Work supported by
U.S. Department of Energy awards numbers
DE-SC0007660, DE-SC0009545, DE-SC0014009, DE-SC0015775 and DE-AC02-05CH11231

Development and Application of CORC® Cables and Wires Wound from HTS ReBCO Coated Conductors

Jeremy Weiss, D.M. McRae, D.C. van der Laan
University of Colorado & Advanced Conductor Technologies
Boulder, CO, USA

D. Abraimov, H. Weijers, and D.C. Larbalestier
Applied Superconductivity Center, NHMFL, Tallahassee, FL, USA

H. Higley, S. O. Prestemon and X. Wang
Lawrence Berkeley Nation Laboratory, Berkeley, CA, USA

T. Mulder and H.H.J. ten Kate
CERN, Geneva, Switzerland, and University of Twente,
Enschede, the Netherlands

R. Gupta
Brookhaven National Laboratory,
Upton, NY, USA

CORC® magnet cables and wires

CORC® wires (2.5-4.5 mm diameter)

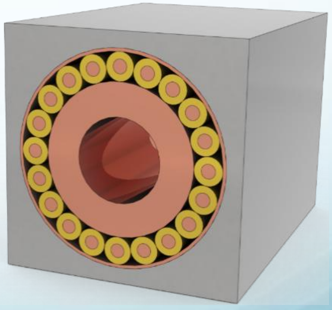
- Wound from 2-3 mm wide tapes with 30 μm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to < 50 mm diameter

CORC® cables (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

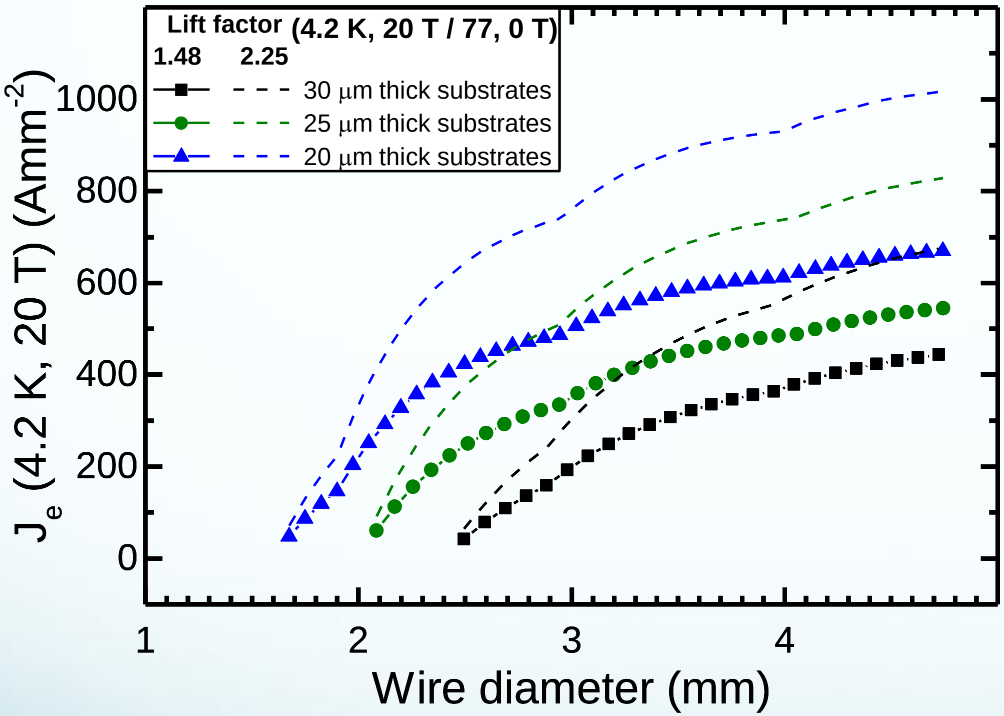


UNIVERSITY OF TWENTE.

CERN

Thinner tapes with better pinning lead to much higher J_e in CORC® wires

Projected J_e vs wire diameter of CORC® wires using received tapes with subpar and best pinning



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 (July 2018)
- 20 µm would enable J_e of 600 Amm^{-2} at 20 T in a 2.4 mm diameter wire (SBIR program starting soon)

Pinning force is increasing

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

Tape lengths are increasing

- Delivered tape lengths exceeding 100-300 m are now a regular occurrence

Tape widths are decreasing

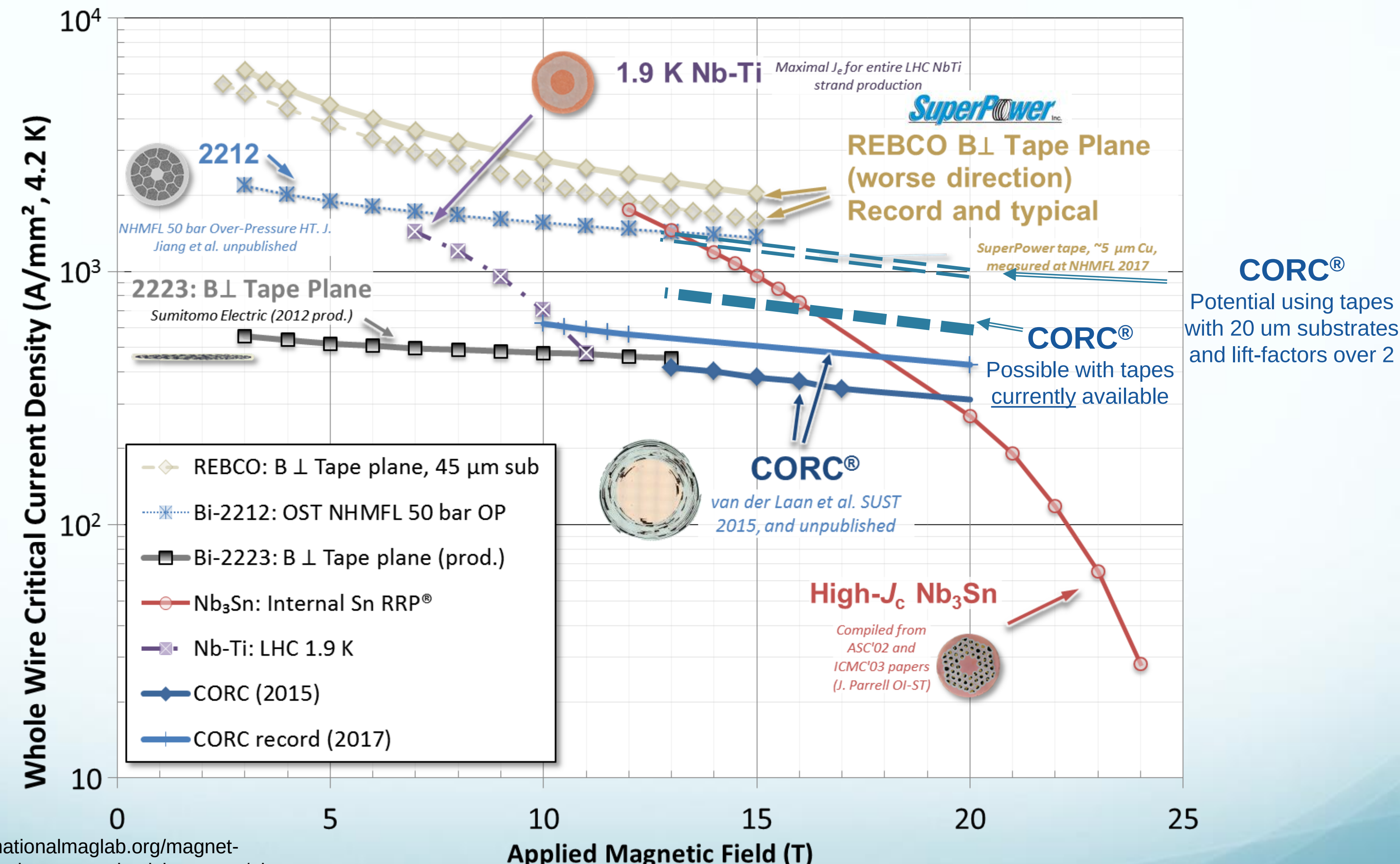
- 1 mm and 1.5 mm slitting

Nod to SuperPower for the rigorous R&D effort!

Advanced Conductor Technologies
www.advancedconductor.com

Assumptions for calculation:
-Realistic winding parameters
-Tape I_c (77K, SF) = 35 A/mm width

CORC® J_e comparison to high-field magnet wires



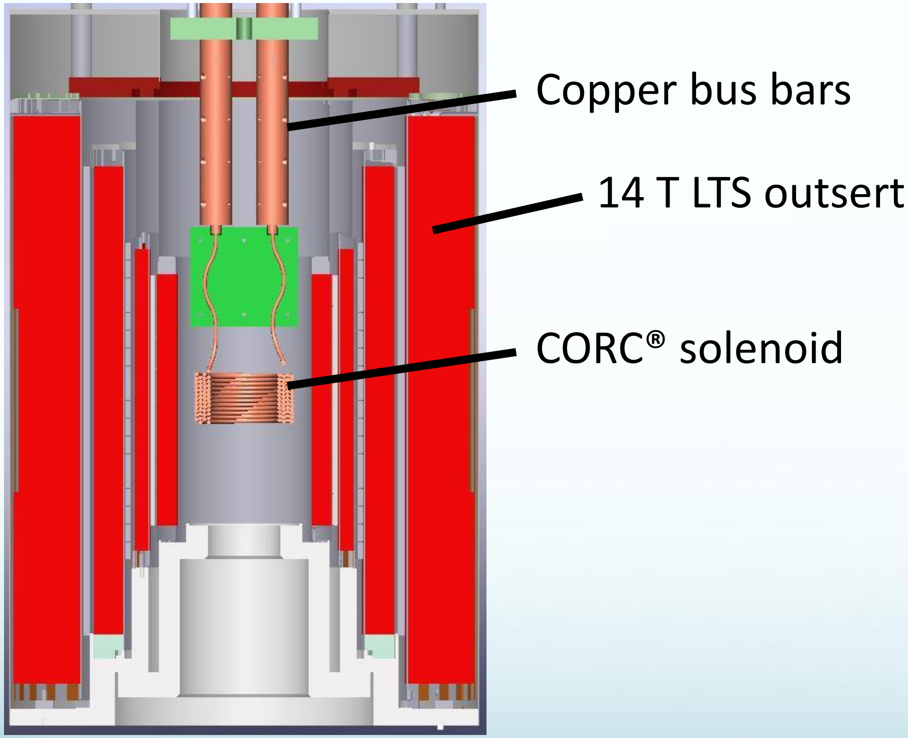
Data from https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

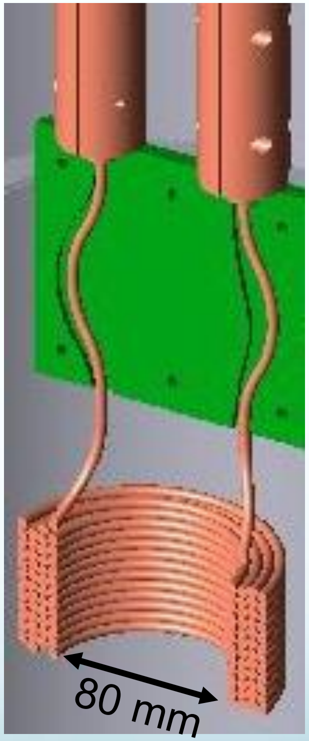
CORC® wires for compact magnets

CORC® high-field insert solenoid

Magnet program with ASC-NHMFL (Dima Abraimov, David Larbalestier, Huub Weijers)

- Develop a 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



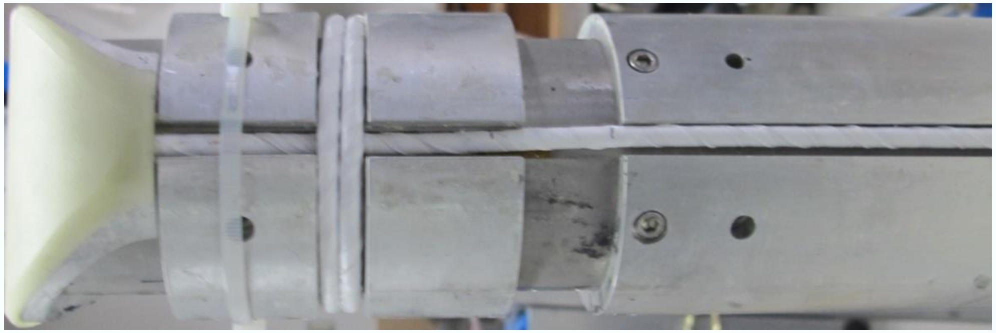


2-turn coil mounted for $I_c(B)$ measurements

Wire Properties

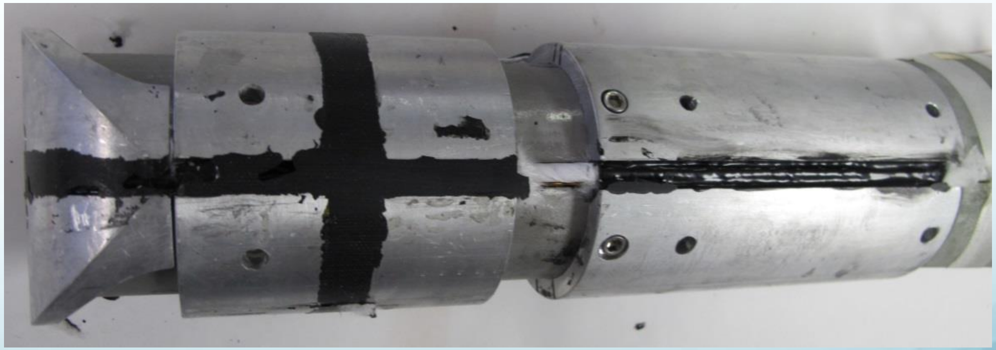
Outer diameter	**4.5**	**mm**
Length	**17**	**m**
Expected I_c (77 K, 0 T)	**2,873**	**A**
Expected I_c (4.2 K, 14 T)	**5,000**	**A**
Expected J_e (77 K)	**125**	**A/mm^2**
Expected J_e (4.2K. 14 T)	**287**	**A/mm^2**

Sample after winding on probe before epoxy impregnation



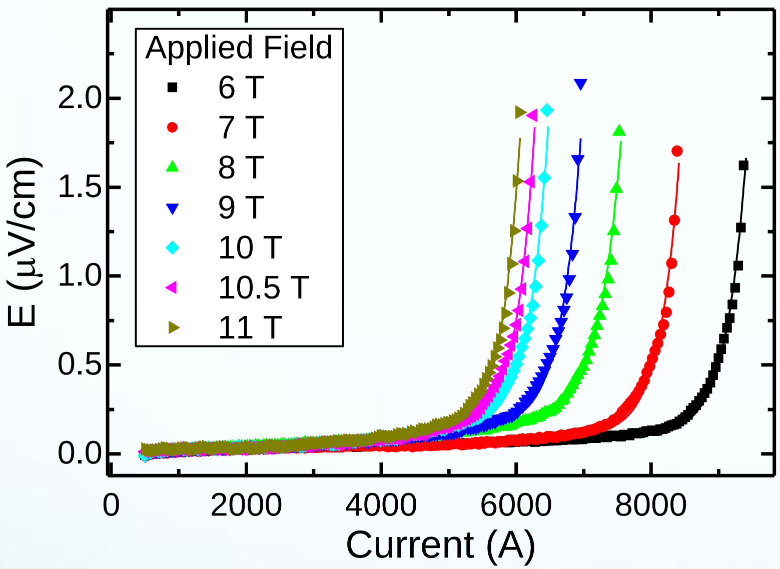
Minimum bending diameter = 63 mm

Sample after epoxy impregnation

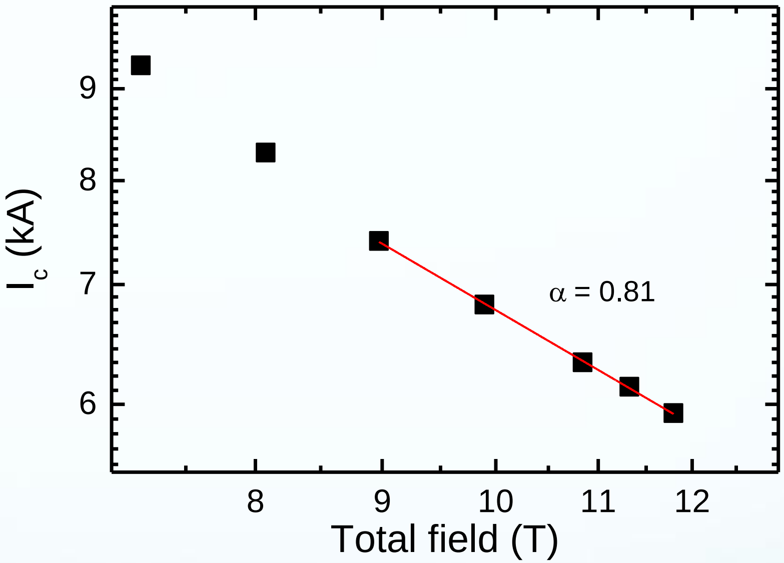


2-turn coil tested infield

V(I) measured across terminals



Projected I_c (4.2K, 20T) = 3866 A
Projected J_e (4.2K, 20T) = 247 A mm^{-2}



1 uV/cm criterion

I_c (B, 4.2K) dependencies fitted with $I_c(B) = I_{co}B^{-\alpha}$ for field range 9 T – 12 T to project to 20 T using derived α=0.81

Winding and testing of CORC® solenoid

Progress towards testing of first multi-layer CORC® insert solenoid

- Bending tests and in-field characterization completed
- July 2018 – Commissioning of 14 T large-bore magnet at FSU
- August/September 2018 – CORC® coil winding
- November 2018 – Complete coil tests

Options for future tests

- Stand-alone operation at various temperatures
- Test in series with a smaller CORC®-based insert solenoid to get combined field of 18-20 T

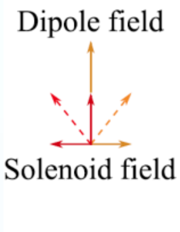
Test winding with dummy conductor

Courtesy of James Gillman

Development of CORC®-CCT magnets

Magnet program with Lawrence Berkeley Nat. Lab. (Xiaorong Wang)

- Develop a canted-cosine theta CORC® insert magnet
- Generate 5 T in a 16 T background field



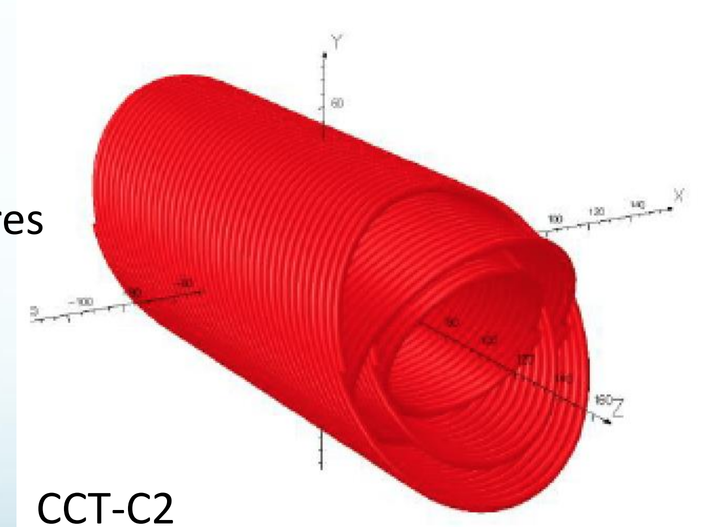
CCT-C1

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

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

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

- Generate **3 T in self-field**
- CORC® wire J_e(20 T) = 200-300 A/mm^2
- Advanced CCT structure and potting procedures



CCT-C2

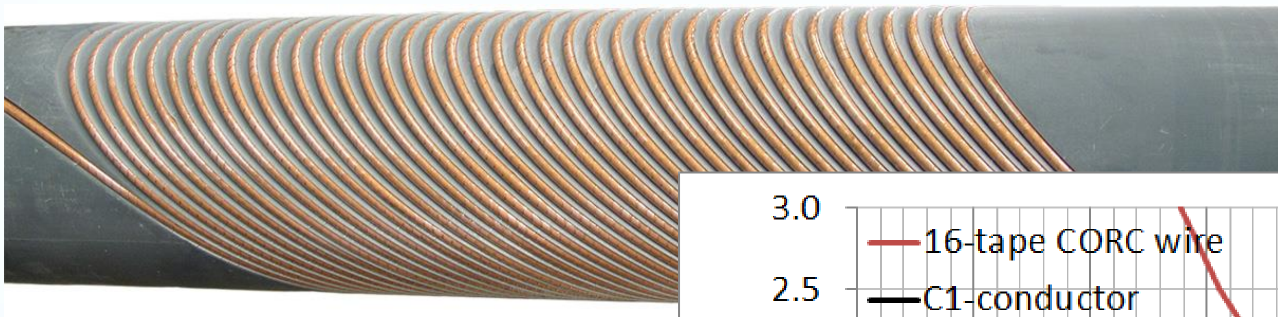
Step 3: 6-Layer, 40-turns CCT magnet (C3)

- Generate **5 T in self-field**
- CORC® wire J_e(20 T) = 300-400 A/mm^2
- CORC® wire bendable to 30 mm diameter

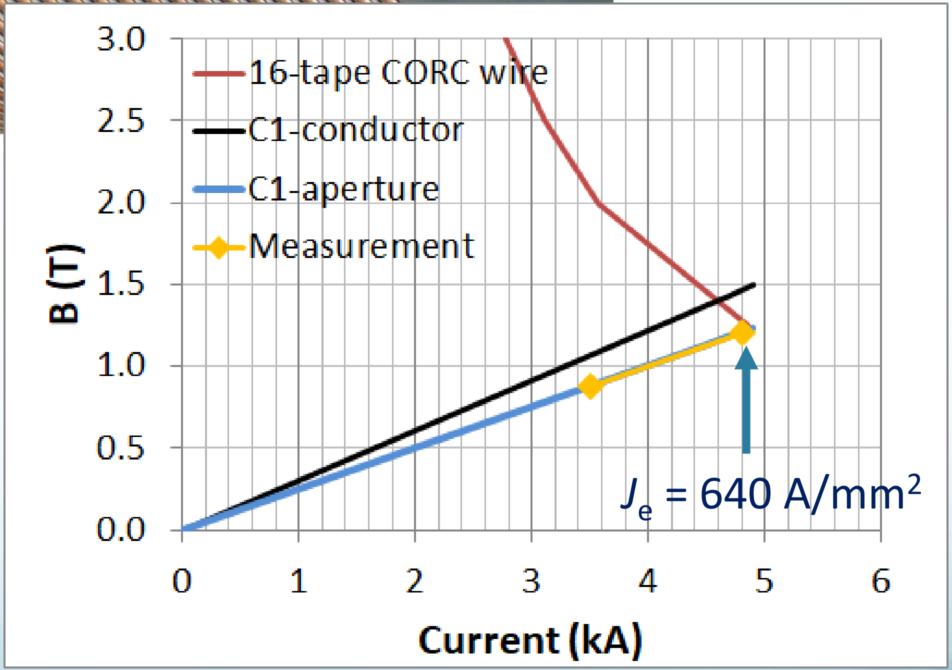
CORC® CCT-C1

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



CCT-C1 generated 1.2 T at 4,800 A (104 % of expected performance)



Advanced Conductor Technologies
www.advancedconductor.com
BERKELEY LAB

Baby coil C0b: CORC® wire test for CCT-C2

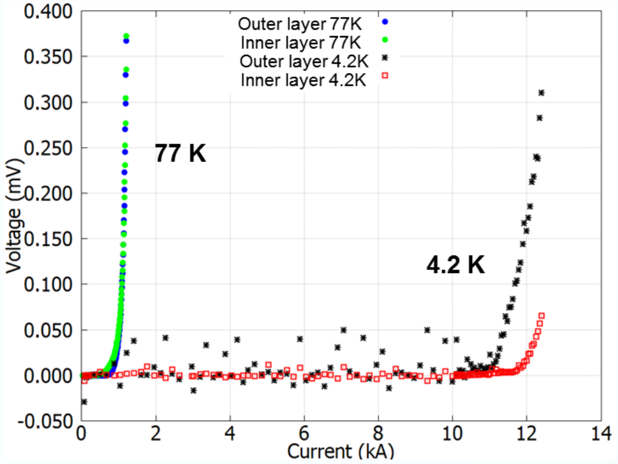
CCT C0b: CORC® wire with 29 tapes

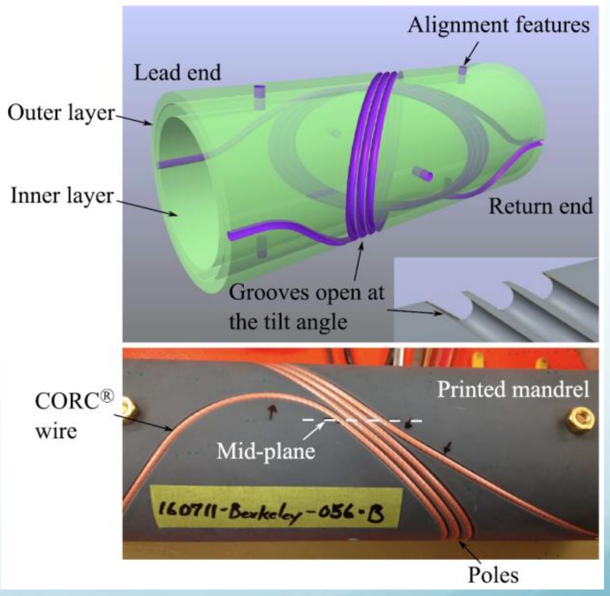
- 3-turn per layer
- Inner layer I.D. 85 mm
- CORC® wire J_e (20 T) = ~300 A/mm²

CCT C0b 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) ~3-4 T**

- **Order for 75 m of high-J_e CORC® wire received from LBNL**
- **Full-size coil C2 expected to be wound in Q3 2018**

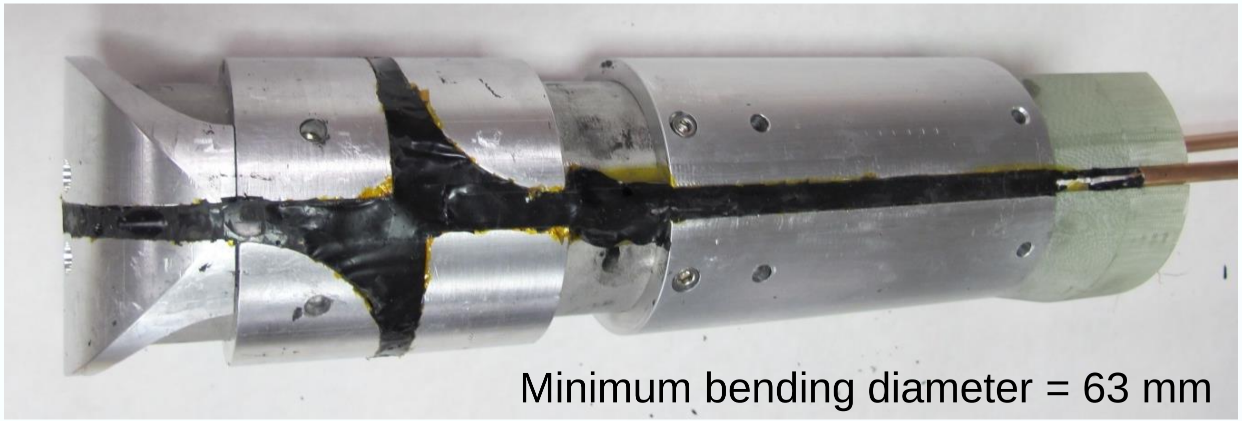




X. Wang *et al.*, "A viable dipole magnet concept with REBCO CORC® wires and further development needs for high-field magnet applications," *Supercond. Sci. Technol.*, vol. 31, no. 4, p. 045007, 2018.

I_c(B) testing of CCT-C2 CORC® wire

Sample after winding on probe and epoxy impregnation

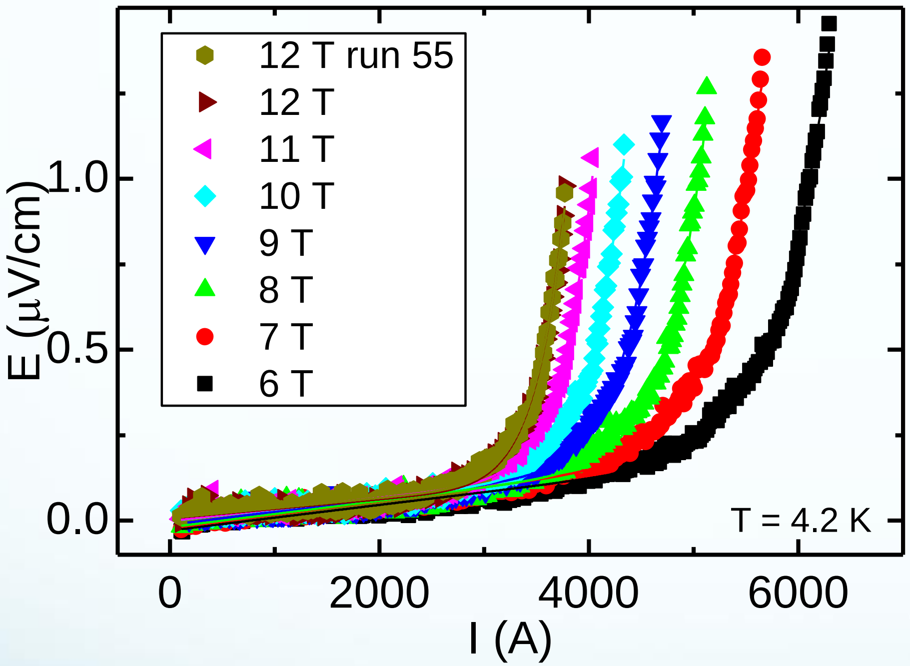


Sample removed from probe following test

Hairpin turn to
return current

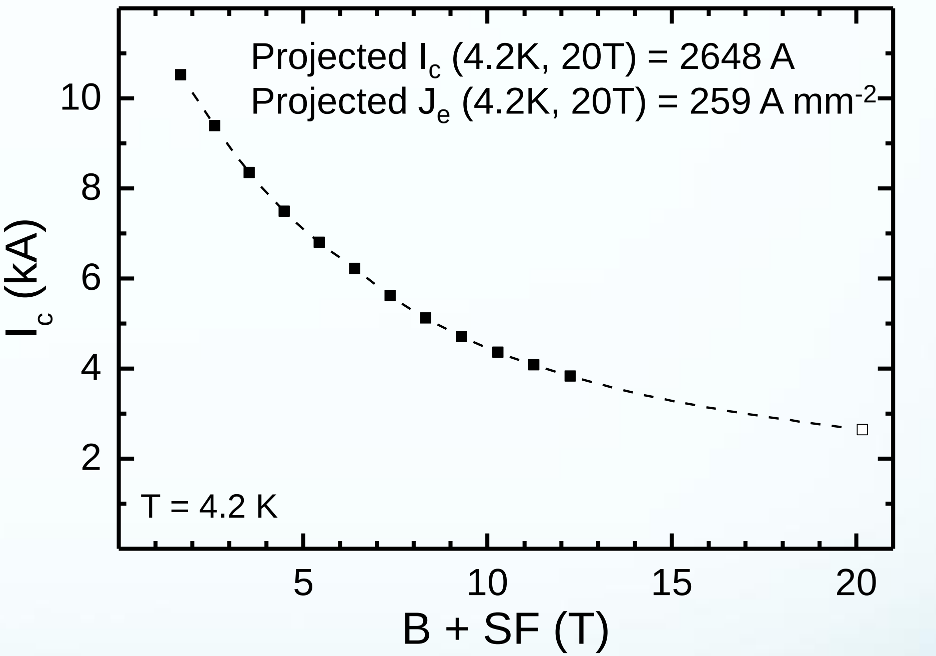
I_c(B) testing of CCT-C2 CORC® wire

E(I,B) tested at 12 T and then cycled over 50 times



Sample cycled to 90 % of the critical current

I_c (B) dependence extrapolated to 20 T



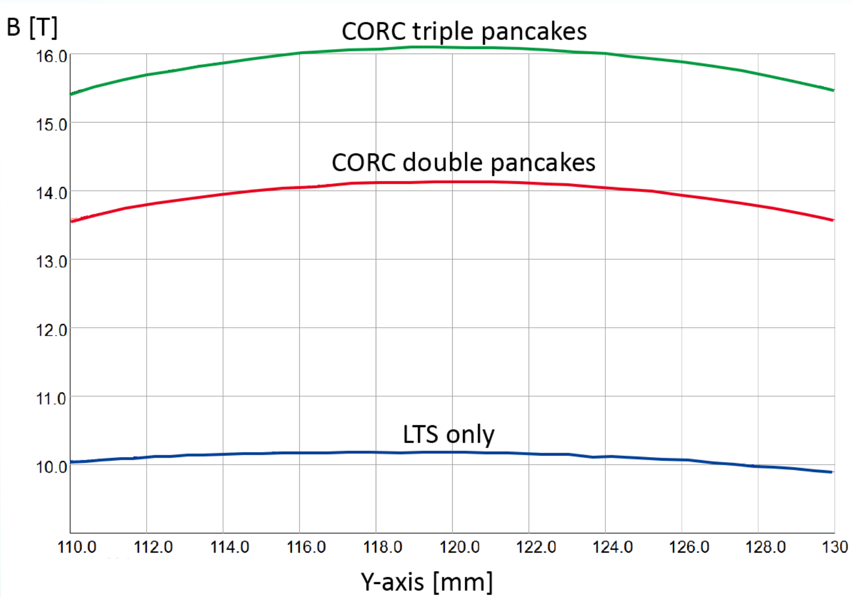
I_c (B, 4.2K) dependencies fitted with $I_c(B) = I_{co}B^{-\alpha}$ for field range 10 T – 15 T to project to 20 T using derived α=0.75

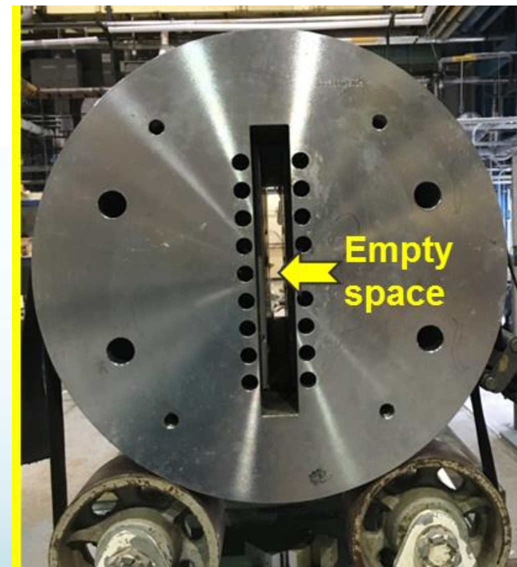
CORC® cables: High currents for large magnets

Common coil magnet from CORC® cables

SBIR Magnet program with Brookhaven National Laboratory (Ramesh Gupta)

- Combine CORC® insert with 10 T LTS common coil outsert
- CORC® cable with expected J_e(20 T) 500 A/mm^2 delivered
- Operating current 10 kA connected in series with LTS outsert





Common coil benefits

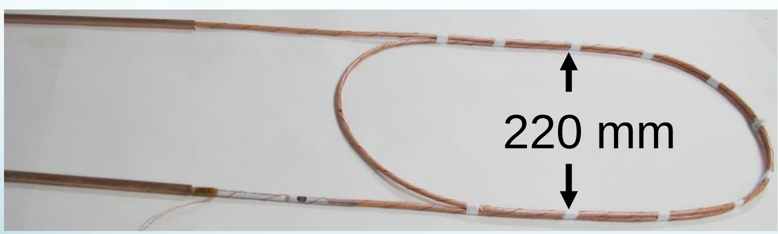
- Only large bending diameters required
- Allowing CORC® cables to be used
- Allowing use of highest J_e cables

Subscale racetrack coil wound and tested at 76 K

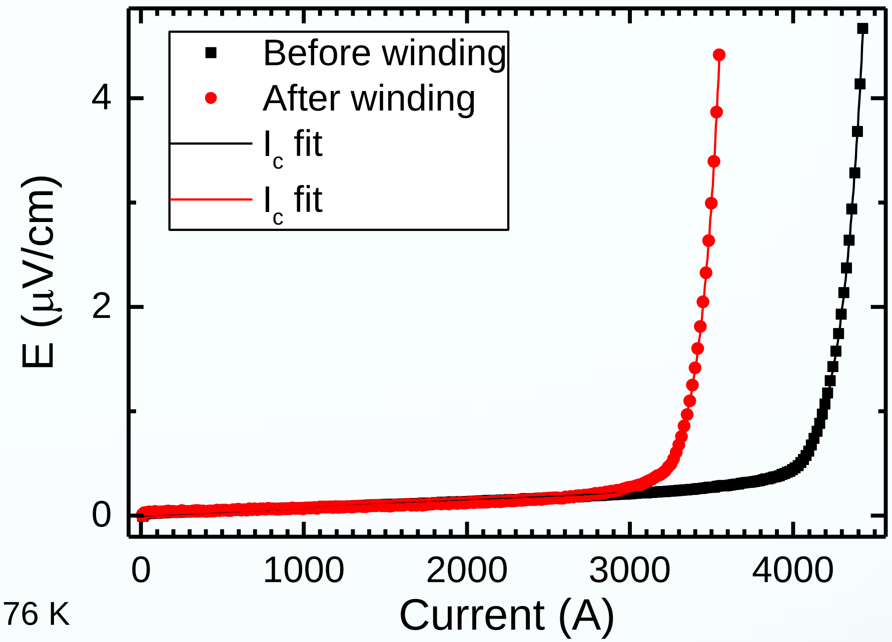
CORC® Wire Properties

Outer diameter	**4.73**	**mm**
# of tapes	**42**	**m**
Expected I_c (76 K, SF)	**4255**	**A**
Expected I_c (4.2 K, 20 T)	**9,377**	**A**
Expected J_e (76 K, SF)	**242**	**A/mm^2**
Expected J_e (4.2K, 20 T)	**534**	**A/mm^2**

1.75-turn racetrack coil



After winding, self-field reduces I_c by 20%



76 K
1 uV/cm criterion
L = 365.4 cm

	Ic (A)	N-value	R (nΩ)
Before winding	4233	32.4	26.4
After winding	3381	29.6	23.4

I_c measured across the terminals

Advanced Conductor Technologies
www.advancedconductor.com

BROOKHAVEN NATIONAL LABORATORY

Testing a high tape-count CORC® cable infield

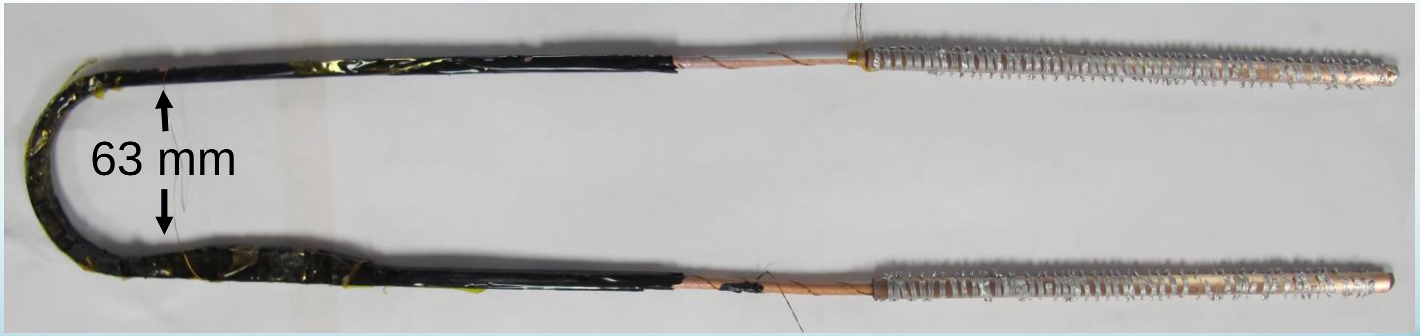
CORC® Wire Properties

Outer diameter	4.5	mm
# of tapes	50	m
Expected I_c (76 K, SF)	3566	A
Expected I_c (4.2 K, 20 T)	9,187	A
Expected J_e (76 K, SF)	224	A/mm^2
Expected J_e (4.2 K, 20 T)	578	A/mm^2

4.5 mm diameter CORC® cable needed to be tested in-field

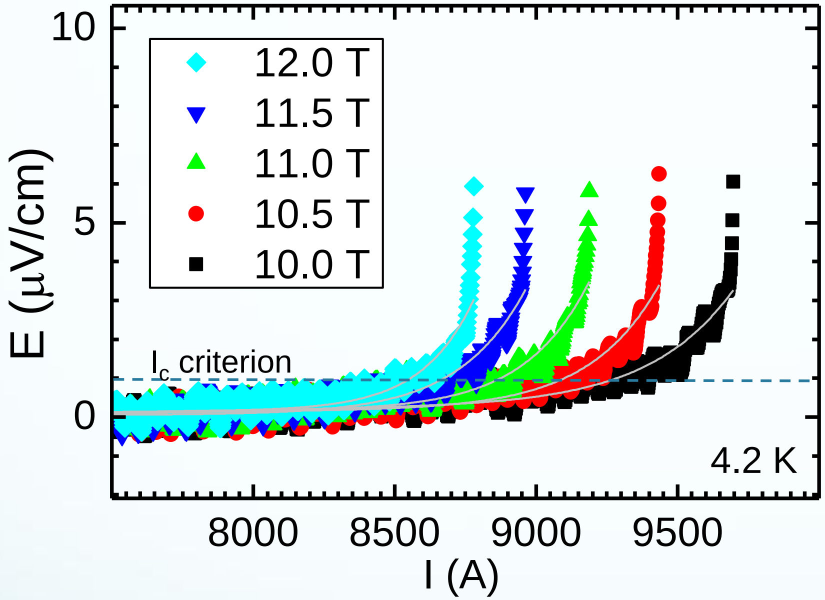
- Required bending to 63 mm diameter to fit in our 12 T magnet
- Since sample was not designed for such tight bending radius, some damage due to bending was expected and a simple hairpin shape was chosen to minimize damage
- High current pushed through conductor also tested the limits of our vapor-cooled current leads

Sample removed from probe following test

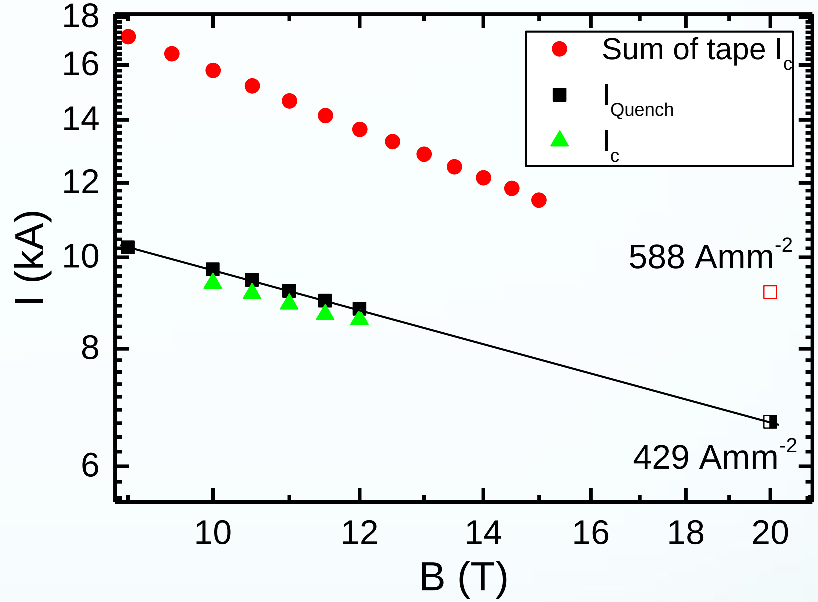


4.5 mm diameter CORC® cable tested infield

E(I,B) dependence shows extremely fast quench develops



I_c ~ 25% lower than expected due to over-bending



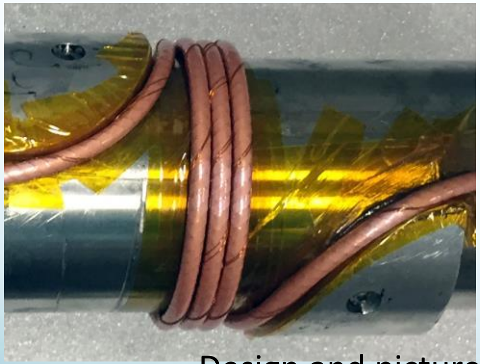
I_c (B, 4.2K) dependencies fitted with $I_c(B) = I_{co}B^{-\alpha}$ for field range 10 T – 15 T to project to 20 T using α=0.54

I_{quench} criterion = 0.5 mV

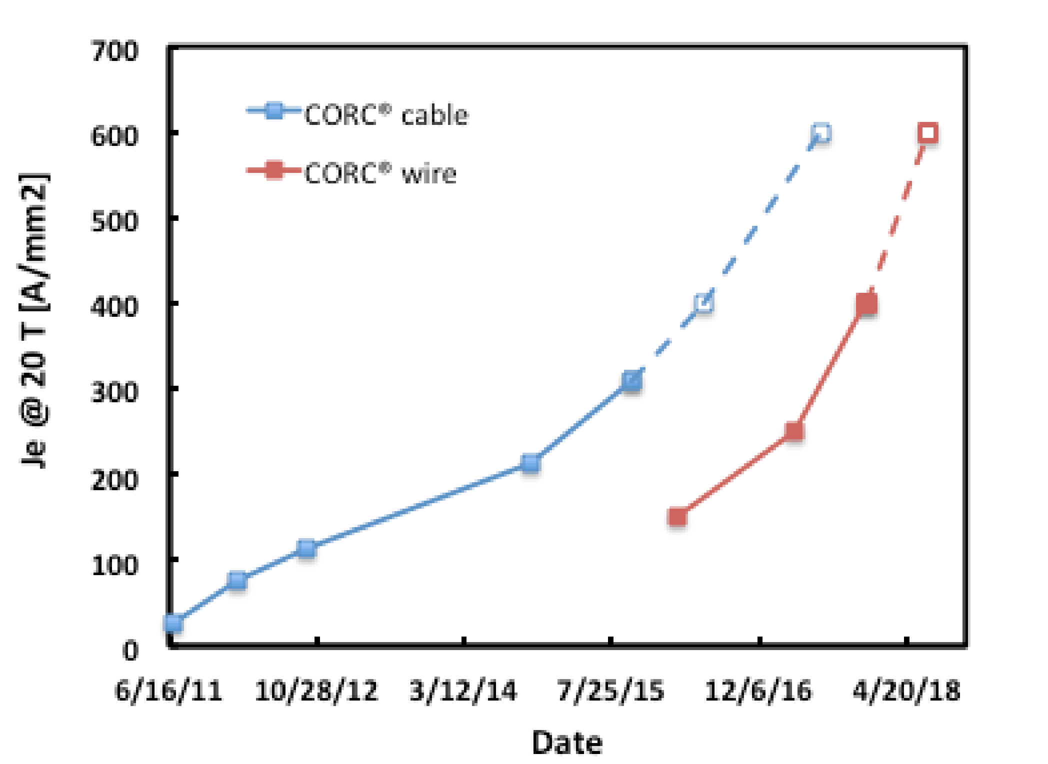
CORC® road to J_e (4.2K, 20T) > 600 Amm^{-2}

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

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



Design and picture
UNIVERSITY OF TWENTE.



Closing in on J_e > 600 A/mm² goal

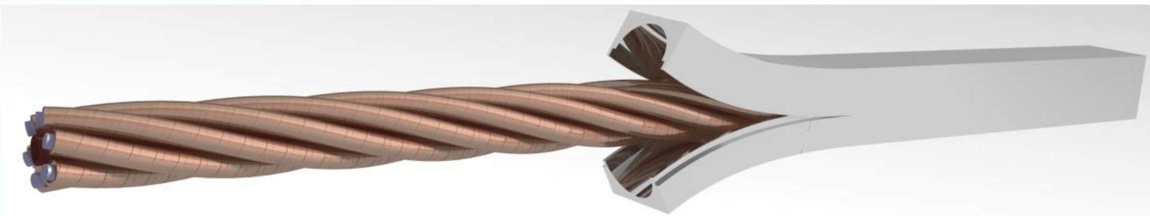
- J_e (20 T) now exceeded 400 A/mm² in CORC® conductor
- Combined with I_{opp}(20 T) > 6,500 A
- Next step is thinner substrates 20 – 25 μm

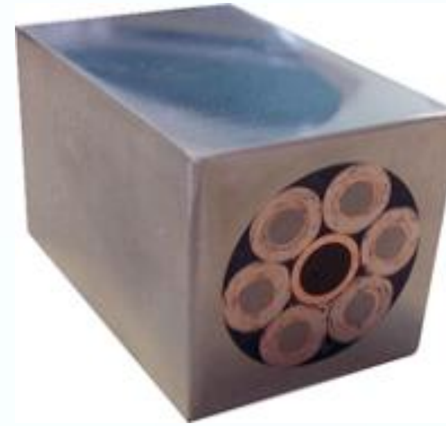
CORC® Cable-in-Conduit-Conductor (CICC): Very high currents for even larger magnets

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

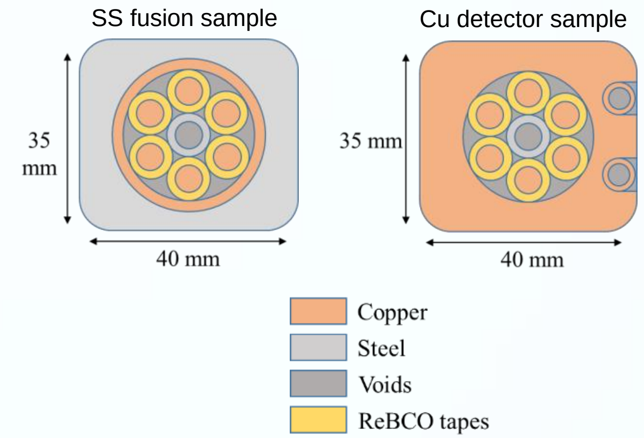
- Power supply of FRESCA limited to 30 kA: no s.c. transition
- Test at 77 K in self-field: I_c = 12.3-13 kA as expected

T. Mulder *et al.*, *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, pp. 1–4, Jun. 2017.

80 kA (10 T) CORC®-CICC test in SULTAN

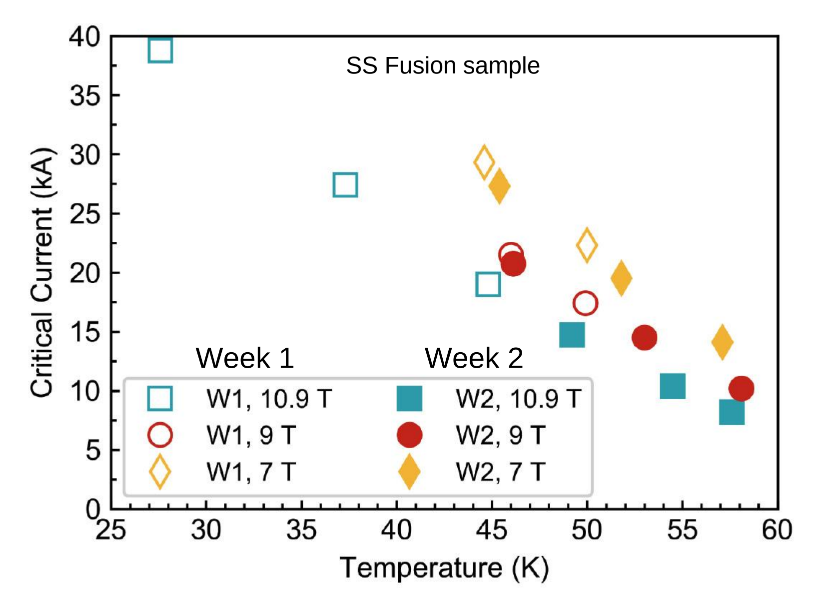
80 kA (4.2 K, 12 T) 6x1 CORC®-CICC built at CERN

- 6 CORC® cables of 7.7 mm diameter
- 42 tapes per CORC® cable
- Two layouts tested in series
  - Stainless steel jacketed sample for Fusion applications
  - Copper jacketed sample for Detector magnets and bus-bars, conduction cooled



CORC®-CICC test results

- Cu detector sample degraded
  - I_c(44 K, 10.9 T) = 11.8 kA
  - Degradation caused by loose packing of tapes and conductor in conduit
- SS fusion sample as expected
  - I_c(50 K, 10.9 T) = 15.6 kA
  - Temperature range of measurements limited by the Cu detector sample in series with the SS fusion sample



17 m CORC cable shipped to CERN for new detector sample

T. Mulder et al, *IOP Conference Series: Materials Science and Engineering*, vol. 279, p. 012033

Future directions for compact fusion magnets

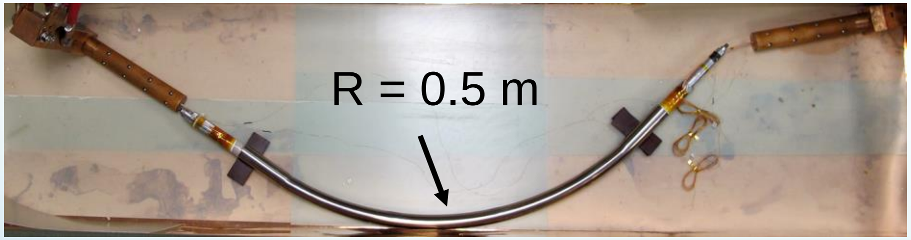
Developing more flexible CICC using CORC® wires

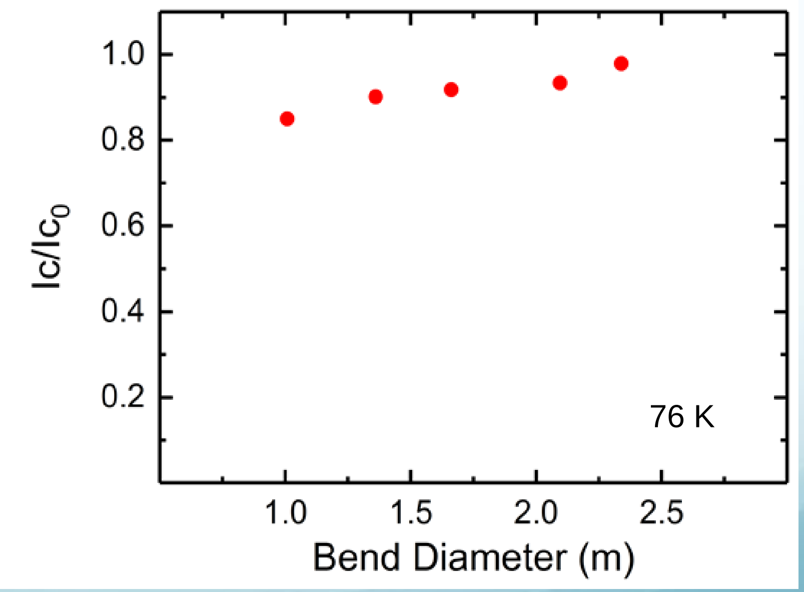
- Relevant for compact fusion magnets
- Shorter transposition length
- Dummy and Subscale CICC tested as a function of bending as part of a phase I SBIR with LBNL

Demountable joints with R(4.2 K) < 1 nohm

Dummy CORC® CICC after bending

CICC with one CORC® strand





Summary

CORC® cables and wires have matured into magnet conductors

- CORC® wire performance 2-3 kA and 250-400 A/mm^2 at 20 T
- CORC® cable performance 10 kA and 300-600 A/mm^2 at 20 T
- CORC® conductor flexibility is being improved – currently limited to bending diameters of around 50 mm, goal is to get to 25 mm minimum bending diameter
- Robust mechanical properties of CORC® conductor being confirmed by in-field cycling and mechanical cycling (See Dustin McRae's talk Wednesday afternoon)
- CORC® wires are practical and ready for magnets!
  - Isotropic bending. Isotropic performance.
  - No reaction needed
  - Cu:non-Cu ratio of about 1
  - ~30% cross section is high-strength Hastelloy