Development of Compact CORC Multi-Layer Racetrack and Solenoid Coils

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ReBCO Multi-Tape Conductors

ReBCO Multi-Tape Cables:
• Large magnets require currents beyond the capacity of a single ReBCO tape.
• Multiple tapes combined to a high-current ReBCO cable.
• Increased stability, single tape defects are less pronounced.
• Reduction of inductive and coupling losses.
• Three main designs: Roebel, Twisted Stacked Tape Cable (TSTC) and Conductor on Round Core (CORC).

TSTC:
• Tape stack with high current density.
• Difficult to bend and long twist pitch.
• Copper shell for practical handling during magnet winding.
• Mainly designed for large-scale magnets for fusion reactors.

Roebel:
• High current density.
• Flexible in the ‘out-of-plane’ bending direction.
• Fully transposed.
• Designed for compact high-field magnets.
**CORC Wires, Cables and Cable-In-Conduit Conductors**

**CORC Wire**: accelerator magnets, high-field insert coils or standalone solenoids.

**CORC Cable**: general purpose, stable SC magnets and power transmission.

**CORC Cable-In-Conduit Conductor** (CICC): high current, high-field magnets and HTS bus bars.

**CORC**:
- High omni-directional flexibility.
- Round shape resilient towards transverse loads.
- Internal core stabilized.
- No tape lost during production.
- For compact high-field magnets and large magnets (detector and fusion) and bus bars.

1st CORC Al-jacketed Cable-In-Conduit Conductor.
Quest for CORC-wire optimized ReBCO tape

CORC Wires:
- Made possible by the reduction in substrate thickness from 50 to 30 µm.
- Narrower tapes of 2 mm wide.
- Designed for high-field magnets.

CORC Strands:
- Thicker medium-current cables.
- Designed for large high-field magnets, requiring high thermal/electrical stability.

Further Cable & Wire Optimization:
- Thinner substrate of 30 -> 25 -> 20 µm.
- Narrower tapes of 2.0 -> 1.5 -> 1.0 mm.
- Higher $I_c$ by increasing ReBCO layer thickness to 2 or 3 µm (or even more!).
**ReBCO High-Field Magnets - Examples**

**Benefits of ReBCO for High Field Magnets:**

- ReBCO conductors by far surpass common LTS conductors in $I_c$ and $B_{c2}$ at 4.2 K.
- User magnetic field far beyond 20 T in 4 to 30 K range.
- Extreme thermal and electrical stability!
- Hybrid HTS/LTS solutions available.

- Several ReBCO Roebel and CORC demonstrator coils have been exercised in the last years.

- CORC’s round shape allows multi-directional bending, thus practical coil winding, i.e. the CCT of LBNL.
CERN CORC demonstrator racetrack coils:

- Layout: 2 layers with each 8 turns
- Minimum bending diameter of 40 mm
- Coil inductance ≈ 50 µH, 0.38 T per kA
- $I_c$ of around 4.5 kA at 10 T and 4.2 K

- First prototype using $\varnothing 3.3$ mm ‘dummy’ CORC wire comprising only a few ReBCO tapes.
- Tested in LN2 before and after winding.
Practice coil using dummy wire with 4 ReBCO tapes.
• Dummy wire: $I_c = 250 \text{ A}$, $n = 10$ @ 77 K before winding

Racetrack wet wound with Stycast 2850FT epoxy resin.
• Racetrack: $I_c = 30 \text{ A}$, $n = 4$ @ 77 K

Bending diameter of 40 mm appeared to be too small for the tapes.
✓ Narrower tapes with thinner substrate required!

Winding Diameter = 40 mm
CORC Racetrack Coil Development at CERN

What is next?
Designs are in preparation for a new prototype CORC dipole.

New CORC Racetrack
- Similar design as the first demonstrator
- Minimum bending radius of 20-25 mm (depends on wire)
- Two individual racetracks of 2 layers and 4 turns
- Intermediate connection between coils
- \( \sim 0.3 \) T/kA

A 1\textsuperscript{st} CORC ‘Block’ Coil
- More complex design
- Minimum bending radius of 20-25 mm (depends on wire)
- Allows relatively homogenous magnetic field in the center over 20 mm and 0.3 T/kA

✓ Thinner and narrower tape requires for small bore, \( d < 50 \text{mm} \), CORC based magnets.
CORC Solenoid – Series of demonstrators

- A series of compact 2-layer CORC solenoids developed at CERN to demonstrate practical handling, materials choices, conductor robustness, and high performance of CORC wires for magnets.
- CORC wire: 27 ReBCO SCS2030 tapes, 2 mm wide, 30 μm substrate.
- Minimum bending radius of 30 mm.
- Magnet scheduled for testing in self-field in liquid nitrogen in Q4-2019, followed by a 4.2K test in background of 15 T at Uni Twente.

### Design Self-Field Performance

<table>
<thead>
<tr>
<th>T (K) *</th>
<th>High-Field $I_c$ (A)</th>
<th>Overall $I_c$ (A)</th>
<th>T (K) **</th>
<th>Peak Field (T)</th>
<th>Central Field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>785</td>
<td>805</td>
<td>77</td>
<td>0.47</td>
<td>0.39</td>
</tr>
<tr>
<td>70</td>
<td>1467</td>
<td>1505</td>
<td>70</td>
<td>0.88</td>
<td>0.72</td>
</tr>
<tr>
<td>65</td>
<td>1968</td>
<td>2019</td>
<td>65</td>
<td>1.19</td>
<td>0.97</td>
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<tr>
<td>60</td>
<td>2438</td>
<td>2500</td>
<td>60</td>
<td>1.47</td>
<td>1.20</td>
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<tr>
<td>50</td>
<td>3405</td>
<td>3494</td>
<td>50</td>
<td>2.05</td>
<td>1.68</td>
</tr>
<tr>
<td>4.2</td>
<td>9517</td>
<td>9755</td>
<td>4.2</td>
<td>5.73</td>
<td><strong>4.69</strong></td>
</tr>
</tbody>
</table>

* 100 μV/m criterion  
** Using the Overall $I_c$
CORC Solenoids – High-Field Test

- CORC coils are tested as insert in a 15T Nb₃Sn magnet at the University of Twente at 4.2 K.
- In 10 T background, the coil is expected to generate an additional 2.5 T.

Calculated in-field performance at 4.2K

<table>
<thead>
<tr>
<th>BG (T)</th>
<th>Ic (kA)</th>
<th>Peak field (T)</th>
<th>Central field (T)</th>
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<tbody>
<tr>
<td>0</td>
<td>9.76</td>
<td>5.73</td>
<td>4.69</td>
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<tr>
<td>2</td>
<td>8.56</td>
<td>7.02</td>
<td>6.12</td>
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<tr>
<td>4</td>
<td>7.39</td>
<td>8.34</td>
<td>7.55</td>
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<tr>
<td>6</td>
<td>6.50</td>
<td>9.81</td>
<td>9.13</td>
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<td>8</td>
<td>5.83</td>
<td>11.4</td>
<td>10.8</td>
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<td>10</td>
<td>5.20</td>
<td>13.0</td>
<td>12.5</td>
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<tr>
<td>12</td>
<td>4.74</td>
<td>14.5</td>
<td>14.3</td>
</tr>
</tbody>
</table>

This CORC solenoid is the first of several CORC demonstrator coils. It will be succeeded by higher-performance CORC solenoid with more layers and higher-I_c tapes and by a CORC dipole magnet.
CORC Solenoid – Coil Preparation

- Two-layer CORC solenoid is prepared at CERN last week.
- The layers are wet-wound with Stycast 2850 FT epoxy.
- Insulation present around the CORC wire to prevent Stycast from leaking in.
- G10 spacers are placed on the coil extremities to fill the larger gaps.
• Joint terminals are outside high-magnetic-field region.
• Two 5-kA vapor-cooled current leads are prepared for the test.
• Al-alloy cylinder is shrink-fitted around the solenoid for mechanical support.
• Test in LN2 is this month at CERN -> Test in high-field and 4.2 K at Uni. Twente afterwards.

✔ Test in LN2 this month

Finished with Al-alloy shrink-fitted cylinder

5 kA joint terminals

More mechanical support will be added

High-Field region
Conclusion

✓ Series of CORC wire based demonstrator magnets are under development at CERN.
✓ CORC wire in the first trial CORC Racetrack coil degraded due to small winding radius.
✓ New CORC Racetrack coils are in development.
✓ A 1\textsuperscript{st} compact CORC Solenoid prepared now for testing.
✓ Research on CORC Coils is going forward!
✓ Narrower & Thinner tape required for more compact CORC coils!