This work was in part supported by the US Department of Energy under agreement numbers DE-SC0009545, DE-SC0014009, DE-SC0015775, DE-SC0018127 and DE-SC0018710.

Recent progress on CORC® cable, wire and magnet development

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

Drew Hazelton
SuperPower Inc., Schenectady, New York, USA

Tim Mulder, Alexey Dudarev and Herman ten Kate
CERN, Geneva, Switzerland

H. Higley, S. O. Prestemon and X. Wang
Lawrence Berkeley National Laboratory, Berkeley, California, USA

Dima Abraimov, Ulf Trociewitz, Huub Weijers and James Gillman
National High Magnetic Field Laboratory, Tallahassee, Florida, USA

Ramesh Gupta
Brookhaven National Laboratory, Upton New York, USA

Advanced Conductor Technologies
www.advancedconductor.com

CEC-ICMC 2019, July 24th, 2019, Hartford, CT

Advanced Conductor Technologies LLC (ACT)

Advanced Conductor Technologies focuses on the commercialization of high-temperature superconducting (HTS) Conductor on Round Core (CORC®) cables for high-density power transmission and high-field magnets.

SBIR/STTR programs

- **25 SBIR/STTR programs awarded since 2012**
- 16 Phase I, 8 Phase II and 1 Phase IIB awards
- Funding from: the U.S. Navy (25 %), U.S. Department of Energy (75 %) (Offices of Fusion Energy Sciences and High Energy Physics)

Selected as a DOE SBIR success story in 2018

SBIR·STTR America's Seed Fund | U.S. DEPARTMENT OF ENERGY SBIR/STTR Programs Office

Close-up of the CORC® cable made from individual tapes of second generation high-temperature superconductor REBCO.

ADVANCED CONDUCTOR TECHNOLOGIES

High-temperature superconductor (HTS) cables offer a potential breakthrough for developing a lower cost path to fusion energy, as well as for the next generation of proton-proton colliders. Current fusion and accelerator magnets are built using low-temperature superconductors (LTS) made of Nb-Ti and Nb_3Sn, in which superconductivity breaks down not far above the temperature of liquid helium (4.2 K) and at relatively small applied fields of nearly 16 T. In Fusion Energy applications, limitations in current vs. magnetic field characteristics of LTS result in very large reactor structures like ITER and in associated costs in the range of tens of billions. Because HTS can sustain much larger operating currents at higher magnetic fields than LTS, HTS cables can be used to produce fusion magnets generating fields of over 20 T in a much smaller machine.

FACTS

PHASE III SUCCESS
Three years from the end of its first SBIR award Advanced Conductor Technologies has achieved a sales revenue of over $0.5M, including several purchases by LBNL to build the first CORC®-based accelerator magnet.

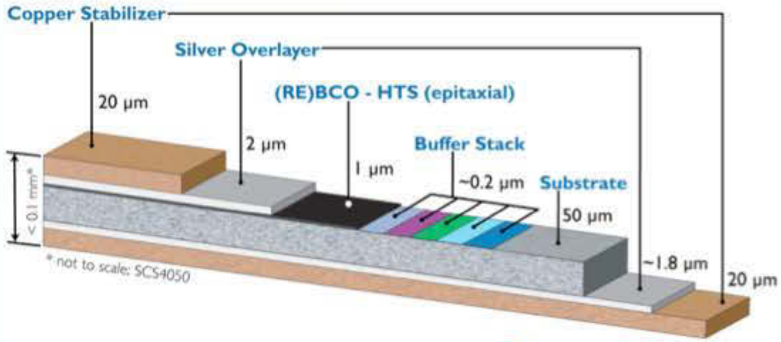
IMPACT
Advanced Conductor Technologies' CORC® cable will enable magnets producing fields of 20 T and above for the next generation fusion reactors, research and medical particle accelerators.

DOE PROGRAMS
Fusion Energy Sciences (FES), High Energy Physics (HEP).

WWW.ADVANCEDCONDUCTOR.COM

Advanced Conductor Technologies
www.advancedconductor.com

CORC® magnet cables and wires



SuperPower Inc. A Furukawa Company

Single tape wound into a CORC® cable

CORC® wires (2.5 – 4.5 mm diameter)

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

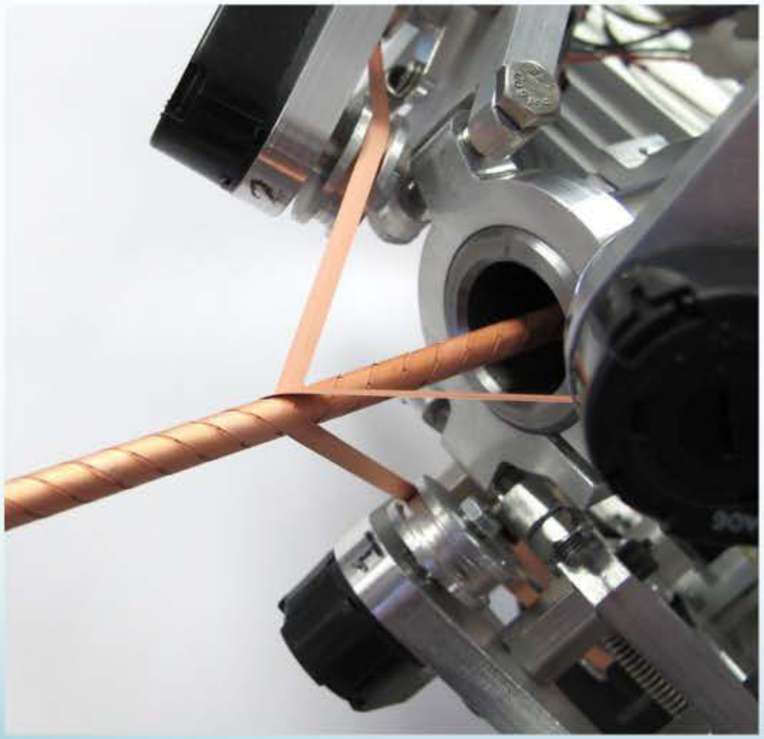
CORC® cable (5 – 8 mm diameter)

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

CORC® cable production

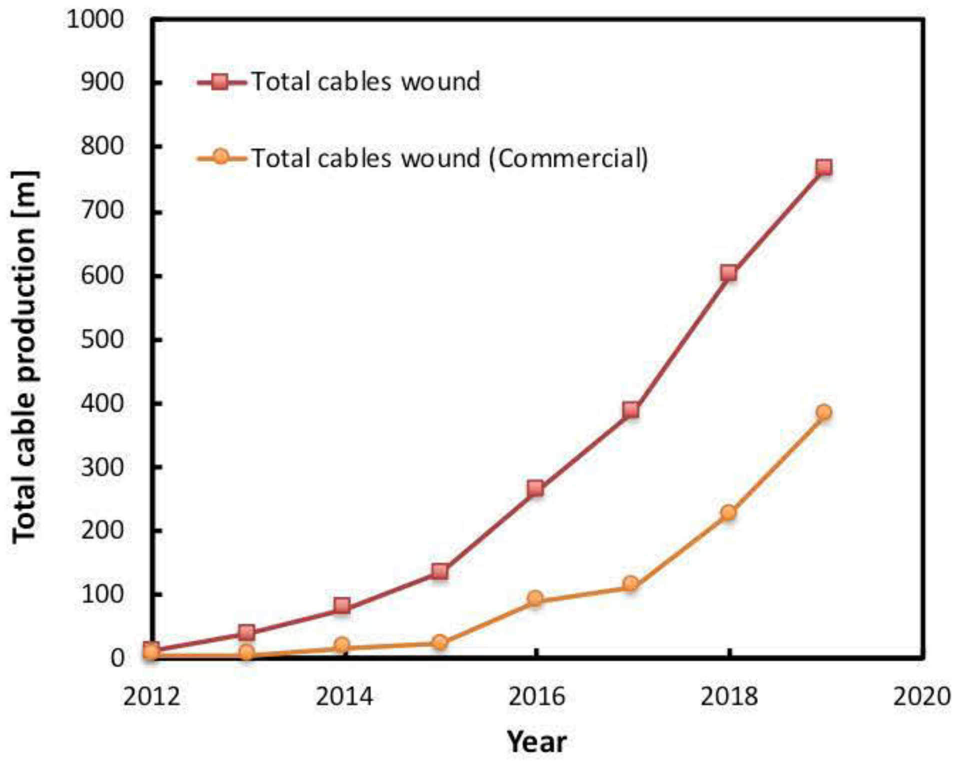
Winding of long CORC® cables with custom cable machine

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



Cumulative CORC® production

- about 800 meters since 2012
- includes 400 meters for commercial orders (including about 150 meters for open orders)



CORC® production expansion

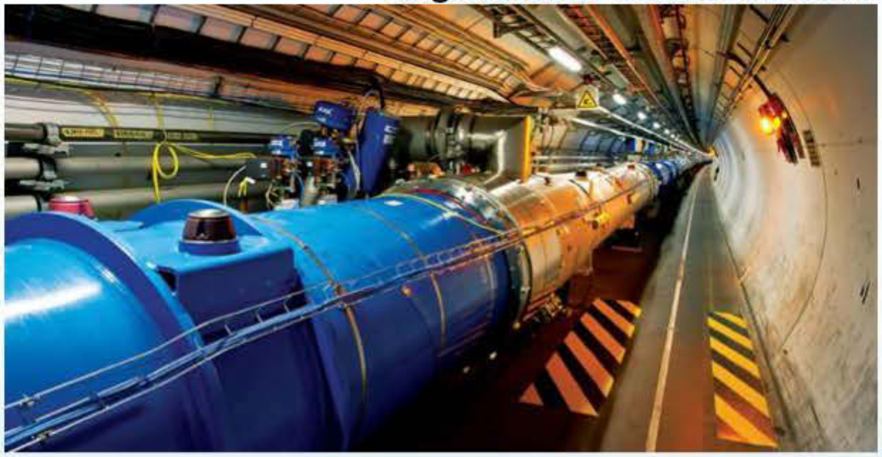
We successfully moved the CORC® cable production to the cloud!

CORC® conductor development for magnet applications

CORC® conductors for accelerator magnets
(Main sponsor DOE – High Energy Physics)

- Engineering current density J_e(20 T) > 600 A/mm^2
- Operating currents 10 – 20 kA
- Small cable bending diameters 20 – 50 mm

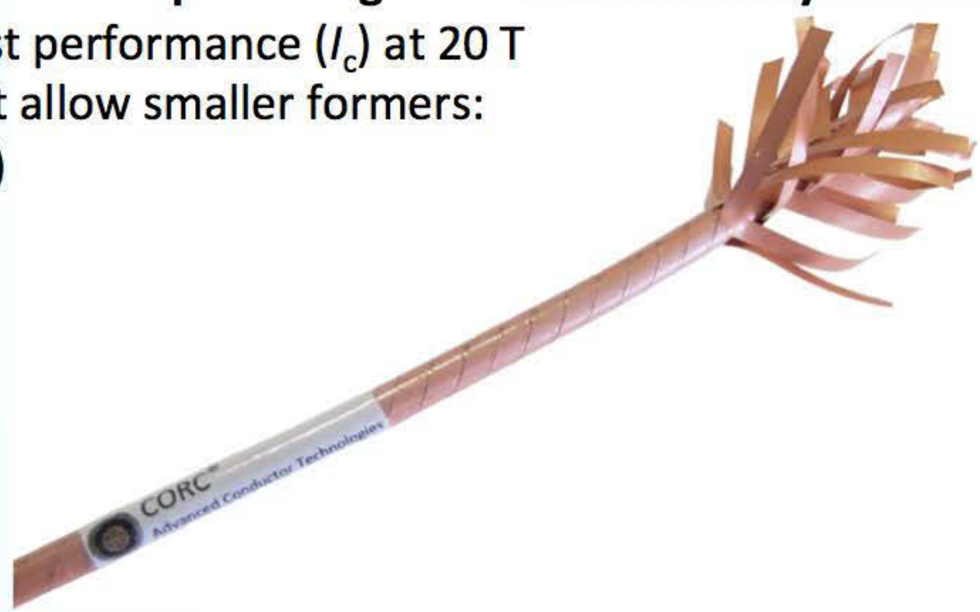
Large Hadron Collider at CERN

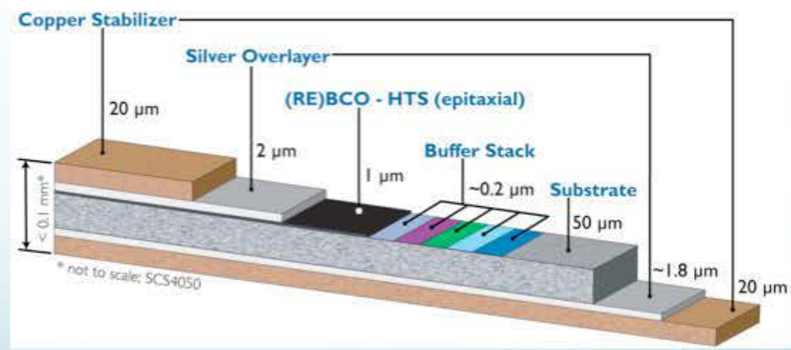


CORC® conductors for accelerator magnets

Increasing J_e (> 600 A/mm^2) and I_c (> 10 kA) of CORC® cables at 4.2 K and 20 T

1. Winding many REBCO tapes, **while not compromising conductor flexibility**
2. Incorporating tapes with the highest performance (I_c) at 20 T
3. Using tapes with thin substrate that allow smaller formers:
    - 50 μm substrate (2012 – 2013)
    - 38 μm substrate (2014)
    - 30 μm substrate (2015 –)
    - 25 μm substrate (2019 –)



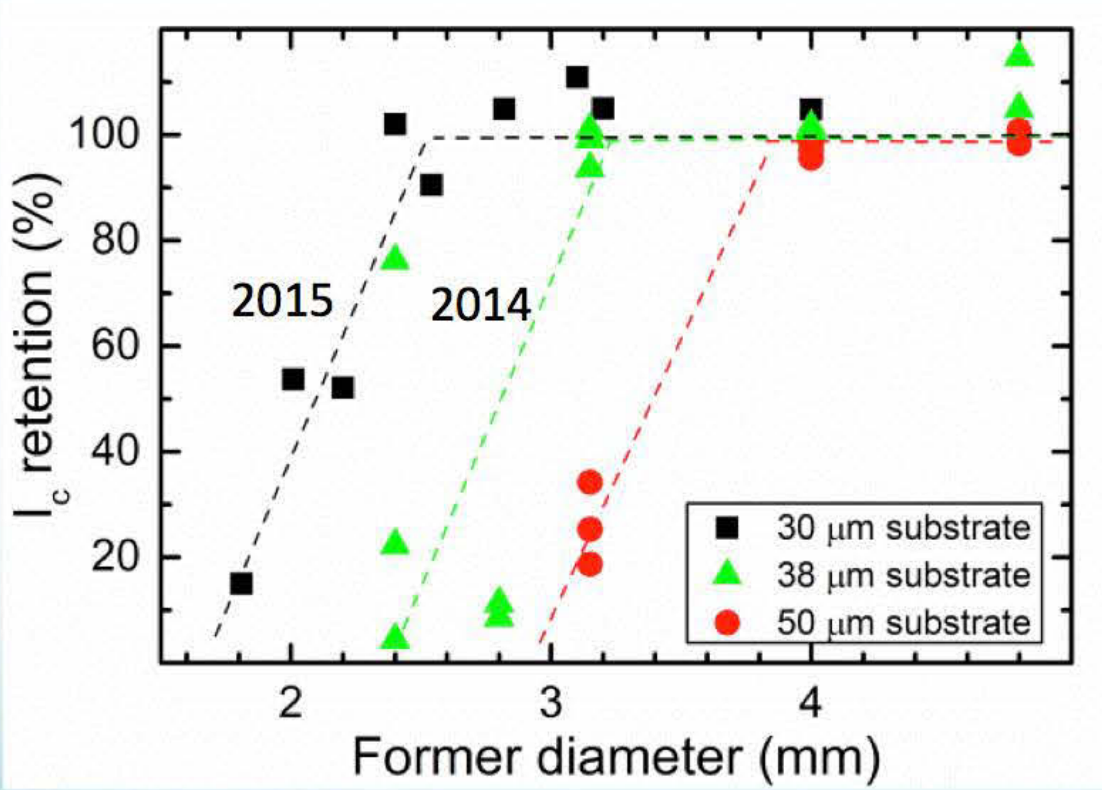


37-tape CORC® cable

Increase J_e(20 T) by reducing the former size

Thinner substrates allow smaller formers in CORC® cables

- Winding a tape at 45 degrees with the REBCO layer under compression
- Measure I_c at different former diameters



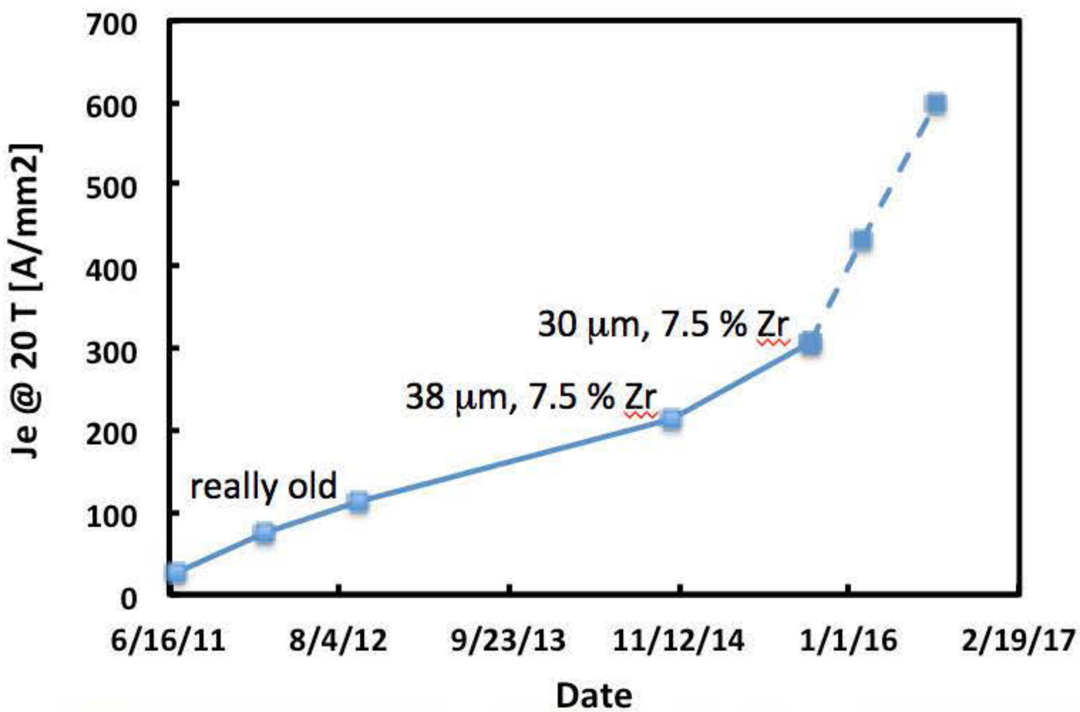
Minimum former diameter

- 4 mm for 50 µm substrate
- 3.2 mm for 38 µm substrate
- 2.4 mm for 30 µm substrate

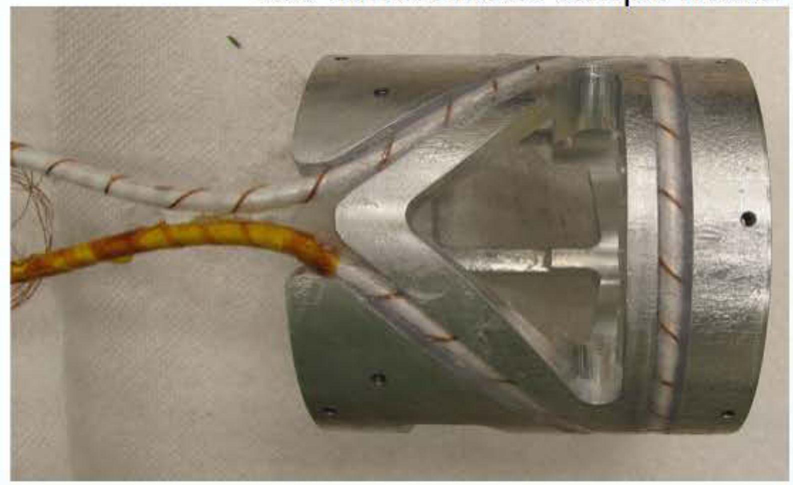
Increasing J_e(20 T) in CORC® cables

CORC® cables limited to 100 mm bending diameter

- Wound from 3 and 4 mm wide REBCO tapes
- Tested on a 10 mm diameter sample holder
- Main test facility used to be the 17 T large bore resistive magnet at the NHMFL
- Test bed decommissioned Nov. 2015



100 mm diameter sample holder



CORC® cable performance end of 2015

- Operating current about 10 kA at 20 T
- J_e(20 T) of 309 A/mm² achieved in Oct. 2015 using 30 μm substrates

New test bed needed to continue the push to J_e(20 T) > 600 A/mm²

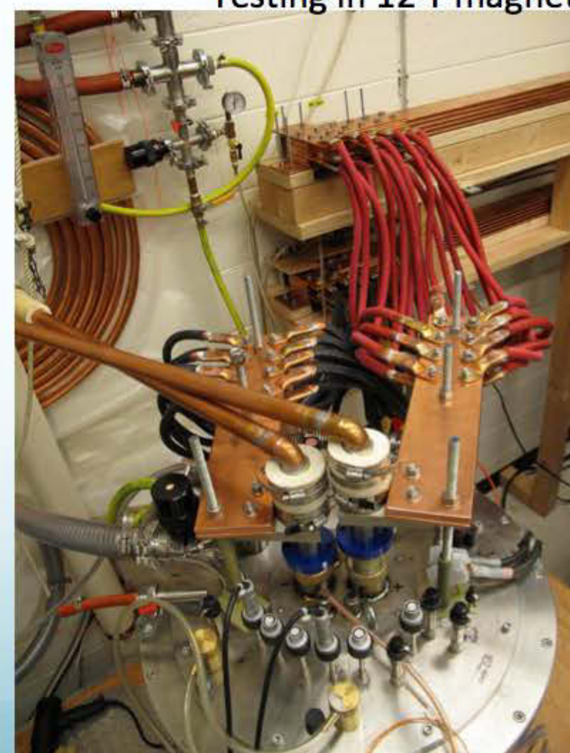
Advanced Conductor Technologies
www.advancedconductor.com

Increasing J_e(20 T) in CORC® wires

CORC® wires introduced 2016

- Typically smaller than 4 mm thickness
- Wound from 2 and 3 mm wide tapes
- Wound from tapes with 30 μm substrates
- Bending down to 50 mm diameter allows testing in typical superconducting R&D magnets
- Testing now in 12 T solenoid magnet

Testing in 12 T magnet



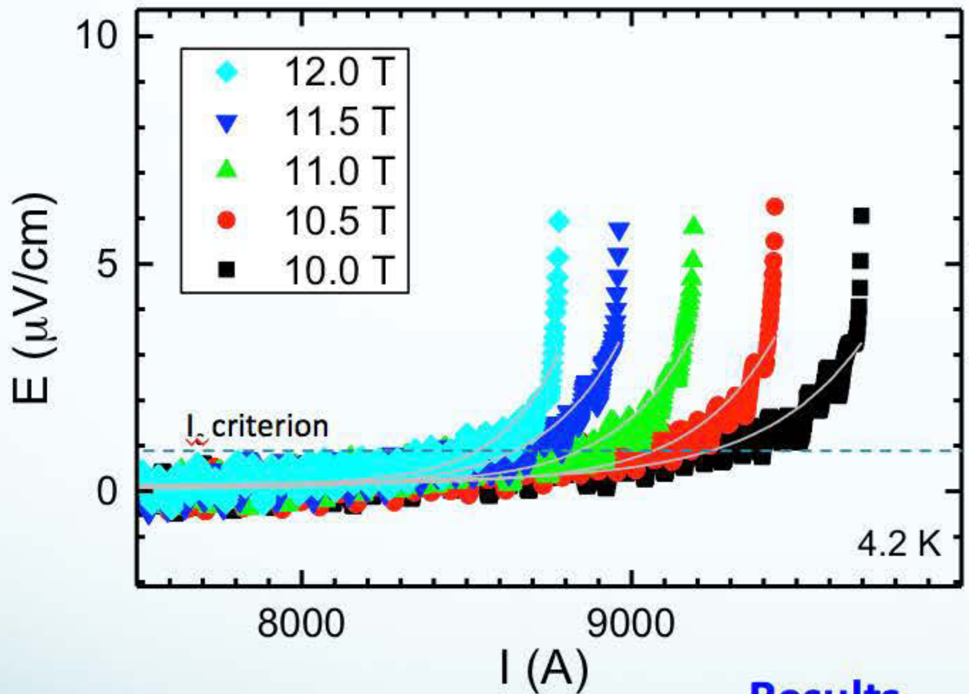
CORC® wire mounted on 60 mm diameter probe

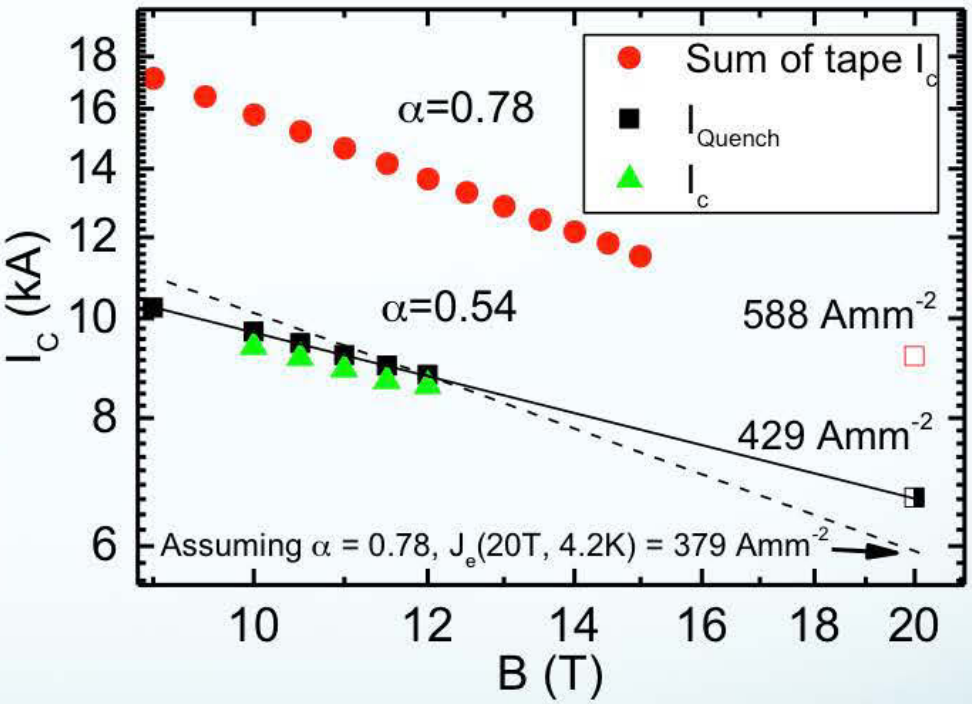
Advanced Conductor Technologies
www.advancedconductor.com

Record J_e(20 T) in CORC® wires with 30 μm substrates

High-J_e CORC® wire layout (pushing the limits)

- 50 tapes, 2 – 3 mm wide, 30 μm substrate
- 4.46 mm CORC® wire diameter
- Relatively inflexible conductor





Results

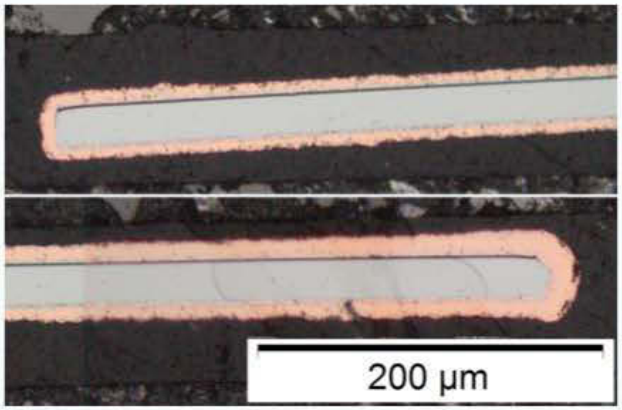
- I_c = 8,591 A (4.2 K, 12 T, 1 μV/cm)
- Projected J_e(20 T) between 379 and 429 A/mm²
- Retention in I_c only 74.5 %
- Slope of I_c(B) deviates from that of the tapes

Advanced Conductor Technologies
www.advancedconductor.com

Introduction of REBCO tape with 25 μm substrates

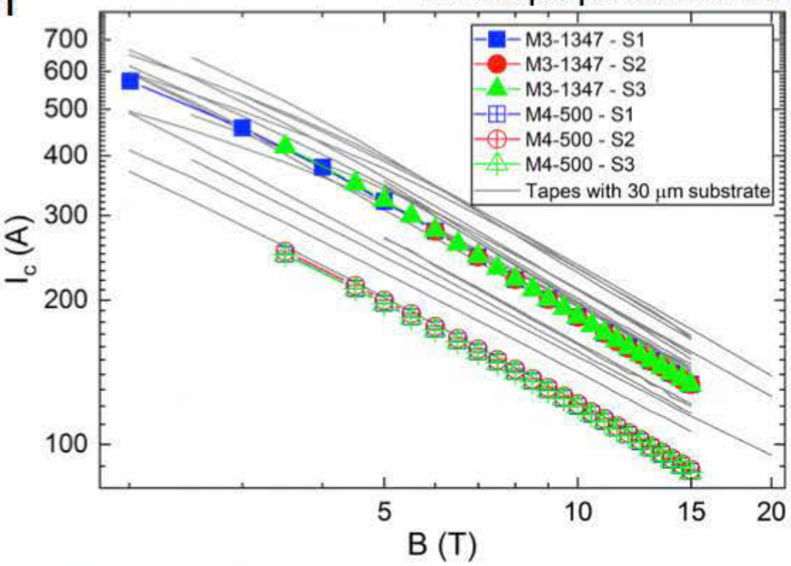
SuperPower produced first batch of tape with 25 μm substrate

- 400 meters of high-quality tape of 2 mm width delivered
- I_c(77 K) = 65 A and 4.2 K pinning similar to 30 μm
- Piece lengths in the order of 30 meters
- Actual substrate 22 – 23 μm thick
- Enables CORC® wires with 2 mm former



Picture courtesy of Michael Small (ASC-NHMFL)

4.2 K tape performance



TapeStar I_c(77 K) data

Advanced Conductor Technologies
www.advancedconductor.com

SuperPower Inc. A Furukawa Company

Next generation CORC® wires with 25 μm substrate

Tapes with 25 μm substrate

- Allow CORC® wires with 2 mm thick formers instead of 2.5 mm
- Result is a significant reduction in CORC® wire thickness

29-Tape CORC® wire used in CCT-C2

- 30 μm substrate: 3.75 mm thick
- 25 μm substrate: 3.33 mm thick

Record J_e(20 T) wires

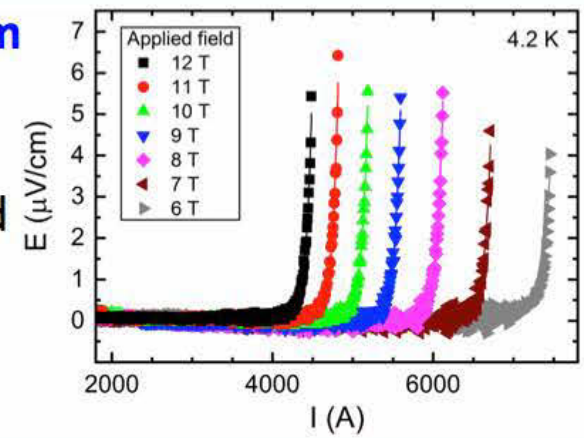
- 25 μm substrate: 3.42 mm thick (next slide)
- 30 μm substrate: 4.46 mm thick (few slides back)

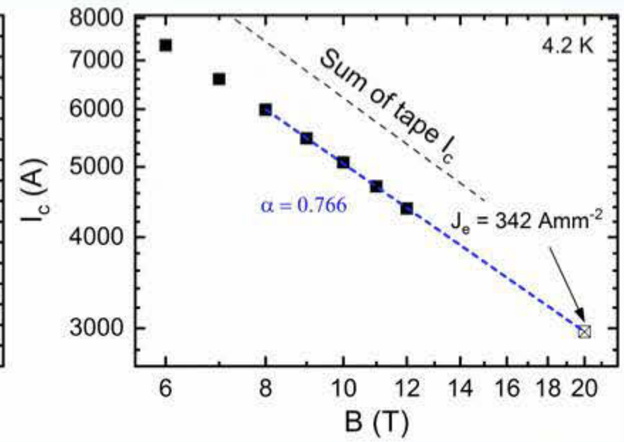
Advanced Conductor Technologies
www.advancedconductor.com
SuperPower Inc.
A Furukawa Company
National High Magnetic Field Laboratory
FSU · UF · LANL

Performance of next generation CORC® wires

CORC® wire CCT-C2 based on 25 μm

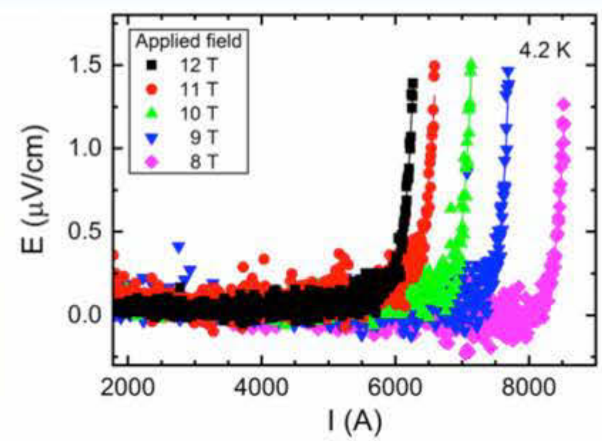
- Same as CORC® wire for CCT-C2
- 29 tapes with 25 μm substrate
- Outer diameter 3.33 mm instead of 3.75 mm
- Average pinning of tapes
- 81 % I_c retention

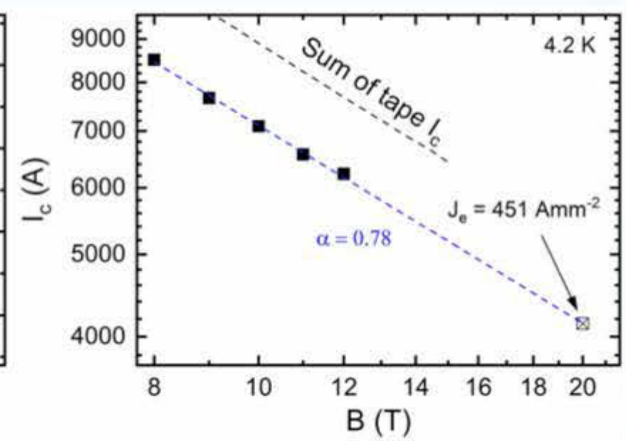




CORC® wire to increase J_e(20 T)

- 32 tapes (2 mm (25 μm) and 3 mm (30 μm) width)
- Outer diameter 3.42 mm
- Average pinning
- 81 % I_c retention





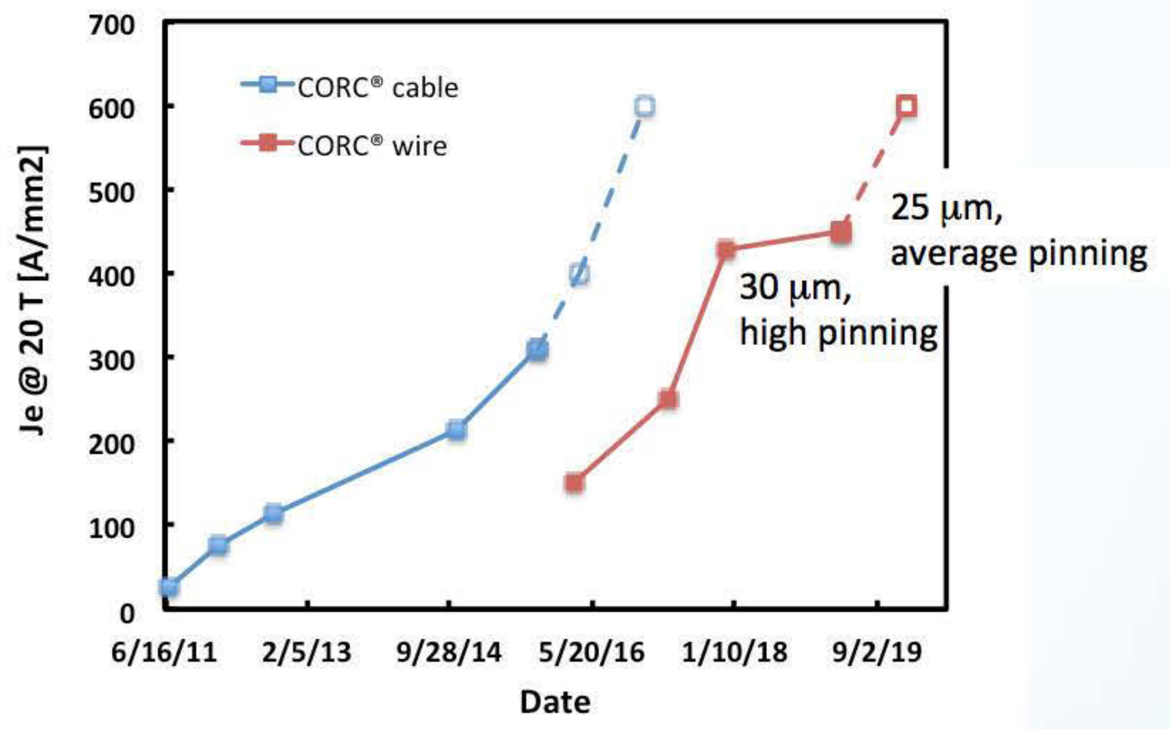
New record J_e (12 T) 678 A/mm²
Extrapolated J_e (20 T) 451 A/mm²
I_c(B) closely follows that of the tapes

Advanced Conductor Technologies
www.advancedconductor.com

CORC® cable and wire performance summary

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

- J_e (20 T) now exceeded 450 A/mm² in CORC® wire
- Combined with I_{opp}(20 T) > 6,500 A
- Next step are taper with 25 μm substrates with above average to high pinning

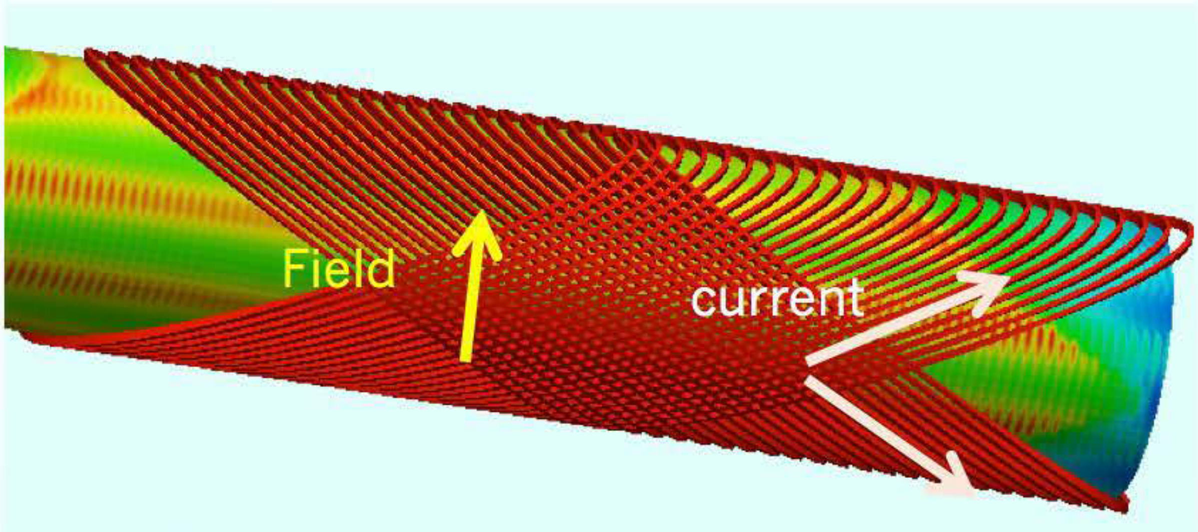
Advanced Conductor Technologies
www.advancedconductor.com

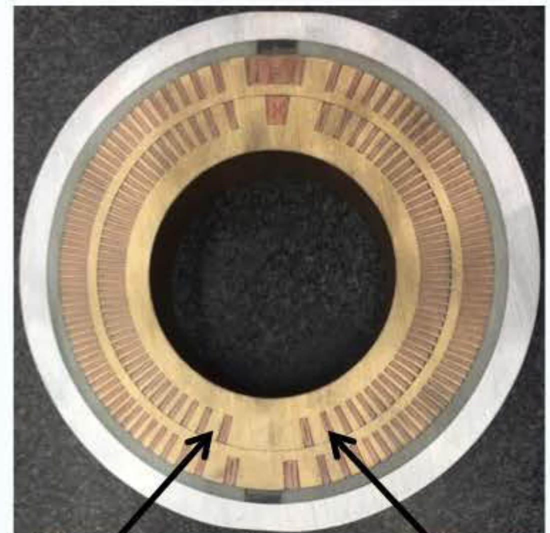
SuperPower Inc.
A Furukawa Company

Program 1: Canted-Cosine-Theta accelerator magnets

Collaboration with Berkeley National Laboratory (Xiaorong Wang)

- Develop CORC®-based Canted-Cosine Theta (CCT) magnets
- Develop the magnet technology for CORC®-CCT magnets





Rib

Conductor

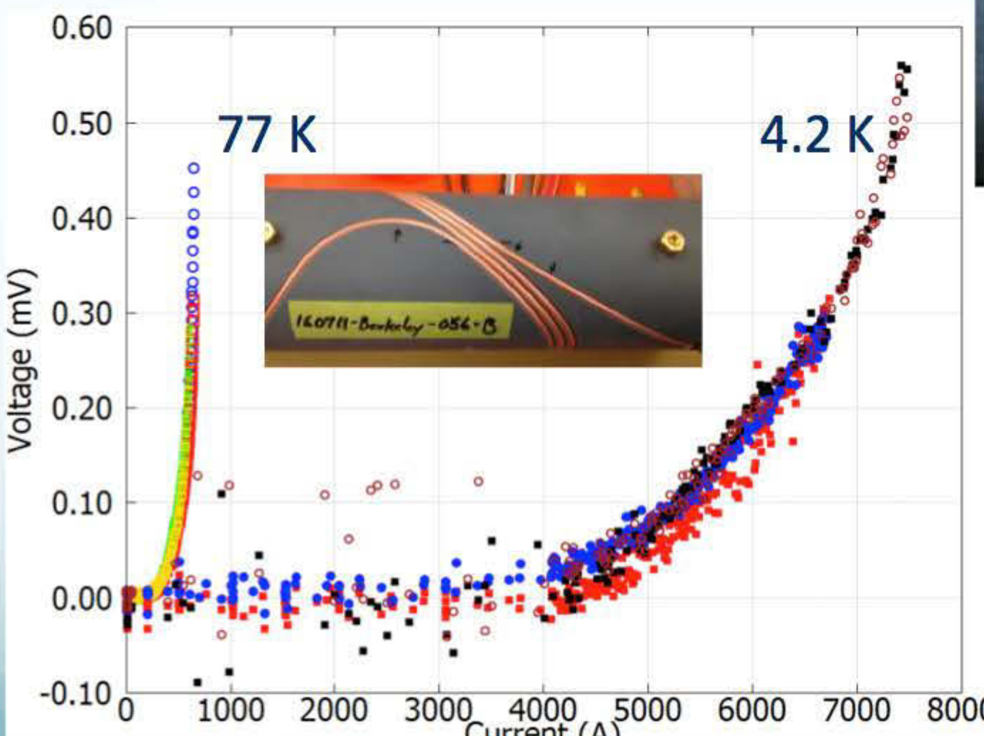
Towards 20 T CORC®-based CCT magnets

- Demonstrate 1 T (CCT-C1), 3 T (CCT-C2) and 5 T (CCT-C3) magnets
- When LTS CCT outserts become available, develop 5 – 7 T CORC®-CCT inserts that operate in 13 – 15 T outserts to deliver 20 T field

Baby coil and actual coil CCT-C1

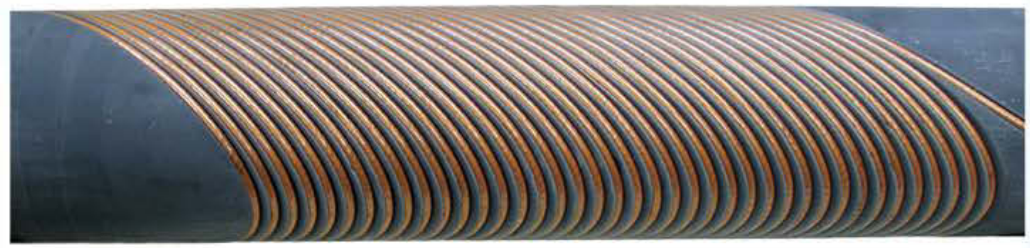
Baby coil CCT C1

- 16-tape CORC® wire
- 2 Layers, 3 turns per layer
- Inner layer I.D. 70 mm, min. bend 50 mm
- I_c (77 K) = 646 – 675 A
- I_c (4.2 K) = 6,700 A (both layers)

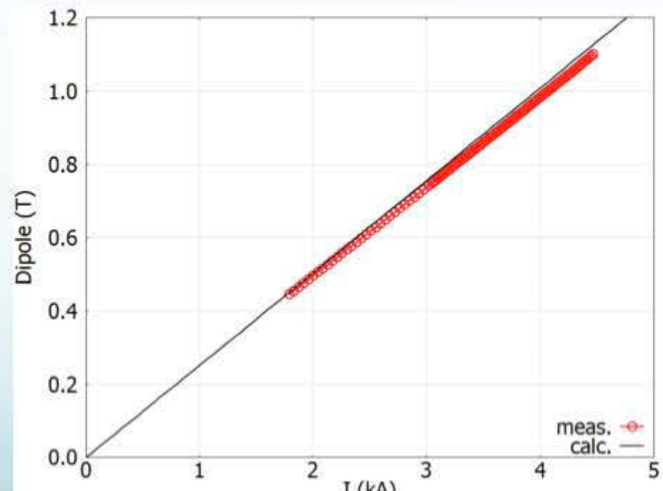


CCT-C1 Magnet wound at LBNL

- 2 Layers, 40 turns per layer
- LBNL ordered 25 m of CORC® wire in 2016
- CORC® wire contains 16 tapes, J_e (20 T) = ~150 A/mm^2



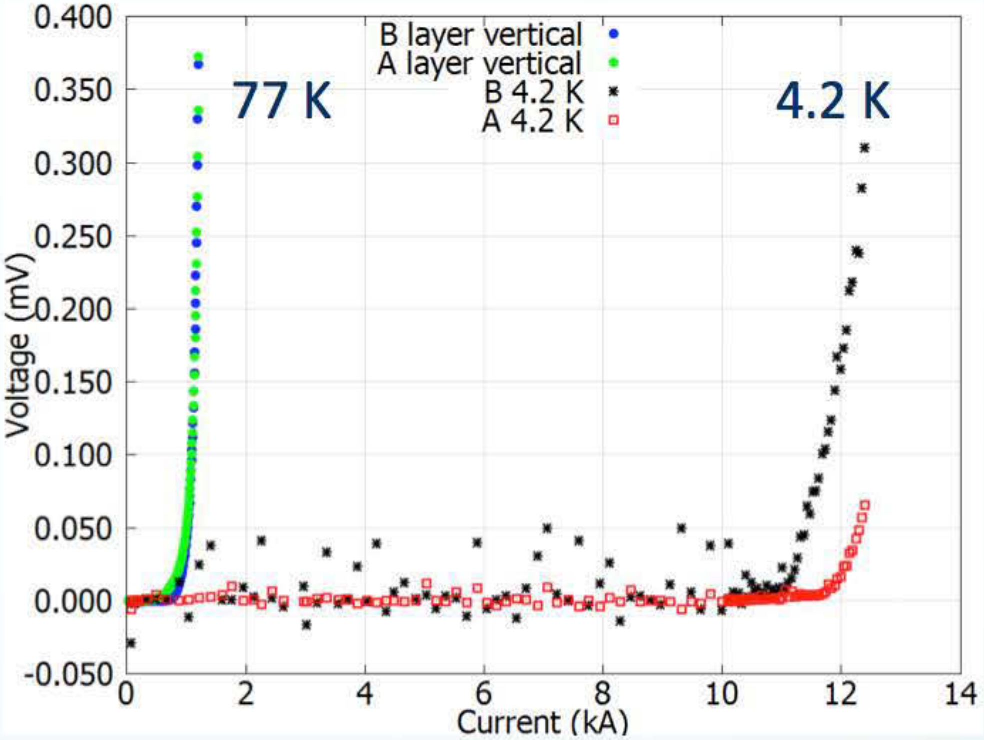
Goal of 1 T has been exceeded: 1.1 T reached at 4,500 A



Baby coil for CCT-C2

CCT C2-0: CORC® wire with 27 tapes

- 2 Layers, 3 turns per layer
- Inner layer I.D. 85 mm
- I_c (77 K) = 1.067 – 1,092 A
- I_c (4.2 K) = 11,078 – 12,141 A



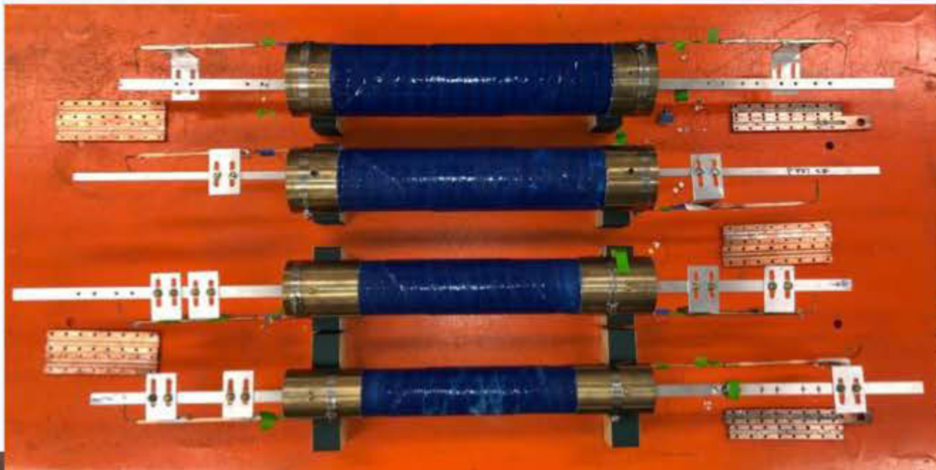
80 m of CORC® wire for CCT-C2 was delivered to Berkeley Sept. 2018

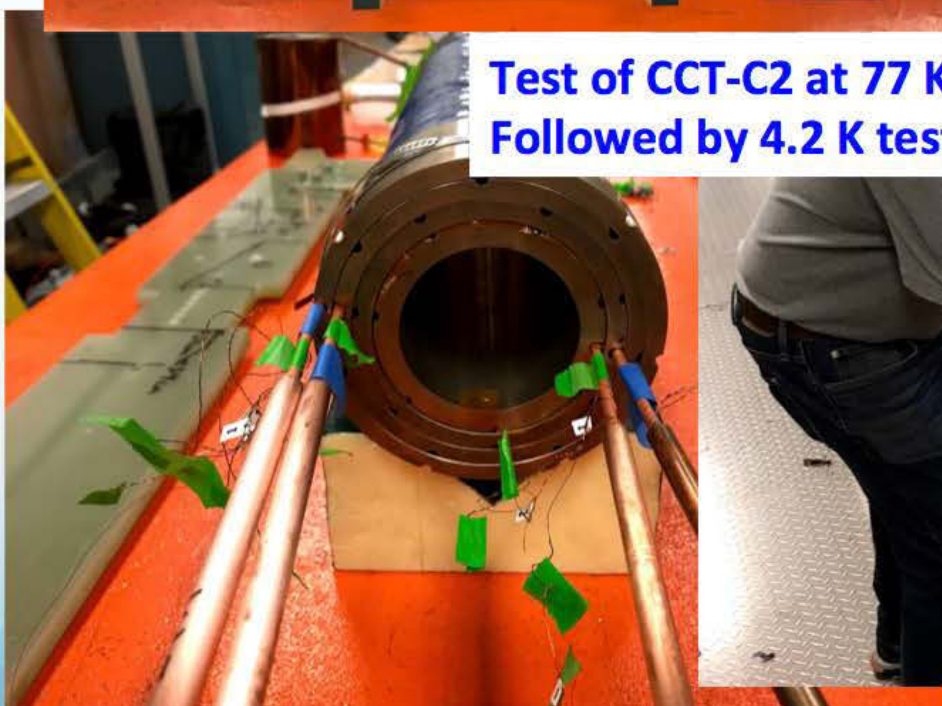
Manufacturing of CCT-C2 layer 1

CCT-C2 layout

- 3 T at 4.2 K
- 4 Layers, 40 turns per layer
- Aperture 85 mm
- Minimum bending diameter 60 mm

CCT-C2 Assembly





Test of CCT-C2 at 77 K expected in the next 2 weeks
Followed by 4.2 K test in August 2019

CORC®-CCT magnet development: CCT-C3

Magnet specifications CCT-C3

- Should deliver 5 T at 4.2 K
- 6-layer, 40-turns/layer
- 70 mm aperture, 60 mm min. bend

CORC® wire specifications CCT-C3

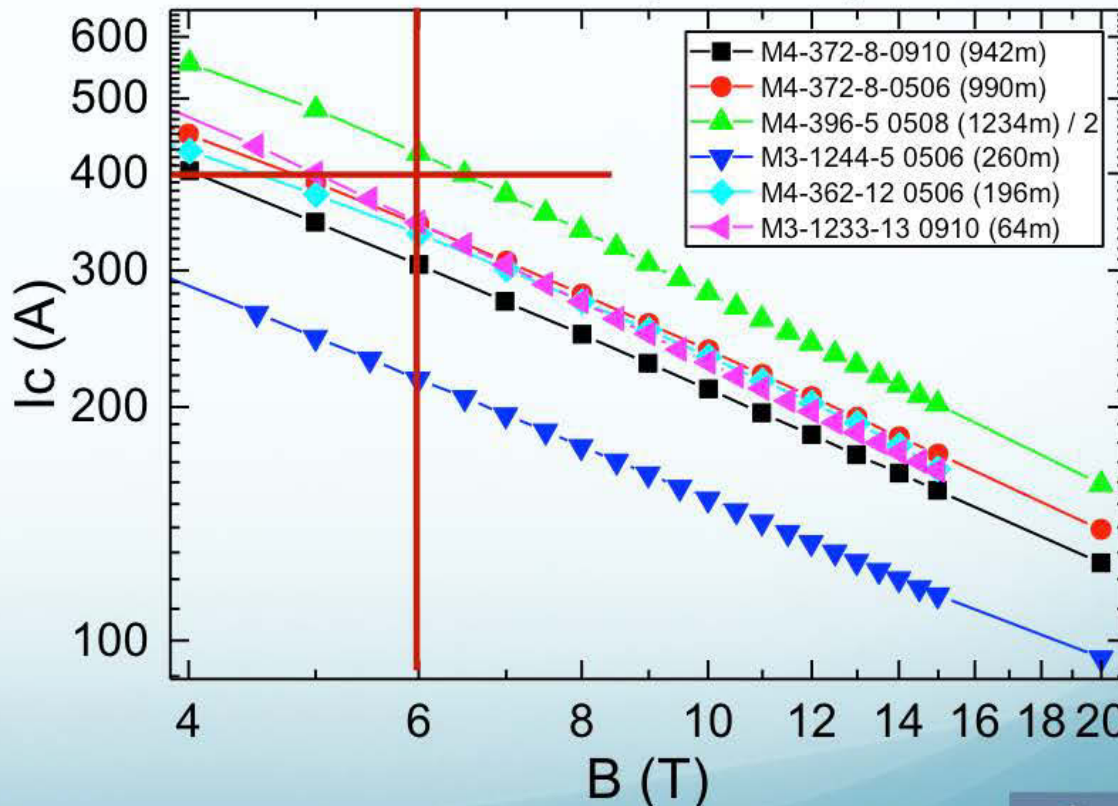
- 30-tape CORC® wire (30 μm)
- Total length about 140 meters
- Short sample limit (4.2 K): 9,920 A

REBCO tape requirements

- Minimum average I_c (4.2 K, 6 T) = 400 A for 2 mm wide tape
- Would result in CORC® wire I_c (4.2 K, 6 T) = 12 kA
- CORC® wire performance after winding at 70 % I_c retention: 8.4 kA
- Magnet performance could be as high as 6 T

CORC® wire for CCT-C3 was ordered by Berkeley Q1, 2019

Performance of 2 mm wide tape over the years



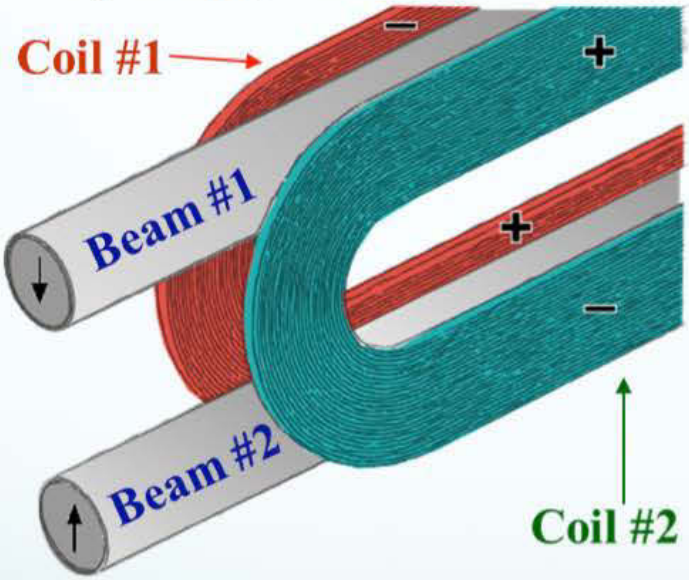
Advanced Conductor Technologies
www.advancedconductor.com

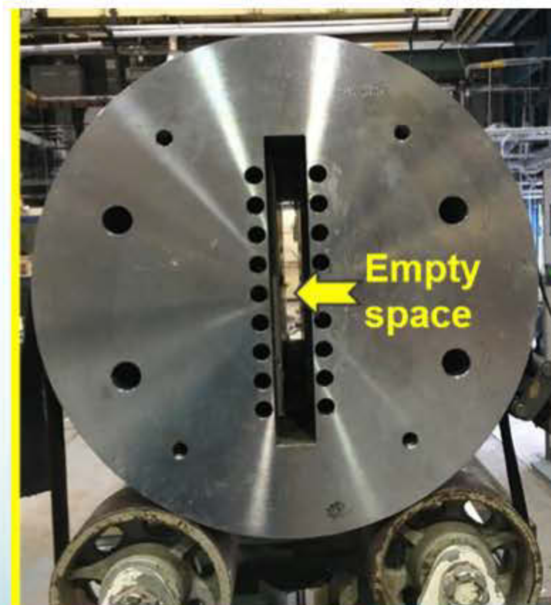
BERKELEY LAB

Program 2: Common coil magnet from CORC® cables

Collaboration with Brookhaven National Laboratory (Ramesh Gupta)

- 4 T CORC® cable common coil insert
- Combine with 10 T LTS common coil outsert
- Operating J_e 400 – 500 A/mm^2 (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

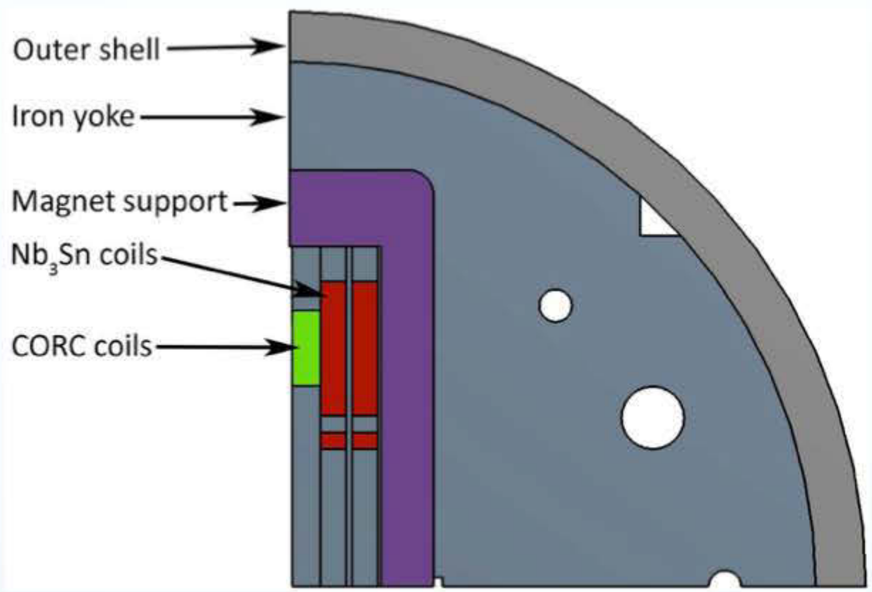
Advanced Conductor Technologies
www.advancedconductor.com

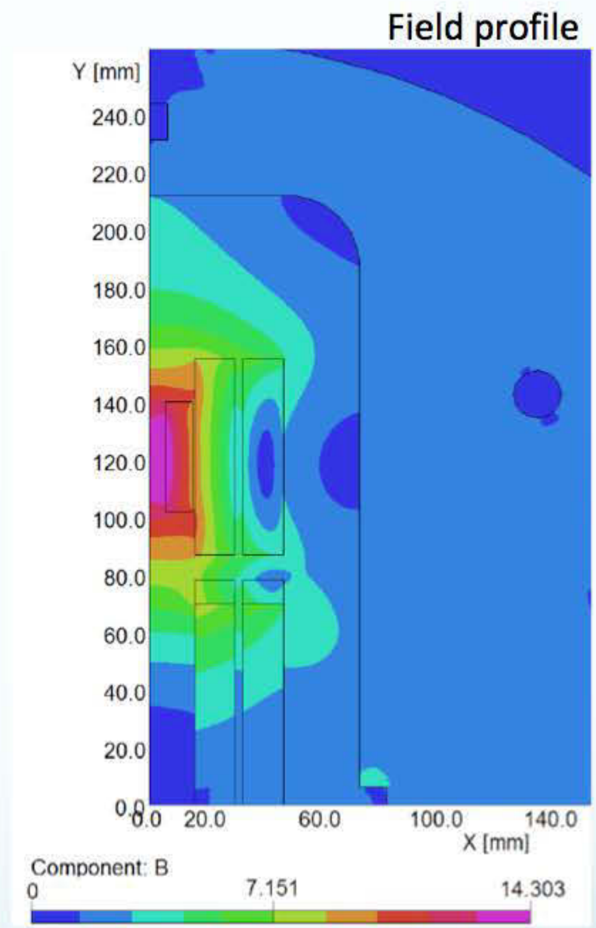
BROOKHAVEN NATIONAL LABORATORY

Common Coil magnet design and construction

Common Coil insert design to reach 14 T

- Based on a pair of double CORC® pancakes
- Overall CORC® cable length about 50 meters
- Conductor layout depends on tape I_c





Magnet design and construction timeline

- Tapes expected Q3 2019
- CORC® cable layout and testing finalized Q4 2019
- Insert design and construction Q1 2020 – Q2 2020
- Insert test in 10 T outsert Q3 2020

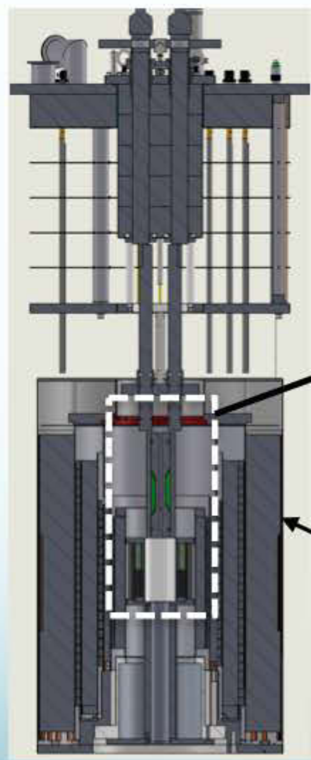
Advanced Conductor Technologies
www.advancedconductor.com

BROOKHAVEN
NATIONAL LABORATORY

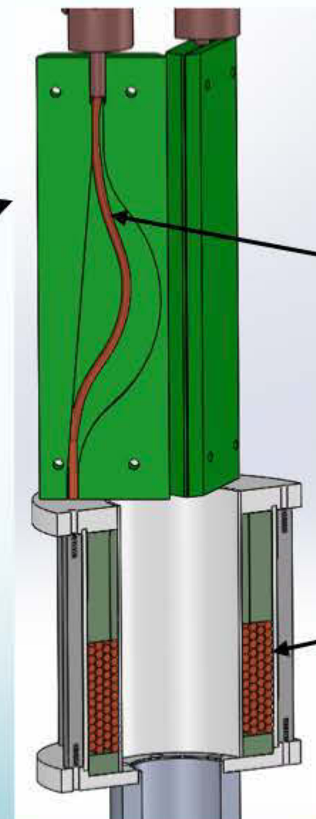
High-field insert solenoid wound from CORC® wires

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 T with 100 mm inner diameter
- Operating current density > 200 A/mm^2
- Hoop stress about 250 MPa



14 T LTS w/
161 mm
bore



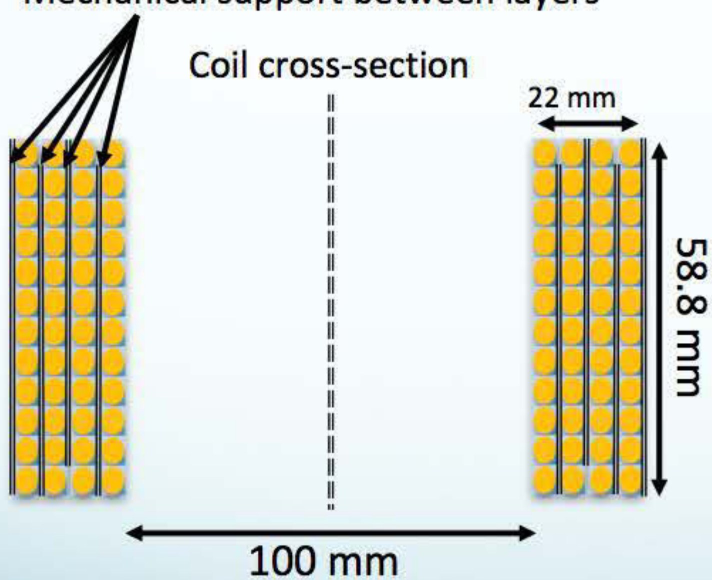
Flexible CORC® S-Bend
allows Vertical travel
of insert due to CTE
mismatch between
probe/coil-insert and
LTS magnet

2 T CORC® coil
with 100 mm bore

CORC® insert design

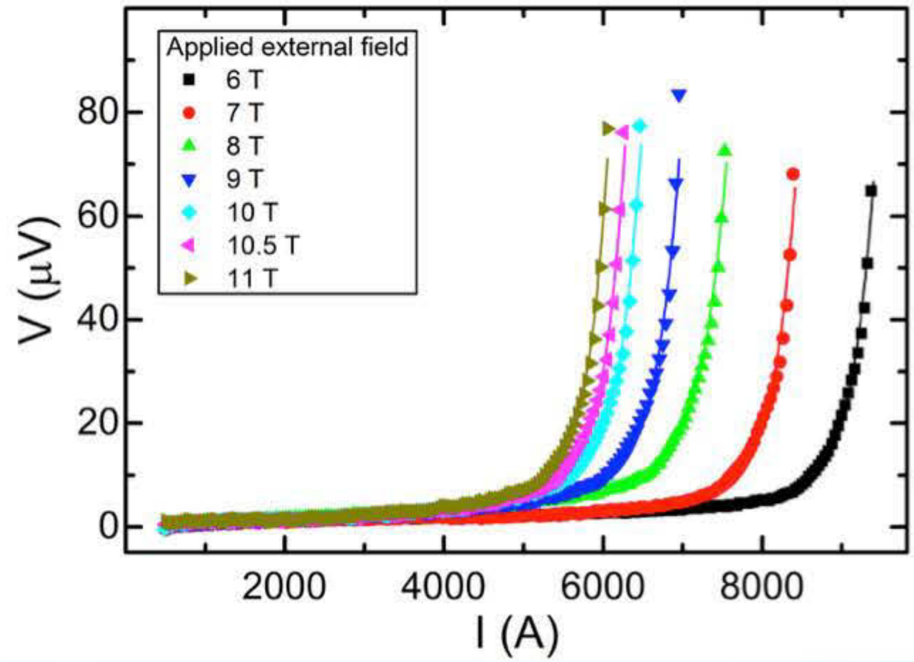
CORC® insert coil details

- Wound from ~17 meters of CORC® wire
- Coil I_c about 5,000 A
- J_e(16 T) about 250 A/mm²
- Total of 48 turns in 4 layers
- Field generated about 2 T in 14 T



CORC® wire performance

- 4.4 mm CORC® wire
- 28 tape of 3 mm width



- I_c(12 T) = 5,932 A (low lift factor tape)
- J_e(17 T) expected around 300 A/mm²

Magnet construction and test Q3 2019 – Q4 2019

Advanced Conductor Technologies
www.advancedconductor.com

Summary

CORC® wires and cables have matured into magnet conductors

- High currents have been demonstrated: > 8,500 A (4.2 K, 12 T)
- High current densities have been reached: > 450 A/mm^2 (4.2 K, 20 T)
- Introduction of the next generation of CORC® wires based on 25 μm substrates

Canted Cosine-theta magnets based on CORC® wires

- Goal to reach 20 T in an LTS outsert
- Demonstrations of 1 T, 3 T and 5 T to develop conductor and magnet technologies
- CCT-C1 successfully demonstrated 1.1 T
- CCT-C2 (3 T) ready for testing
- Conductor for CCT-C3 was ordered

Common Coil insert based on CORC® cables

- Goal to reach 14 T in combination with a 10 T LTS outsert
- CORC® insert and outsert connected in series at 10 kA operating current
- Final design and start of construction expected late 2019

Solenoid magnet based on CORC® wires

- Goal to reach 16 T in a 14 T LTS outsert
- Operating current of 100 mm I.D. CORC® insert about 5,000 A
- Operating at 200 A/mm^2 overall current density and 250 MPa Hoop stress