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High-field magnets wound from CORC® cables and wires

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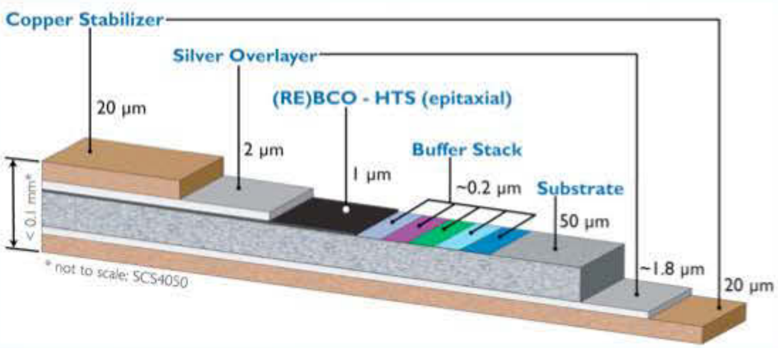
CHATS 2017, December 10th, 2017, Sendai, Japan

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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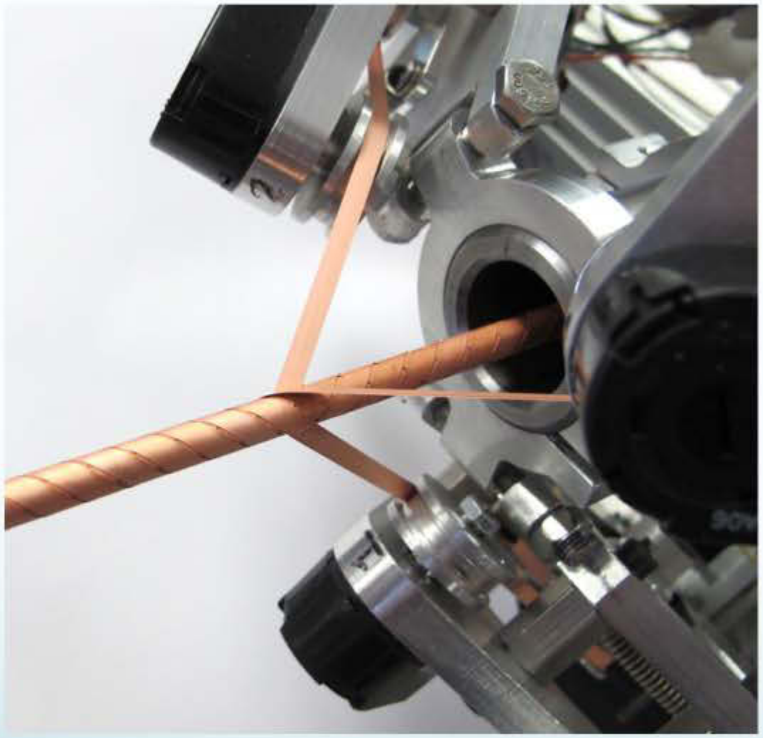
CORC® cable production at ACT

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

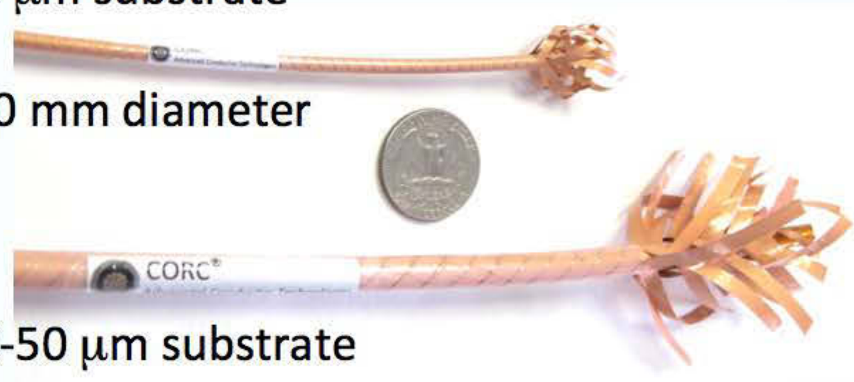
Many commercial orders followed

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

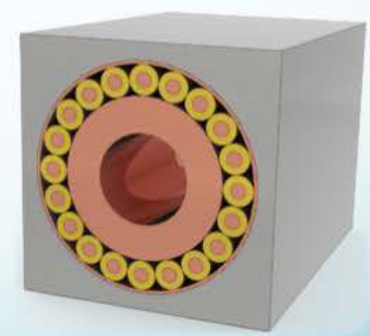


CORC® cable (5-8 mm diameter)

- 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

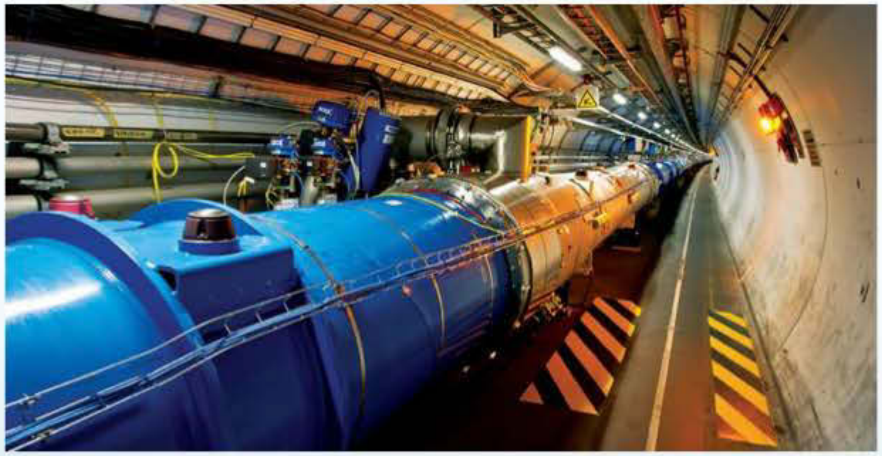


CORC® cable development for accelerator magnets

Overall goals

1. High engineering current density J_e (20 T) > 600 A/mm²
2. Small cable bending diameters 20 – 50 mm
3. Develop CORC® cables and wires for new magnet configurations

LHC

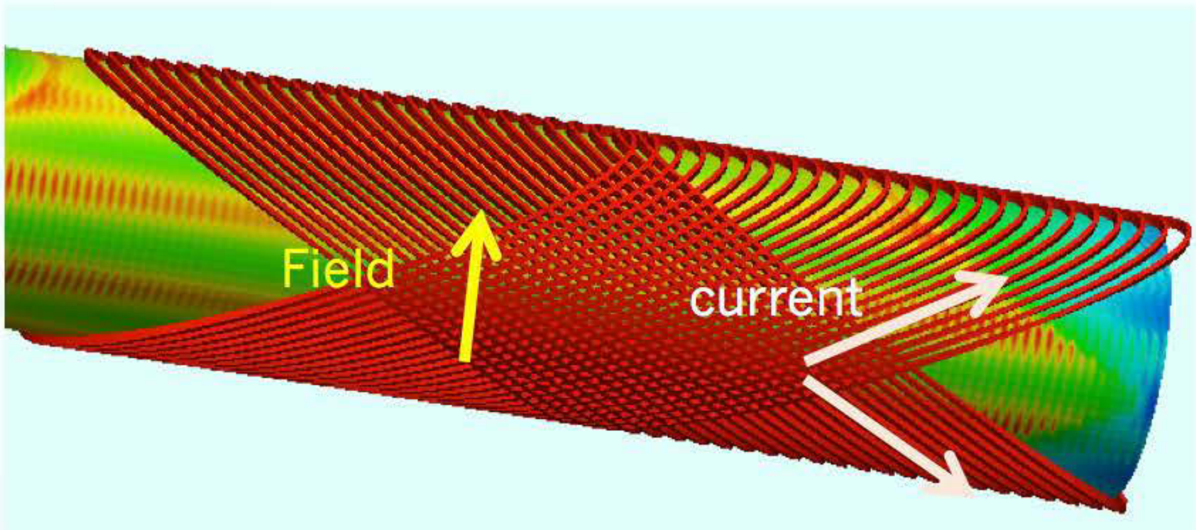


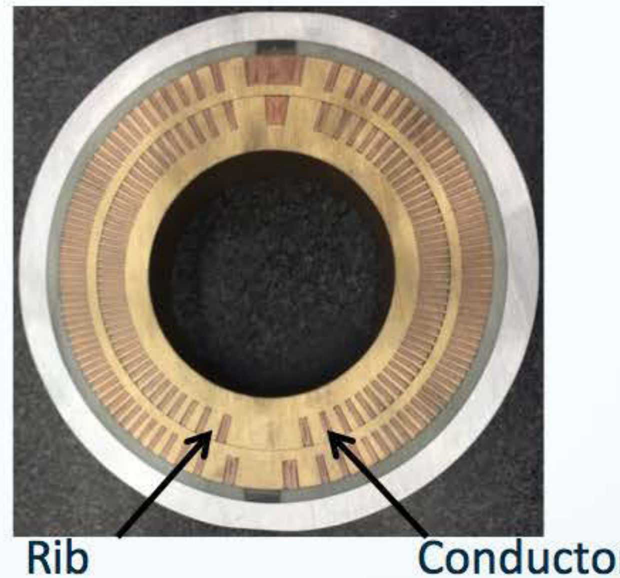
Heidelberg PBT gantry

Canted-Cosine-Theta accelerator magnets

CORC® magnet program #1 with Berkeley National Laboratory

- Develop CORC® wires that enable Canted-Cosine Theta (CCT) magnets
- Develop the magnet technology for CORC®-CCT magnets





Canted-Cosine-Theta magnets

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

The road to 20 T in CORC®-CCT magnets

Overall goal

- Generate 5 T in a 15 T background field
- Multi-year program performed in several steps

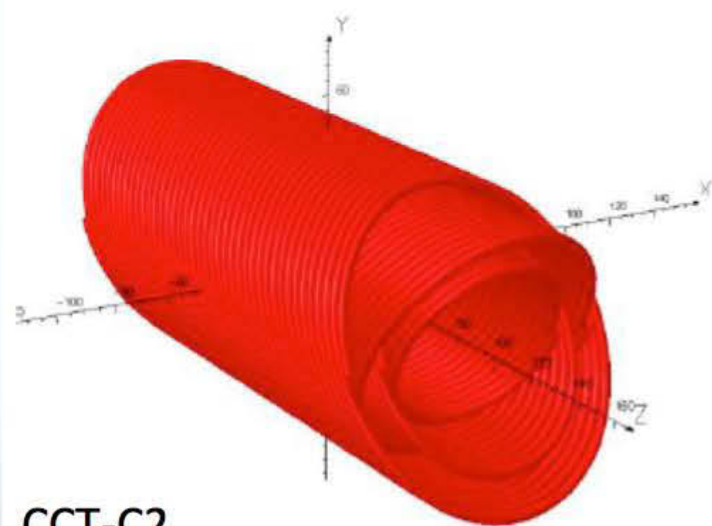
Step 1: 2-Layer, 40-turns CCT magnet (C1)

- Generate **1-2 T in self-field**
- CORC® wire J_e(20 T) = 150-200 A/mm^2
- Learn to wind and protect CORC®-CCT magnets

CCT-C1

Step 2: 4-Layer, 40-turns magnet (C2)

- Generate **2.5 - 3 T in a 10 T background field**
- CORC® wire J_e(20 T) = 300-400 A/mm^2
- CORC® wire bendable to 30 mm diameter



CCT-C2

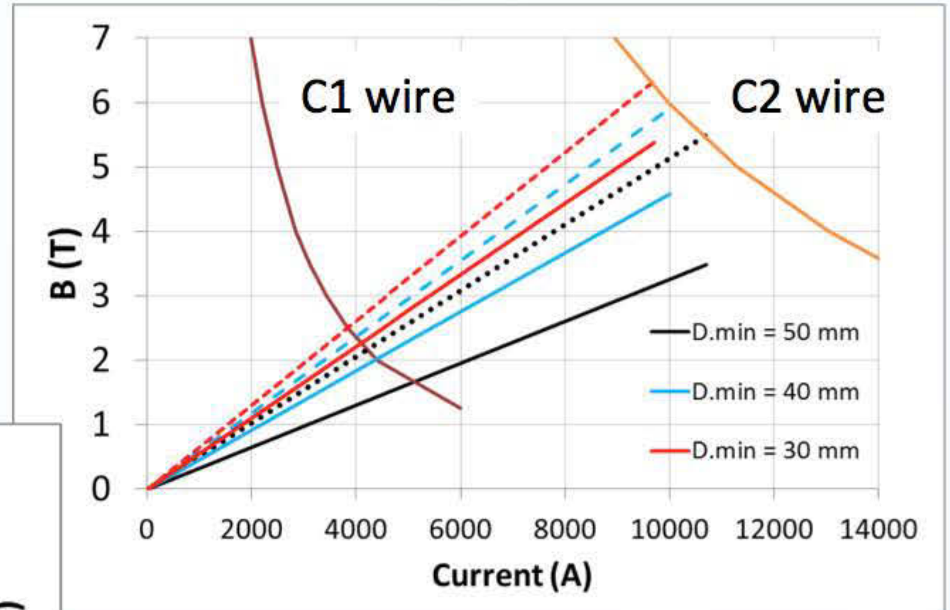
Step 3: 6-Layer, 40-turns CCT magnet (C3)

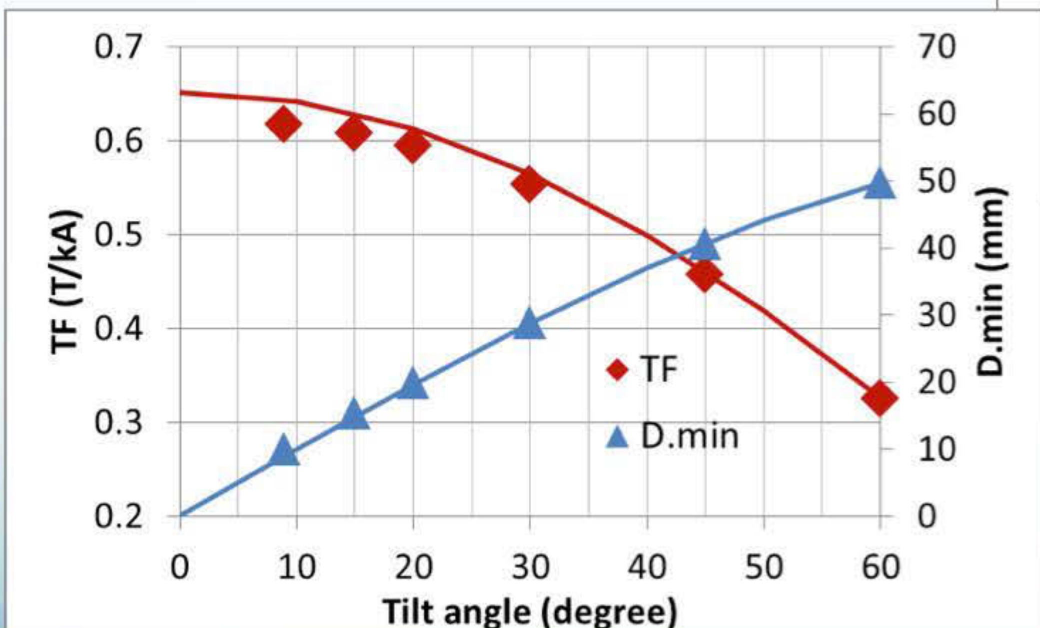
- Generate **5 T in a 15 T background field**
- CORC® wire J_e(20 T) = 600 A/mm^2
- CORC® wire bendable to 20 mm diameter

CORC® wires in Canted-Cosine-Theta magnets

CORC®-CCT parameters to consider

- Fixed aperture of 50 mm
- Tilt angle determines field efficiency
- CORC® wire needs to be flexible
- Current and current density of the CORC® wire needs to be sufficient to deliver the required field performance





Currently focusing on 40-50 mm bending diameter, hoping to allow 20-30 mm in the coming years

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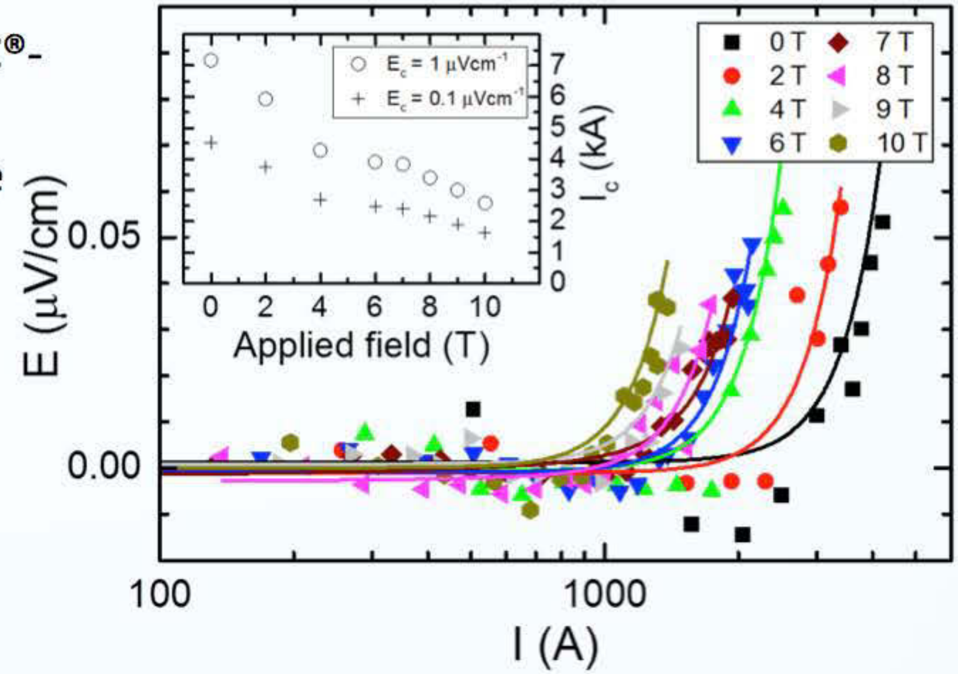
BERKELEY LAB

16-Tape CORC® magnet wire for C1

Low-J_e CORC® wire layout

- Developed to learn how to wind CORC®-CCT magnets
- 16 tapes, 2 mm wide, 30 μm substrate
- 3.0 mm diameter
- 5 turns on 60 mm diameter mandrel for testing at 10.5 T



- I_c = 2,560 A (4.2 K, 10 T, 1 μV/cm)
- Projected J_e(20 T) = 210 A/mm²

50 Meter long CORC® wire delivered to LBNL to wind CCT-C1

Fabrication of 3-turn baby CCT coils

3-Turn baby coils C1-0 and C2-0

- Evaluate the CORC® wire performance and identify potential issues before moving to the 40-layer coils

Printed mandrels

Individual layers

Assembly before test

Assembling two layers

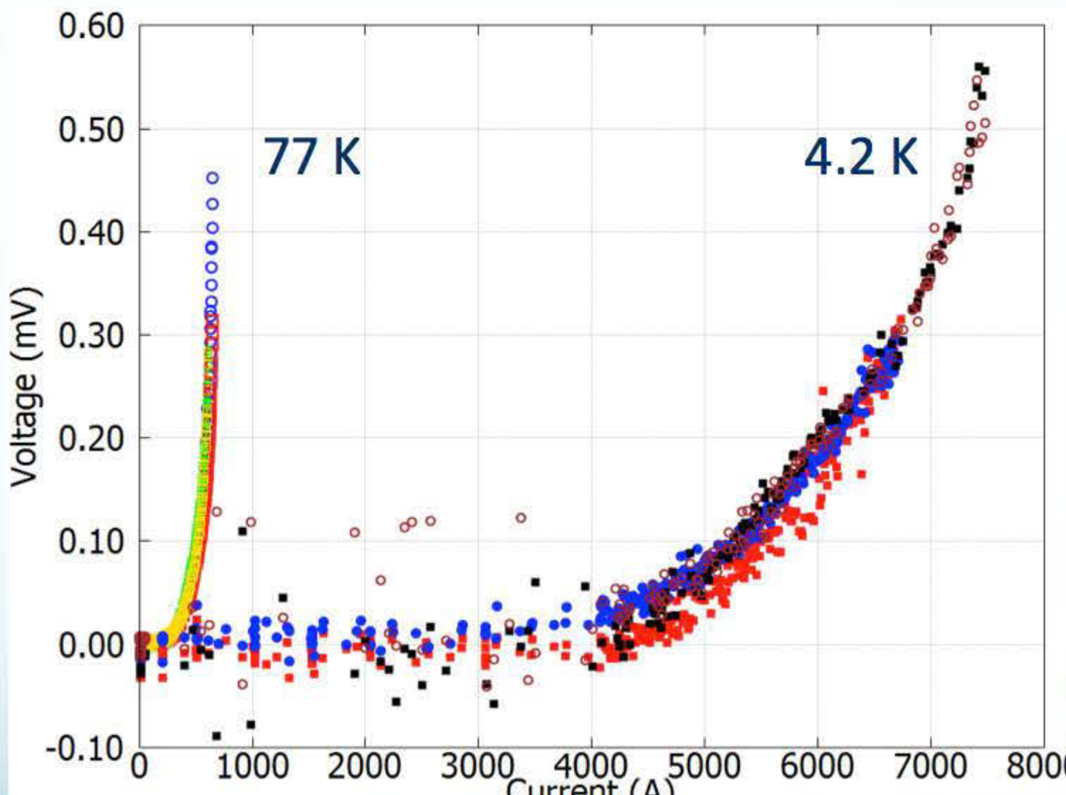
Baby coil C1-0: CORC® wire test for CCT-C1

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)

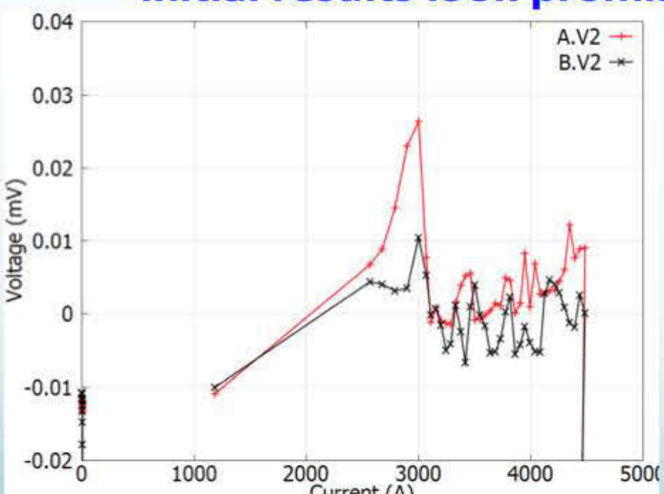


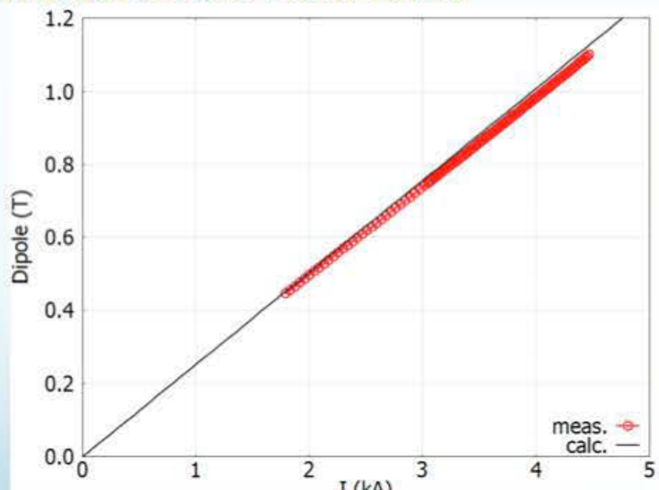
CORC® CCT-C1

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, will continue Dec. 2017

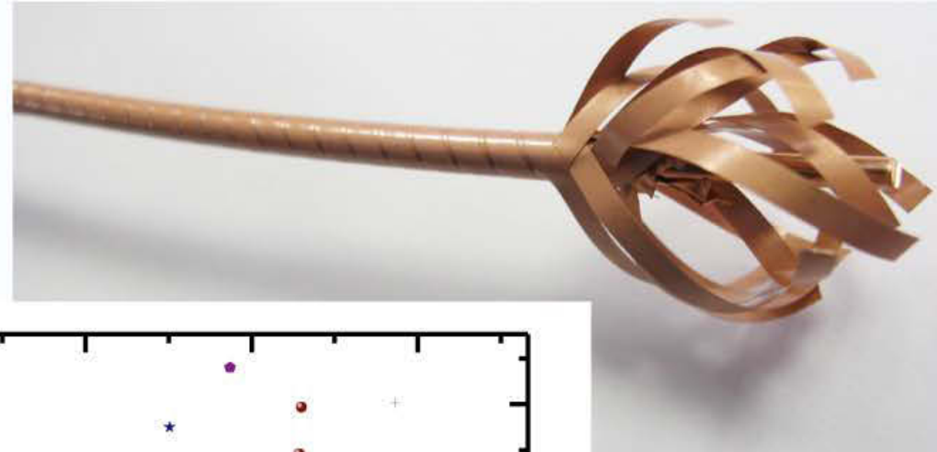


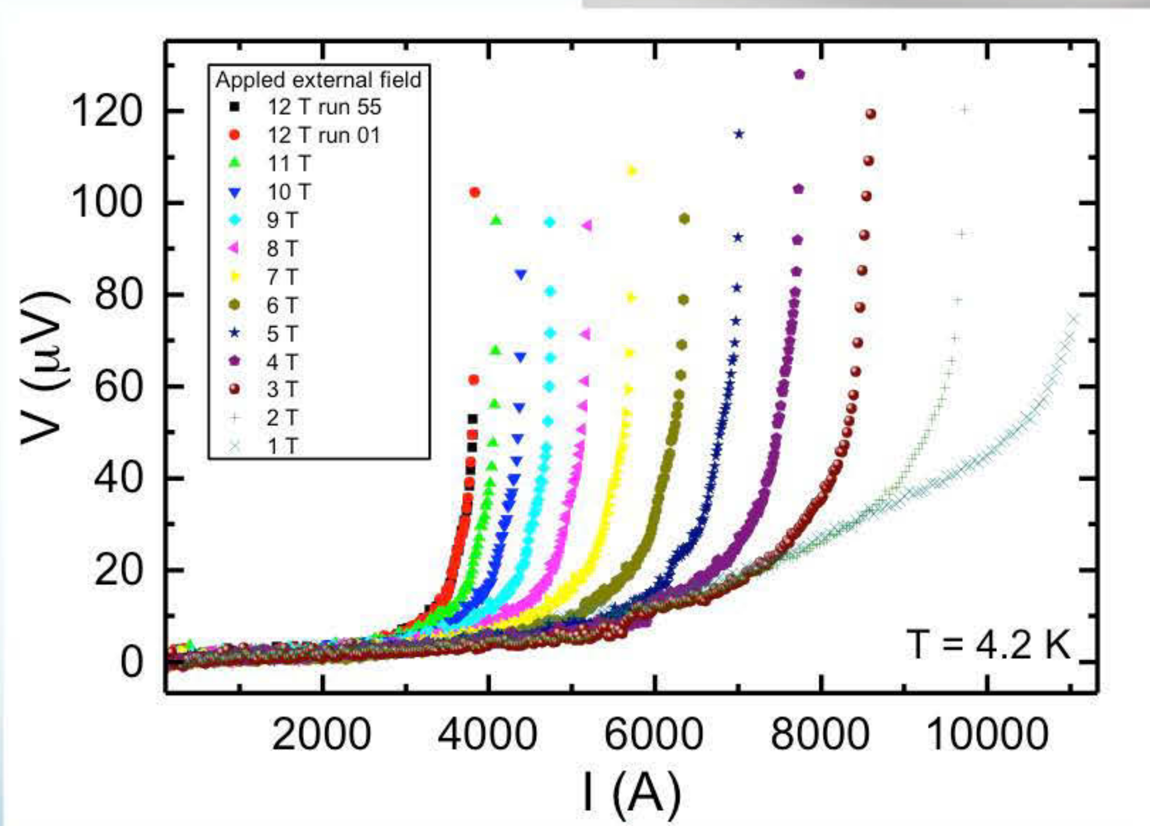


27-Tape CORC® magnet wire for C2

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





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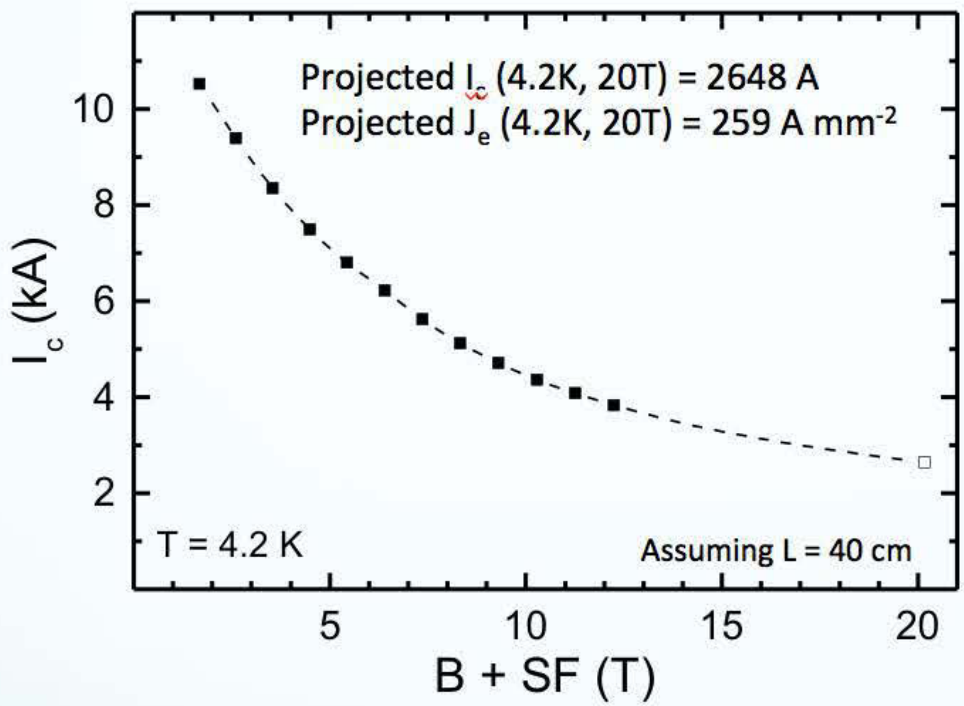
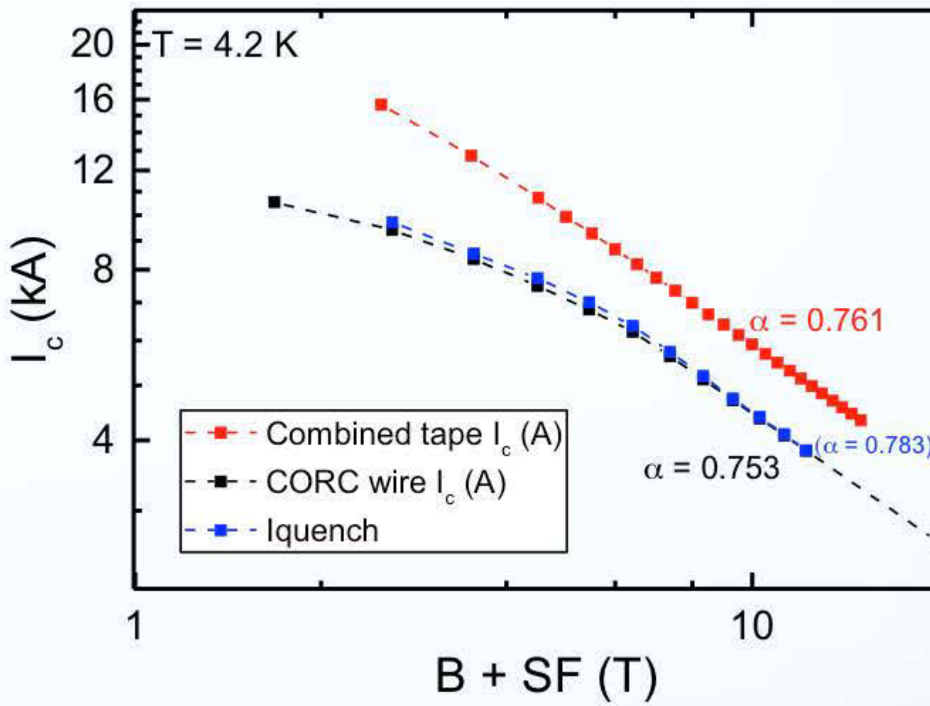
J_e in CORC® wires for CCT-C2





- *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**
- *I_c* retention is 75.7 % of initial tape *I_c*

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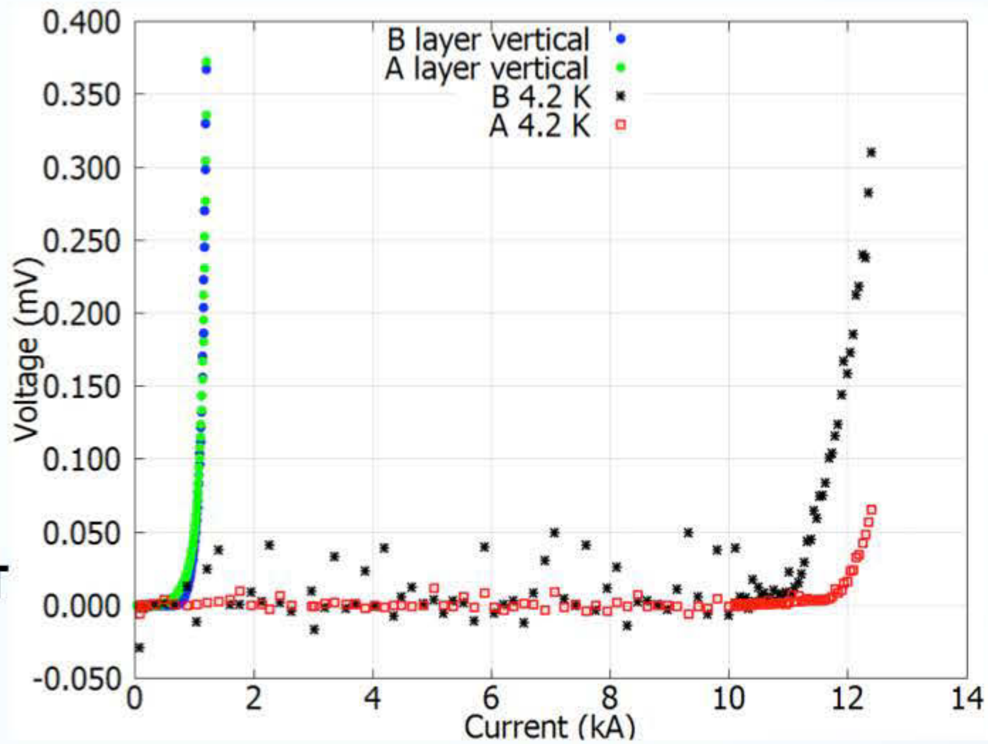
Baby coil C2-0: CORC® wire test for CCT-C2

CCT C2-0: CORC® wire with 29 tapes

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

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BERKELEY LAB

CORC® wire racetrack coil

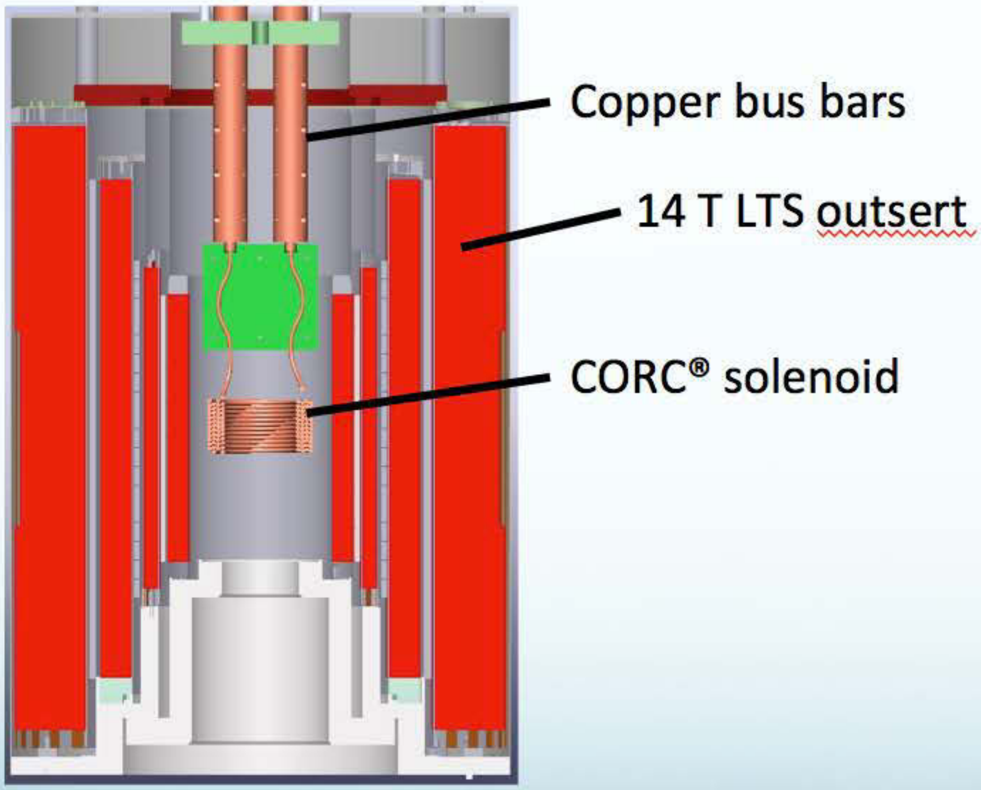
CORC® wire magnet program #2 in collaboration with CERN

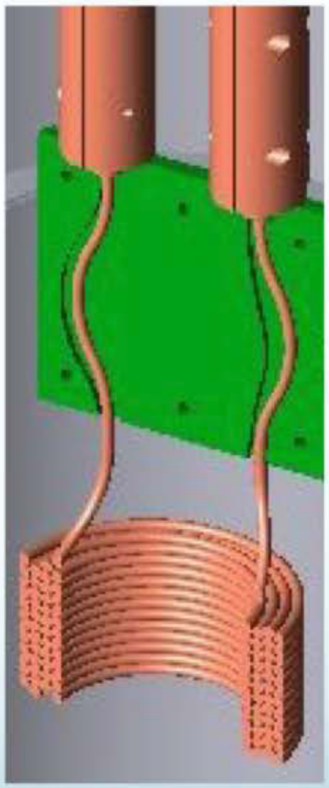
- Develop CORC® wire technology for 20 T racetrack coils for accelerators
- 8 meters of CORC® wire (29 tapes) delivered last month
- Racetrack with 2 layers and 8 turns per layer
- Coil performance of 0.38 T per kA
- Expected performance 4.5 kA at 10 T

High-field insert solenoid wound from CORC® wires

CORC® wire magnet program #3 in collaboration 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





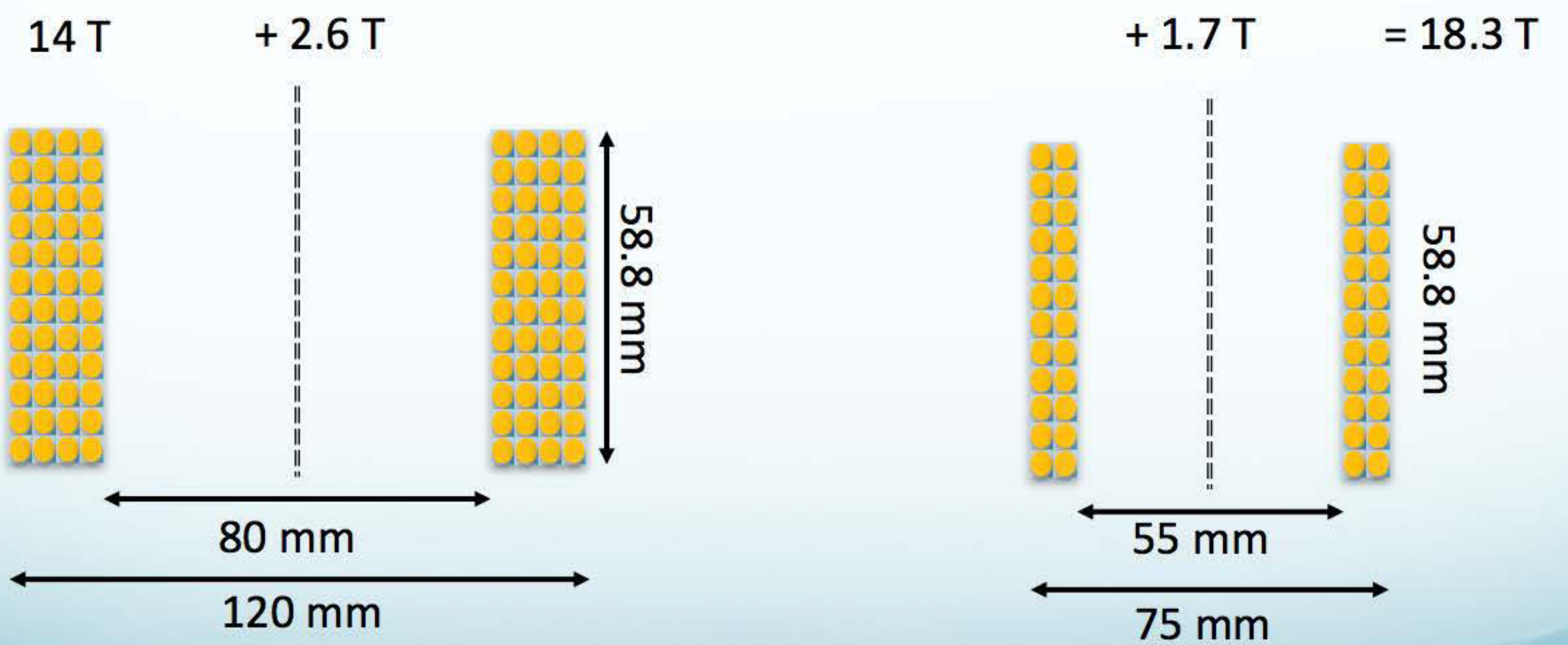
CORC® insert wire details

Coil 1

- Wound form ~17 meters of CORC® wire
- Coil I_c at 100 % retention about 5,000 A
- J_e(17 T) about 200 A/mm^2
- Total of 48 turns in 4 layers
- Field generated 2.6 T in 14 T background

Coil 2

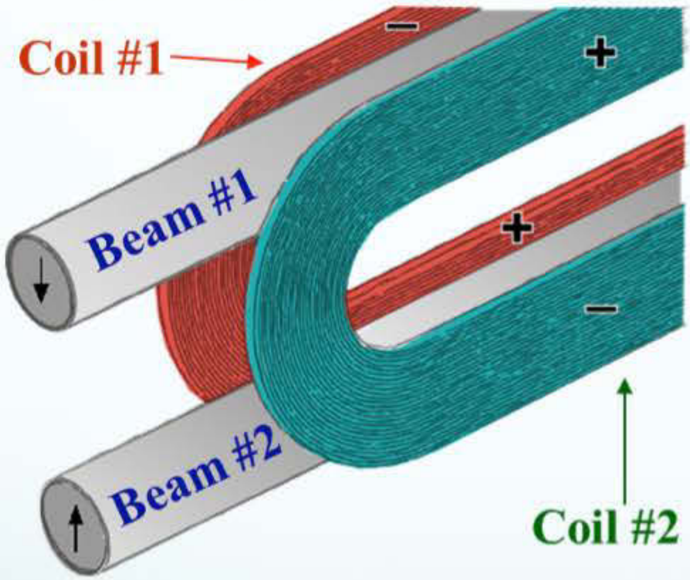
- Wound form ~6 meters of CORC® wire
- Coil I_c at 100 % retention about 5,000 A
- J_e(17 T) about 200 A/mm^2
- Total of 24 turns in 2 layers
- Field generated 1.7 T in 16-17 T background

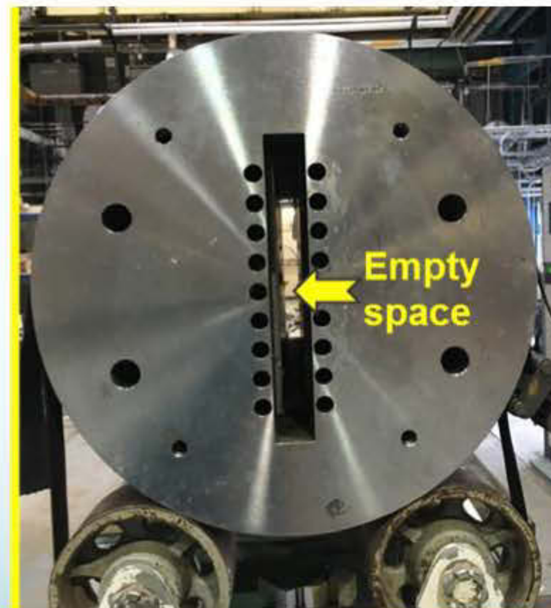


Common coil magnet from CORC® cables

CORC® cable magnet program #4 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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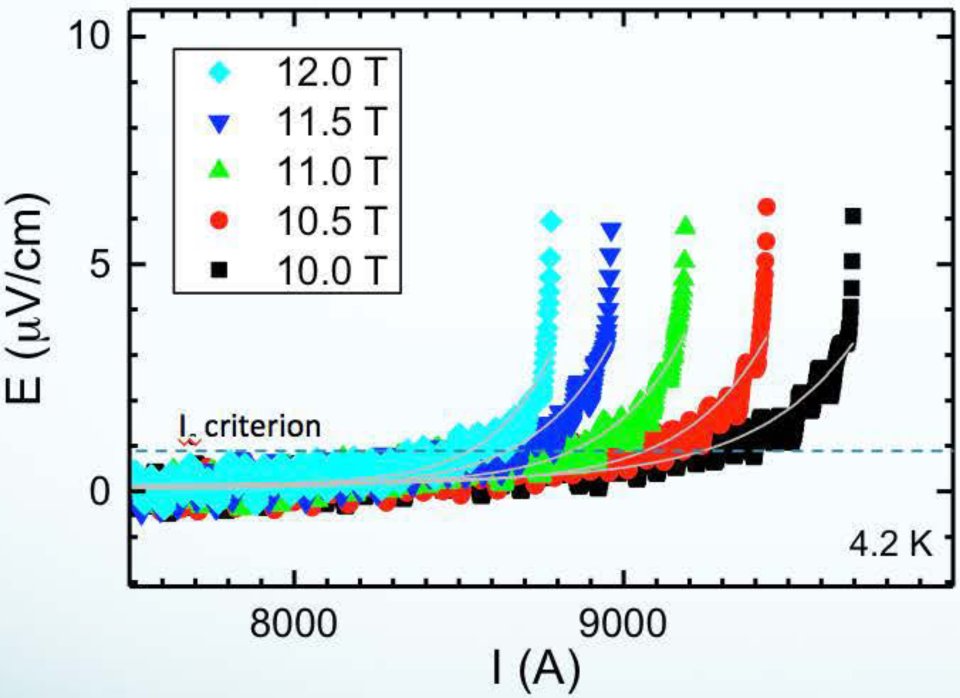
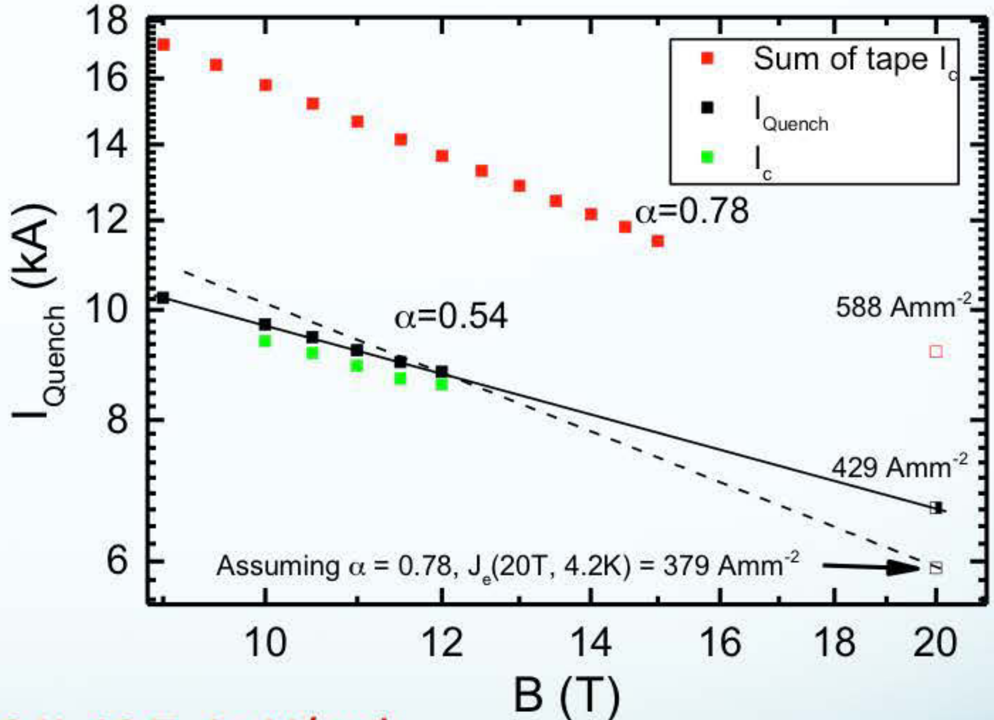
BROOKHAVEN NATIONAL LABORATORY

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

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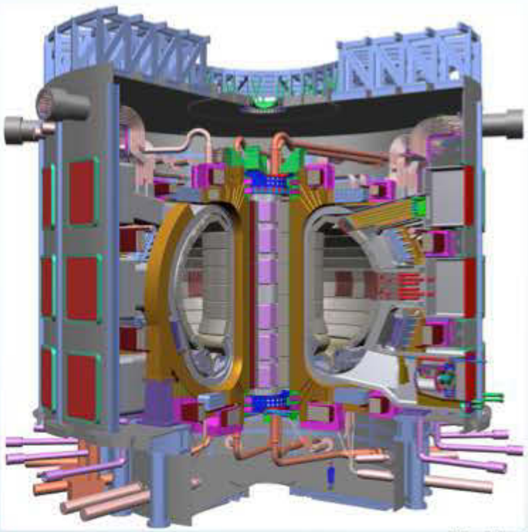
CORC® cable development for fusion magnets

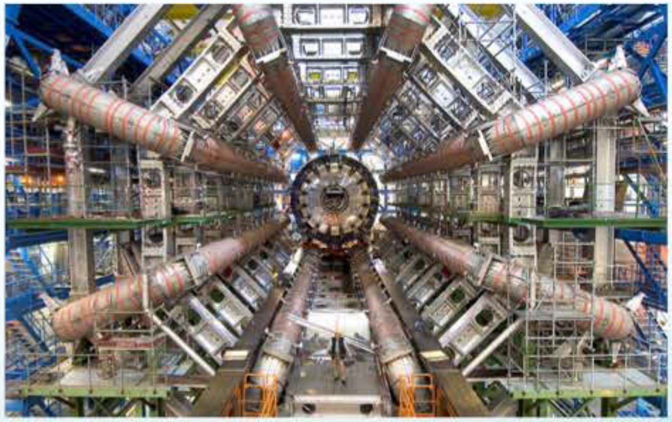
Main program goals

- Develop CORC®-CICC with operating current 50-100 kA at 4.2 K and 12-20 T
- Develop CORC® cable terminations that allow for high-current cable joints



ITER

Tokamak Energy Ltd



ATLAS detector

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CORC®-CICC for fusion and detector magnets

6-around-1 CORC®-CICC

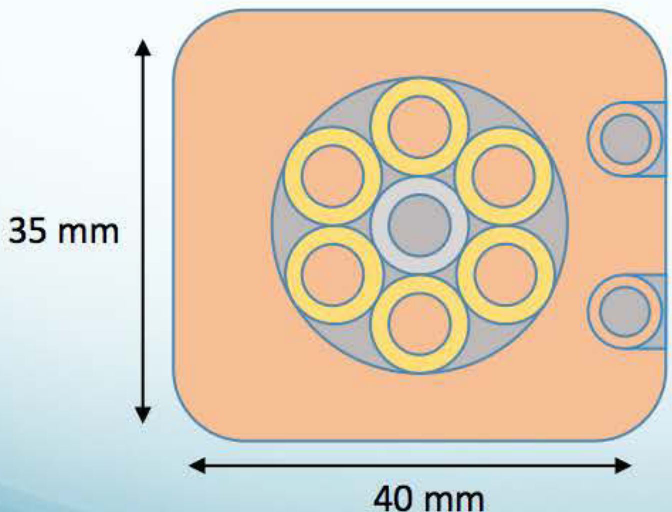
- 80 kA (4.2 K, 11 T)
- 42 tapes per CORC® cable
- Stainless steel or copper jacket

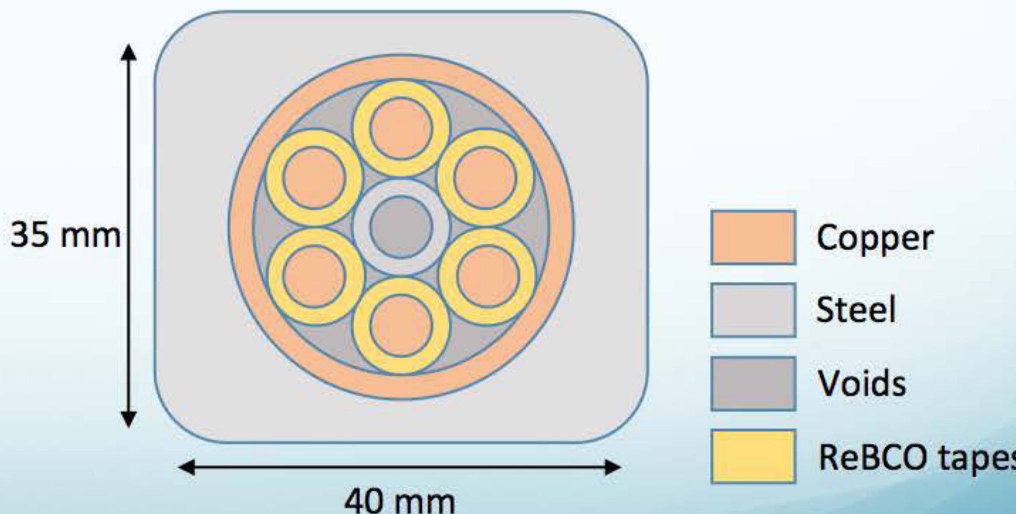
Sample 1 for detector magnets

- High thermal & electrical stability
- Practical cooling
- 80 kA at 12T/4K

Sample 2 for fusion magnets

- Can sustains High Stress
- Can cope with large heat loads
- 80 kA at 12T/4K





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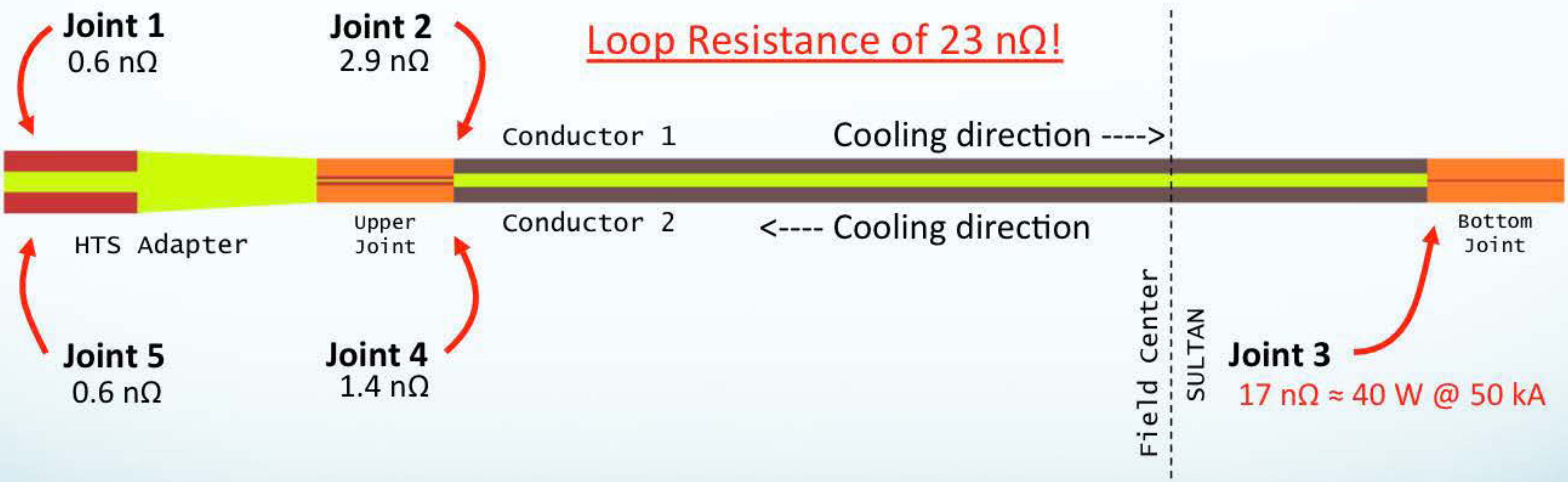
CORC®-CICC SULTAN test

Some issues were encountered:

- One bad joint (in field)
- Exotic hydraulic layout

→ Only $I_c(B, T)$ measurements at 40-55 K were possible



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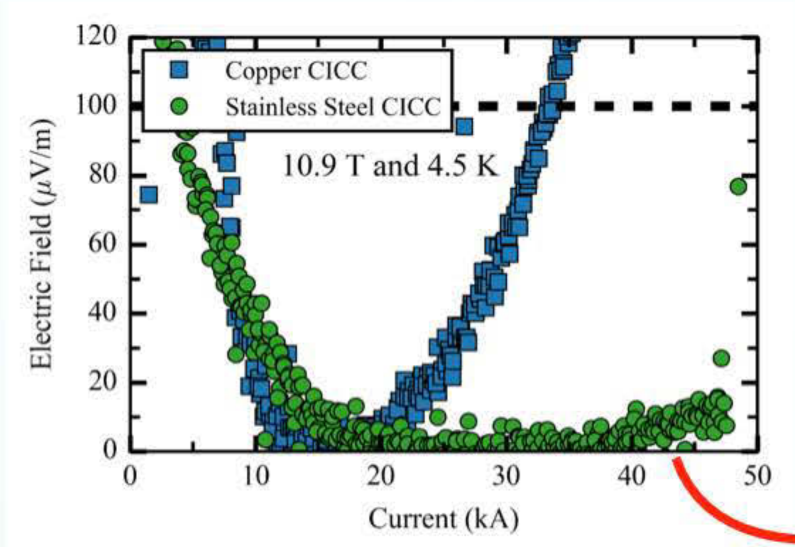
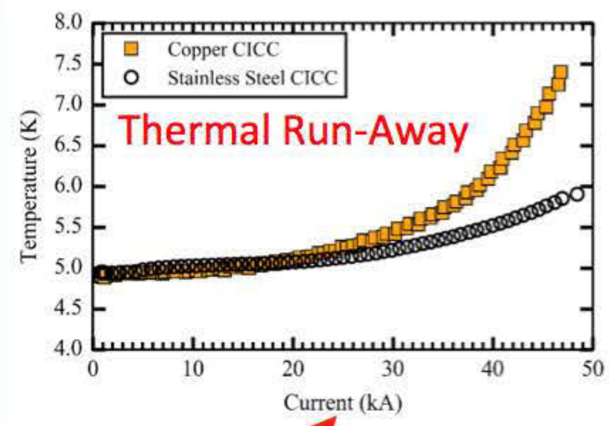
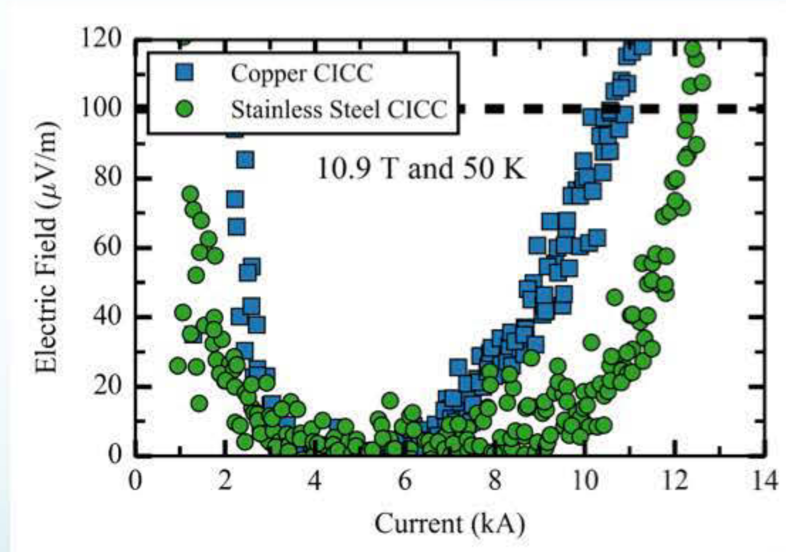
CORC®-CICC SULTAN test: 4.5 K vs. 50 K





Effect of heating at joint

- Heating at bottom joint causes thermal runaway at 4.5 K
- Only the fusion sample could be measured at 4.5 K
- Heating not much of a problem at 50 K
- Both samples perform as expected at 50 K, 10.9 T



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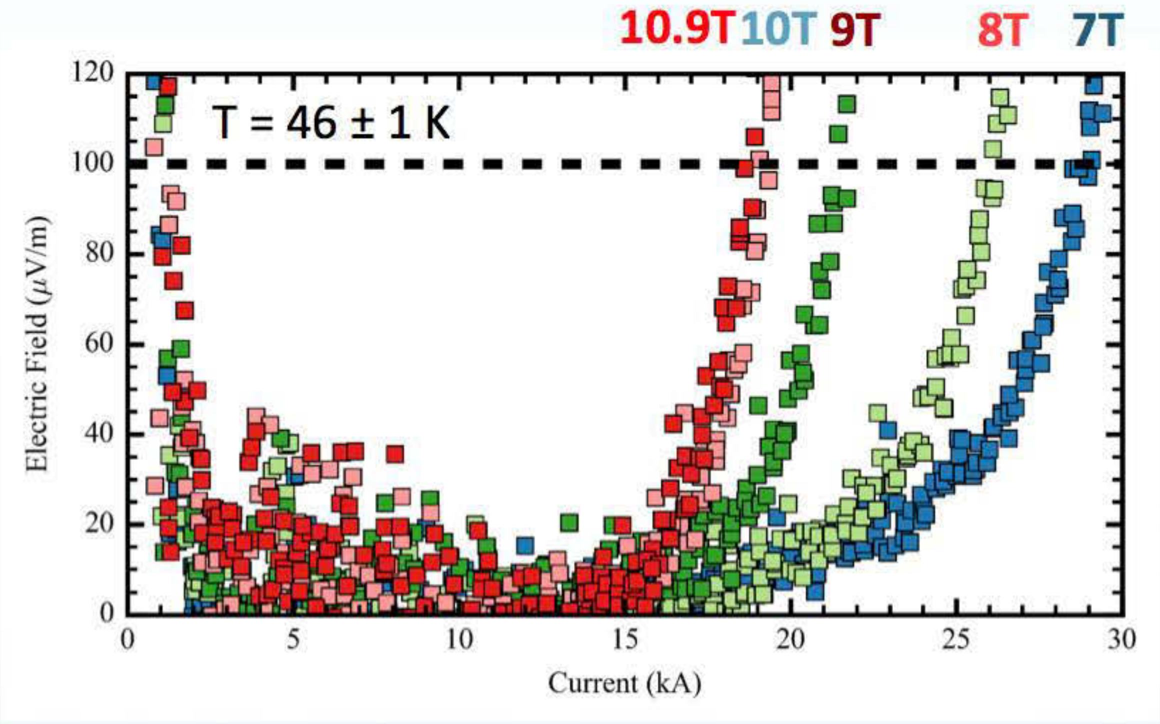
CORC®-CICC fusion sample at 46 K

Fusion CORC®-CICC at 46 K

- Field dependence could be measured up down to 7 T
- Sample performed as expected



- Bottom joint has been, but detector sample still showed lower I_c
- Detector sample now being inspected and may possibly be replaced

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

- 15 T Canted Cosine Theta magnets from CORC® wires
- 12 T Racetrack coil from CORC® wires
- 18 T CORC® wire insert solenoid
- 15 T Common Coil from CORC® cables

CORC®-CICC for fusion and detector magnets

- 80 kA (4.2 K, 11 T) 6-around-1 CORC®-CICC test ongoing
- Technical problems with one of the samples is being resolved
- SULTAN test will continue in coming months