Development of 100 kA high-temperature superconducting Cable in Conduit Conductors from CORC® cables and wires

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

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

Tim Mulder & Herman ten Kate
University of Twente, Enschede, the Netherlands & CERN, Geneva, Switzerland

Leslie Bromberg & Phil Michael
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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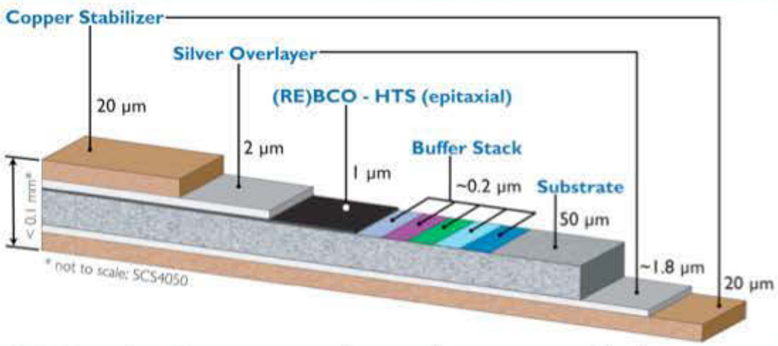
CORC® magnet cables and wires



RE-$Ba_2Cu_3O_{7-\delta}$ coated conductor made by SuperPower Inc.

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 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® development for fusion magnets

CORC®- based fusion magnet cables should

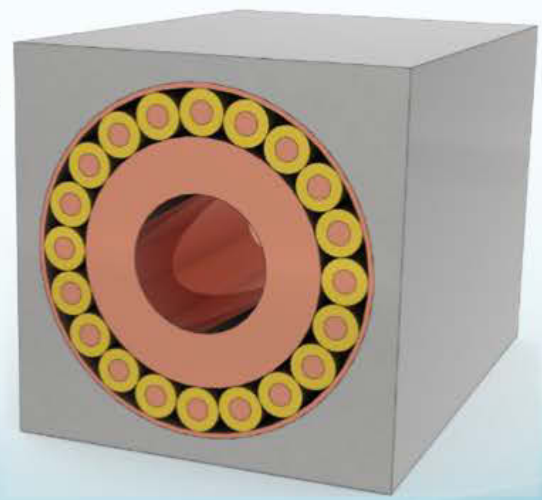
- Have operating currents as high as 100 kA at fields as high as 20 T
- Have a large degree of transposition
- In some designs allow for small bending diameters < 1 meter
- Have low-resistance joints => see talk Jeremy Weiss later today

The goals require high-performance CORC® conductors

- Bundle multiple CORC® conductors in a CICC configuration
- 6-around-1 CORC®-CICC based on CORC® cables
- Multistrand CORC®-CICC based on CORC® wires

6-around-1 CORC®-CICC

Multi strand CORC®-CICC



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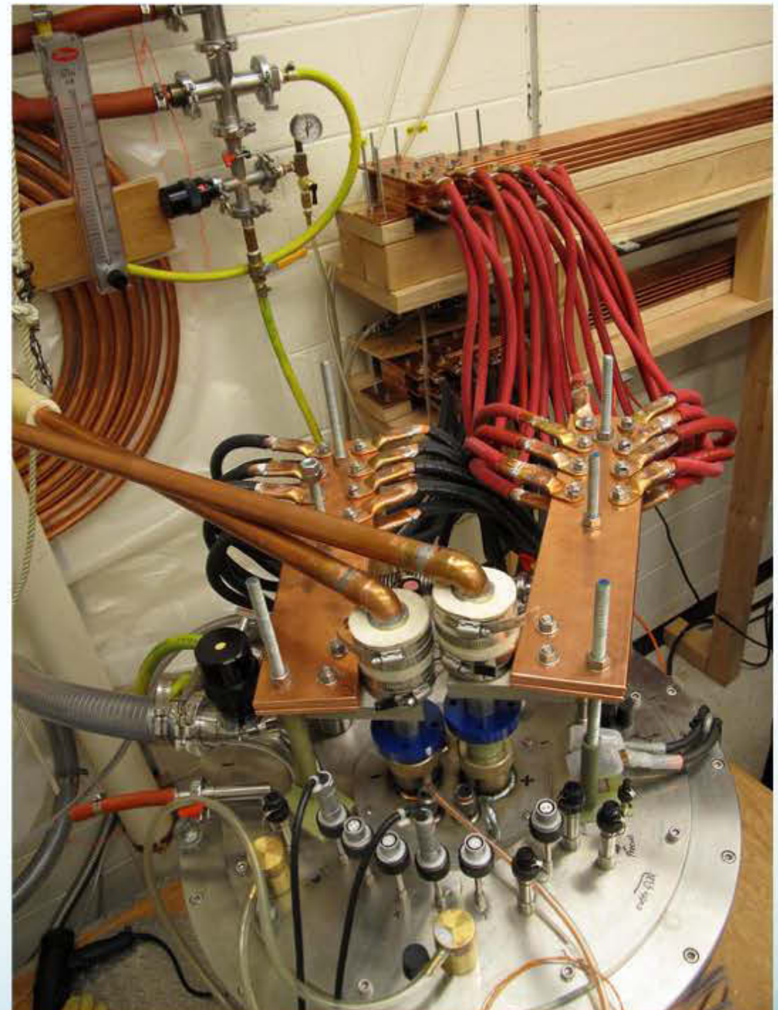
In-house CORC® test facility

Advanced Cond. Tech./Univ. of Colorado

- 12 T superconducting solenoid magnet
- 16,500 A sample current



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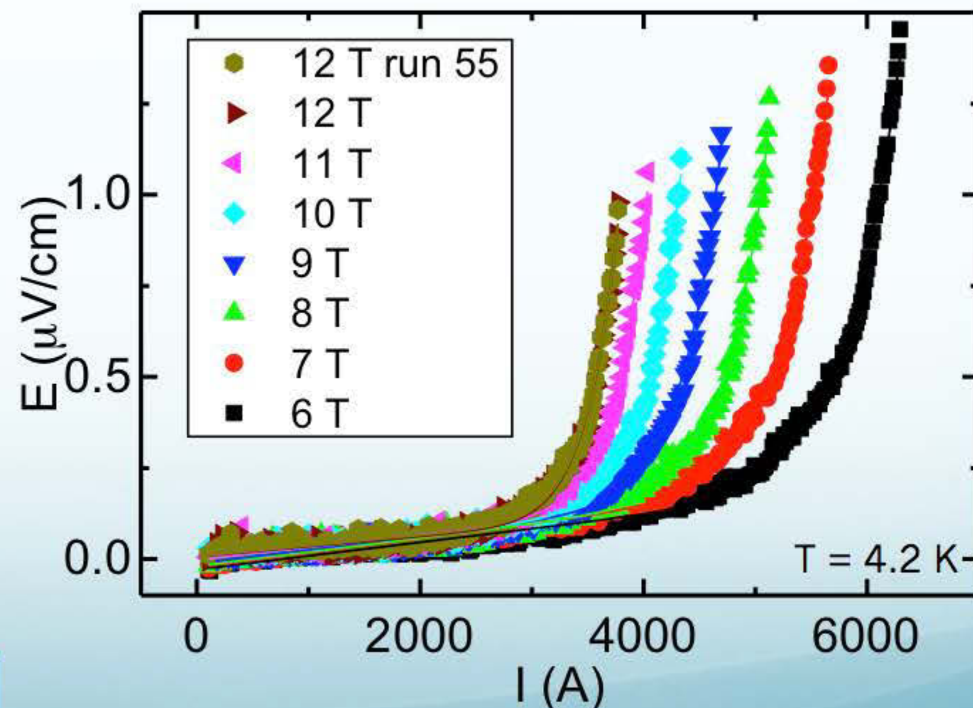
Highly flexible CORC® magnet wires (3.6 mm thick)

CORC® wires based on 2 mm wide tapes

- 27 tapes, 2 mm wide, 30 μm substrate
- 3.6 mm diameter
- 5 turns on 60 mm diameter mandrel



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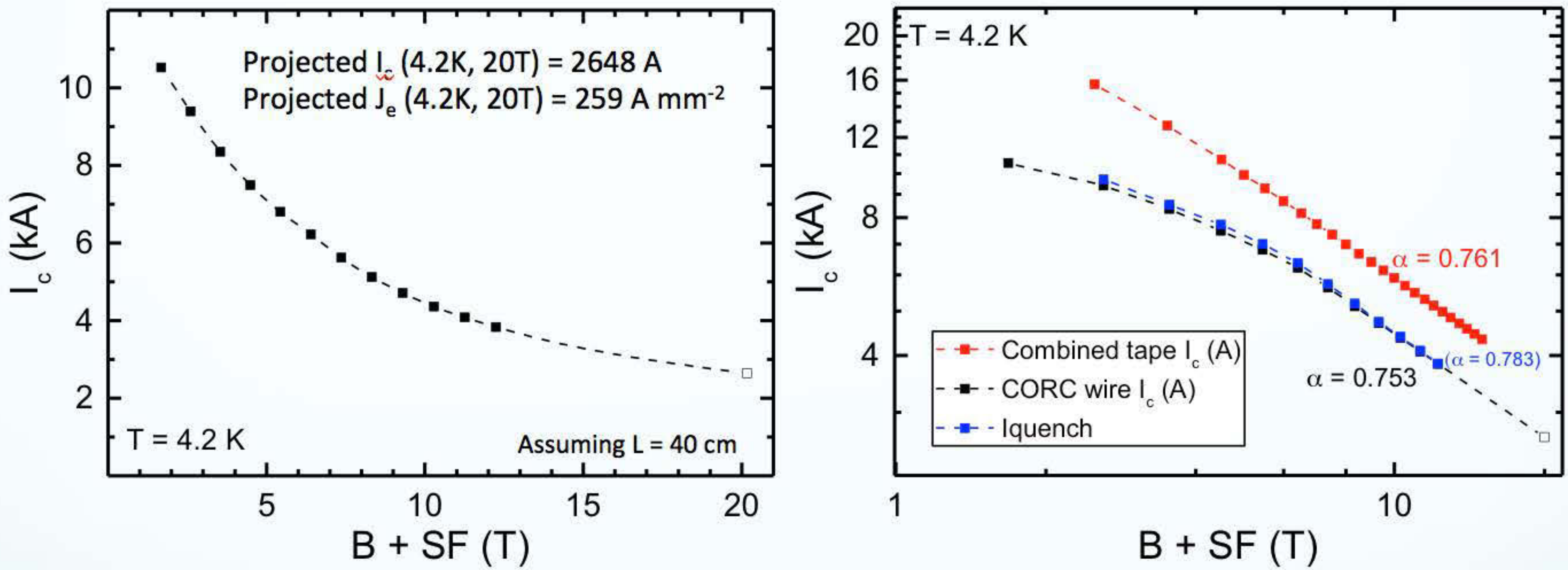
3.6 mm CORC® wire performance at 20 T

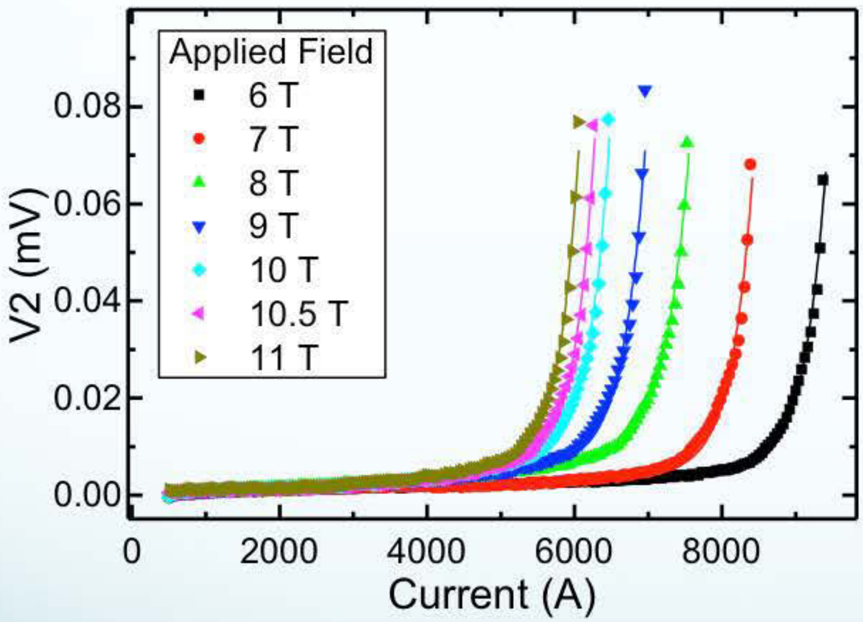


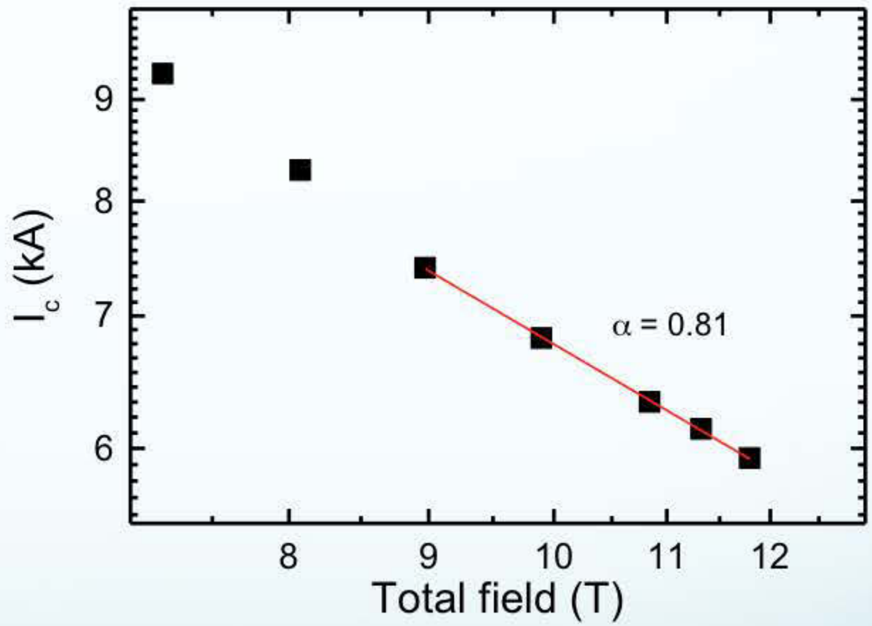
- I_c = 3,831 A (4.2 K, 12 T, 1 μV/cm)
- **Projected J_e(20 T) 259 A/mm² and I_c(20 T) = 2,648 A**

High-performance CORC® magnet wires (4.5 mm thick)

CORC® wires based on 3 mm wide tapes

- 27 tapes, 3 mm wide, 30 μm substrate
- 4.5 mm diameter
- 2 turns on 60 mm diameter mandrel



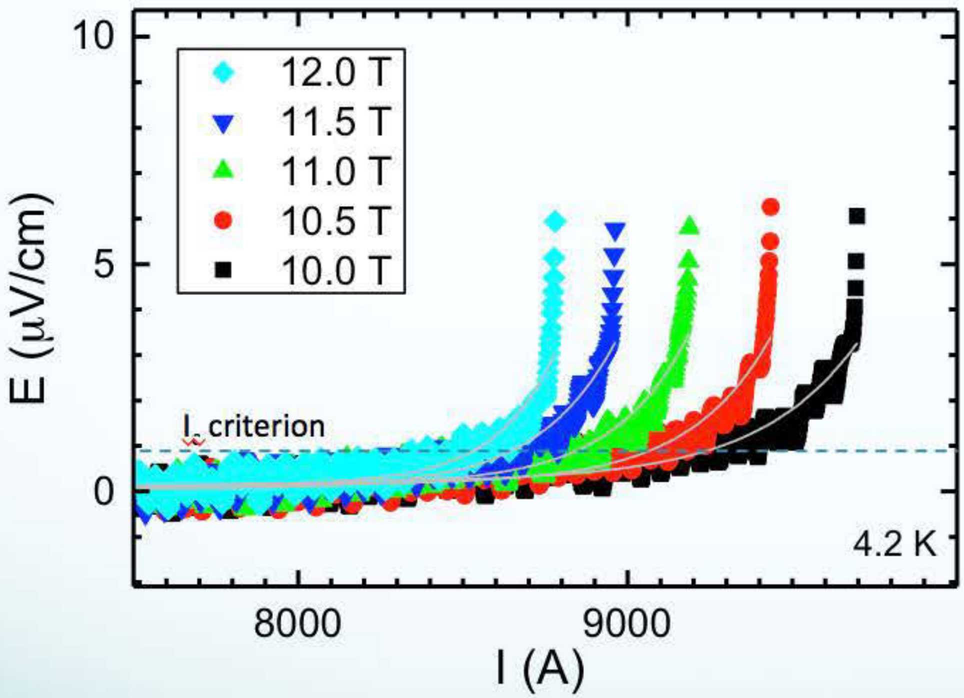


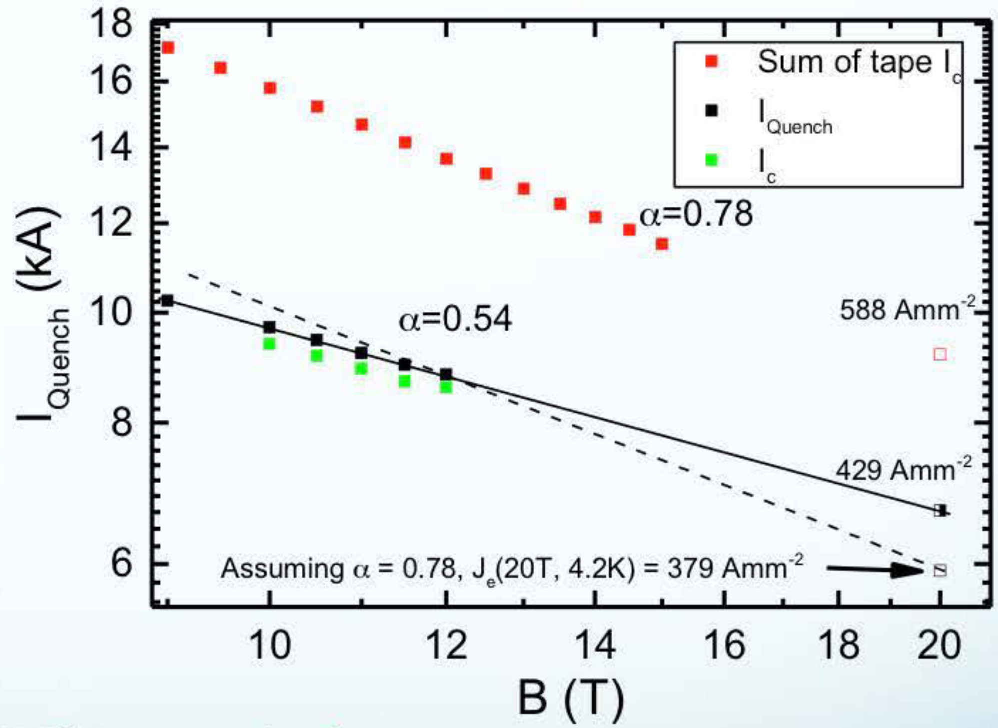
- I_c = 5,900 A (4.2 K, 11.8 T, 1 μV/cm)
- **Projected J_e(20 T) 247 A/mm^2 and I_c(20 T) = 3,866 A**

Record CORC® magnet cable performance

High-J_e CORC® cable layout with limited flexibility (therefore not a wire)

- 50 tapes, 2-3 mm wide, 30 μm substrate
- 4.46 mm CORC® wire diameter
- 62 mm hairpin (much tighter bend than suitable for CORC® cables)





- I_c = 8,591 A (4.2 K, 12 T, 1 μV/cm) (74.5 % Ic retention)
- **Projected J_e(20 T) ~ 400 A/mm² and I_c(20 T) ~ 6,250 A at 62 mm diameter bend**
- **Projected J_e(20 T) ~ 537 A/mm² and I_c(20 T) ~ 8,400 A at >100 mm diameter bend**

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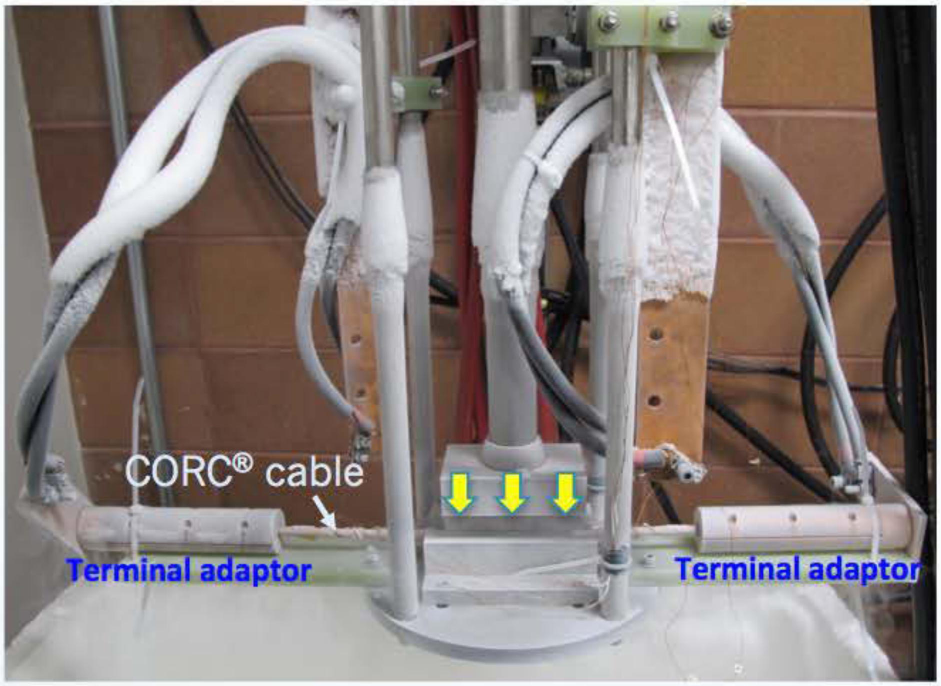
CORC®-cables under transverse compression

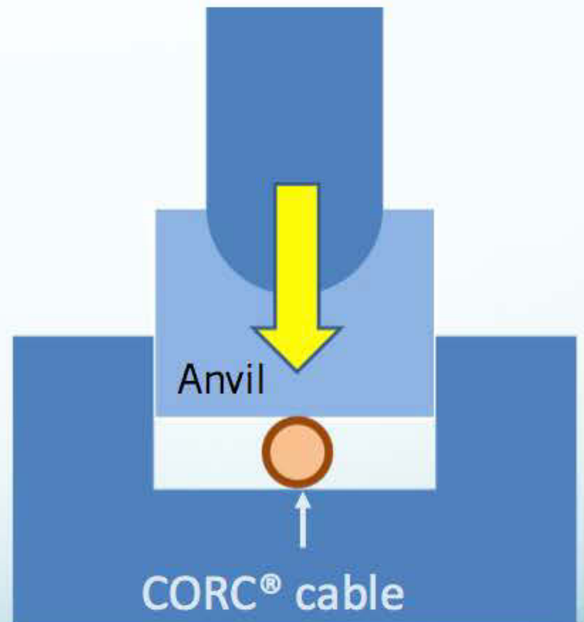
MTS test setup, loading up to 10,000 Lbs (44 kN)



Side view

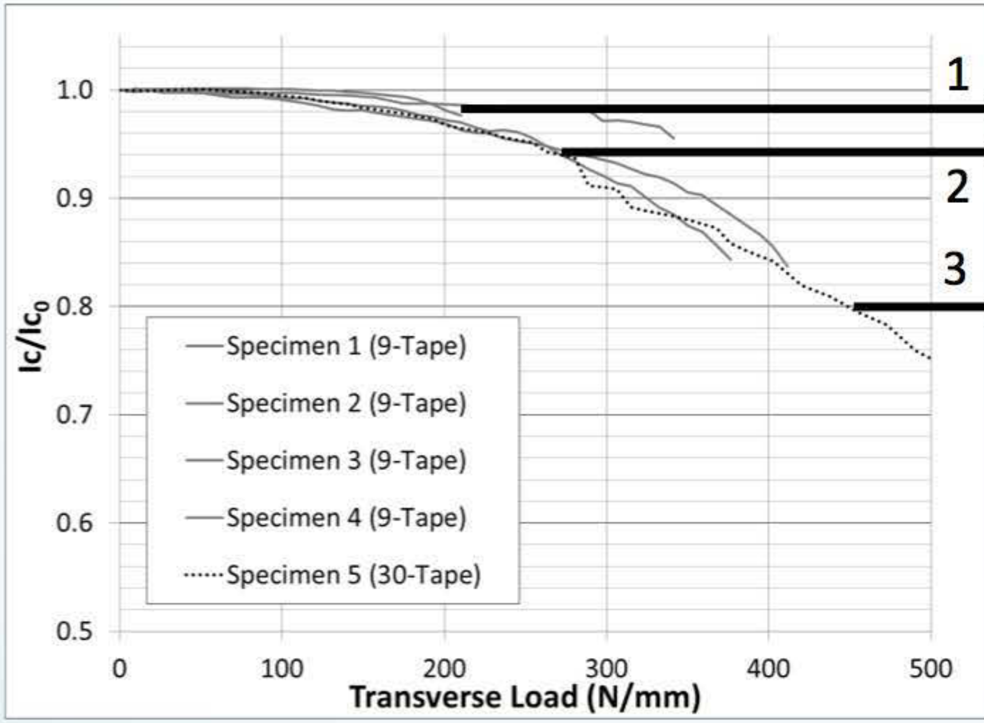
Load applied results in a line-contact against the conductor

	Specimen 1-4	Specimen 5
CORC® former size	5 mm	5 mm
Former material	C101	C101
# of SC tapes	9	30
# of tape layers	3	10

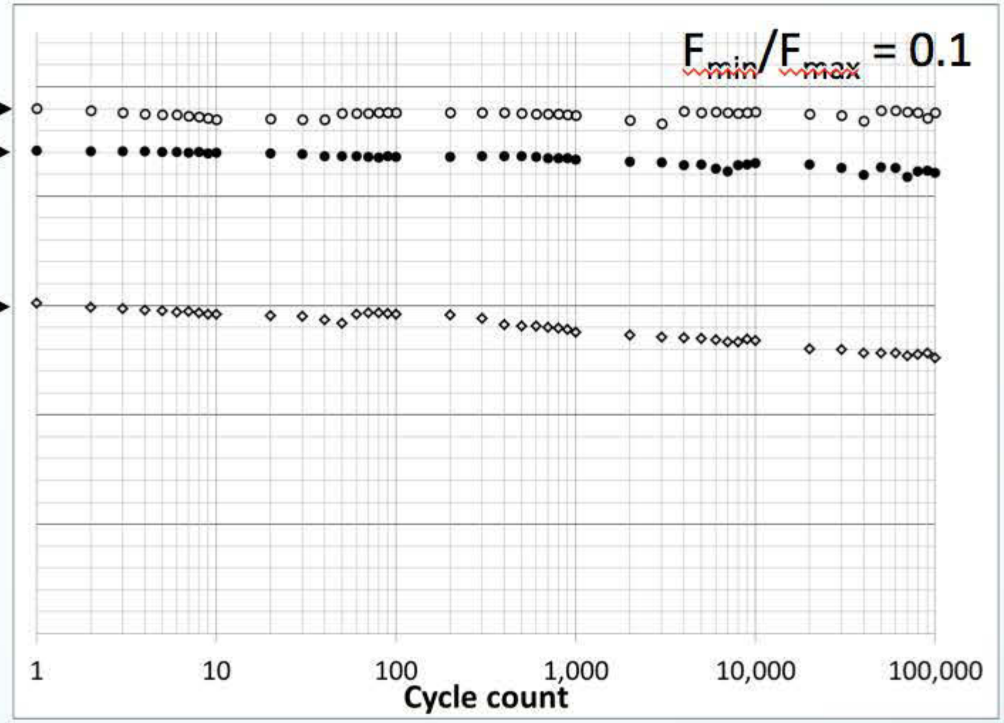


CORC®-cables under transverse compression

Critical current vs compressive load



I_c vs load cycling up to 100,000 cycles



1. 210 N/mm: 97 % I_c => 100,000 cycles: 97 % I_c
2. 271 N/mm: 94 % I_c => 100,000 cycles: 92 % I_c
3. 341 N/mm: 80 % I_c => 100,000 cycles: 75 % I_c

The CORC® cables are surprisingly robust due to compressive state of REBCO layer!

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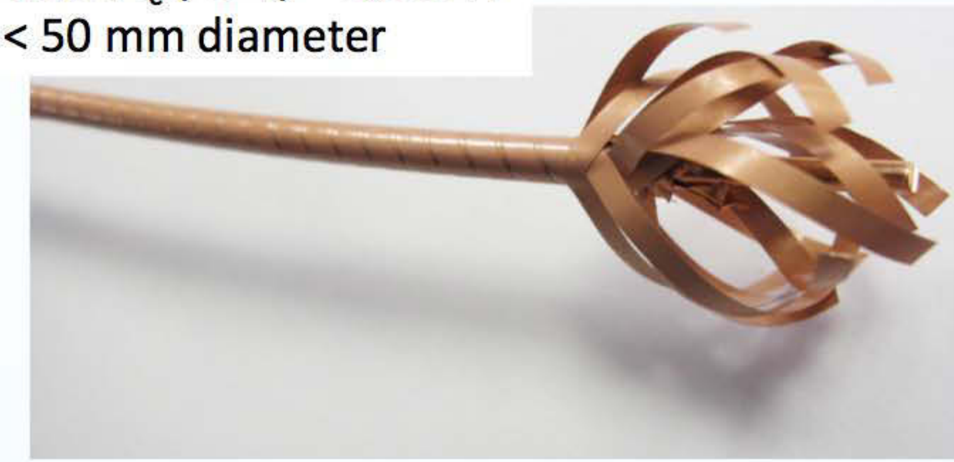
CORC®-CICC based on wires

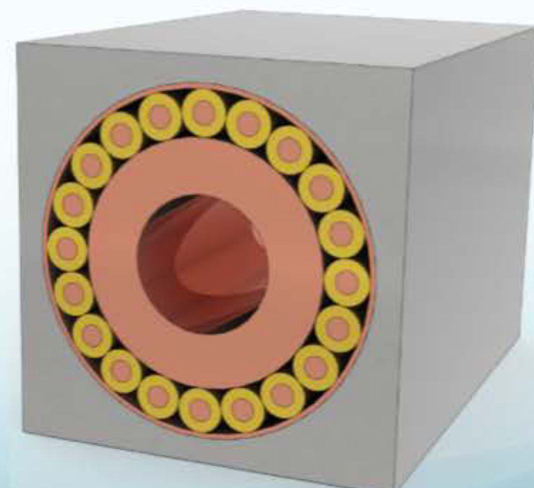
CORC® wire performance

- 3.6 mm CORC® wire: J_e(20 T) = 259 A/mm², I_c (20 T) = 2,650 A
- 4.5 mm CORC® wire: J_e(20 T) = 250 A/mm², I_c (20 T) = 3,866 A
- Highly flexible with bending down to < 50 mm diameter



Multistrand CORC®-CICC wire performance

- High level of conductor transposition
- Relatively flexible
- 20 x CORC® wire (3.6 mm): I_c(20 T) = 53 kA
- 20 x CORC® wire (4.5 mm): I_c(20 T) = 77 kA
- 20 x record CORC® cable: I_c(20 T) = 125 kA
- CORC®-CICC bundle diameter 26.5 – 33 mm



6-around-1 CORC®-CICC development

FRESCA

Step 1: 45 kA CORC®-CICC test in FRESCA (CERN)

- Close collaboration with CERN
- Their interest is CORC®-CICC for detector magnets
- Commercial CORC® cable order (2014)
- 45 kA (4.2 K, 10 T) CORC®-CICC to be tested in FRESCA
- Tested successfully in May 2016

CERN

Step 2: 80 kA CORC®-CICC test in SULTAN (PSI)

- Close collaboration with Paul Scherrer Institute and CERN
- Final deliverable of Phase II STTR
- 80 kA (4.2 K, 11 T) CORC®-CICC to be tested in SULTAN
- Measurement between 4.2-50 K
- Testing started August 2017 and is ongoing

SULTAN

PAUL SCHERRER INSTITUT PSI

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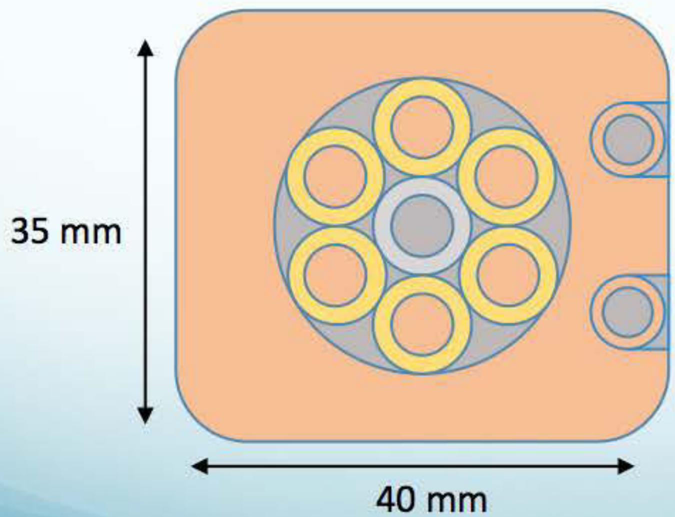
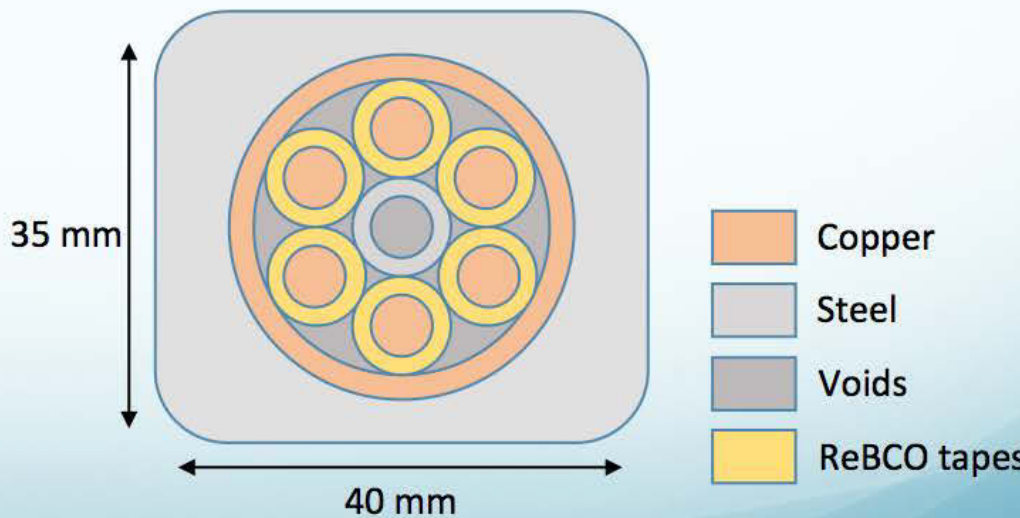
6-around-1 CORC®-CICC for testing in SULTAN

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 11T

Sample 2 for fusion magnets
- Can sustains high stress
- Can cope with large heat loads
- 80 kA at 11T





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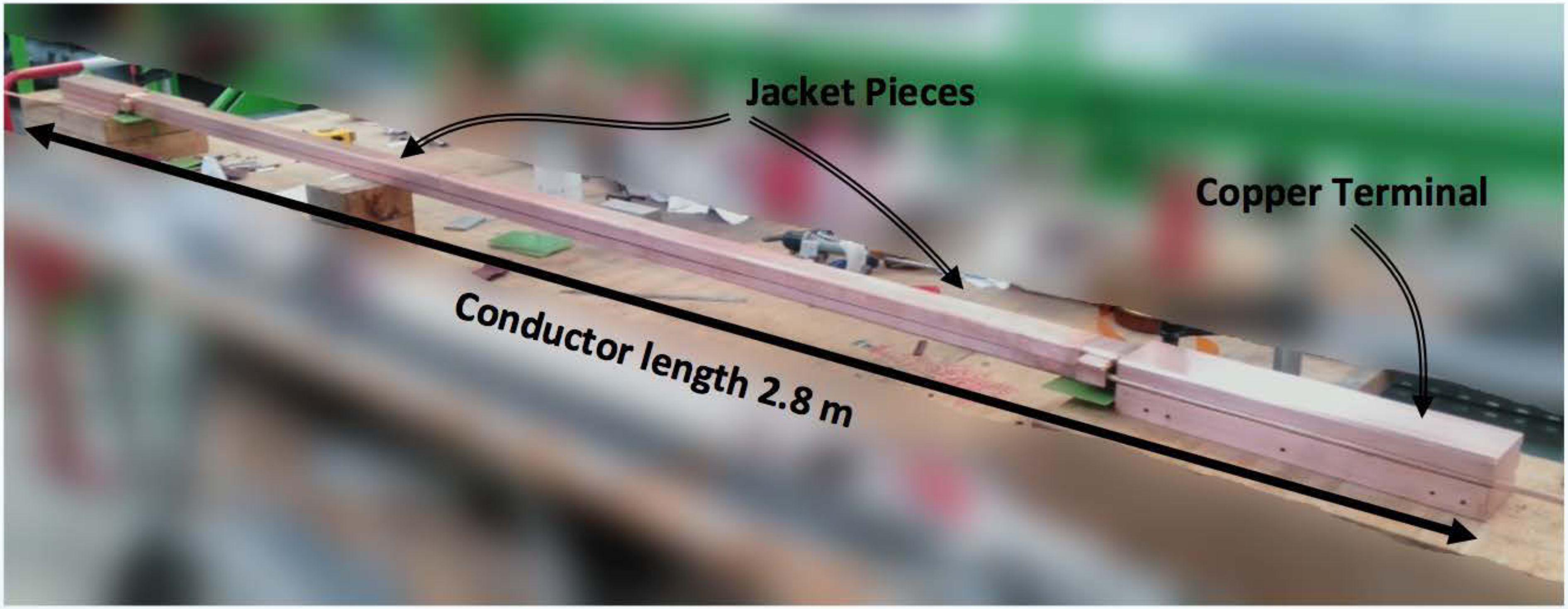
CORC®-CICC cabling at CERN

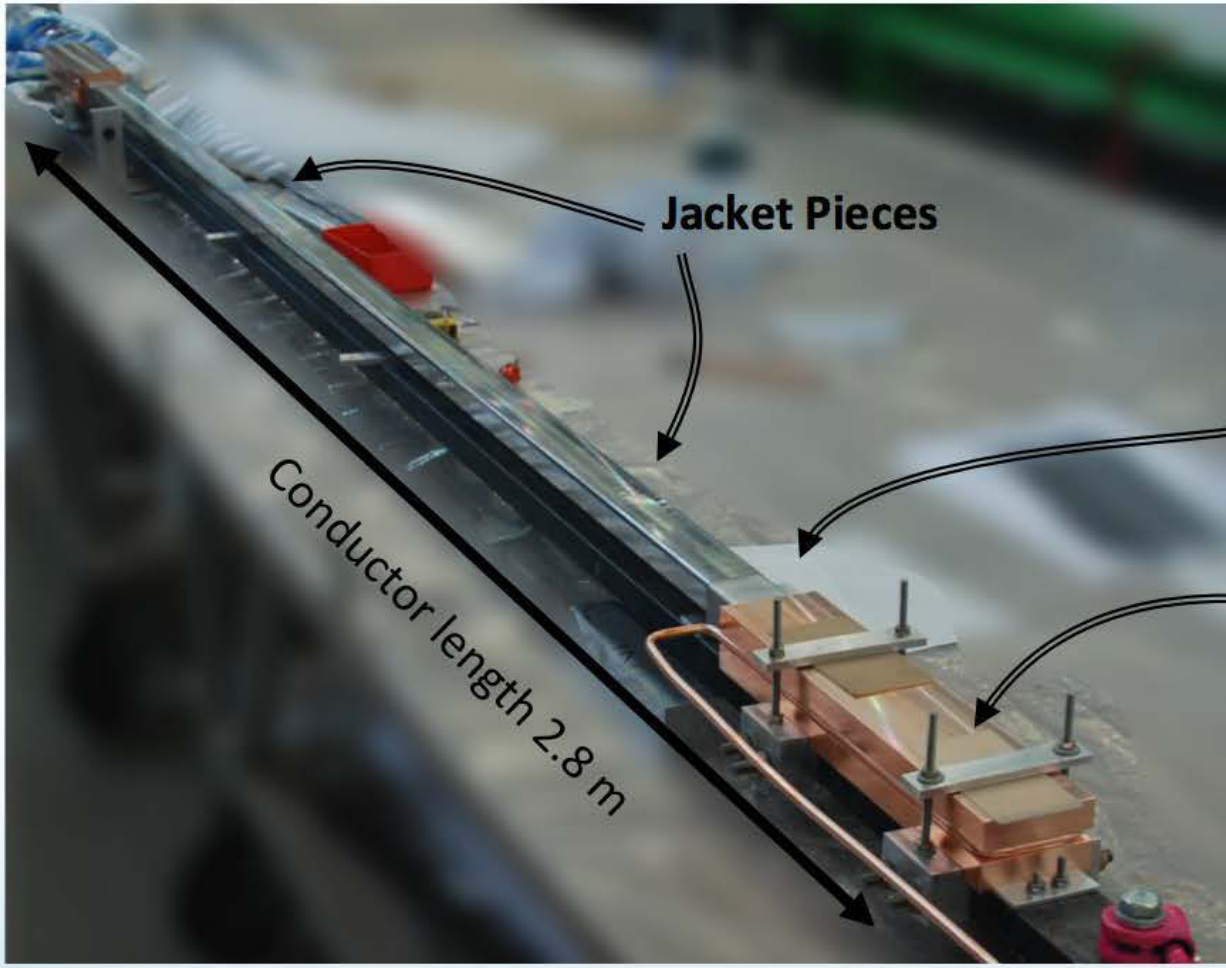
CORC®-CICC construction

- Cabling of the six-around-one cable is done manually
- A cable pitch is 400 mm
- 4.5 pitches in between the joint terminals

CORC®-CICC detector sample



CORC®-CICC fusion sample



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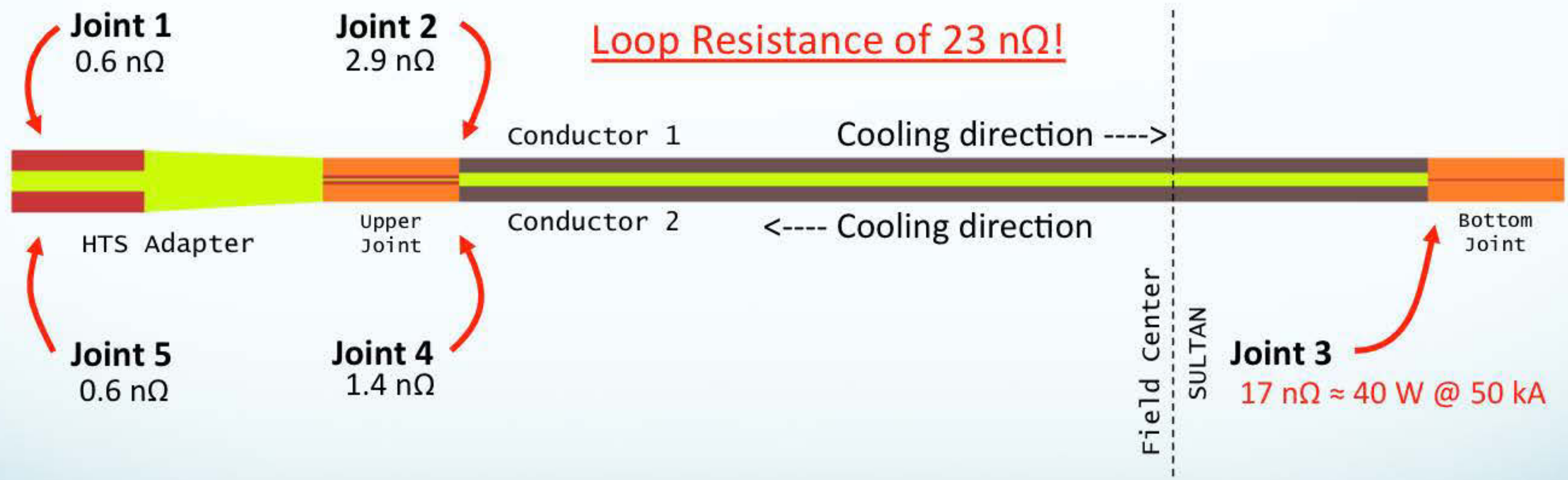
CORC®-CICC SULTAN test #1 (Aug. 2017)

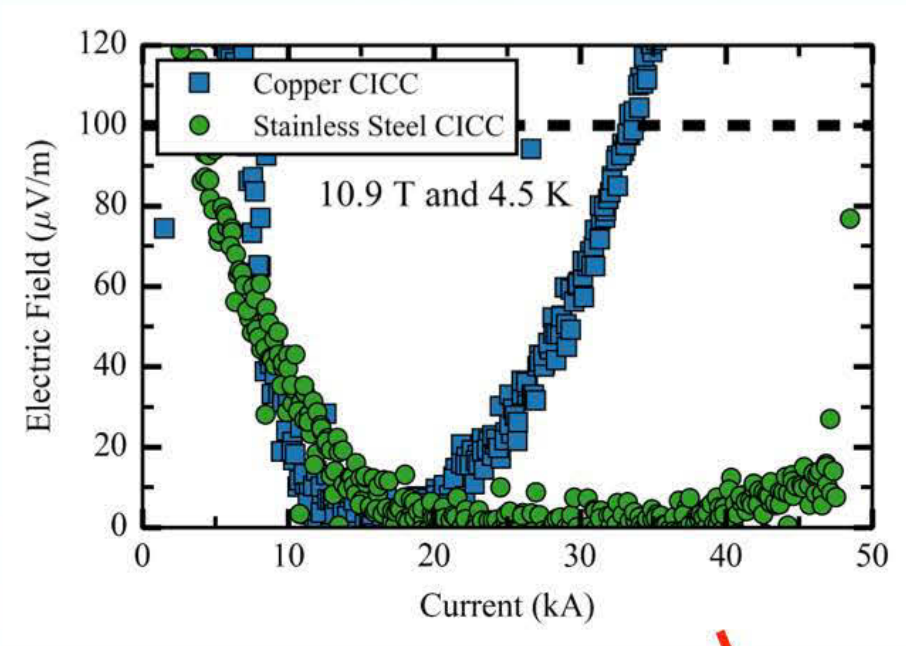
Some issues were encountered:

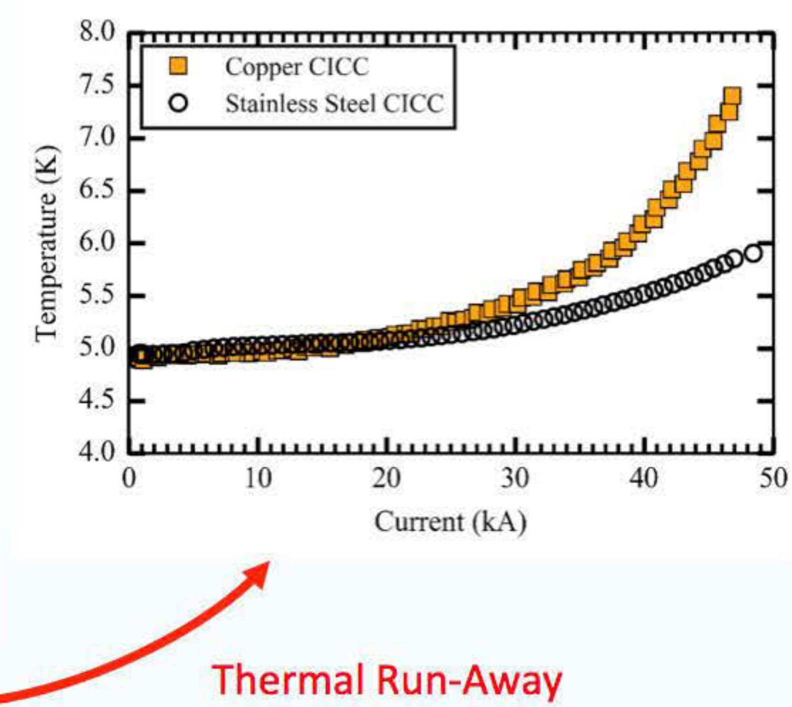
- One bad joint (in field)
- Exotic hydraulic layout

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



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





Effect of heating at joint

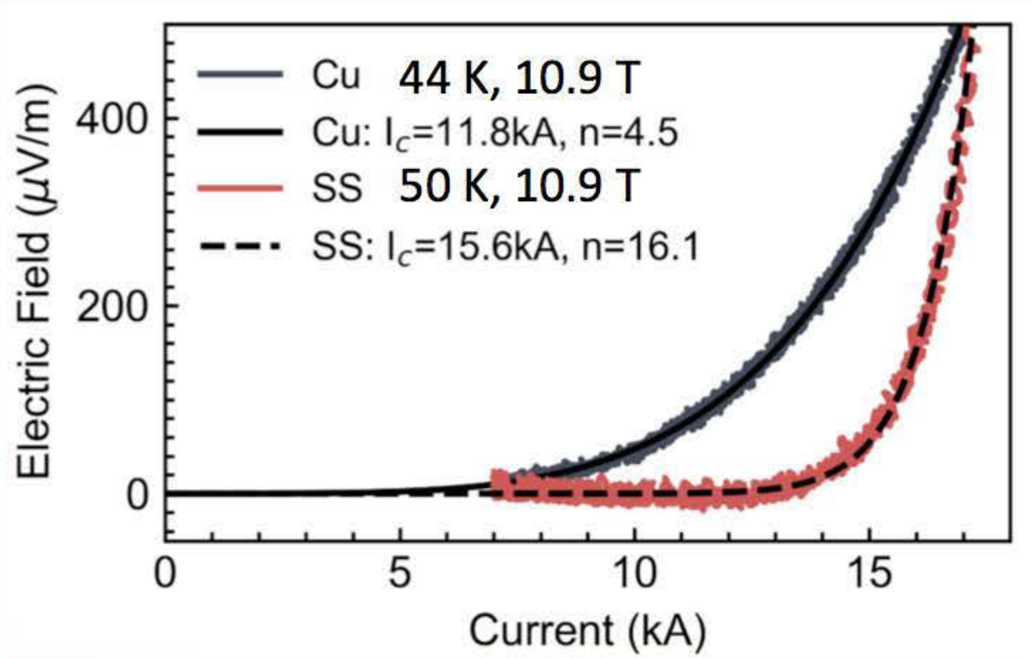
- Heating at bottom joint causes thermal runaway at 4.5 K
- Only the fusion sample could be measured at 4.5 K up to 50 kA

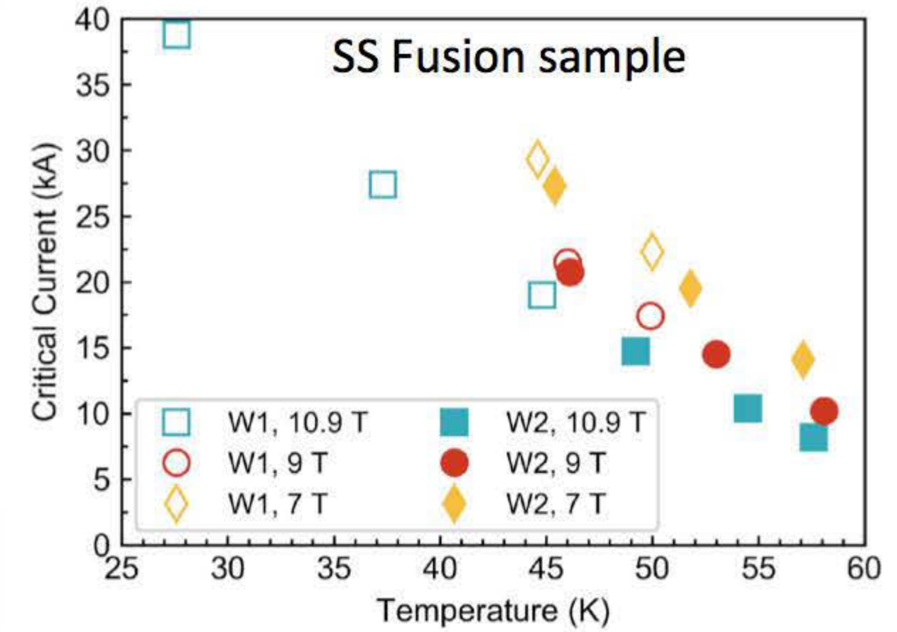
Sample warmed up and bottom joint has been repaired, followed by new test run

CORC®-CICC SULTAN test #2 (Nov. 2017)

Detector sample has degraded

- Cu Detector sample I_c(**44 K**, 10.9 T) = 11.8 kA
- SS Fusion sample I_c(**50 K**, 10.9 T) = 15.6 kA





- Fusion sample shows same performance between week 1 and 2
- Highest Fusion CICC I_c measured at 27 K: I_c(10.9 T) = 38 kA
- Detector sample is being inspected and will be replaced

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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)
- Initial results of mechanical cycling shows robustness of CORC® cables

CORC®-CICC development for 50 – 100 kA at 20 T

- 6-around-1 CORC®-CICC based on less flexible CORC® cables
- Multi strand CORC®-CICC based on much more flexible CORC® wires
- Multi strand CORC®-CICC offer high flexibility and high level of transposition

CORC®-CICC for fusion and detector magnets

- Designed 80 kA (4.2 K, 10.9 T) 6-around-1 CORC®-CICC
- First test in SULTAN was limited by bottom joint
- Second test in SULTAN revealed degradation in detector sample
- Detector sample will be replaced and third measurement will follow