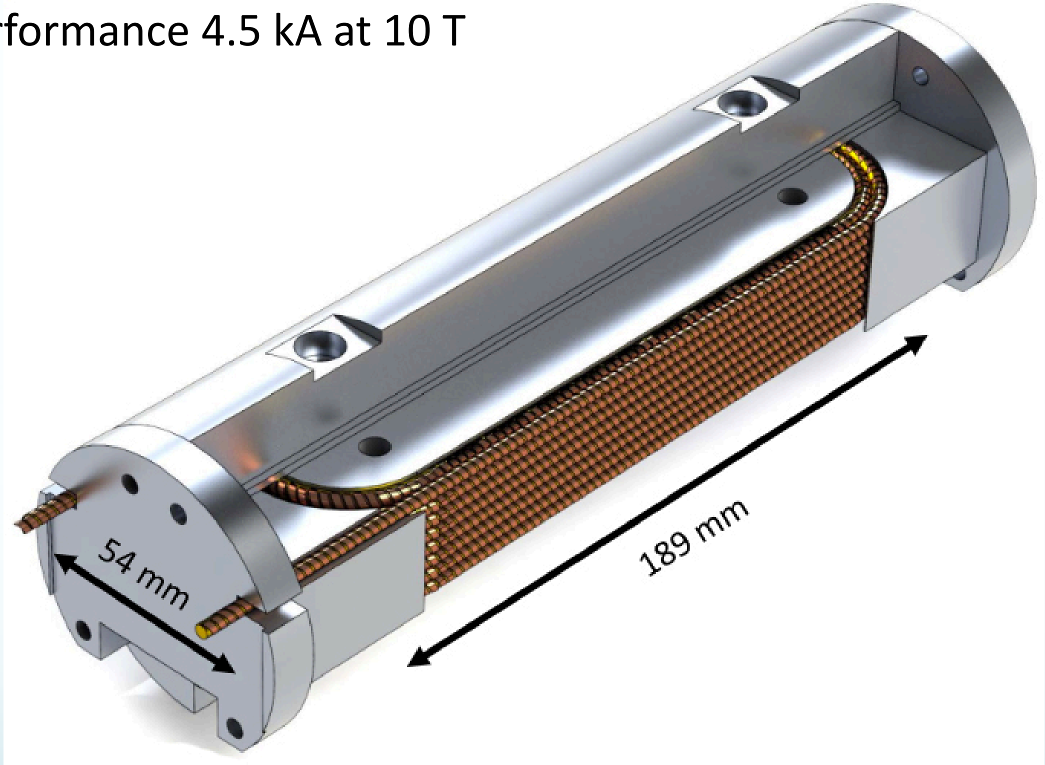
# Racetrack coil from CORC® wire

**Development of CORC® racetrack at CERN**

- 8 meters of CORC® wire (29 tapes) delivered last week
- Racetrack with 2 layers and 8 turns per layer
- Coil performance of 0.38 T per kA
- Expected performance 4.5 kA at 10 T



# 45 kA (10 T) CORC®-CICC test in FRESCA (CERN)

**45 kA (4.2 K, 10 T) 6-around-1 CORC®-CICC built at CERN**

- 6 CORC® cables of 7.5 mm diameter
- 38 tapes per CORC® cable (commercial order 2014)

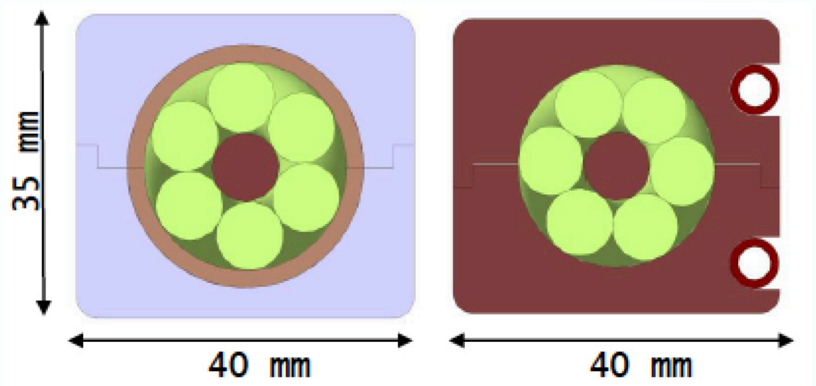
**CORC®-CICC test results**

- Power supply of FRESCA limited to 30 kA: no s.c. transition
- Test at 77 K in self-field: $I_c$ = 12.3-13 kA as expected

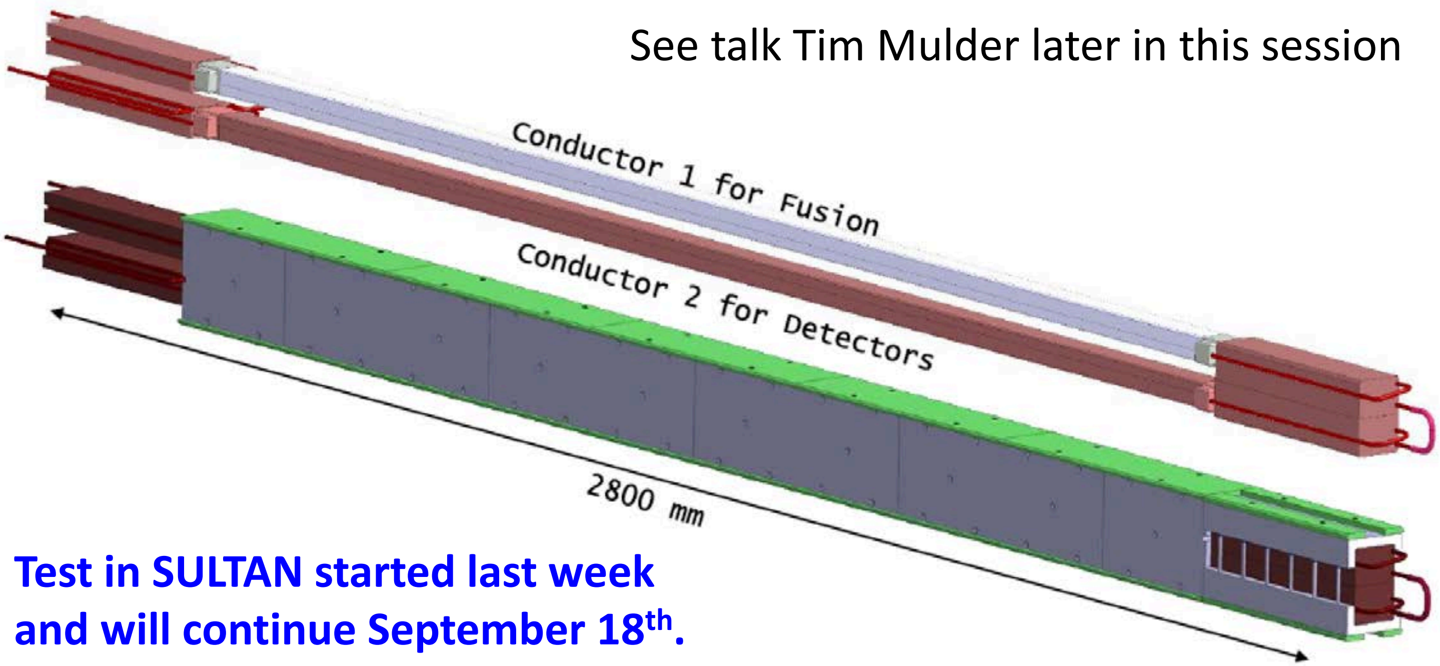
# 80 kA (12 T) CORC®-CICC test in SULTAN

**6-around-1 CORC®-CICC built at CERN**

- Sample 1: fusion magnet CORC®-CICC forced flow cooling
- Sample 2: detector magnet CORC®-CICC conduction cooling
- Both rated at 80 kA at 4.2 K and 12 T




See talk Tim Mulder later in this session




**Test in SULTAN started last week and will continue September 18th.**

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# Summary

**CORC® cables and wires are maturing into magnet conductors**

- CORC® cable performance 10 kA and 300-500 A/mm$^2$ at 20 T
- CORC® wire performance 2-3 kA and 250-350 A/mm$^2$ at 20 T

**Magnet programs aimed at CORC® cables and wires**

- Common coil magnet (Brookhaven National Laboratory)
- Canted-Cosine-Theta magnets (Berkeley National Laboratory)
- Solenoid insert coil (National High Magnetic Field Laboratory)
- Racetrack coil (CERN)

**CORC®-CICC development**

- 80 kA CORC®-CICC currently being tested in Sultan
- Results expected middle of September 2017