AC Loss and inter-strand resistance in Impregnated ReBCO Roebel cables

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Outline of this presentation:

1. Motivation
2. Introduction
3. Inter-strand resistance of impregnated Roebel cable
4. AC losses of impregnated Roebel cable
5. Conclusions
1. Motivation

**LHC 8.3T**
- Source: CERN

**HL-LHC 11T**
- Source: CERN
- Nb_Sn

**FCC-EuroCirCol 16T**
- Source: Fermilab

**EuCARD-2 ≥ 20T**
- Source: CERN
- ReBCO Roebel

Source: KIT
1. Motivation

**EuCARD-2 ≥ 20 T**

Transverse pressure tolerance?

![Graph showing critical current versus transverse pressure](image)

**Impregnation ⇒ \( \sigma_{\text{trans}} > 400 \text{MPa} \) !

1. Motivation

Inter-strand resistance?

EuCARD-2 ≥ 20T

Current redistribution

Field Quality

Stability

AC loss

Source: KIT

ReBCO Roebel
Outline

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## 2. Introduction: samples

CABLE I (KIT), impregnated with CTD101G, filled with alumina powder, 5MPa (CERN)

CABLE II (KIT), impregnated with CTD101K 5MPa (CERN)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_S$</td>
<td>15</td>
<td>Number of strands</td>
</tr>
<tr>
<td>$d_s$</td>
<td>0.1 mm</td>
<td>Strand thickness</td>
</tr>
<tr>
<td>$d_c$</td>
<td>0.8 mm</td>
<td>Cable total thickness</td>
</tr>
<tr>
<td>$d_i$</td>
<td>0.1 mm</td>
<td>Insulation thickness</td>
</tr>
<tr>
<td>$W_s$</td>
<td>5.5 mm</td>
<td>Strand width</td>
</tr>
<tr>
<td>$W_t$</td>
<td>12.0 mm</td>
<td>Cable width</td>
</tr>
<tr>
<td>$W_x$</td>
<td>5.5 mm</td>
<td>Cross over width</td>
</tr>
<tr>
<td>$W_c$</td>
<td>1.0 mm</td>
<td>Channel width</td>
</tr>
<tr>
<td>$\phi$</td>
<td>30°</td>
<td>Cross over angle</td>
</tr>
<tr>
<td>$L_{10}$</td>
<td>226 mm</td>
<td>Transposition pitch</td>
</tr>
<tr>
<td>$r_i$</td>
<td>6.0 mm</td>
<td>Inner radius</td>
</tr>
<tr>
<td>$r_o$</td>
<td>6.0 mm</td>
<td>Outer radius</td>
</tr>
</tbody>
</table>
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EUCAS 2017 – P. Gao– 3LO3-08: Geneva, Switzerland- September 2017
3. $R_c$ of impregnated Roebel cable

- 2 neighbors per stand
- 15 soldered contact taps
- $V_1 \sim V_{15}$: equipotential (S.C. layer)
- $R_{ij}$: contact resistance between neighboring stands $i$ & $j$
3. $R_c$ of impregnated Roebel cable

**Method:**
- 2 taps as current lead (e.g. 1 and 8)
- $V_{15}$ is grounded, as a ref. volt. potential
- $U_{i/15}$ are measured (e.g. purple data)
- cycle current lead position

$R_{ij}$ can then be calculated by solving system of equations.
3. $R_c$ of impregnated Roebel cables

<table>
<thead>
<tr>
<th>$T$</th>
<th># 1 $R_c$ ($\mu\Omega$)</th>
<th># 2 $R_c$ ($\mu\Omega$)</th>
<th># 3 $R_c$ ($\mu\Omega$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>77K</td>
<td>15.9</td>
<td>2.9</td>
<td>9.9</td>
</tr>
<tr>
<td>77K polished</td>
<td>18.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4.2K</td>
<td>9.1</td>
<td>1.4</td>
<td>4.6</td>
</tr>
<tr>
<td>$R_c(77K)/R_c(4.2K)$</td>
<td>1.8 ~ 2.0</td>
<td>2.1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Avg. $R_c$ between neighbors
3. $R_c$ of impregnated Roebel cable

Assuming

$R_{c,Cu/Cu} (77K) \sim 10$ to 20 nΩ·m²
$R_{c,Cu/Cu} (4.2K) \sim 0.5$ to 10 nΩ·m²

<table>
<thead>
<tr>
<th>$T$</th>
<th>$R_{c,S.C./Ag} (\mu\Omega)$</th>
<th>$R_{c,S.C./Ag/Cu(b)} (\mu\Omega)$</th>
<th>$R_{c,Cu(c)} (\mu\Omega)$</th>
<th>$R_{c,Cu(d)+Cu-Cu(e)} (\mu\Omega)$</th>
<th>$R_{c,Cu(c)} (\mu\Omega)$</th>
<th>$R_{c,Cu(c)/Ag/S.C.} (\mu\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>77K</td>
<td>0.31~0.44</td>
<td>0.11~0.15</td>
<td>8.5E-2</td>
<td>6.5E-5</td>
<td>2.3E-3~4.7E-3</td>
<td></td>
</tr>
<tr>
<td>4.2K</td>
<td>1.6E-3~1.6E-2</td>
<td>4.4E-3~4.4E-2</td>
<td>3.6E-2</td>
<td>2.8E-5</td>
<td>9.3E-5~9.3E-4</td>
<td></td>
</tr>
</tbody>
</table>

Ref. C. Zhou, “Intra wire resistance and strain affecting the transport properties of Nb₃Sn strands in Cable-in-Conduit Conductors”, PhD dissertation, University of Twente, 2014

T. Holúbek, M. Dhallé and P. Kováč, “Current transfer in MgB₂ wires with different sheath materials”, University of Twente, SUST, 2007

$R = \frac{\rho l}{A}$
$R = \frac{R_{c,Cu/Cu}}{A}$
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4. AC losses : Instrumentation

AC loss measured by gas flow calorimetry and magnetisation methods.

Sample holder

Dipole magnet

± 1.5 T , ≤ 1 Hz, 4.2 K

Solenoidal magnet

± 1.4 T , ≤ 0.09 Hz, 4.2 K
4. AC losses @ $B \perp$, 4.2K

**Amplitude dependence**

- AC losses are dominated by hysteresis
- No coupling losses are observed in exp. window
- Tested: $B_{\perp} \approx 1T$; Modelling: $B_{\perp} = 0.769T$

**Frequency dependence**

- Both in model prediction & experiment

**Carr’s $Q_h$ model**, ref.: **W. J. Carr Jr.** “AC Loss and Macroscopic Theory of Superconductors”, CRC Press, 5 Jul 2001, USA
4. AC losses @ $B_{//}$, 4.2K

**Amplitude dependence**

- AC losses are dominated by hysteresis
- No coupling losses are observed in exp. window
- Tested: $B_{p//} \approx 0.03T$; Modelling $B_{p//} = 0.06T$
- $Q_c$ is much lower than measured $Q_h$ in exp. window, which is identical with modelling estimation

**Frequency dependence**

CABLE I
- $0.02T$
- $0.4T$

CABLE II
- $0.02T$
- $0.4T$

CABLE III
- $0.02T$
- $0.4T$
3. AC losses @ $B_a = \pm 0.02T(\theta)$, f=1Hz, 4.2K

**CABLE I: AC losses-$B_a$ angle $\theta$**

- The predominant role of AC losses: from Coupling to Hysteresis with the increase $\theta(0^\circ \sim 90^\circ)$
- $Q_h$ model fits well with data when use $\mu_0 H_{p,\perp} \approx 1.7T$

**CABLE II: AC losses-$B_a$ angle $\theta$**

- AC losses are dominated by hysteresis
- $Q_h$ model doesn’t fit well with exp. data, but the observed & predicted trends do correspond

Tested $\mu_0 H_{p,\perp} \approx 1.7T$, ref.: J. Pelegrin, I. Falorio, E. A. Young, Y. Yang et.al. University of Southampton.
4. AC loss @B↑, 4.2K

**Amplitude dependence**

- Coupling losses are observed in the exp. window $5 \text{ mT} \leq \mu_0 H_0 \leq 50 \text{ mT}$
- Hysteresis losses are observed in the exp. window $80 \text{ mT} \leq \mu_0 H_0 \leq 0.4 \text{ T}$
- Modelling: $B_p \approx 0.11 \text{ T}$

**Frequency dependence**
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5. Summary

- $R_c$ of Roebel cables ($L_{tp}=226\text{mm}$) at $4.2\text{ K}$ is around $1.5 - 10\ \mu\Omega$, at $77\text{ K}$ is about $3 - 20\ \mu\Omega$, with about 30% variation within a cable and up to a factor 6 variation from cable-to-cable.

- Coupling losses can be predicted by using the measured $R_c$ values.

- The inter-strand resistance is dominated by the contact resistance of the Cu-Cu interface.

- AC losses are dominated by hysteresis @ $B_{\perp}$, at $4.2\text{ K}$, $B_{\perp} \approx 1\text{ T} \sim 1.7\text{ T}$.

- Coupling losses might be observed @ $B_{\parallel}$ and $B_{\uparrow}$, at $4.2\text{ K}$, depending on impregnation details; $B_{\parallel} \approx 0.03\text{ T}$.

- AC losses @ inclined field mostly ($\theta \geq \sim 15^\circ$) dominated by the perpendicular field component.

- Analytical models show same trends as measured data, a better fit probably requires numerical modelling.
Thanks for your attention