High-field magnets wound from CORC® cables and wires

Danko van der Laan & Jeremy Weiss
Advanced Conductor Technologies & University of Colorado, Boulder, Colorado, USA

Dustin McRae
University of Colorado, Boulder, Colorado, USA

H. Higley, S. O. Prestemon and X. Wang
Lawrence Berkeley National Laboratory, Berkeley, California, USA

Huub Weijers, Dima Abraimov, Youri Vouchkov and David Larbalestier
National High Magnetic Field Laboratory, Tallahassee, Florida, USA

Tim Mulder & Herman ten Kate
University of Twente, Enschede, the Netherlands & CERN, Geneva, Switzerland

Ramesh Gupta
Brookhaven National Laboratory, Upton New York, USA

This work was in part supported by the US Department of Energy under agreement numbers DE-SC0007891, DE-SC0007660, DE-SC0009545, DE-SC0014009, DE-SC0015775 and DE-SC0018127.
Conductor on Round Core (CORC®) cables

**CORC® cable principle based on strain management**
Winding many high-temperature superconducting YBCO coated conductors from SuperPower in a helical fashion with the YBCO under compression around a small former to obtain high cable currents.

RE-Ba₂Cu₃O₇-δ coated conductor made by SuperPower Inc.

**Single tape wound into a CORC® cable**

**Benefits of CORC® cables and wires**
- Very high currents and current densities
- Mechanically very strong
- Very flexible
- High level of conductor transposition

Advanced Conductor Technologies LLC
www.advancedconductor.com
CORC® cable production at ACT

Winding of long CORC® cables with custom cable machine
- Accurate control of cable layout
- Long cable lengths possible (> 100 meters)
- $l_\infty$ retention after winding 95-100%

First commercial sale (CERN)
- 12 meter CORC® cable (38 tapes)
- Cable for detector magnets
- Delivered August 2014

Many commercial orders followed
About 200 meters of CORC® cable and wire total between 2014 and Oct. 2017
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 30-50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to > 100 mm diameter

CORC®-Cable In Conduit Conductor (CICC)
- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 1 meter
CORC® cable development for accelerator magnets

Overall goals
1. High engineering current density $J_e$ (20 T) > 600 A/mm²
2. Small cable bending diameters 20 – 50 mm
3. Develop CORC® cables and wires for new magnet configurations

LHC

Heidelberg PBT gantry

Advanced Conductor Technologies LLC
www.advancedconductor.com
Canted-Cosine-Theta accelerator magnets

**CORC® magnet program #1 with Berkeley National Laboratory**
- Develop CORC® wires that enable Canted-Cosine Theta (CCT) magnets
- Develop the magnet technology for CORC®-CCT magnets

**Canted-Cosine-Theta magnets**
- Conductor-friendly magnet design resulting in low stresses
- Delivers excellent geometric field quality in straight section and coil ends
The road to 20 T in CORC®-CCT magnets

**Overall goal**
- Generate 5 T in a 15 T background field
- Multi-year program performed in several steps

**Step 1: 2-Layer, 40-turns CCT magnet (C1)**
- Generate 1-2 T in self-field
- CORC® wire $J_e(20\ T) = 150-200\ \text{A/mm}^2$
- Learn to wind and protect CORC®-CCT magnets

**Step 2: 4-Layer, 40-turns magnet (C2)**
- Generate 2.5 - 3 T in a 10 T background field
- CORC® wire $J_e(20\ T) = 300-400\ \text{A/mm}^2$
- CORC® wire bendable to 30 mm diameter

**Step 3: 6-Layer, 40-turns CCT magnet (C3)**
- Generate 5 T in a 15 T background field
- CORC® wire $J_e(20\ T) = 600\ \text{A/mm}^2$
- CORC® wire bendable to 20 mm diameter
CORC® wires in Canted-Cosine-Theta magnets

CORC®-CCT parameters to consider

• Fixed aperture of 50 mm
• Tilt angle determines field efficiency
• CORC® wire needs to be flexible
• Current and current density of the CORC® wire needs to be sufficient to deliver the required field performance

Currently focusing on 40-50 mm bending diameter, hoping to allow 20-30 mm in the coming years
16-Tape CORC® magnet wire for C1

**Low-$j_e$ CORC® wire layout**
- Developed to learn how to wind CORC®-CCT magnets
- 16 tapes, 2 mm wide, 30 μm substrate
- 3.0 mm diameter
- 5 turns on 60 mm diameter mandrel for testing at 10.5 T

![Graph showing $E$ vs. $I$](image)

- $I_c = 2,560$ A (4.2 K, 10 T, 1 μV/cm)
- Projected $j_e(20 T) = 210$ A/mm²

50 Meter long CORC® wire delivered to LBNL to wind CCT-C1
Fabrication of 3-turn baby CCT coils

3-Turn baby coils C1-0 and C2-0
- Evaluate the CORC® wire performance and identify potential issues before moving to the 40-layer coils

Printed mandrels  Individual layers  Assembly before test

Assembling two layers
Baby coil C1-0: CORC® wire test for CCT-C1

CCT C1-0: CORC® wire with 16 tapes
- 2 Layers
- 3 Turns per layer
- Inner layer I.D. 70 mm
- Minimum bending diameter 50 mm

CCT C1-0 performance
- $I_c$ (77 K) = 646 A (layer A) and 675 A (layer B)
- $I_c$ (4.2 K) = 6,700 A (both layers)
CORC® CCT-C1

CCT-C1 Magnet wound at LBNL
- 2 Layers, 40 turns per layer
- LBNL ordered 50 m of CORC® wire in 2016
- CORC® wire contains 16 tapes, $J_e$ (20 T) = ~150 A/mm²

Initial results look promising, will continue Dec. 2017
High-$J_e$ CORC® wire layout

- 27 tapes, 2 mm wide, 30 μm substrate
- 3.6 mm diameter
- 5 turns on 60 mm diameter mandrel
$J_e$ in CORC® wires for CCT-C2

- $I_c = 3,831 \, \text{A} (4.2 \, \text{K}, 12 \, \text{T}, 1 \, \mu\text{V/cm})$
- Projected $J_e (20 \, \text{T}) \, 259 \, \text{A/mm}^2$
- No degradation due to stress cycling
- $I_c$ retention is 75.7% of initial tape $I_c$
Baby coil C2-0: CORC® wire test for CCT-C2

CCT C2-0: CORC® wire with 29 tapes
- 3-turn per layer
- Inner layer I.D. 85 mm
- CORC® wire $J_e$ (20 T) = ~300 A/mm²

CCT C2-0 performance
- $I_c$ (77 K) = 1.092, 1,067 A (layer A, B)
- $I_c$ (4.2 K) = 12,141, 11,078 A (layer A, B)
- Dipole field 0.68 T (4.2 K)
- Peak $J_e$ (4.2 K) = 1,198 A/mm²
- Expected field of CCT-C2 (40 turns) ~5 T

- Coil B burned out at 12,400 A at 4.2 K due to unprotected quench
- CORC® wire has been replaced to finalize testing
- Order for 75 m of high-$J_e$ CORC® wire received from LBNL
- Full-size coil C2 expected to be wound in Q2 2018
CORC® wire magnet program #2 in collaboration with CERN

- Develop CORC® wire technology for 20 T racetrack coils for accelerators
- 8 meters of CORC® wire (29 tapes) delivered last month
- Racetrack with 2 layers and 8 turns per layer
- Coil performance of 0.38 T per kA
- Expected performance 4.5 kA at 10 T
High-field insert solenoid wound from CORC® wires

**CORC® wire magnet program #3 in collaboration 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® insert wire details**

**Coil 1**
- Wound form ~17 meters of CORC® wire
- Coil $I_c$ at 100% retention about 5,000 A
- $J_e(17 \text{T})$ about 200 A/mm²
- Total of 48 turns in 4 layers
- Field generated 2.6 T in 14 T background

**Coil 2**
- Wound form ~6 meters of CORC® wire
- Coil $I_c$ at 100% retention about 5,000 A
- $J_e(17 \text{T})$ about 200 A/mm²
- Total of 24 turns in 2 layers
- Field generated 1.7 T in 16-17 T background

**Diagram**
- 14 T + 2.6 T = 18.3 T
- 58.8 mm
- 80 mm
- 120 mm

- 55 mm
- 75 mm
Common coil magnet from CORC® cables

CORC® cable magnet program #4 with Brookhaven National Laboratory
- CORC® cable common coil insert
- Combine with 10 T LTS common coil insert
- Operating $J_e$ 400-500 A/mm² (15-20 T)
- Operating current 10 kA in series with LTS insert

Common coil benefits
- Only large bending diameters required
- Allowing CORC® cables to be used
- Allowing use of highest $J_e$ cables

Advanced Conductor Technologies LLC
www.advancedconductor.com

Brookhaven National Laboratory

CU
Record CORC® magnet wire performance

High-$J_e$ CORC® wire layout
- 50 tapes, 2-3 mm wide, 30 μm substrate
- 4.46 mm CORC® wire diameter
- 62 mm hairpin (much tighter bend than in Common Coil)

\[
\begin{align*}
E & \text{ (μV/cm)} \\
I & \text{(A)} \\
\end{align*}
\]

- $I_c = 8,591 \text{ A (4.2 K, 12 T, 1 μV/cm)}$
- Projected $J_e(20 \text{ T})$ between 379 and 429 A/mm$^2$
- $I_c$ retention is 74.5% of initial tape $I_c$
CORC® cable development for fusion magnets

Main program goals
- Develop CORC®-CICC with operating current 50-100 kA at 4.2 K and 12-20 T
- Develop CORC® cable terminations that allow for high-current cable joints

ITER
Tokamak Energy Ltd
ATLAS detector
CORC®-CICC for fusion and detector magnets

6-around-1 CORC®-CICC
- 80 kA (4.2 K, 11 T)
- 42 tapes per CORC® cable
- Stainless steel or copper jacket

Sample 1 for detector magnets
- High thermal & electrical stability
- Practical cooling
- 80 kA at 12T/4K

Sample 2 for fusion magnets
- Can sustain high stress
- Can cope with large heat loads
- 80 kA at 12T/4K

Advanced Conductor Technologies LLC
www.advancedconductor.com

UNIVERSITY OF TWENTE.
CORC®-CICC SULTAN test

Some issues were encountered:
- One bad joint (in field)
- Exotic hydraulic layout

Only $I_c(B, T)$ measurements at 40-55 K were possible

Loop Resistance of 23 nΩ!

Joint 1
0.6 nΩ

Joint 2
2.9 nΩ

Joint 5
0.6 nΩ

Joint 4
1.4 nΩ

Conductor 1

Upper Joint

Conductor 2

Cooling direction ---->  <---- Cooling direction

Field Center

SULTAN

Joint 3
17 nΩ ≈ 40 W @ 50 kA
**CORC®-CICC SULTAN test: 4.5 K vs. 50 K**

**Effect of heating at joint**
- Heating at bottom joint causes thermal runaway at 4.5 K
- Only the fusion sample could be measured at 4.5 K
- Heating not much of a problem at 50 K
- Both samples perform as expected at 50 K, 10.9 T
Fusion CORC®-CICC at 46 K

- Field dependence could be measured up down to 7 T
- Sample performed as expected

T = 46 ± 1 K

- Bottom joint has been, but detector sample still showed lower $I_c$
- Detector sample now being inspected and may possibly be replaced
CORC® wires and cables have matured into magnet conductors
- High currents have been demonstrated (> 8,000 A (4.2 K, 12 T))
- High current densities have been reached (> 400 A/mm² (4.2 K, 20 T))
- CORC® wires are highly flexible (< 50 mm bending diameter)

Several CORC® magnet programs underway
- 15 T Canted Cosine Theta magnets from CORC® wires
- 12 T Racetrack coil from CORC® wires
- 18 T CORC® wire insert solenoid
- 15 T Common Coil from CORC® cables

CORC®-CICC for fusion and detector magnets
- 80 kA (4.2 K, 11 T) 6-around-1 CORC®-CICC test ongoing
- Technical problems with one of the samples is being resolved
- SULTAN test will continue in coming months