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

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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 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
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!

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
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

**CORC® high-field insert solenoid**

- Copper bus bars
- 14 T LTS outsert
- CORC® solenoid

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

### Wire Properties

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>4.5</td>
<td>mm</td>
</tr>
<tr>
<td>Length</td>
<td>17</td>
<td>m</td>
</tr>
<tr>
<td>Expected $I_c$ (77 K, 0 T)</td>
<td>2,873</td>
<td>A</td>
</tr>
<tr>
<td>Expected $I_c$ (4.2 K, 14 T)</td>
<td>5,000</td>
<td>A</td>
</tr>
<tr>
<td>Expected $J_e$ (77 K)</td>
<td>125</td>
<td>A/mm²</td>
</tr>
<tr>
<td>Expected $J_e$ (4.2 K, 14 T)</td>
<td>287</td>
<td>A/mm²</td>
</tr>
</tbody>
</table>

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

$1 \mu\text{V/cm} \text{ criterion}$

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

Step 1: 2-Layer, 40-turns CCT magnet (C1)
- Generate 1 T in self-field
- CORC® wire $J_e(20 \, \text{T}) = 150$-$200 \, \text{A/mm}^2$
- Learn to wind and protect CORC®-CCT magnets

Step 2: 4-Layer, 40-turns magnet (C2)
- Generate 3 T in self-field
- CORC® wire $J_e(20 \, \text{T}) = 200$-$300 \, \text{A/mm}^2$
- Advanced CCT structure and potting procedures

Step 3: 6-Layer, 40-turns CCT magnet (C3)
- Generate 5 T in self-field
- CORC® wire $J_e(20 \, \text{T}) = 300$-$400 \, \text{A/mm}^2$
- 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, $J_e (20 \text{T}) = \sim 150 \text{ A/mm}^2$

**CCT-C1 generated 1.2 T at 4,800 A (104 % of expected performance)**
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 $J_e (20\,\text{T}) = \sim 300\,\text{A/mm}^2$

CCT C0b performance
- $I_c (77\,\text{K}) = 1,092, 1,067\,\text{A (layer A, B)}$
- $I_c (4.2\,\text{K}) = 12,141, 11,078\,\text{A (layer A,B)}$
- Dipole field 0.68 T (4.2 K)
- Peak $J_e (4.2\,\text{K}) = 1,198\,\text{A/mm}^2$
- Expected field of CCT-C2 (40 turns) $\sim 3-4\,\text{T}$

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

**$I_c(B)$ testing of CCT-C2 CORC® wire**

Sample after winding on probe and epoxy impregnation

![Sample after winding on probe and epoxy impregnation](image)

Minimum bending diameter = 63 mm

Sample removed from probe following test

![Sample removed from probe following test](image)

Hairpin turn to return current

High field region
(Homogeneity > -1.2%)

Single loop adding to external field
$I_c(B)$ tested at 12 T and then cycled over 50 times

$I_c(B)$ dependence extrapolated to 20 T

Sample cycled to 90% of the critical current

$E(I,B)$ tested at 12 T

$I_c(B, 4.2K)$ dependencies fitted with $I_c(B) = I_{c0}B^{-\alpha}$

for field range 10 T – 15 T to project to 20 T using derived $\alpha=0.75$

Projected $I_c(4.2K, 20T) = 2648 A$
Projected $J_e(4.2K, 20T) = 259 A \text{mm}^{-2}$
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 $J_e (20 \, \text{T}) \ 500 \, \text{A/mm}^2$ 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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>4.73 mm</td>
</tr>
<tr>
<td># of tapes</td>
<td>42 m</td>
</tr>
<tr>
<td>Expected $I_c$ (76 K, SF)</td>
<td>4255 A</td>
</tr>
<tr>
<td>Expected $I_c$ (4.2 K, 20 T)</td>
<td>9,377 A</td>
</tr>
<tr>
<td>Expected $J_e$ (76 K, SF)</td>
<td>242 A/mm²</td>
</tr>
<tr>
<td>Expected $J_e$ (4.2K, 20 T)</td>
<td>534 A/mm²</td>
</tr>
</tbody>
</table>

1.75-turn racetrack coil

220 mm

After winding, self-field reduces $I_c$ by 20%

Before winding

After winding

$I_c$ measured across the terminals

<table>
<thead>
<tr>
<th></th>
<th>$I_c$ (A)</th>
<th>N-value</th>
<th>R (nΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before winding</td>
<td>4233</td>
<td>32.4</td>
<td>26.4</td>
</tr>
<tr>
<td>After winding</td>
<td>3381</td>
<td>29.6</td>
<td>23.4</td>
</tr>
</tbody>
</table>

$76$ K

1 uV/cm criterion

$L = 365.4$ cm
Testing a high tape-count CORC® cable infield

**CORC® Wire Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>4.5 mm</td>
</tr>
<tr>
<td># of tapes</td>
<td>50 m</td>
</tr>
<tr>
<td>Expected $I_c$ (76 K, SF)</td>
<td>3566 A</td>
</tr>
<tr>
<td>Expected $I_c$ (4.2 K, 20 T)</td>
<td>9,187 A</td>
</tr>
<tr>
<td>Expected $J_e$ (76 K, SF)</td>
<td>224 A/mm²</td>
</tr>
<tr>
<td>Expected $J_e$ (4.2 K, 20 T)</td>
<td>578 A/mm²</td>
</tr>
</tbody>
</table>

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

![Image of sample](image-url)
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 $\alpha$=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 – )

Closing in on $J_e > 600$ A/mm$^2$ goal

- $J_e$ (20 T) now exceeded 400 A/mm$^2$ in CORC® conductor
- Combined with $I_{opp}$ (20 T) > 6,500 A
- Next step is thinner substrates 20 – 25 μm

Design and picture
UNIVERSITY OF TWENTE.

Advanced Conductor Technologies
www.advancedconductor.com
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

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
  - \( I_c (44 \text{ K}, 10.9 \text{ T}) = 11.8 \text{ kA} \)
  - Degradation caused by loose packing of tapes and conductor in conduit
- SS fusion sample as expected
  - \( I_c (50 \text{ K}, 10.9 \text{ T}) = 15.6 \text{ kA} \)
  - 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
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

CICC with one CORC® strand

\[ R = 0.5 \text{ m} \]
CORC® cables and wires have matured into magnet conductors

- CORC® wire performance 2-3 kA and 250-400 A/mm² at 20 T
- CORC® cable performance 10 kA and 300-600 A/mm² 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