High-temperature superconducting Conductor on Round Core magnet cables operated at high current ramp rates in background fields of up to 19 T

Danko van der Laan & Xifeng Lu
Advanced Conductor Technologies & University of Colorado, USA

Anne de Jager
University of Colorado, USA

Leslie Bromberg & Joe Minervini
Massachusetts Institute of Technology, USA

Patrick Noyes, George Miller & Huub Weijers
National High Magnetic Field Laboratory, USA
<table>
<thead>
<tr>
<th></th>
<th>Programs supporting CORC cable development.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Mechanical testing of CORC cables.</td>
</tr>
<tr>
<td>3.</td>
<td>CORC cables for power transmission.</td>
</tr>
<tr>
<td>4.</td>
<td>CORC magnet cables for fusion.</td>
</tr>
<tr>
<td>5.</td>
<td>CORC magnet cables for accelerators.</td>
</tr>
<tr>
<td>7.</td>
<td>Summary.</td>
</tr>
</tbody>
</table>
Conductor on Round Core cables

**CORC cable principle:**
Winding many high-temperature superconducting YBCO coated conductors from SuperPower in a helical fashion with the YBCO under compression around a small former.

**Benefits:**
- Very flexible, capable of bending diameters less than 10 cm.
- Very high currents ( > 7 kA) and current densities (> 100 A/mm²)
- Mechanically very strong
- Minimum degradation from cabling (< 10 %)
Mechanical testing of CORC cables

Test facility at NIST for determining the effect of axial stress on the cable $I_c$:

- Cable installed with flexible current leads.
- Current lead capacity > 1.5 kA at 77 K.
- Mechanical load up to 3,000 lbs.
- $I_c$ measurement while at load.

Current leads can handle >1500 A at 76 K.
Mechanical strength of CORC cables

Various options are explored regarding the formers and cable layout:

3/16” O.D. Cu former, with 0.032” wall thickness:

- 6 tapes in 2 layers: $\sigma_{irr} = 228$ MPa
- 12 tapes in 4 layers: $\sigma_{irr} = 277$ MPa

No reversible strain effect on $I_c$ before sharp irreversible drop-off!
Anisotropic in-plane reversible strain effect in CC

MOCVD-IBAD: \( a\)- and \( b\)-axes aligned with conductor axis!

Bridges cut from CC allow us to apply strain at different in-plane angles:

Reversible strain effect on \( I_c \) depends on the in-plane orientation of the applied strain!
Strain effect on $I_c$ in CORC cables

Comparing the effect of strain in coated conductors and CORC cables:

Tape: $I_c (\sigma_{irr}) = 0.90 I_c(0)$
Cable: $I_c (\sigma_{irr}) > 0.98 I_c(0)$

The strain effect in CORC cables is highly reduced because strain is applied at about 45 degrees!
“Conventional” low power density HTS power transmission cables:

High power density HTS cables:
- Twisted Stack-Tape Cable (MIT)
- Roebel Cable (KIT)

High current density, but inflexible.

CORC cable
- I.D. 9 cm

High power density and very flexible.
CORC cables for dc-power transmission

Development of a 2-phase CORC power transmission cable:
Collaboration with Tim Haugan, AFRL:

- 79 tapes in 17 layers
- 2-phase configuration
- **cable O.D. 10 mm**

\[ I_c (\text{Phase 1}) = 3745 \ A; \ I_c (\text{Phase 2}) = 3816 \ A \]

When phases operated in series:
\[ I_c (\text{total}) = 7561 \ A \]
Collaborators at Center for Advanced Power Systems:
Chul Kim and Sastry Pamidi

**Purpose of GHe system:**
To test HTS cables in helium gas for Navy and Air Force applications.

**Cryogenic helium gas setup at CAPS:**
- 4 cryocoolers: He gas at $T > 50$ K.
- High-speed cryo fans allow for 20 bar pressure.
- Short sample cryostat with 1 meter GHe section
- Cable ends located in LN$_2$ baths at cryostat ends.
$I_c(T)$ in pumped LN$_2$ and GHe of 9-tape (3 layers) CORC cable:

Measurements in GHe and LN$_2$ coincide: near-linear $T$-dependence of $I_c$. 

GHe: 62-73 K
LN$_2$: 68-77 K
Temperature rise during operation in GHe

\( T \)-rise (K/5 min.) in GHe as a function of current (0.5\( I_c \) < \( I \) < \( I_c \)=1300 A):

- Flow rate: 2.1 g/s
- Flow rate: 3.6 g/s

Temperature rise may be caused by resistive heating of the copper leads.
Goal is to reach a cable current >30 kA at 4.2 K and B > 12 T.

Cables tested at the NHMFL in 19.8 T background field:
52 YBCO coated conductors, 17 layers, cable O.D. 7.5 mm:

\[ I_{\text{quench}} = 6000 \text{ A @ 4.2 K, 19 T} \]
\[ I_c = 5021 \text{ A @ 4.2 K, 19 T, 1 } \mu \text{V/cm} \]
\[ J_e = 114 \text{ A/mm}^2 \text{ @ 4.2 K, 19.0 T} \]
High-current ramp rates at 19 T

Will current distribution become inhomogeneous in cables with many layers at high current ramp rates?

Cable: 52 CC in 17 layers.

Current ramp rates at 4.2 K, 19 T to 90% of $I_{\text{quenc}}$
- 2017 A/s
- 9500 A/s

No effect of high current ramp rates!
CORC cable for fusion magnets – Phase II

CORC triplet rated at potentially \( 3 \times 5 \, \text{kA} = 15 \, \text{kA} \) at 4.2 K, 19 T.

CORC 6-around-1 rated at potentially \( 6 \times 5 \, \text{kA} = 30 \, \text{kA} \) at 4.2 K, 19 T.
Room for improvement

\( I_c = 5021 \, \text{A} @ 4.2 \, \text{K}, \, 19 \, \text{T} \)

During cable inspection after test at 19T:

Many damaged tapes in outer layers due to cable bending!

Caused by loose winding pack.

Winding pack needs to be controlled:

=> Cabling machine is needed.
Early CORC performance at 6 cm diameter

Improving the flexibility of CORC cables for application in accelerators:

**Earlier cable (2012):**
26 YBCO CC, 11 layers, cable O.D. 6.0 mm

- Straight: \( I_c = 2425 \text{ A} @ 76 \text{ K} \)

- 6 cm diameter:
  - \( I_c = 1057 \text{ A} @ 76 \text{ K} \)
  - \( I_c = 1264 \text{ A} @ 4.2 \text{ K}, 19 \text{ T} \)
  - \( J_e = 29 \text{ A/mm}^2 \)

Large degradation of 56 % due to bending!
Improved CORC cable (2013):

Irreversible degradation of only 2.5 % due to bending to 40 mm diameter!
Winding of long CORC cables with a machine:

Dummy CORC cable: 12 meter long 28 layers

Sponsored by the Department of Energy Office of High Energy Physics grant DE-FG02-12ER41801
In-field testing of CORC cables at CU/NIST

Magnet insert for 8.75 T solenoid magnet for CORC cable testing at NIST:

- Actual probe:
- Sample holder for 10 cm diameter cables:
- Sample holder for 6 cm diameter cables:

5 kA vapor cooled leads

copper current leads

cable support

Sponsored by the Department of Energy
Office of High Energy Physics grant DE-FG02-12ER41801
CORC cable performance projections

Improved performance due to winding machine and reduced copper thickness:

- Hand wound
- Cable machine
- Machine, 5 micron Cu

Graphs showing performance metrics for different cable diameters.
Cable optimization:

Raise $J_e(4.2 \text{ K}, 20 \text{ T})$ to above 200 A/mm$^2$ and reduce degradation at low cable bending radius.

**Raising $J_e$ further by:**
- Pinning: 2x in $I_c$ at 4.2 K, 20 T?
- Thicker YBCO or thinner substrates: 2x in $I_c$?

This would bring current $J_e(4.2 \text{ K}, 20 \text{ T})$ to $2 \times 2 \times 110$ A/mm$^2 = 440$ A/mm$^2$!

**Or two methods combined:**

$J_e(4.2 \text{ K}, 20 \text{ T}) = 4 \times 200$ A/mm$^2$ = 800 A/mm$^2$!
- CORC cables are currently the only high-current, **flexible** HTS cables.

- Proven performance of CORC cables:
  - 7500 A in liquid nitrogen at cable O.D. of 10 mm.
  - 5000 A in liquid helium at 19 T.

- CORC cables experience no strain effect on $I_c$.

- No effect of current ramp rates up to 68 kA/s on the in-field performance.

- CORC cable machine fully operational.

- Large improvements of CORC $I_c$ expected due to cable machine and CC layout.