CORC®: Results and Perspectives

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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® cable (5-8 mm diameter)
• Wound from 3-4 mm wide tapes with 30 or 50 μm substrate
• Typically no more than 50 tapes
• Flexible with bending down to >100 mm diameter

CORC®-CICC
• Performance up to 100,000 A (4.2 K, 20 T)
• Combination of multiple CORC® cables or wires
• Bending diameter about 1 meter

Courtesy Tim Mulder (CERN/Univ. Twente)
Winding CORC® cables
• Accurate control of cable layout
• Long cable lengths possible
• $I_c$ retention after winding 95-100%
• 120 meters wound in 2016, of which 70 meter for commercial orders

CORC® cable
• 50 tapes with 30 μm substrate
• 3 mm wide tape $I_c$ (77 K) = 108 A
• Lift factor $I_c(4.2K, 20T)/I_c(77K, \text{s.f.}) = 1.72$
• Bent to 100 mm diameter

Extrapolated $I_c$ (4.2 K, 20 T) = 6,354 A

Extrapolated $J_e$ (4.2 K, 20 T) = 309 A/mm$^2$
\( J_e \) in CORC\textsuperscript{®} accelerator cables: current and future

CORC\textsuperscript{®} cable \( J_e \) on track to 600 A/mm\(^2\) at 20 T
- \( J_e \) of 309 A/mm\(^2\) at 20 T achieved in Oct. 2015
- Projected \( J_e \) 450 A/mm\(^2\) mid 2016
- Projected \( J_e \) 600 A/mm\(^2\) early 2017

In-field CORC\textsuperscript{®} cable testing @ 100 mm
- Large bore magnet at NHMFL (17 T)
- Large bore magnet at CU (8.75 T)

Problems!
- NHMFL magnet decommissioned
- Cable \( I_c \) at 8.75 T >> 10 kA
  - No new tests after Oct. 2015!
  - New 14 T large bore magnet expected at NHMFL in 2017
Current CORC® cable performance (untested!)

Performance of commercial tapes
- Purchased 8,300 meters from SuperPower in 2016
- Tapes with 30 and 50 μm substrates

Record 2016 samples
- M4-396: lift factor $I_c(4.2K, 20T)/I_c(77K, s.f.) = 2.65$
- Typical lift factor (20 T) = 1.9
- $I_c (77 K) = 167$ A (4 mm, 50 μm)
- $I_c (77 K) = 82$ A (2 mm, 30 μm)
- Typical $I_c$ (4 mm) 150 A, (2 mm) 68 A

CORC® cable Oct. 2015 $J_e(20T)$
- All estimates with $I_c$ retention of 70 %
- Typical $I_c$ and lift factor: $J_e(20 T) = 375$ A/mm$^2$
- Highest $I_c$ and lift factor: $J_e(20 T) = 560$ A/mm$^2$
- At 90 % $I_c$ retention: $J_e(20 T) = 480-720$ A/mm$^2$

- On track to $J_e(20 T) > 600$ A/mm$^2$
- Need magnet to demonstrate!
CORC® cables are ready for the next step

• R&D for their application into magnets
• Cable bending diameter > 100 mm
• Cable $J_e (20 \, \text{T}) > 400 \, \text{A/mm}^2$
• Operating current > 10,000 A (20 T)

Common Coil magnet ideal for CORC® cables

• Conductor friendly design
• Performance determined by coil separation, not cable bending diameter
• Allows for large bending diameters > 250 mm

Proposed program to Department of Energy

• Teaming with Ramesh Gupta (BNL)
• 10 T LTS Common Coil outsert magnet
• Phase I SBIR funding requested to develop 5 T CORC® insert magnet
Introduction of flexible CORC® magnet wires

**CORC® cables**
- Cable diameter 5 – 8 mm
- Bendable to >100 mm diameter
- Typically 50 tapes or less (3 mm or 4 mm wide)
- Easier to reach high $J_e$ (20 T)

**CORC® wires**
- Tapes with 30 μm substrate
- Wire diameter 2.5 – 4.5 mm
- Bendable to < 50 mm diameter
- Typically 30 tapes or less (2 mm and 3 mm)
- Size and flexibility requirements make it harder to reach high $J_e$(20 T)

First round, isotropic YBCO wire!
Thinner substrates enable CORC® wires

\[ I_c \] retention test
- tapes with 30, 38 and 50 µm sub.
- ensuring a winding angle of 45°

**Degradation starts at compressive strain exceeding -1.2 %**

**Minimum former diameter**
- 4 mm for 50 µm substrate
- 3.2 mm for 38 µm substrate
- 2.4 mm for 30 µm substrate
Strain tolerance depends on substrate quality

**Tapes on 30 μm substrate from two Hastelloy batches**
- Earlier batch of softer substrate material
- Latest batch with harder substrate material

**Substrate hardness or overall quality likely to affect minimum former size**
Testing of CORC® wire flexibility

**CORC® wire layout**
12 tapes of 2 mm width (3.3 mm O.D.)

**Bending wire followed by $I_c$ measurement**

**Bending wire sections followed by extracted tape $I_c$ measurements**

35 mm diameter

75 mm
50 mm
35 mm
12-tape CORC® wire bending results

Bending wire sections followed by 2 mm wide tape $I_c$ measurements

- Degradation in inner layer due to surface roughness

- $I_c$ measurements after wire bending

- $I_c$ retention even at 35 mm bending diameter

% nominal $I_c$ vs. Winding diameter (mm)

- 100%
- 80%
- 60%
- 40%
- 20%
- 10%
- 0%

Tape layer (in to out)

- 1
- 2
- 3
- 4
- 5
- 6

T = 76 K

% nominal $I_c$ vs. Bending Diameter (cm)

- 100%
- 80%
- 60%
- 40%
- 20%
- 10%
- 0%

T = 76 K

$I_c$ before bending

Advanced Conductor Technologies LLC
www.advancedconductor.com
In-field performance of 16-tape CORC® wire

**CORC® wire layout**
- 16 tapes of 2 mm width
- 3 mm diameter
- Expected $I_c(10 \, \text{T}) = 2,900 \, \text{A}$

**Test layout**
- 5 turns at 60 mm diameter
- Stycast reinforcement

**Results**
- $I_c = 1,695 \, \text{A} (4.2 \, \text{K}, 10 \, \text{T}, 0.1 \, \text{µV/cm})$
- $I_c = 2,560 \, \text{A} (4.2 \, \text{K}, 10 \, \text{T}, 1 \, \text{µV/cm})$
- Projected $J_e(20 \, \text{T}) = 145-210 \, \text{A/mm}^2$

80 % $I_c$ retention after extracted tape measurements agrees with CORC® wire measurement

Courtesy Tim Mulder (Univ. Twente/CERN)
Projected $J_e$ of CORC® wires

Advanced Conductor Technologies is working with SuperPower to further decrease the substrate thickness to 20-25 μm

$J_e(20 \text{ T})$ of a 3.5 mm CORC® wire likely to increase from 300 A/mm² to 1,000 A/mm² when combining lift factor of 2.65 with 20 μm thick substrates

29-Tape CORC® wire with $J_e(20 \text{ T}) > 300 \text{ A/mm}^2$ to be tested next week
Final deliverable Phase II SBIR with ASC-NHMFL

- Develop 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, maybe 5 T depending on tape performance

CORC® wire solenoid details

- CORC® wires wound from 3 mm wide tape with 30 µm substrate
- 1,500 meter tape ordered, 1/3 already delivered
- CORC® wire length 20-30 meters depending on tape performance
- Potential for second insert using CORC® wires with 2 mm wide tape
CORC® wires in Canted-Cosine-Theta magnets

Teaming up with Lawrence Berkeley National Laboratory
- Develop 5 T Canted-Cosine-Theta insert
- Insert wound from CORC® wires
- More details Xiaorong Wang talk tomorrow

Several steps
1. 2-layer insert C1
2. 4-layer insert C2
3. ... C1

CCT insert C1
- 2-layers, 40 turns per layer
- Determine feasibility and field quality
- 16-tape CORC® wire

CCT insert C2
- 4-layers, 40 turns per layer
- Push for field: 2-3 T in 10 T external field
- 29-tape CORC® wire, expected $J_e(20 T) 300 A/mm^2$
- 100 meter CORC® wire order expected 2017

50 m, 16-tape CORC® wire for CCT-C1
CCT C1
• Inner layer I.D. 70 mm
• Minimum bending diameter 50 mm

16-tape CORC® wire
• $I_c$ (77 K) before winding = 718 A
• $I_c$ (77 K) after winding = 662 A
• Only 8% lower after winding

• Feasibility of using CORC® wires in CCT magnets has been demonstrated
• 4.2 K measurement needs better power supply (end of February)
CORC® magnet feeder cables

CORC® magnet feeders
- Bi-2212 insert of the 23.5 T Platypus NMR magnet ($I_{\text{opp}} = 400$ A) (Ulf Trociewitz)
- REBCO insert coils of the 32 T magnet ($I_{\text{opp}} = 200$ A) (Huub Weijers)

Platypus

500 A vapor cooled leads

CORC® feeders

7.1 T Bi-2212 Magnet System

16.4 T magnet

32 TESLA SUPERCONDUCTING MAGNET

YBCO

NbSn

NbTi

745 mm

$\phi 32 \text{mm}$

$\phi 574 \text{mm}$
CORC® feeder cables: 32 T magnet

CORC® feeders for 32 T magnet

- $I_{\text{opp}} = 200$ A
- Background field 23 T
- Vertical motion of 4-8 mm during cool down and field ramping

Feeders delivered in 2016 and are installed into the 32 T magnet
Summary

**CORC® cables with bending diameter > 100 mm**
- Demonstrated $J_e(20 \text{ T}) = 309 \text{ A/mm}^2$
- On track to reach $J_e(20 \text{ T}) > 600 \text{ A/mm}^2$
- No new CORC® cables measured at high field after Oct. 2015 due to decommissioning of large-bore magnet at NHMFL
- CORC® cables are ready for conductor friendly accelerator magnets such as Common Coil magnets

**CORC® wires with bending diameter < 50 mm**
- Demonstrated $J_e(20 \text{ T}) = 145-210 \text{ A/mm}^2$
- On track to reach $J_e(20 \text{ T}) > 300 \text{ A/mm}^2$ (Twente test next week)
- CORC® wires with thinner substrates and $J_e(20 \text{ T}) > 1,000 \text{ A/mm}^2$ on the horizon
- CORC® wires now wound into high-field solenoid and CCT insert magnets

**CORC® magnet feeder cables now available**
- CORC® feeder cables incorporated in 32 T REBCO magnets at NHMFL