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Recent Progress on CORC® Cable and Wire Development for Magnet Applications

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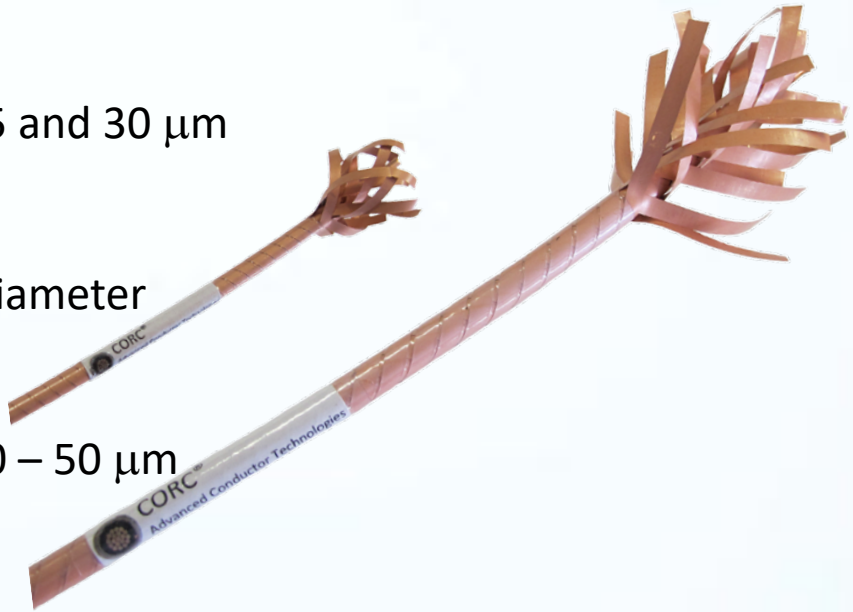
CORC® magnet cables and wires

CORC® wires (2.5 – 4.5 mm diameter)

- Wound from 2 – 3 mm wide tapes with 25 and 30 μm substrate
- Typically no more than about 30 tapes
- Flexible with bending down to < 50 mm diameter

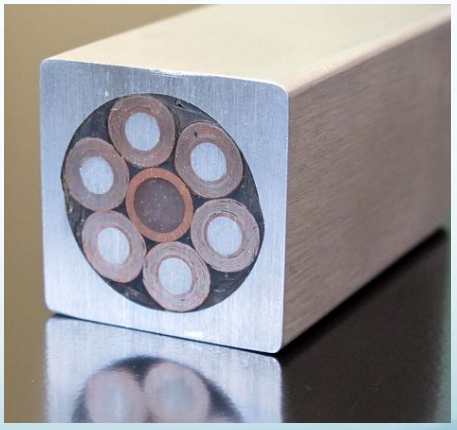


CORC® cable (5 – 8 mm diameter)

- 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 In Conduit Conductor (CICC)

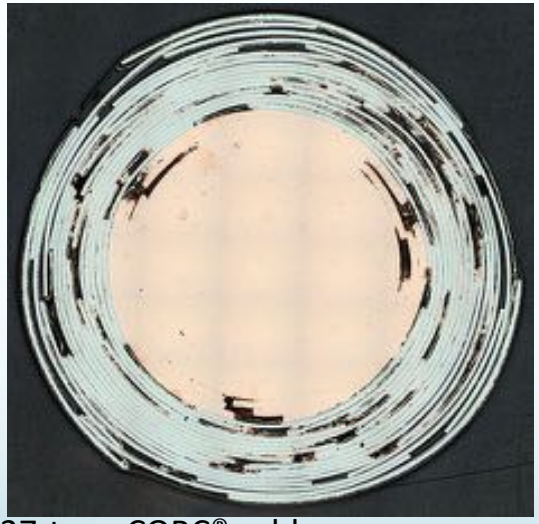
- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 1 meter



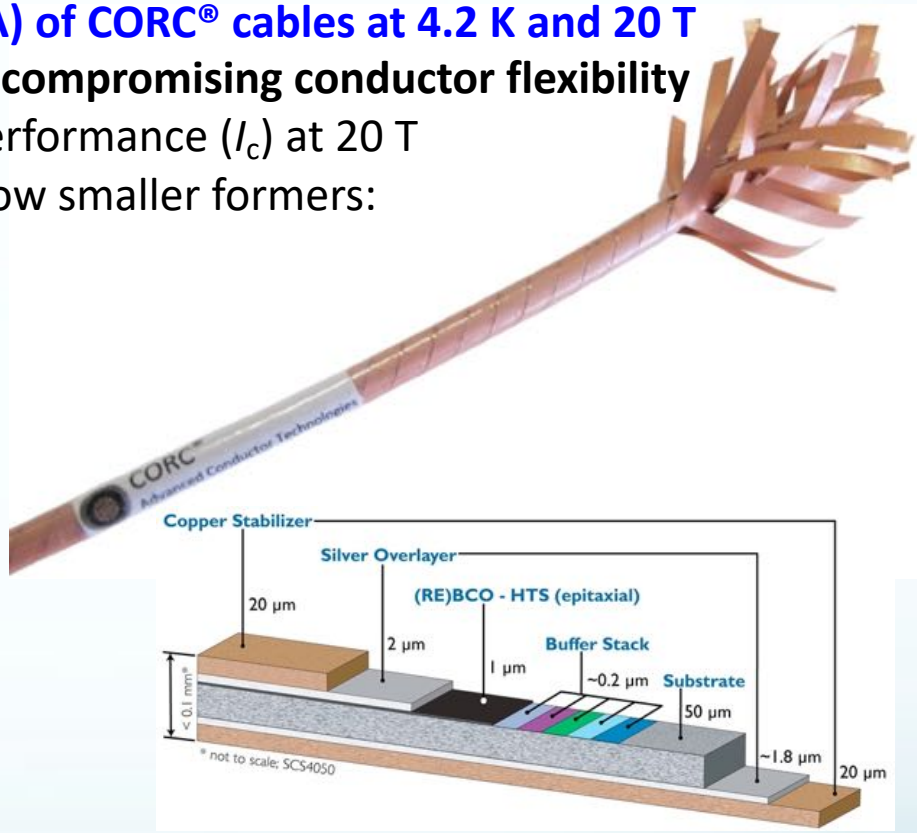
CORC® conductors for accelerator magnets

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 –)
   - 38 μm substrate (2014)
   - 30 μm substrate (2015 –)
   - 25 μm substrate (2019 –)



37-tape CORC® cable

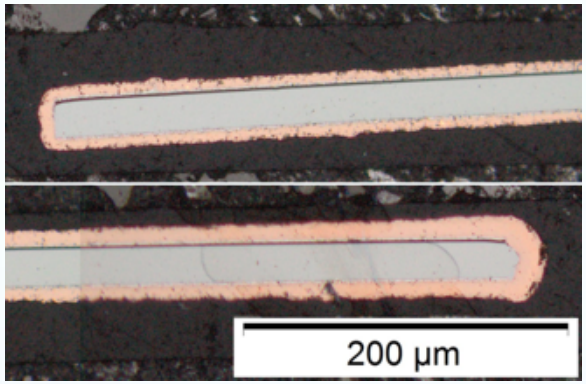


Magnet applications require very long conductor lengths and CORC® performance should thus be achieved using industrial-scale tape production

Introduction of REBCO tapes with 25 μm substrates

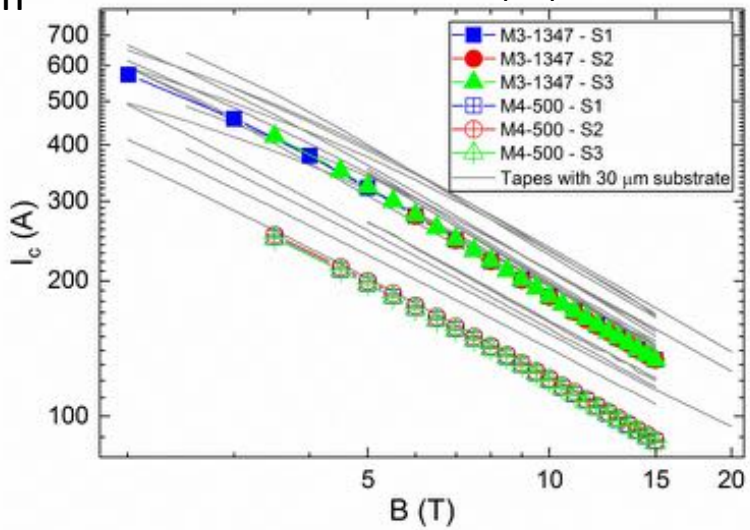
SuperPower produced first batch of tape with 25 μm substrate

- 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



Courtesy of Michael Small (ASC-NHMFL)

4.2 K tape performance



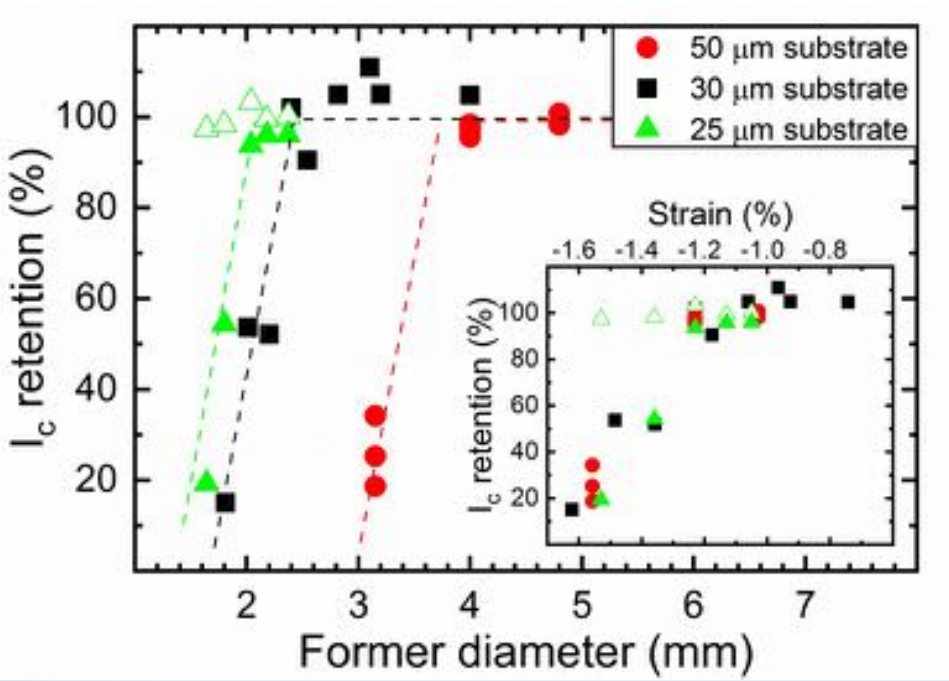
Courtesy of A. Francis and D. Abraimov (ASC-NHMFL)

TapeStar I_c(77 K) data

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
- 2.0 mm for 25 μm substrate

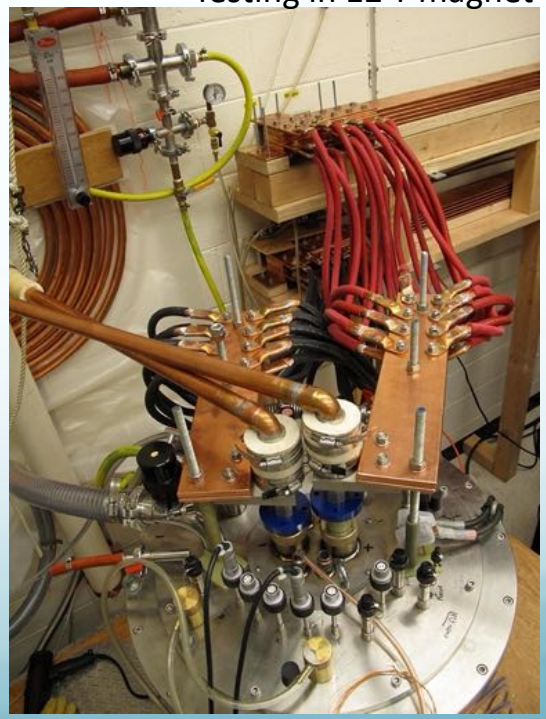
Increasing J_e(20 T) in CORC® wires

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

CORC® wire mounted on 60 mm diameter probe

Testing in 12 T magnet



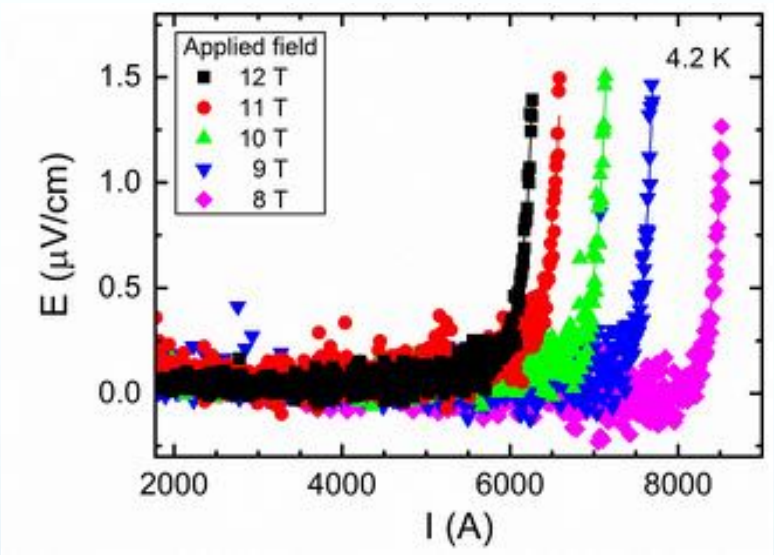
Performance of next generation CORC® wires

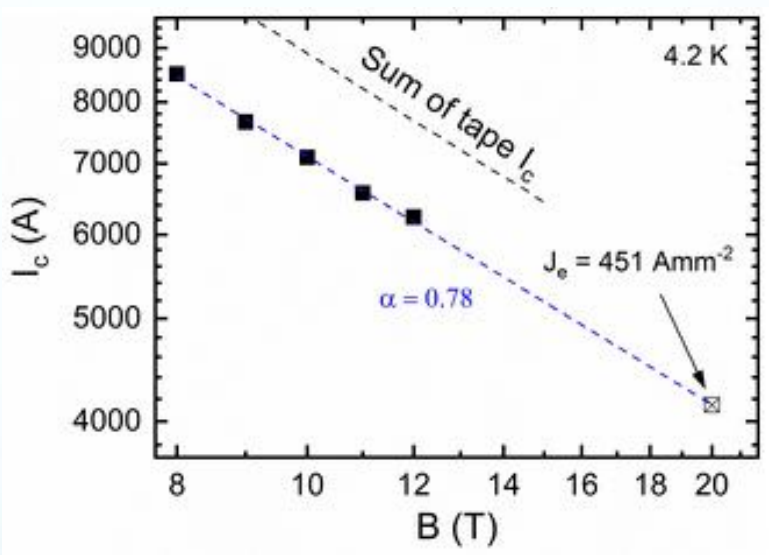
CORC® wire to increase J_e(20 T)

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

New record CORC® wire (25 μm) 451 A/mm² (20 T)

Previous record CORC® wire (30 μm) 429 A/mm² (20 T)





New record J_e (12 T) 678 A/mm²
Extrapolated J_e (20 T) 451 A/mm²

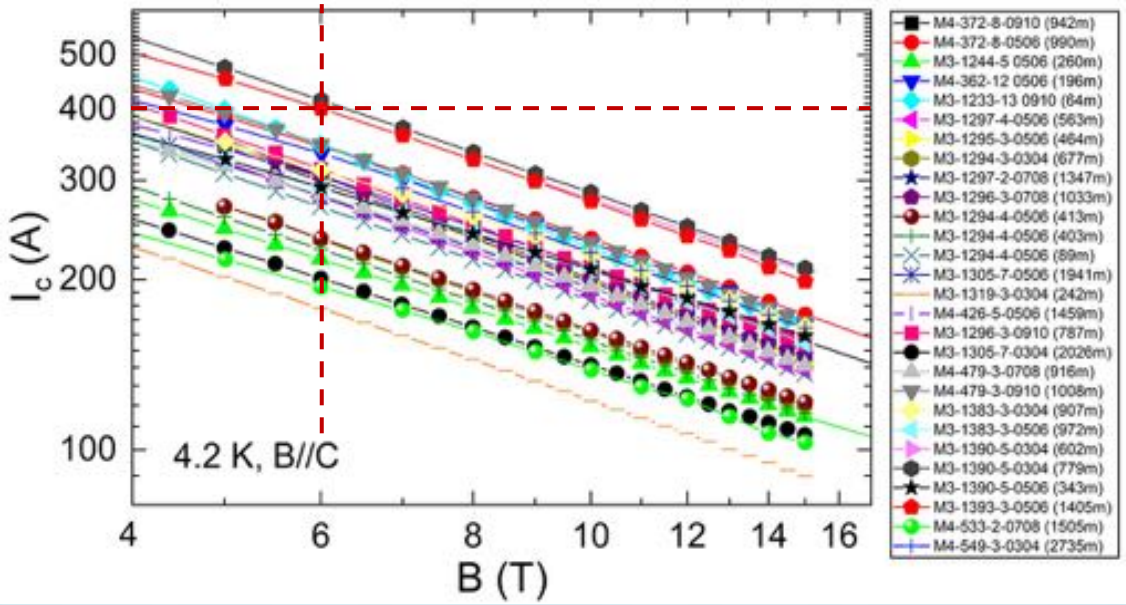
"Introduction of the next generation of CORC® wires with engineering current density exceeding 650 A mm(-2) at 12T based on SuperPower's ReBCO tapes containing substrates of 25 μm thickness", J.D. Weiss, et al., *Supercond. Sci. Technol.* **33**, 044001 (2020)

Next step in development of long CORC® wires

Minimum in-field tape I_c specification

- In past tape orders, minimum in-field I_c at 4.2 K couldn't be specified
- Now, SuperPower allows for minimum I_c(4.2 K, 6T) of 400 A (2 mm wide tapes)
- This presents a 30 % increase in in-field tape I_c
- 10 km of 2 mm wide tape with this specification was ordered and is expected before the end of 2020

Performance of 2 mm wide tape (30 μm) over the years



Courtesy of A. Francis and D. Abraimov (ASC-NHMFL)

The effect of axial tensile strain on CORC® wires

Testing CORC® wires under axial tension

- Test performed in LN_2 at 77 K
- Maximum load of 13 kN applied to terminations
- Sample strain measured with pair of clamp-on extensometers

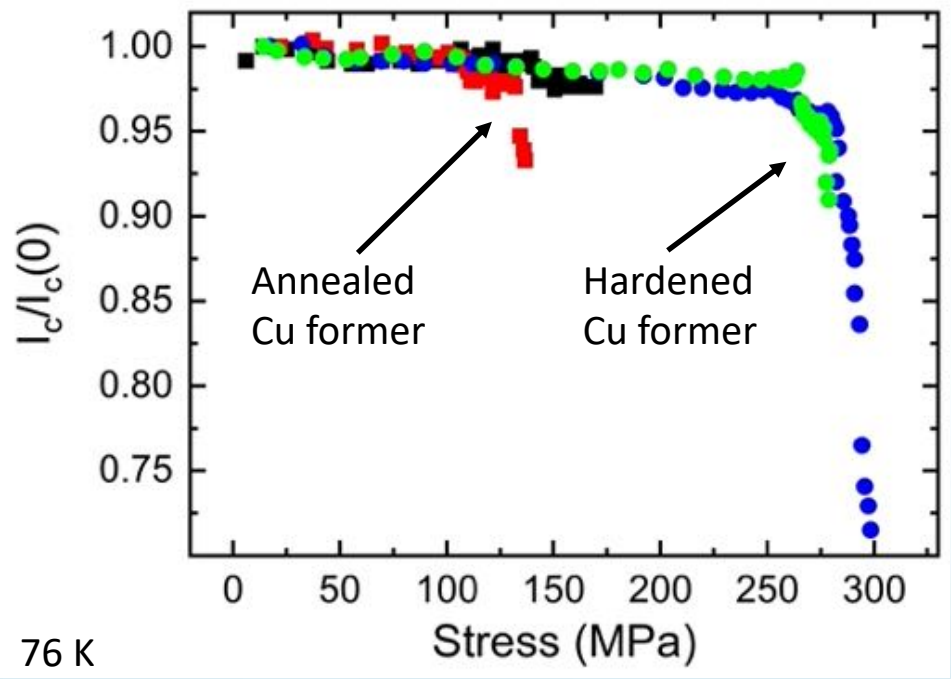
Simplified description of CORC® wire structure

- REBCO tapes wound in a helical fashion on solid core
- Tapes behave as springs; extending axially and contracting radially under tensile load
- The core acts a central support, but also confines the radial contraction of the springs

CORC® wires with improved mechanical tensile strength

Irreversible stress limit under tension

- Is dominated by the CORC® wire former
- All tests on 12-tape CORC® wires (2 mm tape width)
- Irreversible stress limit with soft annealed copper former: 134 MPa
- Irreversible stress limit with half hard copper former: 280 MPa

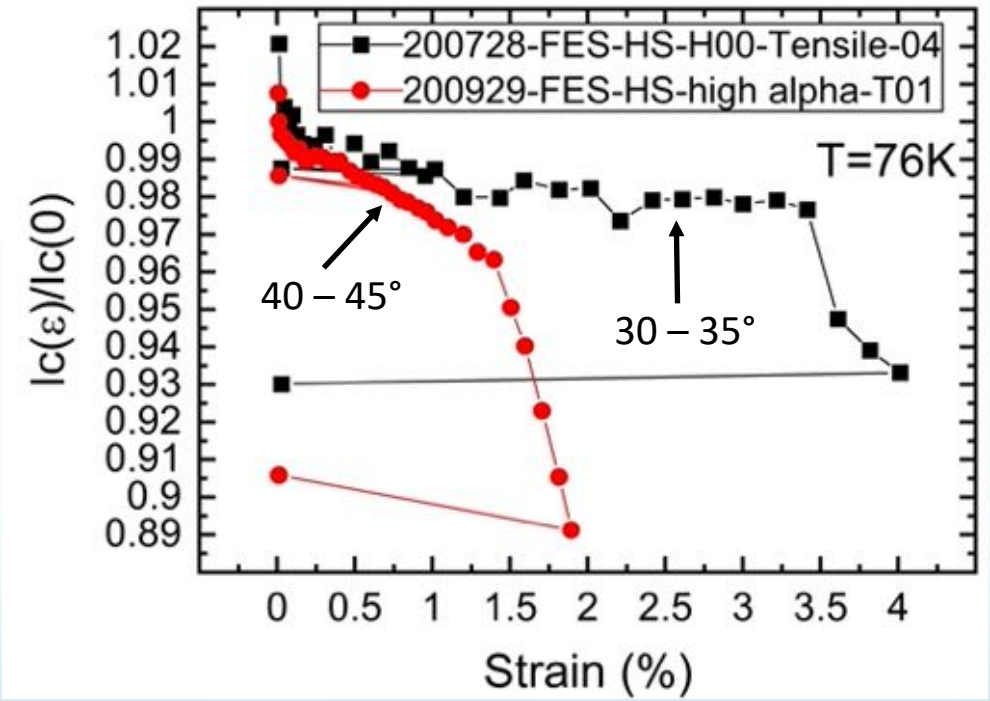


Irreversible tensile stress limit of CORC® wires approaches 300 MPa at 77 K

Extended irreversible strain limit of CORC® wires

Irreversible stress limit under tension

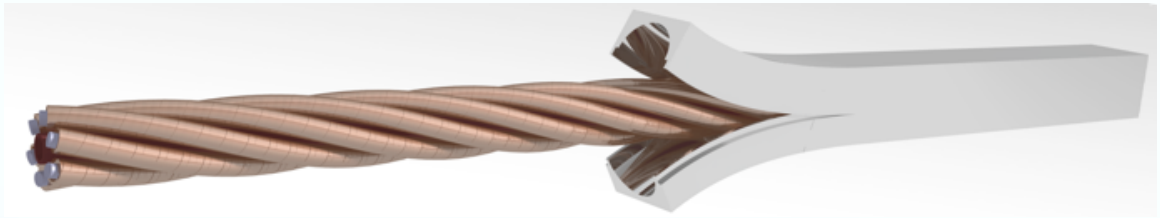
- Depends on the tape winding angle
- 12-tape CORC® wires with winding angles
  a) 30 – 35°: ε_{irr} = ~3.5 %
  b) 40 – 45°: ε_{irr} = ~1.4 %

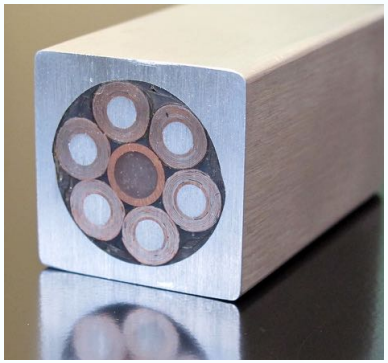


Irreversible tensile strain limit of CORC® wires can exceed 3 % at 77 K!

CORC®-CICC development for fusion magnets

Develop CORC®-CICC with operating current 50 – 100 kA at 4.2 K and 12 – 20 T



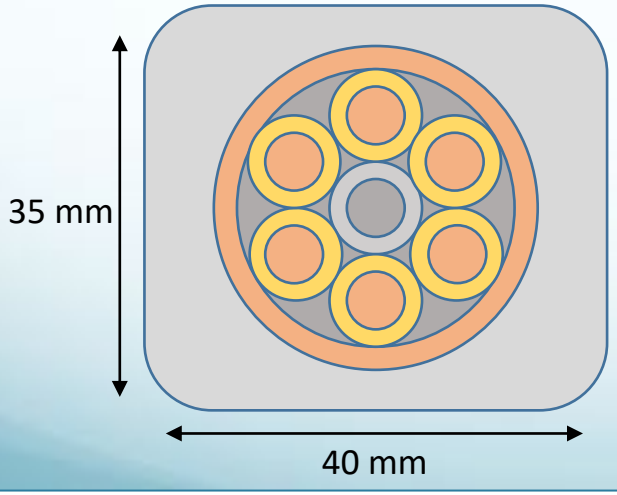


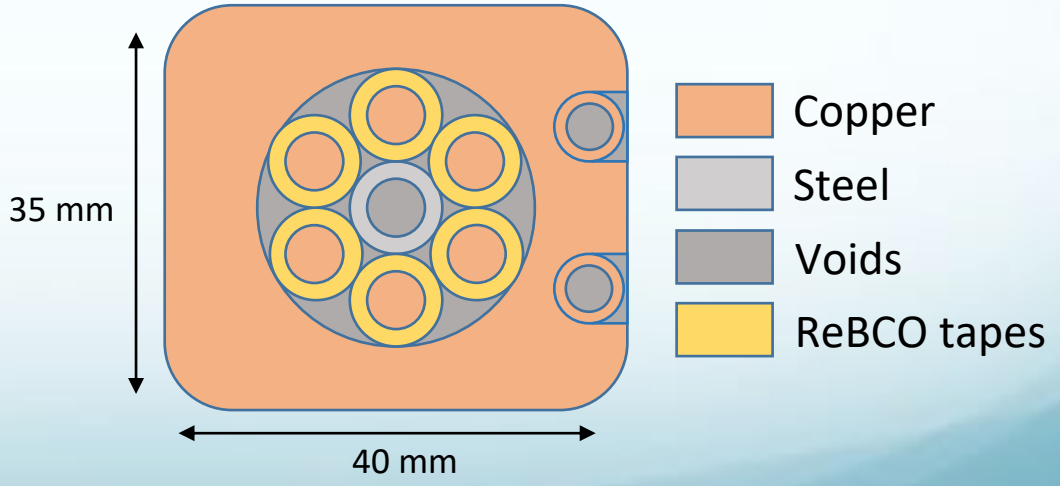
CORC®-CICC #1

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

CORC®-CICC #2

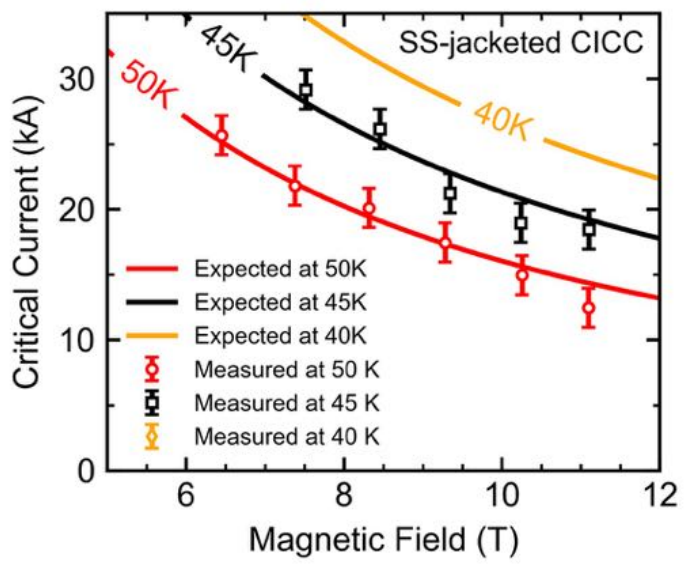
- High thermal & electrical stability
- Practical cooling
- 80 kA at 12T/4K



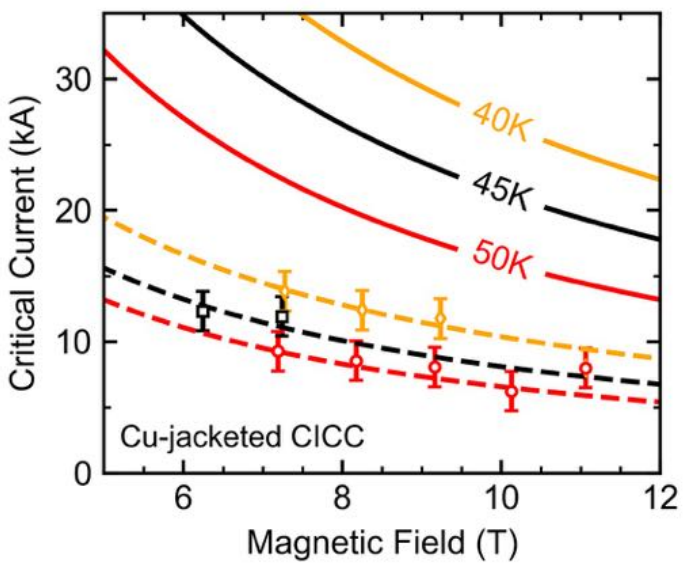


SULTAN Test CORC®-CICC #1&2: Results (2017)

CORC®-CICC #1 (SS jacket)

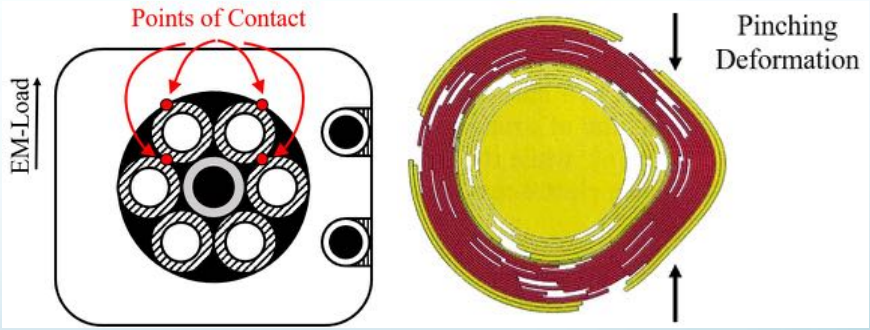


CORC®-CICC #2 (Copper jacket)



Test range limited by CORC®-CICC #2

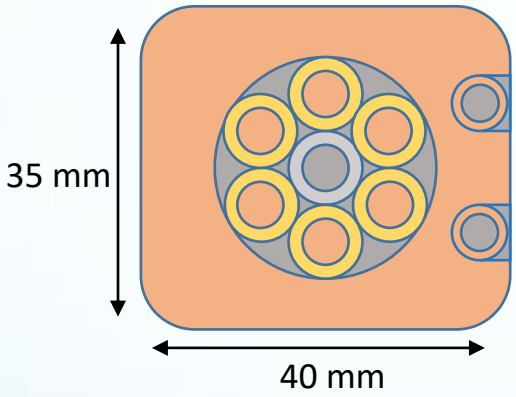
- Cooling with helium gas
- Maximum current 45 kA
- Sample #1 performed as expected
- Sample #2 degraded



SULTAN Test CORC®-CICC #1&3: Results (2019)

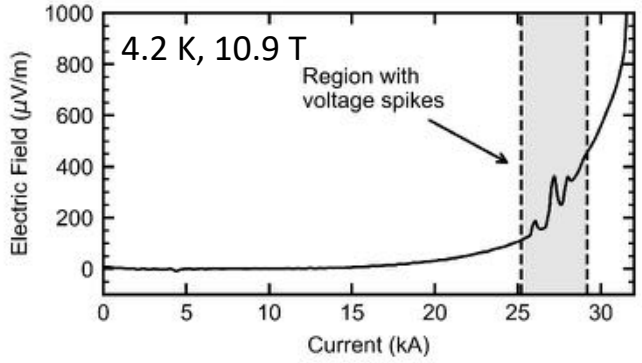
CORC®-CICC #3

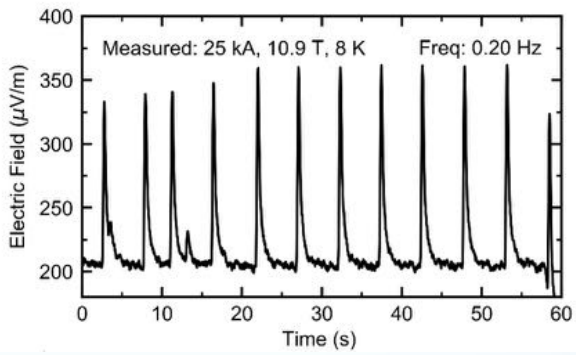
- Same layout as CORC®-CICC #2
- Solder-filled the voids between cables
- 80 kA at 12T/4K



SULTAN test CORC®-CICC #1&3

- CORC®-CICC #3 limited the current to 30 kA at 4.2 K, 10.9 T
- Voltage spikes at frequency of 0.2 Hz where observed at constant current current (25 kA)





Source of low performance CORC®-CICC #3

- Solder in jacket (Bi-based) alloyed with solder in termination (Indium)
- Large variety of contact resistance between cables caused current distribution to become highly uneven

Solder has been replaced by indium solder and test is planned for the near future

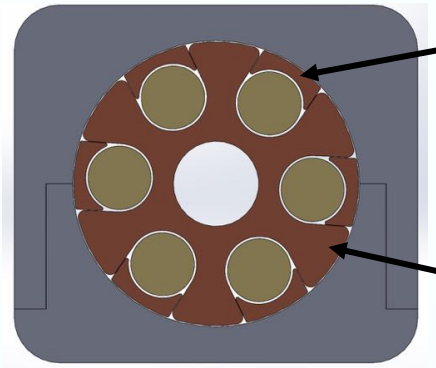
"Recent Progress in the Development of CORC® Cable-In-Conduit Conductors", T. Mulder, J.D. Weiss, D.C. van der Laan, A. Dudarev, H.H.J. ten Kate, *IEEE Trans. Appl. Sup.* **30(4)**, 4800605 (2020)

SULTAN CORC®-CICC samples #4&5

CORC®-CICC #4 for testing in SULTAN

- 6-around-1 CICC based on CORC® cables
- Goal is 80 kA at 10.8 T background field
- Using internal support to decouple CORC® strands
- Improved CORC®-CICC terminals
- SULTAN test early 2021

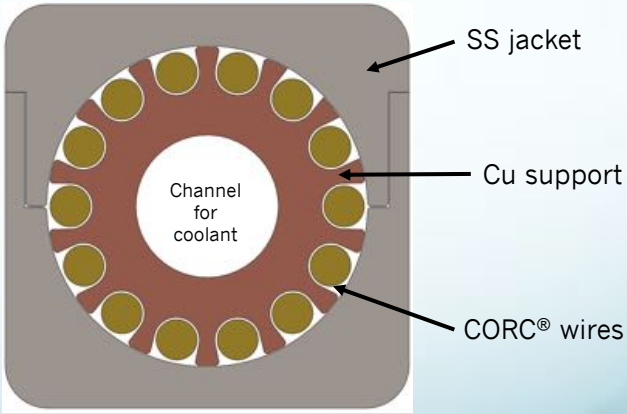
Sample #4



CORC®-CICC #5 for testing in SULTAN

- Based on CORC® 12 – 14 wires for higher degree of transposition and higher flexibility
- Goal is 80 kA at 10.8 T background field
- Using internal support to decouple CORC® strands
- SULTAN test 6 – 9 months from now

Sample #5



Summary

CORC® wires and cables have matured into magnet conductors

- High-quality, long-length CORC® conductors routinely produced for commercial orders
- 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

Improved mechanical strength under tension of CORC® wires

- Irreversible stress limit of CORC® wires with hardened formers exceeds 300 MPa at 77 K
- Irreversible strain limit of CORC® wires under tension exceeds 3 % when tapes are wound at angles below 35°
- CORC® wires offer the highest mechanical strength and elastic range of any superconductor

CORC®-CICC development for fusion and detector magnets is accelerating

- Initial SULTAN test showed degradation due to transverse compression
- Replacement sample has issues with solder alloying in terminations and has been repaired with SULTAN test following shortly
- Several new CORC®-CICC layouts have been develop to reduce the compressive stress on each strand and will be tested after the current CICC sample test are completed