Record $J_e$ of 246 A/mm$^2$ at 17 T in CORC
cables made by Advanced Conductor Technologies

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Outline

• Introduction to CORC cables
• Early results on CORC cables for high-field magnet applications
• Quality improvements of CORC cables and their terminations
• Current status of CORC cable development for high-field magnet applications
• Future improvements in CORC cables as a result of conductor development
• Summary
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**
- The most flexible HTS cable available
- Very high currents and current densities
- Mechanically very strong
- Current sharing between tapes
- Partially transposed

D.C. van der Laan, **SUST 22, 065013 (2009).**
Science behind CORC cables: strain management

Reversible effect of axial strain on $I_c$ of REBCO coated conductors

Large margin in compressive axial strain.
Relation between $T_c(\varepsilon)$ and $J_c(\varepsilon)$ in YBCO

YBa$_2$Cu$_3$O$_{7-\delta}$: Anisotropic effect of pressure on $T_c$

Effect of pressure on $T_c$ is opposite for pressure applied along $a$-axis compared to $b$-axis

Films in YBCO CC are twinned:
In case $T_c(\varepsilon)$ defines $J_c(\varepsilon)$:

Competing domains likely result in a maximum in $I_c$

From:

Local competing changes in $T_c(\varepsilon)$ may result in a $I_c(\varepsilon)$ dependence seen in YBCO.
Anisotropic in-plane reversible strain effect in CC

MOCVD-IBAD: $a$ - and $b$ -axes aligned with conductor axis!

Cutting bridges at various angles from CC allows us to change the in-plane orientation of the strain.

Reversible strain effect disappears when strain is aligned $45^\circ$ with the tape axis!
Strain effect on $I_c$ of CORC cables

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

CORC cable: $I_c (\sigma_{\text{irr}}) > 0.98 \ I_c(0)$

The strain effect in CORC cables is highly reduced when tapes are wound close to 45°!
CORC cable development for accelerator magnets

Main program goals
- Develop CORC cables with an engineering current density \( J_e > 300 \text{ A/mm}^2 \) at 4.2 K and 20 T
- Improve the cable flexibility to allow bending to diameters of 60 mm or less

CORC cable development for accelerators is supported by the Department of Energy, Office of High Energy Physics
- At the University of Colorado: award number DE-SC0007891
- Phase II SBIR at Advanced Conductor Technologies: award number DE-SC0009545
- Support from NIST in the form of lab space and equipment
Testing of CORC cables at high fields

High-current insert with sample holder at bottom:

Sample holder for 10 cm diameter cables:
CORC cable test facilities in the U.S.

**NIST/Univ. of Colorado:**
- 8.75 T superconducting solenoid magnet.
- 12,800 A sample current.

**NHMFL:**
- 17 T resistive solenoid user magnet.
- 12,100 A sample current (switchers), 20,000 A in-house.

University of Colorado program sponsored by:
DOE - Office of High Energy Physics, award DE-SC0007891
Early CORC accelerator cable development

CORC cables wound by hand until 2014
- 52 YBCO coated conductors
- 17 layers
- cable O.D. 7.5 mm

52 tape CORC cable tested at the NHMFL
- 4.2 K
- 19 T

\[ I_c = 5,021 \, \text{A} \, @ \, 4.2 \, \text{K}, \, 19 \, \text{T}, \, 1 \, \mu\text{V/cm} \]

\[ J_e = 114 \, \text{A/mm}^2 \, @ \, 4.2 \, \text{K}, \, 19.0 \, \text{T} \]
CORC cable machine

Winding of long CORC cables with custom cable machine:
• Accurate control of cable layout
• Long cable lengths possible (>100 meters)

Commercial order from CERN:
• 12 meter CORC magnet cable
• Delivered August 2014
Improvement in CORC cable quality

CORC cables wound by hand
- 80% density results in deformation during bending
- Variable gap spacing allows tapes to kink

CORC cables wound by machine
- >95% density
- Even gap spacing allows for better cable flexibility
Early CORC cable terminations

Tapes each soldered to copper terminal
- long and difficult process
- large in size
- significant change of damage
- inhomogeneous contact resistance

Kink indicates inhomogeneous current distribution in cable

Voltage measured on copper terminals
New CORC cable terminations

Cable end inserted in solder-filled copper tube
- less chance of damaging tapes
- much more practical
- smaller
- tapering the superconducting layers ensures each tape is in direct contact with copper tube
- more homogeneous current distribution in cable

Voltage measured on copper terminals
Current densities in early CORC cables

CORC cables made from “standard” SuperPower tapes
50 μm thick substrate, \( I_c = 100 – 120 \text{ A @ } 77 \text{ K}, I_c = 100 – 140 \text{ A @ } 4.2 \text{ K}, 20 \text{ T} \)

Each added layer increases \( J_e \), but also the cable size.

Adding tapes becomes less effective at some point.

“Standard” tapes limit \( J_e(20 \text{ T}) \) to about 200 A/mm²

Accelerators need “advanced” tapes: - thinner substrates
- better pinning
- higher \( I_c \) through thicker films
Thinner tape substrates are coming!

“Advanced Conductor Technologies has been eagerly awaiting this new, thinner profile conductor for incorporation into our high current density Conductor on Round Core (CORC) cable,” said Dr. Danko van der Laan, founder and chief executive officer of the start-up company located in Boulder, Colorado...”

http://superpower-inc.com/content/superpower-adds-thinner-substrate-options-superconducting-wire-offerings
**Effect of substrate thickness on minimum former size**

**Ic retention test**
- tapes with 38 and 50 μm sub.
- ensuring a winding angle of 45°
- copper tape to ensure constant gap spacing
- 3 samples per diameter

**Minimum former diameter**
- 4 mm for 50 μm substrate
- 3.2 mm for 38 μm substrate
- 2-2.4 mm is expected for 30 μm substrate

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**Degradation starts between -1.2 and -1.5 % strain**
CORC cable wound from tapes with 38 μm substrate

**CORC cable**
- 50 tapes with 38 μm substrate
- tapes are 4 mm wide.
- standard 7.5 % Zr doping
- Ic (77 K) = 116 – 129 A
- former diameter 3.45 mm
- cable outer diameter 5.9 mm
- cable wound with machine
- overall tape length 1.41 m/m cable
- tube terminations

<table>
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<th>Layer</th>
<th># tapes</th>
<th>ID [mm]</th>
<th>Gap [mm]</th>
<th>Pitch [mm]</th>
<th>α [%]</th>
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Contact resistance at 4.2 K and 17 T

- Fit of voltage over terminals shows a **contact resistance of 5.8 nΩ per terminal.**
- Voltage contacts broke at 3,500 A due to incorrect sample current direction.
Performance at 4.2 K and 17 T

New voltage contacts no longer co-wound with cable, resulting in significant noise:

\[
I_c (4.2 \text{ K, 17 T}) = 6,898 \text{ A}
\]

\[
J_e (4.2 \text{ K, 17 T}) = 246 \text{ A/mm}^2
\]

\[
I_c (4.2 \text{ K, 17 T}) = 6,966 \text{ A}
\]
Projected $J_e$ 4.2 K and 20 T

Determining performance at 20 T through $I_c = I_o B^{-0.72}$

Projected $I_c$ (4.2 K, 20 T) = 6,023 A

Projected $J_e$ (4.2 K, 20 T) = 213 A/mm²
Current status

CORC cable wound by machine has 75% $I_c$ retention at 20 T
Tapes with enhanced pinning are becoming available

**Tapes with enhanced pinning**
- 15% Zr doping, instead of 7.5% Zr
- currently only on 50 µm substrate
- initial 600 meters received
- $I_c(4.2 \text{ K}, 20 \text{ T})/I_c(77 \text{ K}, \text{s.f.})= 1.9$ (instead of 1.4)
Tapes with thicker films are becoming available.

Tape batch on 38 μm substrate received last week

<table>
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<tr>
<th>Spool ID.</th>
<th>Length (m)</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Ic (A)</th>
<th>STDEV (%)</th>
<th>Ic (A) Minimum</th>
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Thicker REBCO film of 1.7 μm results in increase in $I_c$ of 30% and seem to become available soon!
CORC cable performance projections

30 μm substrate: delivery **July 2015**: expected $J_e$ (20 T) $> 300$ A/mm²
30 μm + 15 % Zr: delivery **August 2015**: expected $J_e$ (20 T) $> 450$ A/mm²
30 μm + 15 % Zr + 1.7 μm REBCO: expected $J_e$ (20 T) $> 600$ A/mm²
Summary

CORC cables are available in long lengths, right now
- \( I_c \) up to 6 kA at 20 T
- \( J_e \) of over 200 A/mm\(^2\) at 20 T
- Cable outer diameter of less than 6.0 mm.

Many thanks to SuperPower for making incredible steps toward better conductor performance!

- > 300 A/mm\(^2\) Sept. 2015
- > 450 A/mm\(^2\) Dec. 2015
- > 600 A/mm\(^2\) 2016/2017