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

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• 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 $T_c$

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!

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

The strain effect in CORC cables is highly reduced when tapes are wound close to $45^\circ$!

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

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

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

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

DOE - Fusion, awards DE-SC0007660 and DE-SC0009485
Current densities in early CORC cables

CORC cables made from “standard” SuperPower tapes
50 µm thick substrate, $I_c = 100 – 120$ A @ 77 K, $I_c = 100 – 140$ A @ 4.2 K, 20 T

“Standard” tapes limit $J_e(20$ T) to about 200 A/mm²

Accelerators need “advanced” tapes:
- thinner substrates
- better pinning
- higher $I_c$ through thicker films
“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...”
Effect of substrate thickness on minimum former size

\( I_c \) retention test
- tapes with 38 and 50 \( \mu \)m 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 \( \mu \)m substrate
- 3.2 mm for 38 \( \mu \)m substrate
- 2-2.4 mm is expected for 30 \( \mu \)m substrate

Degradation starts between -1.2 and -1.5 \% strain
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

Layer | # tapes | ID [mm] | Gap [mm] | Pitch [mm] | [°] | Efficiency [-]
------|---------|--------|----------|------------|-----|----------------
1      | 2       | 3.45   | 0.4      | 15.1       | 54.3| 1.24           
2      | 2       | 3.55   | 0.5      | 15.2       | 53.7| 1.25           
3      | 2       | 3.66   | 0.5      | 14.5       | 51.6| 1.28           
4      | 2       | 3.76   | 0.7      | 15.5       | 52.7| 1.26           
5      | 2       | 3.87   | 0.7      | 14.8       | 50.7| 1.30           
6      | 2       | 3.97   | 0.7      | 14.3       | 48.9| 1.33           
7      | 2       | 4.07   | 0.7      | 13.9       | 47.3| 1.37           
8      | 2       | 4.18   | 0.7      | 13.5       | 45.7| 1.40           
9      | 2       | 4.28   | 0.7      | 13.1       | 44.3| 1.44           
10     | 2       | 4.39   | 0.7      | 12.9       | 43.0| 1.48           
11     | 2       | 4.49   | 0.7      | 12.6       | 41.8| 1.51           
12     | 2       | 4.59   | 0.7      | 12.4       | 40.6| 1.55           
13     | 2       | 4.70   | 0.7      | 12.2       | 39.6| 1.58           
14     | 2       | 4.80   | 0.7      | 12.0       | 38.5| 1.62           
15     | 2       | 4.91   | 0.7      | 11.9       | 37.6| 1.65           
16     | 2       | 5.01   | 0.7      | 11.7       | 36.7| 1.69           
17     | 2       | 5.11   | 0.8      | 12.0       | 36.7| 1.68           
18     | 2       | 5.22   | 0.8      | 11.8       | 35.8| 1.72           
19     | 2       | 5.32   | 0.8      | 11.7       | 35.0| 1.75           
20     | 3       | 5.43   | 0.7      | 25.1       | 55.8| 1.21           
21     | 3       | 5.53   | 0.7      | 24.1       | 54.3| 1.24           
22     | 3       | 5.63   | 0.7      | 23.3       | 52.8| 1.26           
23     | 3       | 5.74   | 0.7      | 22.6       | 51.5| 1.28           

Advanced Conductor Technologies LLC
www.advancedconductor.com
- 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:

- Current ramp rate 600 A/s: $I_c (4.2 \text{ K, 17 T}) = 6,898 \text{ A}$
- Current ramp rate 60 A/s: $I_c (4.2 \text{ K, 17 T}) = 6,966 \text{ A}$

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

Phase II SBIR DOE-High Energy Physics Award DE-SC0009545
Projected $J_e$ 4.2 K and 20 T

Determining performance at 20 T through $I_c = I_0 B^{-0.72}$

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)

![Graph showing $I_c(4.2 \text{K}, 20 \text{T}) / I_c(77 \text{K}, \text{s.f.})$ for different substrate thicknesses.]
Tapes with thicker films are becoming available

Tape batch on 38 µm substrate received last week

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.

**Je in CORC cables expected to increase**

- 30 mm thick substrates
- Advanced pinning due to 15% Zr
- Thicker REBCO films

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

Many thanks to SuperPower for making incredible steps toward better conductor performance!
Development and characterization of HTS conductors and cables for use in accelerator and other high-field magnets

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