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Current progress of High-temperature superconducting CORC® magnet cable and wire development

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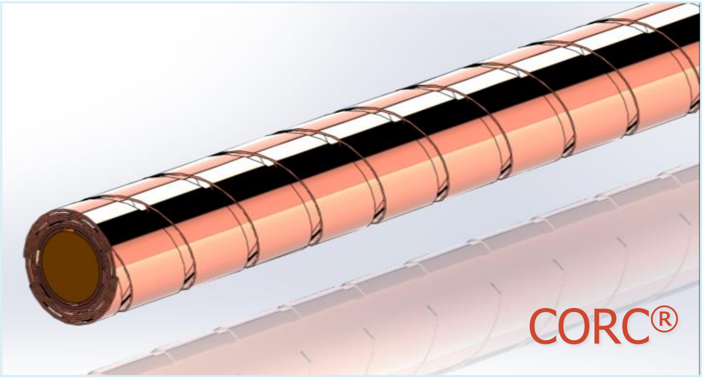
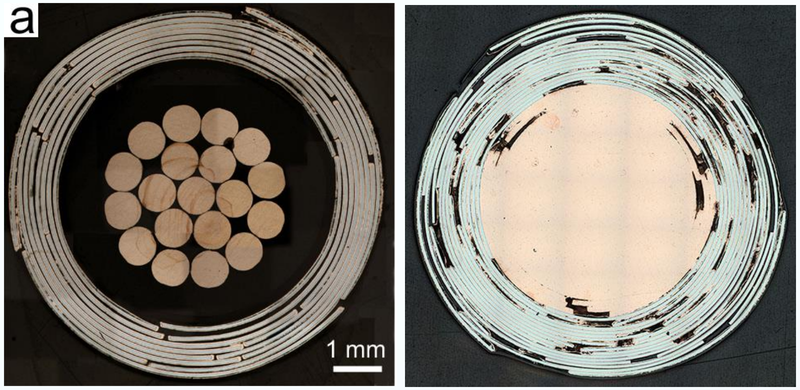
Conductor on Round Core (CORC®) conductors

CORC® cable principle
Winding many high-temperature superconducting YBCO coated conductors in a helical fashion with the YBCO under compression around a small former.





Benefits

- The most flexible HTS cable available
- Very high currents and current densities
- Mechanically very strong
- Partially transposed
- Current sharing between tapes

CORC® magnet cables and wires

CORC® cable (5-8 mm diameter)

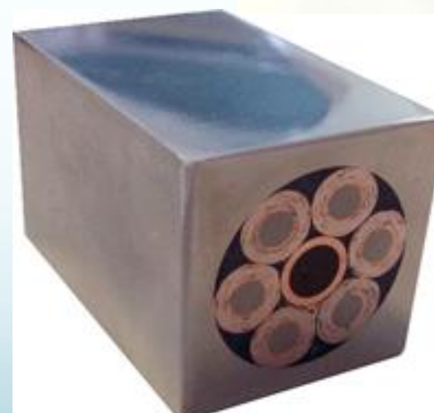
- Wound from 3-4 mm wide tapes with 30-50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to >100 mm diameter

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



See T. Mulder's posters
Thursday morning (4LP4-06, 07)

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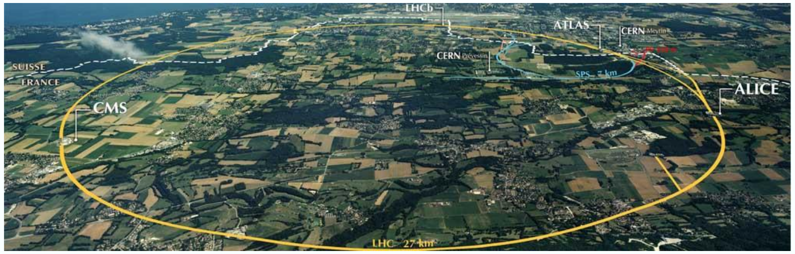
Programs at Advanced Conductor Technologies

1. Department of Energy – Office of High Energy Physics (DOE-HEP)

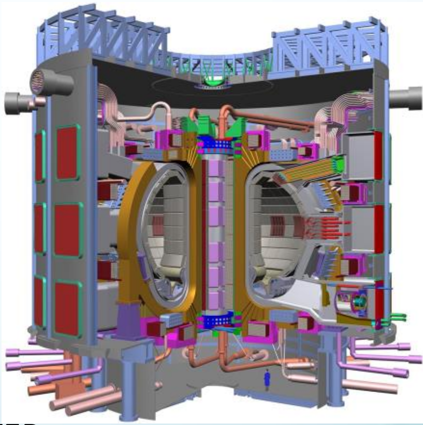
CORC® cables for accelerator magnets including Canted Cosine Theta magnets



LHC at CERN

2. Department of Energy – Office of Fusion Energy Sciences (DOE-OFES)

CORC® cable for fusion magnets, cable joints, and terminations for fusion magnets



ITER

3. Navy

CORC® power transmission, fault current limiting cables, and Dielectrics for CORC® power transmission

NAVSEA
WARFARE CENTERS
Philadelphia

LCS 4 USS Coronado

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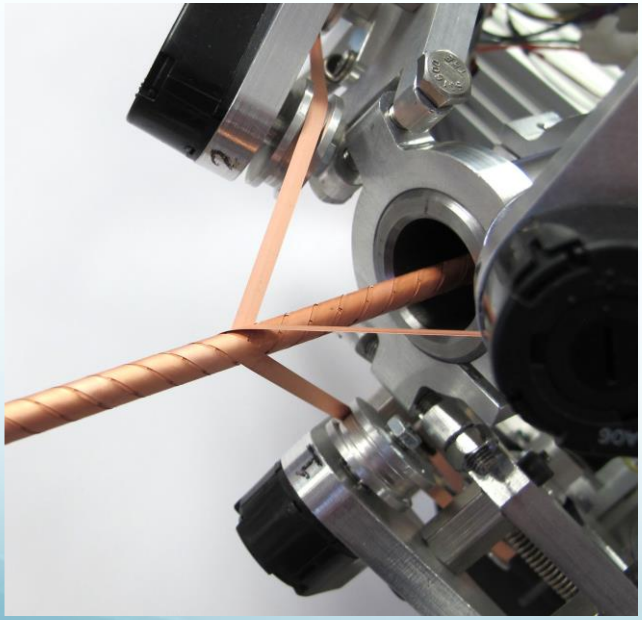
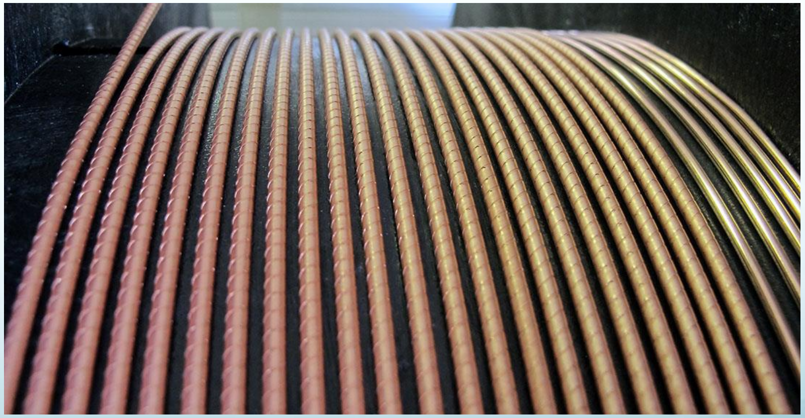
CORC® cable and wire production

Winding CORC® cables

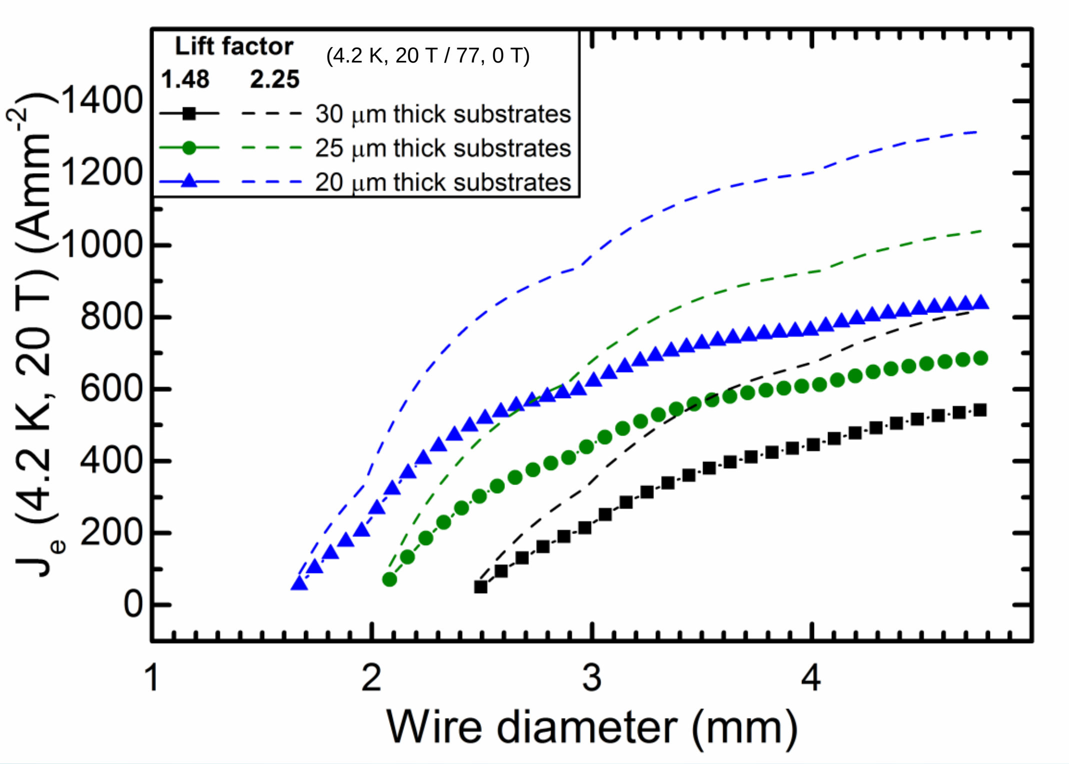
- Accurate control of cable layout
- Long cable lengths possible
- I_c retention after winding 95-100 %
- 120 meters wound in 2016, of which 70 meters were for commercial orders





Thinner tapes with better pinning developed over the last 2 years lead to much higher J_e in CORC® wires

Projected J_e vs wire diameter of CORC® wires using typical and best received tapes



As you add more layers to the CORC wire, its J_e increases towards the tape J_e

Substrate thickness is decreasing

- 30 µm now available
- 25 µm expected soon
- 20 µm would enable J_e of 600 Amm^{-2} at 20 T in a 2.3 mm diameter wire

Pinning force is increasing

- More control over artificial pinning centers
- Evidenced by higher lift factors

Nod to SuperPower for the rigorous R&D effort!

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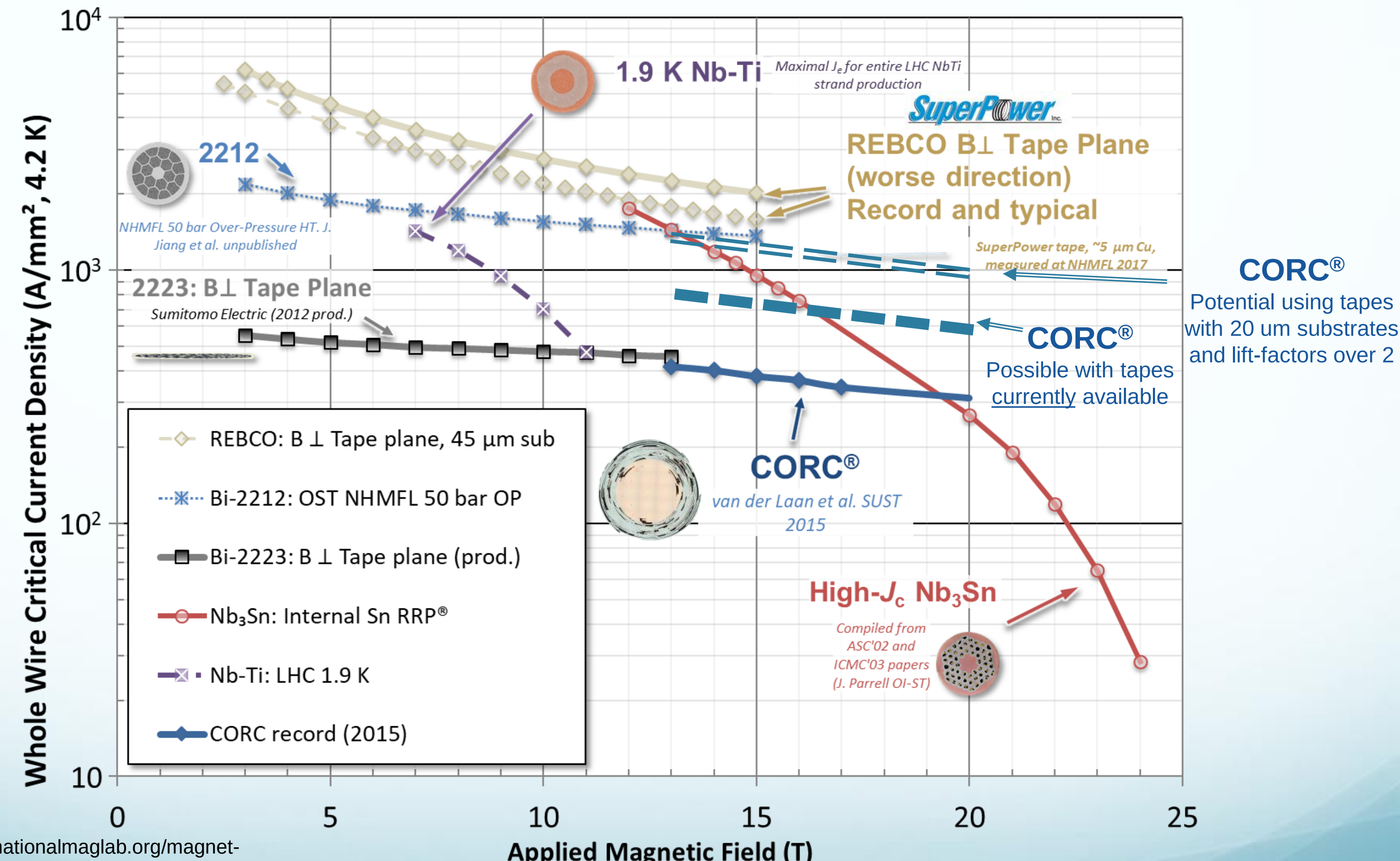
CORC® J_e comparison to high-field magnet wires



Data from https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

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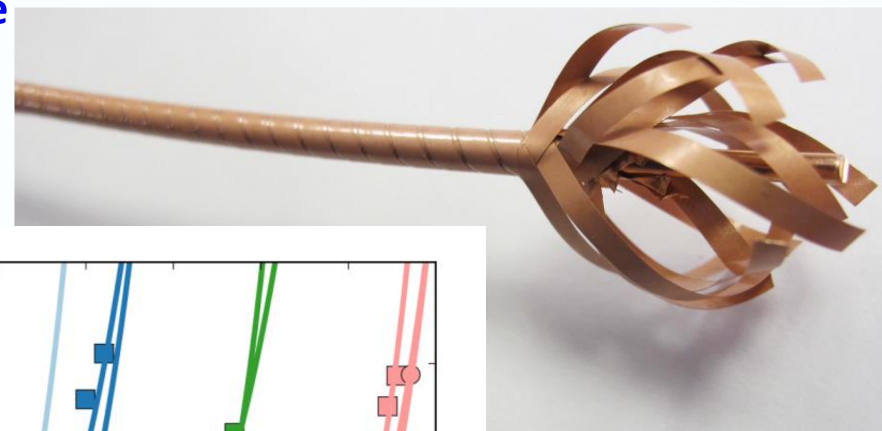
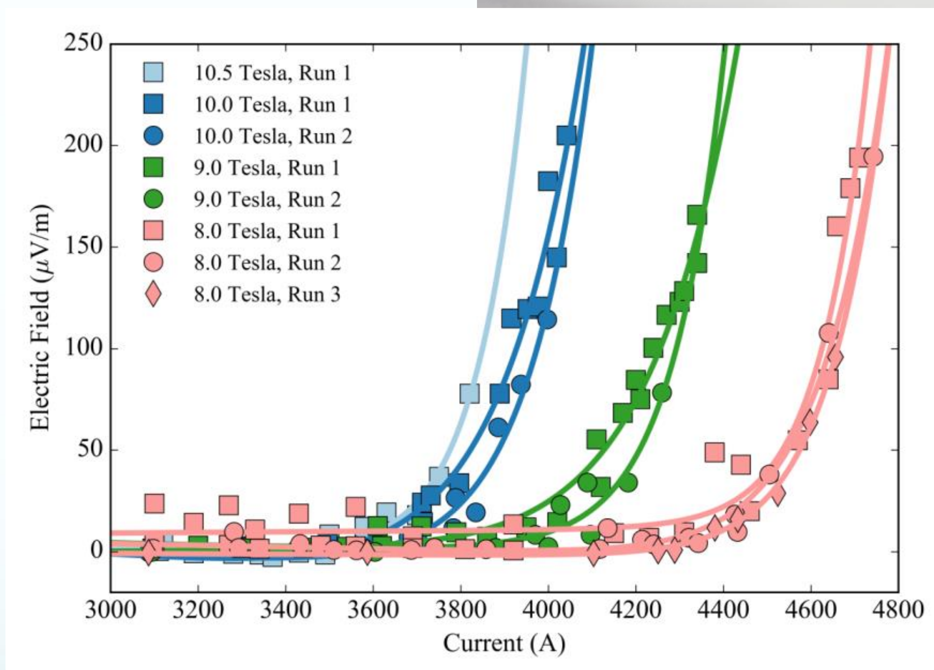
CORC® magnet wire performance (early 2017)

High-J_e CORC® wire layout tested at Twente

- 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/mm^2

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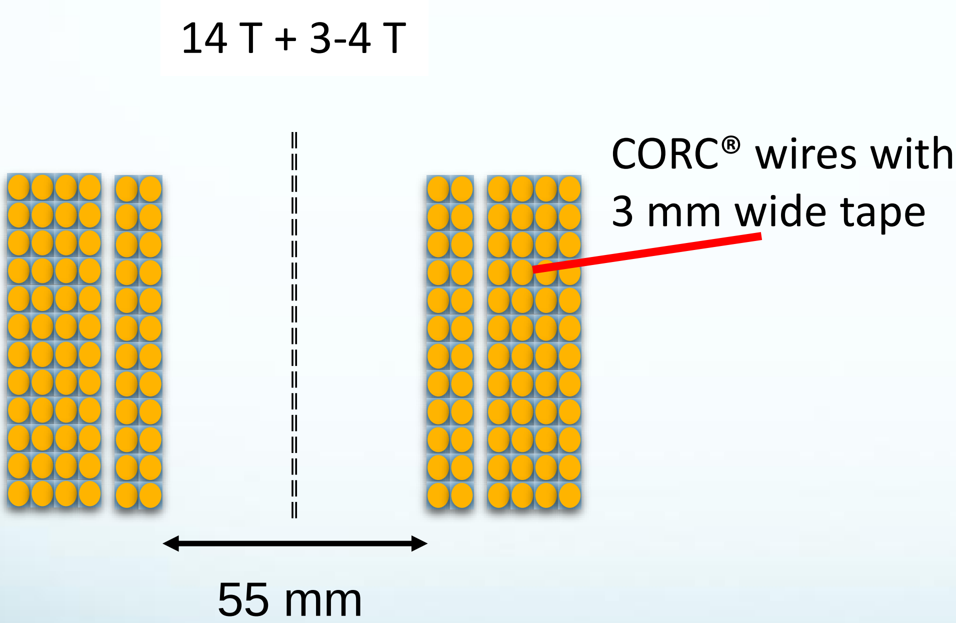
CORC® wires in high-field insert solenoid

Final deliverable Phase II SBIR with ASC-NHMFL (early 2018)

- 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

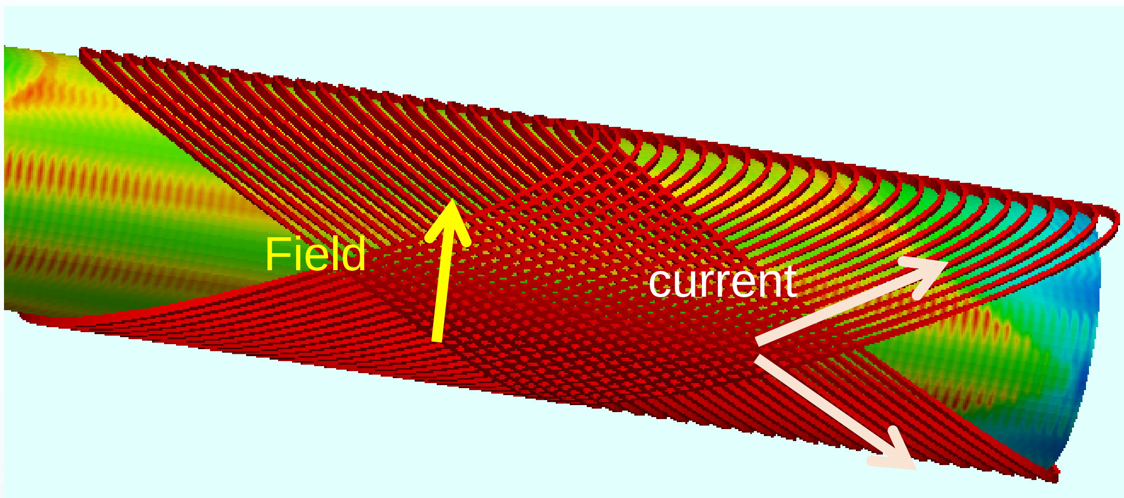


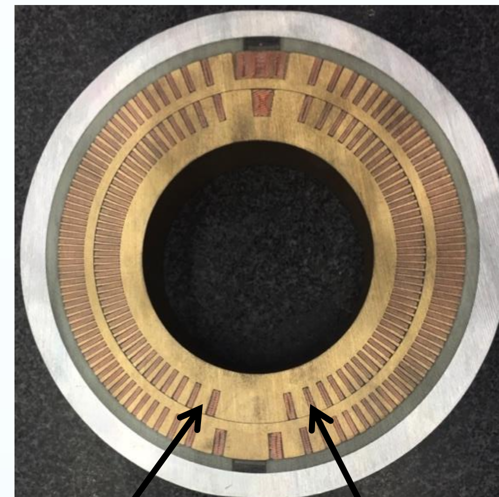
Wire I_c ~ 5,000 A at 14 T
$J_{winding}$ ~ 200 Amm^{-2} at 14 T

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)

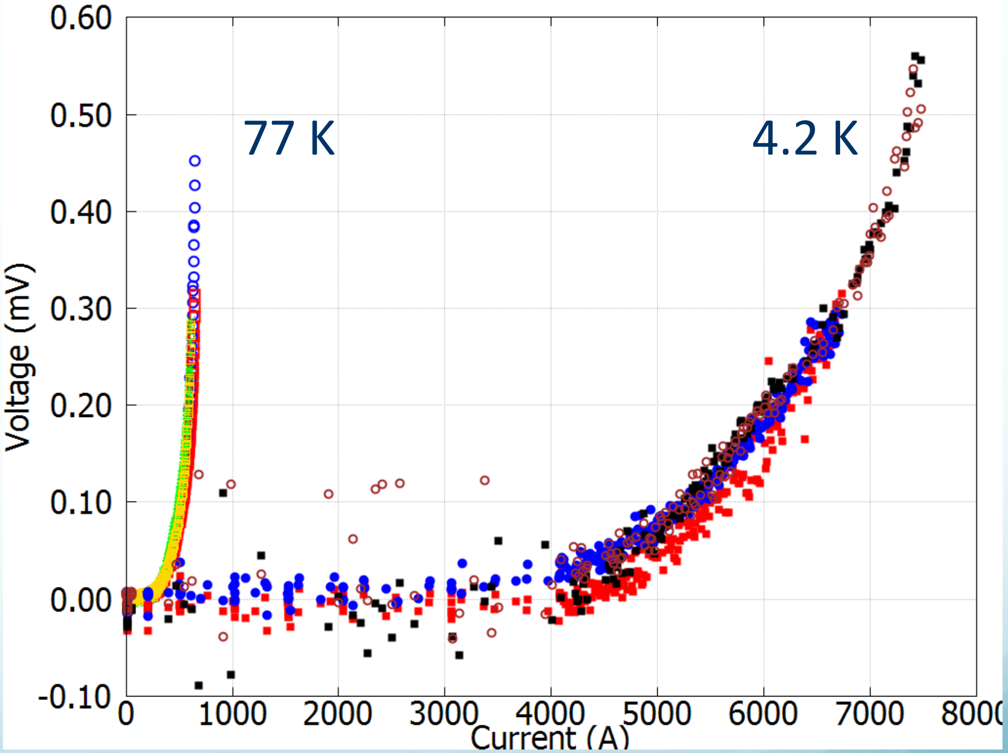
Model coil C1-0: CORC® wire test for CCT-C1

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 this week

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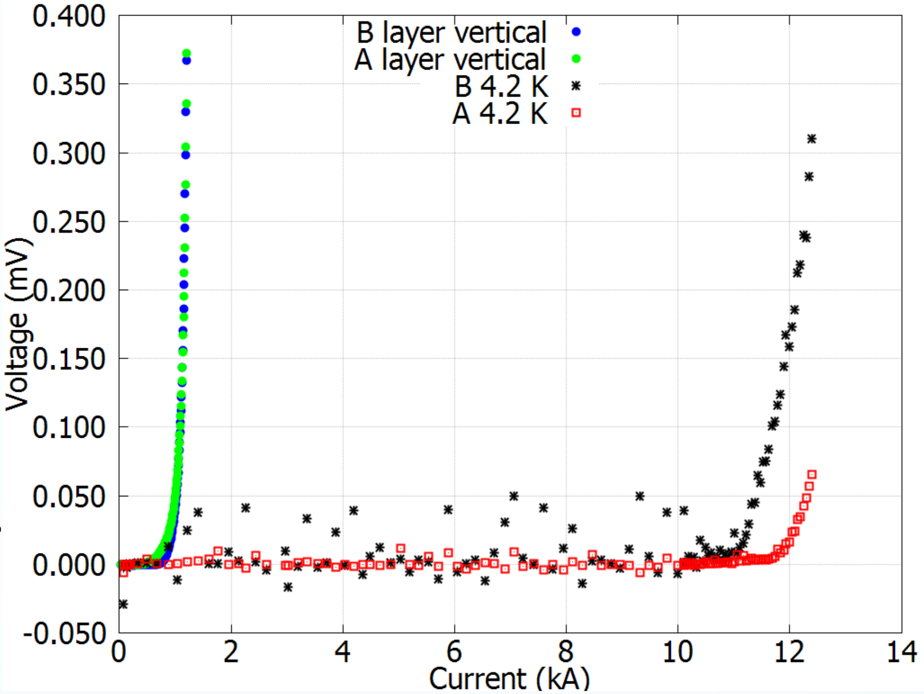
Model coil C2-0: CORC® wire test for CCT-C2

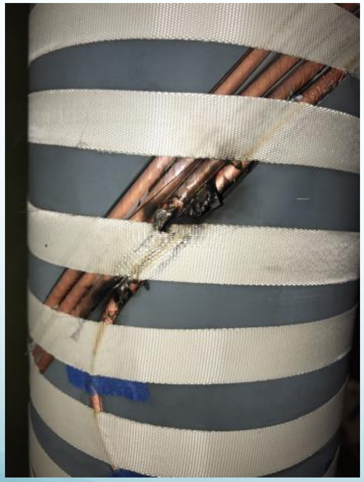
CCT C2-0: CORC® wire with 29 tapes

- 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 has been replaced to finalize testing

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

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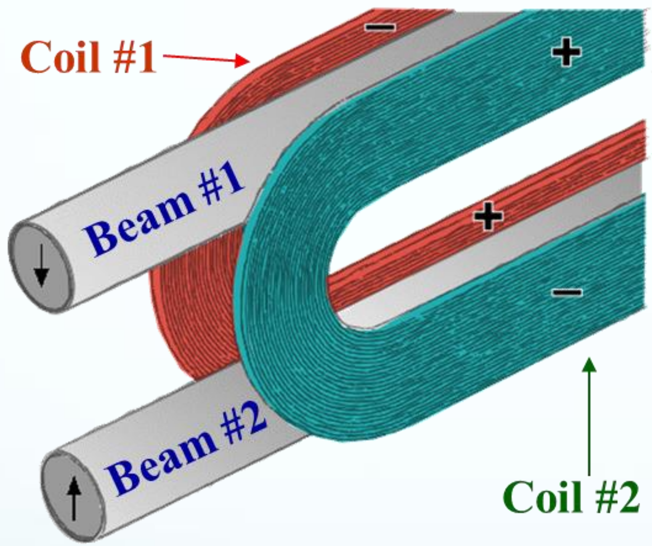
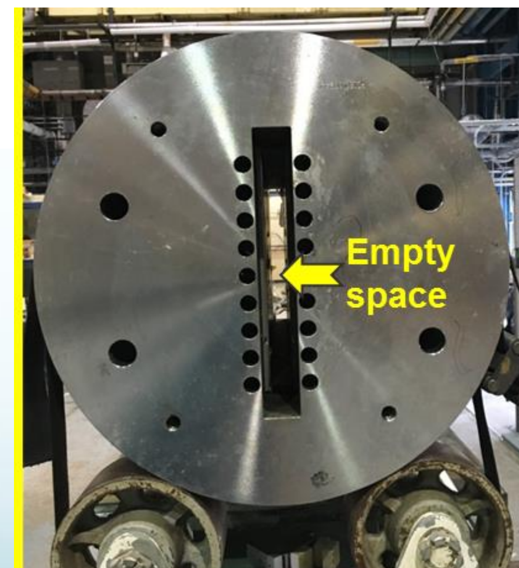
Common coil magnet from CORC® cables

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

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Racetrack coil from CORC® wire

Development of CORC® racetrack at CERN

- 8 meters of CORC® wire (29 tapes) delivered last month
- 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

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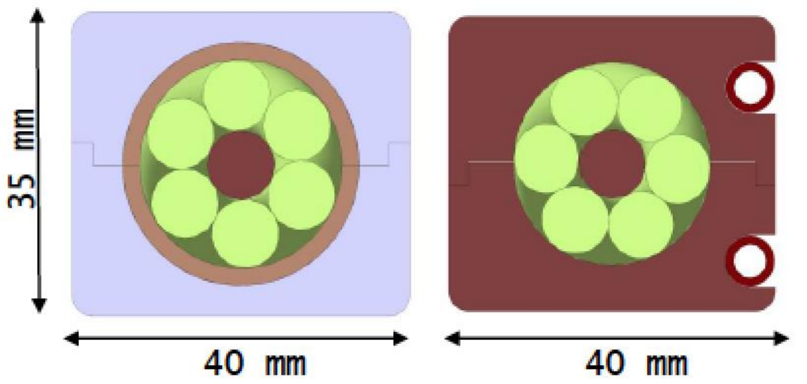
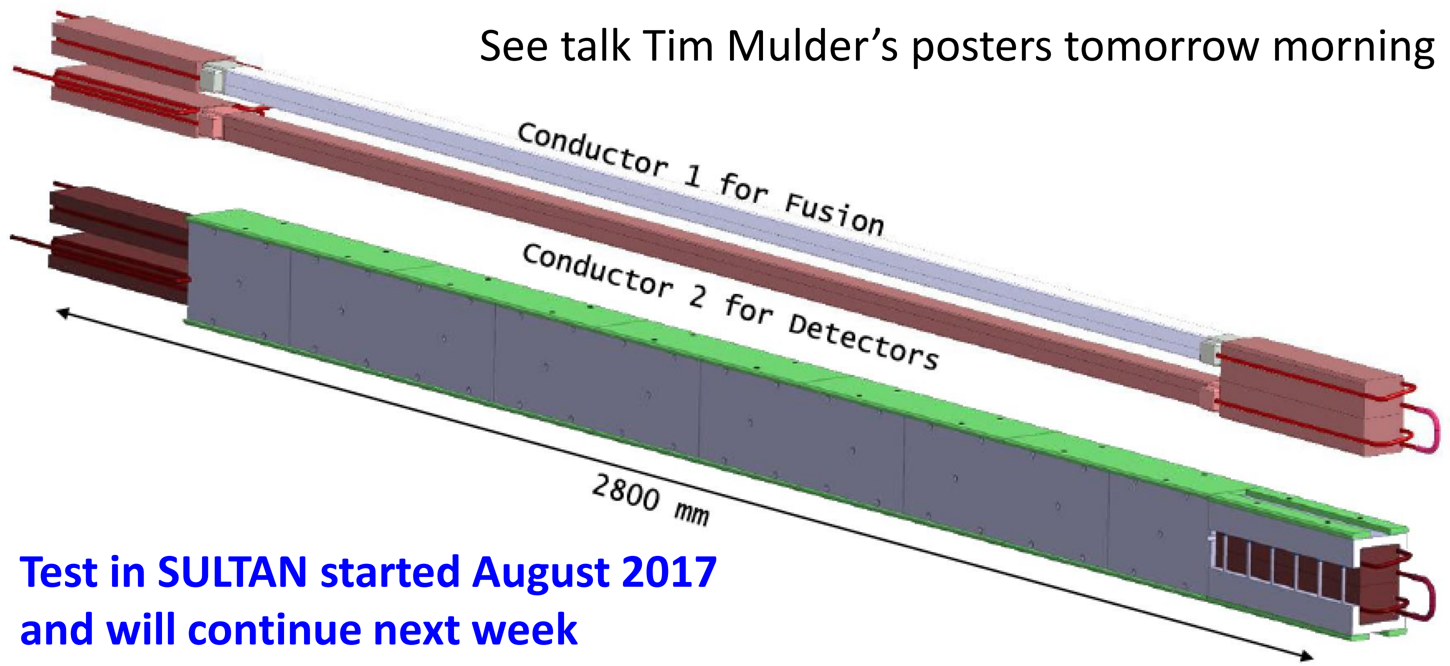
80 kA (12 T) CORC®-CICC test in SULTAN

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's posters tomorrow morning



Test in SULTAN started August 2017 and will continue next week

Summary

CORC® cables and wires are maturing into magnet conductors

- CORC® cable performance 10 kA and 300-600 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

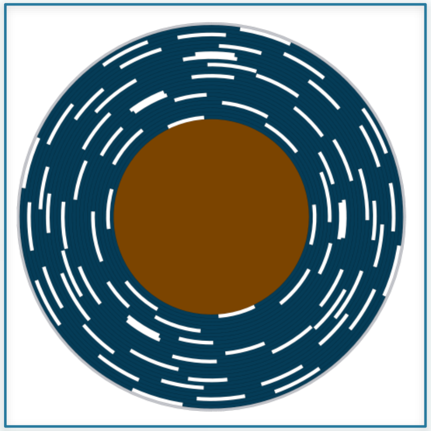
- Common coil magnet (Brookhaven National Laboratory)
- Canted-Cosine-Theta magnets (Berkeley National Laboratory)
- Solenoid insert coil (National High Magnetic Field Laboratory)
- Racetrack coil (CERN)

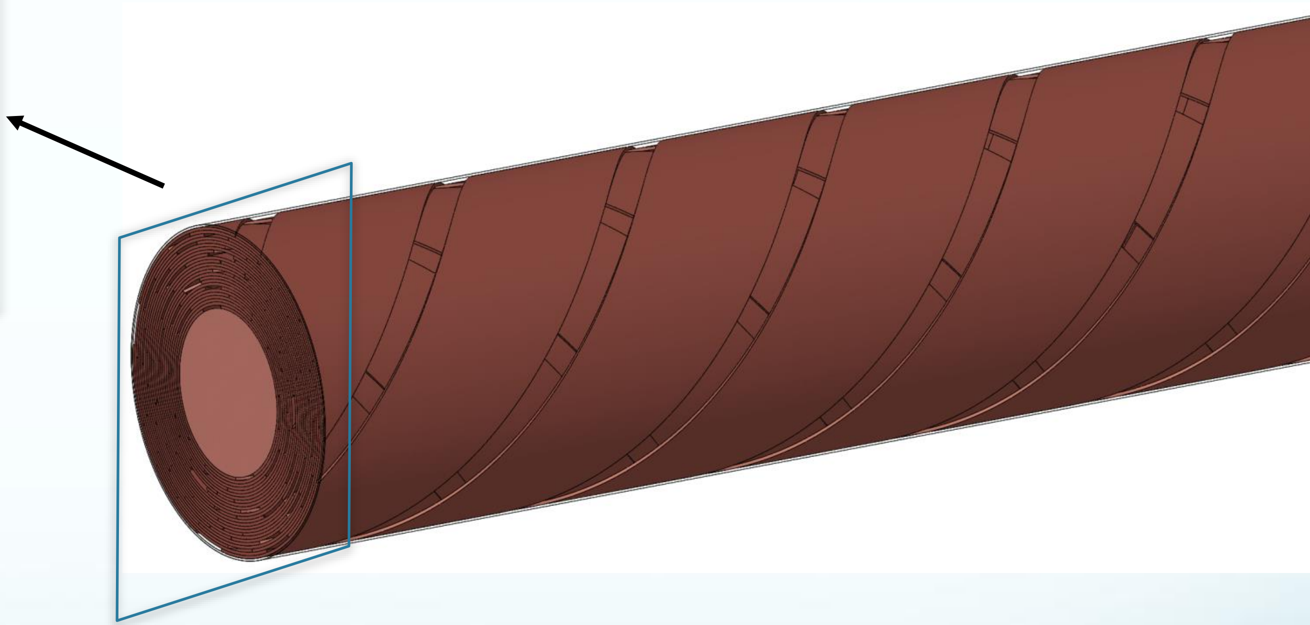
CORC®-CICC development

- 80 kA CORC®-CICC currently being tested in Sultan
- Results expected soon!

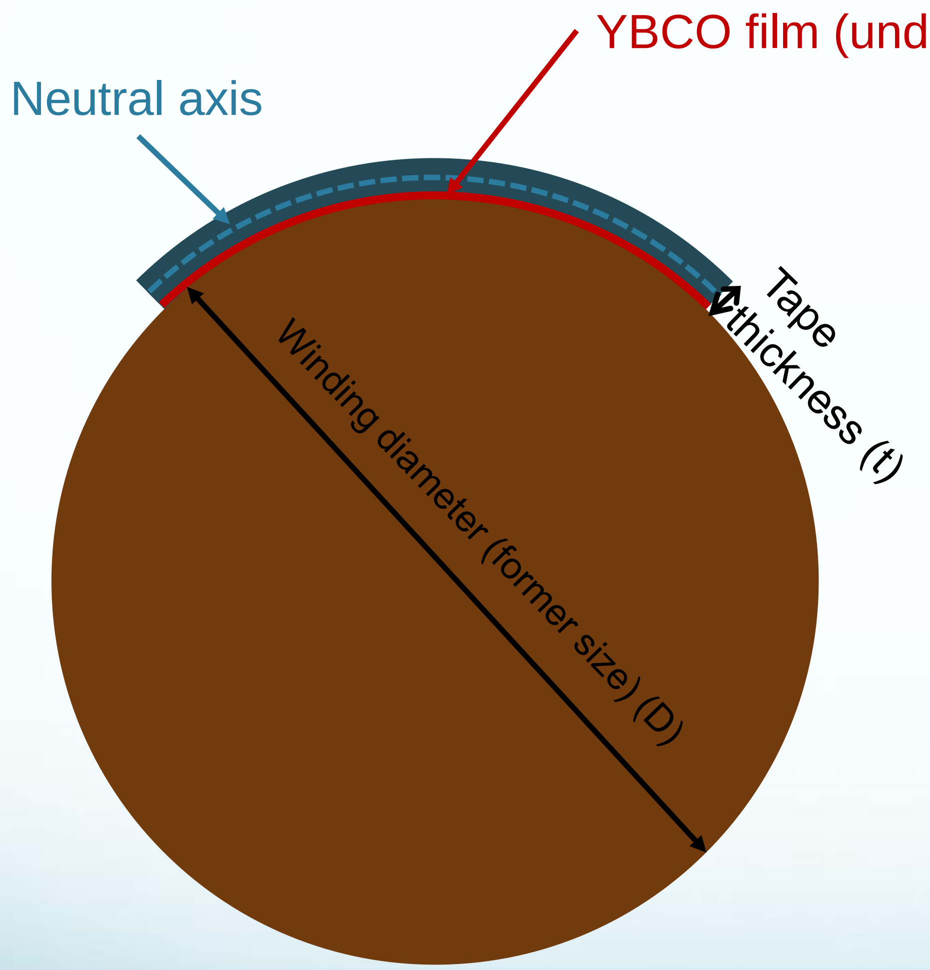
Extra slides

Looking at strain in a CORC® conductor





Looking at strain in a CORC® conductor



Strain on the YBCO

$$\varepsilon \propto \frac{-t}{D+t}$$

Two routes to drastically increase J_e:

1. Decrease tape thickness (t)
   - Intrinsically improves J_e of tape
   - Also, allows for smaller formers (D) i.e. larger tape filling fraction in a CORC wire
2. Increase tape's maximum compressive strain tolerance

Looking at strain in a CORC® conductor

Moving from 50 micron to 30 micron substrates allowed us to use a former with a smaller diameter, incorporating more than a dozen additional tapes into the CORC cross section

- Notice that I_c degrades around -1.2 % strain.