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

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HTS4Fusion 2018, March 22nd, 2018, Nagoya, Japan
CORC® magnet cables and wires

RE-Ba$_2$Cu$_3$O$_{7-δ}$ 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

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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

Work supported by U.S. DOE awards numbers DE-SC0007660, DC-SC14009 and DE-SC0018125
In-house CORC® test facility

Advanced Cond. Tech./Univ. of Colorado
- 12 T superconducting solenoid magnet
- 16,500 A sample current
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
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

![Graph showing applied field vs current and total field vs critical current](image)

- $I_c = 5,900$ A (4.2 K, 11.8 T, 1 μV/cm)
- Projected $J_e(20 \text{ T})$ 247 A/mm² and $I_c(20 \text{ T}) = 3,866$ 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 % $I_c$ retention)
- Projected $J_e(20$ T) $\sim 400$ A/mm² and $I_c(20$ T) $\sim 6,250$ A at 62 mm diameter bend
- Projected $J_e(20$ T) $\sim 537$ A/mm² and $I_c(20$ T) $\sim 8,400$ A at >100 mm diameter bend
CORC®-cables under transverse compression

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

<table>
<thead>
<tr>
<th>Specimen 1-4</th>
<th>Specimen 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORC® former size</td>
<td>5 mm</td>
</tr>
<tr>
<td>Former material</td>
<td>C101</td>
</tr>
<tr>
<td># of SC tapes</td>
<td>9</td>
</tr>
<tr>
<td># of tape layers</td>
<td>3</td>
</tr>
</tbody>
</table>

Load applied results in a line-contact against the conductor

Side view

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CORC®-cables under transverse compression

Critical current vs compressive load

$\frac{I_c}{I_{c0}}$ 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!
CORC®-CICC based on wires

**CORC® wire performance**
- 3.6 mm CORC® wire: $J_e(20 \text{ T}) = 259 \text{ A/mm}^2$, $I_c(20 \text{ T}) = 2,650 \text{ A}$
- 4.5 mm CORC® wire: $J_e(20 \text{ T}) = 250 \text{ A/mm}^2$, $I_c(20 \text{ T}) = 3,866 \text{ A}$
- 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): $I_c(20 \text{ T}) = 53 \text{ kA}$
- 20 x CORC® wire (4.5 mm): $I_c(20 \text{ T}) = 77 \text{ kA}$
- 20 x record CORC® cable: $I_c(20 \text{ T}) = 125 \text{ kA}$
- CORC®-CICC bundle diameter 26.5 – 33 mm
6-around-1 CORC®-CICC development

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

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
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

35 mm 40 mm

Copper Steel Voids ReBCO tapes

[Advanced Conductor Technologies LLC logo]

UNIVERSITY OF TWENTE
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

- Jacket Pieces
- Copper Terminal
- Conductor length 2.8 m
CORC®-CICC fusion sample

- Jacket Pieces
- Adaptor Piece
- Copper Terminal

Conductor length 2.8 m
Some issues were encountered:

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

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

Loop Resistance of 23 nΩ!

- Joint 1: 0.6 nΩ
- Joint 2: 2.9 nΩ
- Joint 5: 0.6 nΩ
- Joint 4: 1.4 nΩ
- Joint 3: 17 nΩ ≈ 40 W @ 50 kA
Effect of heating at joint:
- Heating at bottom joint causes thermal run-away 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
Detector sample has degraded
- Cu Detector sample $I_c(44 \, \text{K}, 10.9 \, \text{T}) = 11.8 \, \text{kA}$
- SS Fusion sample $I_c(50 \, \text{K}, 10.9 \, \text{T}) = 15.6 \, \text{kA}$

- Fusion sample shows same performance between week 1 and 2
- Highest Fusion CICC $I_c$ measured at 27 K: $I_c(10.9 \, \text{T}) = 38 \, \text{kA}$
- Detector sample is being inspected and will 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/mm² (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