Development of ReBCO-CORC Cable-In-Conduit Conductors for Large-Scale Magnets

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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.

CORC Wire

- Ø 2-4 mm
- Ø 5-8 mm

1st CORC Al-jacketed Cable-In-Conduit Conductor.

2015
ReBCO Cable-In-Conduit Conductors

- Superconducting **Cable-In-Conduit Conductors (CICCs)** are commonly designed for large-scale, high-current magnets such as used in experimental fusion reactors and particle detectors.

- *NbTi* and *Nb₃Sn* conductor development are close to their limits, and quest of higher temperature, and no-helium operation — *ReBCO based CICCs to be developed!*

- **ReBCO** based conductors offer a further increase in current density, stability and allows (optional) operation above liquid helium temperatures.

Examples of several **ReBCO** based CICCs are in development around the globe:

- North China Electric Power University Quasi-Isotropic Conductor
- ENEA: Twisted Stacked Round CICC
- Swiss Plasma Center: Twisted Stacked Rectangular CICC
- CERN & ACT: CORC 6-a-1 CICC
Bus bars based on CORC CICC conductor, lighter, taking less space.

**CORC Bus Lines:**
- Reduce weight
- Reduce volume
- Reduce power converter requirements
- Allow power convertor placement on surface

**CORC Magnets:**
- Extreme thermal & electric stability
- Operation at 20 to 50 K
- Simpler cooling with helium gas
- Jacket material application dependent
- Steel for fusion, Aluminum for detectors.....
- Options for internal or external cooling
CORC CICC Development Timeline

Test of two CORC CICCs
- Stainless steel jacket + internal cooling
- Copper jacket + external conduction cooling

2016
Test of 1st CICC with Aluminum jacket

2017

2018
Design & Preparation of new sample

2019
Test of new solder-filled CICC with copper jacket

2020
Testing new layouts of internally cooled CORC CICCs
Detector magnets & Bus Bars:
- High thermal & electrical stability
- Practical conduction cooling

Fusion type magnets:
- Can sustain high stress
- Can cope with large heat loads
- Internal forced-flow cooling

CICCs are 2.8 m long and designed for 80 kA at 12 T and 5 K.
CORC CICC - Joint terminal design

- Short sample current is distributed in terminals.
- Strands are tapered, allows current to flow evenly into each layer of each CORC strand.
- Strands are straight inside the terminal.
- Half a cable pitch difference between terminals improves current distribution among strands.
- Terminals filled with solder, SnPb or Indium (best).
- Design resistance of 0.6 nΩm.
SS and Cu jacketed CORC CICC samples – test results

SS-jacketed CICC for Fusion Magnets:
• Performed according to prediction at 40 to 60 K
• N-value of $14 \pm 3$ (similar to the 2016 sample)
• Low AC-loss of 7 mJ/cycle/cm$^3$

Cu-jacketed CICC for Detector Magnets & Bus Bars:
• Only 30 to 40 % of predicted $I_c$
• Low $n$-value of $5\pm2$ in 40 to 60 K range
• Degradation occurred only in the Cu-jacketed CICC.

✓ Both conduction and forced-flow convection cooling proved valid for such conductors.
Next steps:
- **New CICC** to replace the degraded Cu-jacketed CICC.
- New strand layout is used with a thicker core.
- Mechanical support of CORC strands by *solder filling* of the voids between strands.

Likely cause of the degradation:
- Primary failure mode is a pinching effect.
- Specific for CORC strand layout/winding parameters of the Cu-jacketed CICC.
- Copper tapes layers around the core do not give sufficient mechanical support.

2017 tested CORC CICC samples
Latest CORC CICC Sample (2019)

- Project in collaboration with ACT.
- Similar high-\(I_c\) tape layout in the CORC strands as in the previous sample.
- Solely cooled by conduction cooling via its jacket.
- Improved electrical and mechanical performance by solder filling of conduit.

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<tbody>
<tr>
<td>Number of tapes</td>
<td>38</td>
<td>42</td>
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<tr>
<td>Number of layers</td>
<td>12</td>
<td>14</td>
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<td>Tape Type</td>
<td>SCS 4050</td>
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<td>Copper plating [µm]</td>
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<td>10</td>
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<tr>
<td>Core material</td>
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<td>Solid core diameter [mm]</td>
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<td>5</td>
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<td>5</td>
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<td>Outer diameter [mm]</td>
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<td>7.7</td>
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<td>Critical Current (4K, 10T) [kA]</td>
<td>48</td>
<td>90</td>
<td>90</td>
<td>100</td>
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</table>
Unfortunately, odd current sharing seen, surprise

- Issues with the new sample that prevented accurate $I_c$ measurements.
- Bad current distribution measured leading to oscillating sharing of current, likely resulting from solder alloying in the joint regions.

Voltage & temperature oscillations appear in a small current & temperature window.

- Seen only in this CICC, error!
- Spikes were reproducible.
- Frequency depends on current and temperature.

**Model**

- Same order of magnitude of frequency and amplitude
- Slightly different shape of the spikes
Test of solder metal of the joint terminals

- Solder was extracted from the extremities of the joint terminals.
- Test of the solder confirms suspicions: alloying throughout the entire terminal.
- Result is some In-Bi-Sn-Pb alloy with a highly non-eutectic melting temperature of 60 to 80 °C.
Odd behavior, what we learnt (2019)

What we know:
• Model is able to reproduce similar voltage spikes.
• Small window of parameters where such behavior occurs.
• Unique to HTS multi-strand conductors.
• Model & measurements suggest current distribution issue.
• No direct evidence of strand degradation.
• New joints may resolve the issue.

Next steps (already in progress):
• Extracting all solder from the sample. (√ Done)
• Refilling the joint and sample with indium. (√ This week)
• Test again in autumn 2019.

✓ Each measurement iteration increases our knowledge and experience of CORC CIC conductors.
• It is still a work in progress, more new CORC CICCs are in development.
New CORC CICCs > 2020 and beyond

- Next sample in preparation right now, mainly designed and prepared at ACT, instrumented and integrated at CERN and tested in Sultan early 2020.

Currently in design: X-around-1
- Thinner more flexible CORC strands.
- Shorter twist pitch.
- Internal gas cooling.
- More flexible CICC depending on jacket and core design.

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Conclusion

✓ Research on CORC Cable-In-Conduit Conductors is ongoing in collaboration with ACT
✓ Each measurement iteration increases our knowledge and experience of CORC CICCs.
✓ Odd joint-introduced current sharing seen in last sample.
✓ Latest CICC is being refilled this week and will be tested in the coming month.
✓ Another few CICC variants to come, next version test early 2020, more in coming years.........