RE-Ba$_2$Cu$_3$O$_{7-\delta}$ coated conductor helical cables for electric power transmission and SMES

D.C. van der Laan and X.F. Lu
University of Colorado & National Institute of Standards and Technology, Boulder, Colorado, USA

J.F. Douglas C.C. Clickner, T.C. Stauffer and L.F. Goodrich
National Institute of Standards and Technology, Boulder, CO 80305, USA

T.J. Haugan
Air Force Research Laboratory, Wright-Patterson AFB, OH 45433, USA

D. Abraimov, A.A. Polyanskii and D.C. Larbalestier
Applied Superconductivity Group, NHMFL, Tallahassee, FL 32310, USA

G.E. Miller, P.D. Noyes and H.W. Weijers
National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA

Outline

1. Introduction of the REBCO coated conductor helical cabling concept for power transmission and high-field magnet applications.
2. Overview of initial helical cable prototypes.
3. DC transmission cable for Air Force applications.
4. Effect of strain on $J_c$ and pinning in REBCO CC
5. Mechanical testing on REBCO CC helical cables
6. Cable test at 4.2 K and 20 T
7. Summary.
High-current density REBCO CC helical cables

Requirements for HTS cables:

1. Dc power transmission (Navy/Air Force): Low weight, high current (density).
2. High-field magnets for SMES (plus transformers, HEP/Fusion/Science):
   - High-current and high-current density windings.
   - Low conductor anisotropy.
   - Low magnetization loss.
   - Round conductor.

**REBCO CC helical cabling design:**
Helically-winding CCs with YBCO under => compression around a small former.

**Benefits:**
- Compact/low weight.
- No tape scrap.
- Round cable.
- Isotropic field-dependence.
- Optional cooling channel within former.
- Full conductor transposition/easy striation.
- High mechanical strength (no sharp edges).
- Standard cabling technique applicable.
- Current sharing/distribution adjustable.

Reversible strain effect in YBCO CC

There is a large reversible effect of strain on $I_c$:

$$\frac{I_c(\varepsilon)}{I_c(\varepsilon_m)} = 1 - a|\varepsilon - \varepsilon_m|^{2.2}$$

strain sensitivity

strain at peak

Reversible!

$\varepsilon_{irr} = 0.66\%$

$\varepsilon_m = 0.15\%$

76 K
Helical cable design proof of principle

Question 1: How much compressive strain is possible in CCs?

SuperPower conductor:
- $I_c = 133 \text{ A @ 76 K}$
- 20 μm surround copper plating.
- 1 μm YBCO.
- 50 μm Hastelloy substrate.

Measurement procedure:
- CC soldered to CuBe/brass bending beams,
- strain gage mounted on top of sample.
- beam is bent past its elastic limit.
- reversibility of $I_c$ is confirmed by unloading the strain.

$I_c$ of the MOCVD-IBAD tape decreased reversibly by 95 % at -2 % compressive strain!
The irreversible strain limit hasn’t been reached!
Helical cable design proof of principle (Cont.)

Question 2: Does the YBCO survive the mechanical deformation in the cable?

Helically cabling of YBCO coated conductors is possible! $I_c$ is determined by the strain along the tape axis!

$J_c - \varepsilon$ of GdBa$_2$Cu$_3$O$_{7-\delta}$ vs. YBa$_2$Cu$_3$O$_{7-\delta}$

Benefit of GBCO CC over YBCO: Less strain sensitive!

GBCO is the material of choice for cabling.
**DC transmission cable 1: construction**

**Cable 1:** 5.5 mm former, 4 layers, 12 YBCO tapes @ 100 A each, no insulation.

5.5 mm OD

1st layer

2 layers

4 layers

6.5 mm OD
$I_c$ (s.f., 76 K) = 1232 A

Bending radius 12 cm:
$I_c$ (s.f., 76 K) = 1239 A!

High-current cables are possible!
And you can bend them!

**DC transmission cable 2**

**Cable 2:**
- 5.5 mm former
- 8 layers, 24 GBCO CC @ 130 A
- no insulation.
- Cable O.D. = 7.5 mm.

Air Force power transmission is interested in:
- 5 MW DC power transmission at 270 V => 18,500 A.

Superconducting power transmission cable of 18,500 A at 50-55 K
=> 6200 A at 77 K
=> 6800 A at 76 K (Boulder LN₂ boiling).

Our approach (due to limited current of 5000 A):
=> 2 phase coaxial cable:

Our goal:
\[ I_c \text{ (Phase 1)} + I_c \text{ (Phase 2)} = 6800 \text{ A} \]
Air Force 5 MW cable Phase 1

- 1.2 meter

- 5.5 mm former.
- 5.8 cm OD copper endpieces.
- 10 layers, 39 tapes
Air Force 5 MW cable Phase 1 test 76 K

Taps near center of cable: \( I_c \) (Phase 1) = 3720 A  
\[ B_{self} = 181 \text{ mT} \]

Taps near cable ends: \( I_c \) (Phase 1) > 3720 A  
Limited due to thermal runaway.
Air Force 5 MW cable Phase 2

- 10 mm cable outer diameter.
- 7 layers, 40 tapes

11 4/0 cables per side for testing:
Air Force 5 MW cable Phase 2 test 76 K

$I_c$ (Phase 2) = 4595 A

$B_{self}$ = 186 mT
Air Force 5 MW cable Phase 1&2 in series

Current runs in opposite direction from Phase 1 to Phase 2 => self-fields cancel.
Air Force 5 MW cable Phase 1&2 in series 76 K

$I_c$ (Phase 1)= 3946 A (6 % more than stand-alone).

$B_{self}$ = 192 mT
Air Force 5 MW cable Phase 1&2 parallel

Current runs in the same direction from Phase 1 to Phase 2 => self-fields add.

Air Force 5 MW cable Phase 1&2 parallel 76 K

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

\[ I_c \text{ (total)} = 7561 \, \text{A} \, (10\% \, \text{less than stand-alone}) \]

\[ B_{\text{self}} = 302 \, \text{mT} \]

The cable exceeds the goal of 6800 A at 76 K!
REBCO CC cables for SMES and other high-field apps.

Benefits of high-current cables for SMES:
- Stored energy could be raised by increasing the winding current.
- High-power SMES possible at relatively low voltage.
- Enables operation at higher temperatures.
- Reduced ac-losses.
- Avoiding single-tape related issues (defects, etc.).

Possible issues for HTS in high-field magnets:
- High-strength needed to withstand Lorenz forces.
- Existence of a large effect of axial strain on flux pinning strength.
Measuring of strain effect on pinning in REBCO CC

-1% Compression

1% Tension

Strain spring

- tensile and compressive strain
- variable field angle $\alpha = 0$ to 360
- 4.2 K and 65-90 K
$I_c-\alpha$ for different $\varepsilon$ at 76 K (Bruker)

HRPLD-ABAD: copper plated, 2.5 µm YBCO.

Sample 1

HRPLD-ABAD: copper plated, 2.8 µm YBCO.

Sample 2

- Strain influences pinning in YBCO!
- Strain sensitivity larger at low angle.
- Sample 2 shows comparable pinning strength $B//c$ and $B//ab$. 
$I_c(\varepsilon)-B$ for $B \parallel ab$ in MOD-RABiTS (AMSC)

$I_c(\varepsilon)$ normalized to its peak at $\varepsilon_m = 0\%$:

- Location of peak in $I_c(\varepsilon)$ shifts with field!
- Strain affects pinning through $B_{irr}(\varepsilon)$.

Pinning is affected $\Rightarrow B_{irr}(\varepsilon)$:
$I_c - \varepsilon - B$ for $B \parallel c$ in MOCVD-IBAD (SuperPower)

$I_c(\varepsilon)$ normalized to its peak at $\varepsilon_m = 0.05\%$.

- $I_c(\varepsilon)$ with double maximum at low field.
- Low-B behavior can be interpreted as a dip: role of grain boundary pinning?

Strain affects pinning through $B_{\text{irr}}(\varepsilon)$.

Likely caused by the pressure dependence of $T_c$. 
Relation between $T_c(\varepsilon)$, $J_c(\varepsilon)$ and pinning in REBCO

YBa$_2$Cu$_3$O$_{7-\delta}$

Anisotropic effect of pressure on $T_c$

From:

Local competing changes in $T_c(\varepsilon)$ result in a $J_c(\varepsilon)$ dependence seen in REBCO.
Does the strain effect depend on the in-plane orientation?

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

Bridges at various angles with the conductor axis:

\[
\begin{align*}
\alpha &= 0 \\
\alpha &= 45 \\
\alpha &= 90
\end{align*}
\]

And apply strain along the bridge:
Strain effect at various in-plane angles

\[ \alpha = 0, 90 \]  \hspace{2cm} \[ \alpha = 22.5, 67.5 \]

- Effect of strain decrease when strain is no longer aligned with \(a\)- and \(b\)-axes!

- Strain effect almost absent at \( \alpha = 45 \)!

D.C. van der Laan, et al., accepted for publication SUST (2011).
Anisotropic in-plane strain effect in REBCO

\[ \frac{I_c(\varepsilon)}{I_c(\varepsilon_m)} = 1 - a(\alpha) \left| \varepsilon - \varepsilon_m \right|^{2.2} \]

\[ a(\alpha) = a(0^\circ) |\cos(\alpha) - \sin(\alpha)| \]

Strain sensitivity is highly dependent on \( \alpha \).

Impact of strain effect for high-field applications

Pressure dependence of $T_c$ causes a large reduction in pinning strength in high-B applications that are wound from single conductors.

The change in $T_c$ with strain is expected to be highly-reduced in applications that are wound from helical cables:
Mechanical testing of REBCO helical cables

Solid copper former 5.2 mm diameter:

Important to measure displacement with extensometers!
Mechanical testing of REBCO helical cables cont.

Cable installed with flexible current leads:

Current leads handle >1000 A at 76 K.
Mechanical testing of REBCO helical cables cont.

Cable: 2 layers, 4 tapes plus 2 dummy tapes on solid Cu former:

Initial damage at 144 MPa near current contacts due to stress concentrations.

$\sigma_{irr}$ expected to be >144 MPa.
The strain effect in helical cables is highly reduced!

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

Cable: $I_c (\sigma_{irr}) = 0.97 I_c(0)$
REBCO helical cable tests at 4.2 K, 20 T

**Cable 1:** 2 layers, 6 GBCO CC, preformed Al former:

\[ I_c = 600 \text{ A @ 76 K, s.f.} \]

**Cable 2:** 4 layers, 12 GBCO CC, flexible Cu former:

\[ I_c = 1100 \text{ A @ 76 K, s.f.} \]

Cable 2 ready for testing:
REBCO helical cable tests at 4.2 K, 20 T

\[ I_c = 534 \text{ A @ 4.2 K, 20 T} \]

\[ I_c = 875 \text{ A @ 4.2 K, 20 T} \]

Cable results at 20 T look promising for high-field magnets => next: higher currents!
We’ve demonstrated:

- Possibility of helically winding YBCO coated conductors around very small formers.

- High current DC transmission cables are possible:
  2800 A in 7.5 mm diameter
  7561 A in 10 mm diameter
  => exceeded the performance for Air Force 5 MW power transmission at 50-55 K

- Large reduction in pinning expected in single-tape high-field applications.

- The effect is highly-reduced when the application is wound from helical cables.

- The first successful cable test at 4.2 K in fields up to 20 T
Commercialization of REBCO helical cables

Advanced Conductor Technologies LLC
www.advancedconductor.com

Danko van der Laan 720-933-5674