Characterization of REBCO Tape and Roebel Cable at CERN

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Outline

• CERN strand and cable test facilities
• Tape $I_c$ measurements (transport and magnetization)
• Tape splice resistance
• RRR measurements
• Cable $I_c$ characterization
• Cable splice resistance
• Transverse Effective section of Roebel cable
CERN strand and cable test test facilities

**Strand test stations**
- $I_c$ measurements 1.9-4 K, 15 T and 2 kA
- Magnetization measurements: VSM +/-10.5 T, 1.9-100 K
- RRR measurements
- Quench propagation, inter-strand and splice resistance…

**Cable test stations**
- $I_c$ measurements LHe 1.9-4 K, 9.6 T and up to 70 kA
- $I_c$ measurements GHe 10-40 K, 20 m long and up to 20 kA
- Quench propagation and splice resistance…
Tape $I_c$ measurements (transport)

- Perp and // field up to 15 T and 2 kA
- 4 mm wide or 12 mm wide conductors (including meander tapes)
- Samples mechanically stabilized on thin stainless steel support
- Measurement of 2 samples/cool down
Tape $I_c$ measurements (Magnetization)

- Magnetization measurements with VSM +/-10.5 T, 1.9-100K (measurement performed by D. Richter)
- Tapes from different suppliers were investigated

**Characterization of REBCO Tape and Roebel Cable at CERN**

![Bruker tape graph](image)

4 mm wide

All Ic measurements are fitted using the generic scaling law presented in next slide
Generic $J_c(B,T,\theta)$ scaling for REBCO materials

$J_c(B,T)$ in perp. and parallel field

$J_{c,c} = \frac{\alpha_c}{B} b_c^{p_c} (1 - b_c)^{q_c} (1 - t^n) \gamma_c$

$J_{c,ab} = \frac{\alpha_{ab}}{B} b_{ab}^{p_{ab}} (1 - b_{ab})^{q_{ab}} [ (1 - t^{n_1})^{n_2} + a (1 - t^n) ]^{\gamma_{ab}}$

Adding fit of angular dependence ($\theta$)

$J_c(B,T,\theta) = J_{c,c}(B,T) + \frac{J_{c,ab}(B,T) - J_{c,c}(B,T)}{1 + \left( \frac{\theta - \pi/2}{g(B,T)} \right)^v}$

$g(B,T) = g_0 + g_1 \exp(-[g_2 \exp(g_3 T)]B)$

Unified, accurate and generic scaling law for all manufacturers

Splices: a key technology for HTS magnets

HTS splices for magnet application must satisfy two main requirements:

- reproducible low electrical resistance
- high mechanical strength

=> The use of soft solder for splicing can meet both requirements (Sn-Pb and Sn-In)

Three types of joints can be made between REBCO tapes

⇒ Type 0: direct facing of the HTS films (no substrates interleaved)
⇒ Type 1: no direct facing of the HTS films (one substrate interleaved)
⇒ Type 2: no facing of the HTS films (two substrates interleaved)

Investigations performed on

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Tape width</th>
<th>Tape thickness</th>
<th>Substrate material/thickness</th>
<th>Stabilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperPower</td>
<td>4.00 mm</td>
<td>100 µm</td>
<td>Hastelloy, 50 µm</td>
<td>2x20 µm. Cu electroplated</td>
</tr>
<tr>
<td>SuperOx</td>
<td>4.04 mm</td>
<td>110 µm</td>
<td>Hastelloy, 60 µm</td>
<td>2x20 µm. Cu electroplated</td>
</tr>
<tr>
<td>AMSC</td>
<td>4.4 mm</td>
<td>440 µm</td>
<td>Ni-W, 75 µm</td>
<td>2x160 µm. Cu alloy laminate</td>
</tr>
<tr>
<td>SunaM</td>
<td>4.00 mm</td>
<td>110 µm</td>
<td>Hastelloy, 60 µm</td>
<td>2x20 µm. Cu electroplated</td>
</tr>
<tr>
<td>Bruker</td>
<td>4.1 mm</td>
<td>150 µm</td>
<td>Stainless steel, 100 µm</td>
<td>2x20 µm. Cu electroplated</td>
</tr>
</tbody>
</table>
Splice resistance at 4.2 K

Measured between 0.3-12 T and up to 800 A

- **Type 0**: Lowest resistance (13-40 nΩ· cm²) *
- **Type 1**: High resistance (98-570 nΩ· cm²) *
- **Type 2**: Very High resistance (150-884 nΩ· cm²) *

* Values for Bruker, SPower and SuperOx

J. Fleiter and A. Ballarino, "In-Field Electrical Resistance at 4.2 K of REBCO Splices", presented at ASC 2016.
Change of Splice resistance vs. B and T

- Normalized change of $S_c$ vs. B at 4 K

![Graph showing the normalized change of $S_c$ vs. B for different types of materials at 4 K.](image)

- Ratio of resistance at 4 K and 77 K

<table>
<thead>
<tr>
<th>Lift factor</th>
<th>Type 0</th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_c(4 \text{ K})/S_c(77 \text{ K})$</td>
<td>SuperPower</td>
<td>0.92</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>SuperOx</td>
<td>0.90</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Bruker</td>
<td>1.21</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>SuNam</td>
<td>0.90</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>AMSC</td>
<td>0.84</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Weak dependence of splice resistance on field and temperature for Type 0

Strong dependence of splice resistance on field and temperature for Type 1-2

J. Fleiter and A. Ballarino, "In-Field Electrical Resistance at 4.2 K of REBCO Splices", presented at ASC 2016.
RRR measurements

- RRR measurements required for modelling the electrical resistance of splice and designing the magnet protection.
- Residual Resistivity Ratio (RRR) of the electroplated copper or copper alloy laminations were measured on 80 mm long samples.

**TABLE 2.**

<table>
<thead>
<tr>
<th>Measured Electrical Resistivity of Cu Stabilizer</th>
<th>Electrical resistivity (μΩ·m) at 0 T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>290 K</td>
</tr>
<tr>
<td>SuperPower</td>
<td>16.5</td>
</tr>
<tr>
<td>SuperOx</td>
<td>18.1</td>
</tr>
<tr>
<td>Bruker</td>
<td>15.4</td>
</tr>
<tr>
<td>SuNAM</td>
<td>19.6</td>
</tr>
<tr>
<td>AMSC (Cu alloy)</td>
<td>80.3</td>
</tr>
</tbody>
</table>

Low value of RRR among the different conductors investigated (3-61) with a large spread.
Roebel cable electrical performances at 4.2 K

Measurements at CERN in FRESCA test station in $\perp$ and $/\!/\!$ fields

- Cables from **KIT**: 126 mm pitch, 9, 10 and 16 strands
- Cables from **GCS**: 300 mm pitch 15 strands
- Cable from **SuperOx** 300 mm pitch 15 strands
- Additional 5-12 mm$^2$ cooper shunt, segregated or distributed
- No impregnation at the moment
- Vtaps on each strand
- Low joint resistance ~1 nΩ (256-300 mm long)
Electrical performances at 4.2 K of Roebel cables

- All cables reach their expected $I_c$
- Cable $I_c$ depends on the raw characteristics of REBCO tapes

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The transverse effective section ($E_s$) of Roebel cable

- Driving the transverse stress in bare cable and Interstrand resistance in potted cables.
- Analytical and numerical models developed and validated vs. measurements.

$$E_{s,\text{even}} = \frac{2N}{T_p W \tan \alpha} \left[ \frac{w_c \sin \alpha}{\sin 2\alpha} - \frac{W}{2} + w_t \right]^2$$

$$E_{s,\text{odd}}(N \leq N_c) = \frac{2Nw_t}{T_p W} \left[ \frac{T_p}{2N} \frac{w_c}{\sin \alpha} + \frac{w_t - W}{\tan \alpha} \right]$$

$=>E_s$ is up to about 50% for odd number of strands(→=30°).

$=>$ We should not exceed the critical number of strands to avoid too high Interstrand resistance $R_a$.

Summary (1/2)

- Large variety of tape $I_c$ samples investigated with different doping.
- Elaboration of generic formulation for the $J_c(B,T,\theta)$ of REBCO tapes from different suppliers.
- Systematic investigations on splice resistance vs. field and temperature performed.
- Electrical characterization of full scale Roebel cable at 4.2 K and in field of up to 9.6 T.
Summary (2/2)

• All Roebel cable reached their expected performances in perp field.
• Cable splice resistance are about 1 nΩ (256-300 mm long)
• Analytic formulation for the effective section of Roebel cable were derived for stress distribution and inter-strand resistance computation.
Thank you