REBCO Roebel cables under high transverse stress

M. Dhallé¹, P. Gao¹, W.A.J. Wessel¹, M. Hartman¹, H.H.J. ten Kate¹, ⁴, S. Otten², A. Kario², W. Goldacker², A. Usoskin³, J. van Nugteren¹, ⁴, G. Kirby⁴ and L. Bottura⁴.

¹ University of Twente, ² Karlsruhe Institute of Technology, ³ Bruker HTS GmbH, ⁴ CERN.

Partly funded by the EC under GA 312453 (EUCARD2)
Outline

- Introduction
  - background
  - mechanical behavior Roebel
  - problem / proposed solution

- Experimental

- Results

- Conclusions & outlook

See also S. Otten et al. SUST 28 (2015) 065014
Introduction: background

See talk Glyn Kirby this morning:

5T stand-alone
HTS coil
as insert for
20T-class dipole
Introduction: background

At start EUCARD2 (2013): emphasis on ReBCO ROEBEL

- High cable - $J_E$ (accelerator magnet!)
- Fully transposed (field quality)
- Rutherford - like (magnet design, possibility to wind with cable // field)

Proposed by Wilfried Goldacker @ EUCAS 2005
Recent review by Goldacker @ EUCAS 2015
**Introduction:** mechanical behavior

**Tensile-stress response:** OK


**Bending-stress response:** OK

A. Kario, internal EUCARD2 report (2015)
Introduction: problem...

Naked cable under transverse pressure: degradation starts at ~ 20 – 40 MPa due to stress-concentration

D. Uglietti et al. SUST 26 (2013) 074002

J. Fleiter et al. SUST 26 (2013) 065014
### Introduction: problem...

**Design pressure 150 MPa**

<table>
<thead>
<tr>
<th>parameter name</th>
<th>1 - Aligned block</th>
<th>2 - Normal block</th>
<th>3 - Cosine Theta</th>
</tr>
</thead>
<tbody>
<tr>
<td>coil layout</td>
<td>yoke</td>
<td>yoke</td>
<td>yoke</td>
</tr>
<tr>
<td><strong>5.0T</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| general                              |                   |                  |                  |
| cable width / thickness              | 12 mm / 0.8 mm    | 12 mm / 0.8 mm   | 10 mm / 1.2 mm   |
| required bend radius                 | 16 mm             | 16 mm            | 7.5 mm           |
| number of turns                      | 12/6 (18)         | 12/7 (19)        | 4/5/3 – 6/10/4 (32) |
| block area (all quadrants)           | 790 mm²           | 909 mm²          | 1827 mm²         |
| inductance (w.o. iron)               | 0.29 mH/m         | 0.31 mH/m        | 0.80 mH/m        |

| standalone (in yoke)                  |                   |                  |                  |
| percentage on loadline               | 70%               | 70%              | 60%              |
| current density (block)              | 648 A/mm²         | 635 A/mm²        | 387 A/mm²        |
| critical current density             | 1216 A/mm²        | 1164 A/mm²       | 915 A/mm²        |
| cable operating current              | 7905 A            | 7747 A           | 5526 A           |
| dipole field B1                      | 5.0 T             | 5.0 T            | 5.0 T            |
| harmonics b3 / b5 / b7               | 8 / 5 / 2 units   | 16 / 1 / 0 units | 0 / 0 / 0 units  |
| estimated coil pressure              | 17 MPa            | 17 MPa           | 20 MPa           |

| in 13 T background field             |                   |                  |                  |
| percentage on loadline               | 70%               | 70%              | 70%              |
| current density (block)              | 667 A/mm²         | 530 A/mm²        | 283 A/mm²        |
| critical current density             | 1282 A/mm²        | 1068 A/mm²       | 477 A/mm²        |
| cable operating current              | 8137 A            | 6466 A           | 4041 A           |
| dipole field B1                      | 16.9 T            | 16.2 T           | 15.8 T           |
| harmonics b3 / b5 / b7               | 13 / 3 / 0 units  | 4 / 0 / 0 units  | 6 / 0.4 / 0.1 units (in Fresca2) |
| estimated coil pressure              | 110 MPa           | 87 MPa           | 51 MPa           |
Introduction: … and proposed solution

Proper impregnation (cfr. Nb$_3$Sn Rutherford)!

Nb$_3$Sn RRP cable
Outline

- Introduction
- Experimental
  - Transformer / cryopress
  - Impregnation
- Results
- Conclusions & outlook

See also S. Otten et al. SUST 28 (2015) 065014
Experimental: transformer

- \( I_{\text{max}} = 50 \text{ kA}, T = 4.2 \text{ K}, B_{\text{applied,max}} = 11 \text{ T}; \)
- Cable samples laterally constrained & vacuum impregnated

Experimental: cryo-press

- Double NbTi pancake ($F_{\text{max}} = 260$ kN);
- Steel + 50µm polyimide anvil ($\sigma_{\text{max}} \approx 350$ MPa)

**Experimental: impregnation**

### Karlsruhe method (Araldite + glass beads)

<table>
<thead>
<tr>
<th>Filler</th>
<th>Filling ratio [wt%]</th>
<th>Product name</th>
<th>Thermal expansion T = 300 K</th>
<th>Viscosity [Pa s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>60-80</td>
<td>Duralco 125</td>
<td>-1.04 %</td>
<td>20 (20 °C)</td>
</tr>
<tr>
<td>Graphite</td>
<td>50-60</td>
<td>Duralco 127</td>
<td>-0.58 %</td>
<td>50 (20 °C)</td>
</tr>
<tr>
<td>Carbon particles + CNT</td>
<td>4-8</td>
<td>Carbocond 171/6</td>
<td>-1.18 %</td>
<td>6-8 (20 °C)</td>
</tr>
<tr>
<td>Graphite + CNT</td>
<td>4-8</td>
<td>Carbocond 471/6</td>
<td>-1.11 %</td>
<td>1-2 (20 °C)</td>
</tr>
<tr>
<td>Fused silica</td>
<td>50-66</td>
<td>Araldite CY5538/HY5571</td>
<td>-0.82 % (50 wt%) &lt; 4.5 (80 °C)</td>
<td></td>
</tr>
<tr>
<td>Al(OH)₃</td>
<td>56</td>
<td>Araldite CW5730N/HY5731</td>
<td>-0.60 % (60 wt%)</td>
<td></td>
</tr>
</tbody>
</table>

SS dummy cable with 1 REBCO strand @ 77K, s.f. :

<table>
<thead>
<tr>
<th>Ic[A]</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before impregnation</td>
<td>171.7</td>
</tr>
<tr>
<td>After impregnation (cycle 1)</td>
<td>170.2</td>
</tr>
<tr>
<td>After impregnation (cycle 2)</td>
<td>170.9</td>
</tr>
</tbody>
</table>

A. Kario et al. ICEC-ICMC 2014
Experimental: impregnation

2-step UTwente implementation …

Cable:
- 10 tapes (SuperPower SCS12050-AP)
- 126 mm transposition length
- ReBCO facing holder

(vacuum) impregnation step 1:
- Araldite + 50% silica
- Teflon pushing block
**Experimental: impregnation**

Impregnation step 2:
(for parallelism)

- Stycast 2850 FT + glass
- Actual pushing anvil (30mm)
Outline

- Introduction
- Experimental
- Results
- Conclusions & outlook

See also S. Otten et al. SUST 28 (2015) 065014
Results: 1\textsuperscript{st} cable-type 10 - strand $l_p = 126$ mm SP cable

*Critical current @ 4.2K, 10.5T versus applied pressure*
Results

Some discussion on the role of the side-plate supports …

Sample 1:  
14 mm high side-plates

Additional confirmation:

Sample 2: identical cable & impreg.  
but 3 mm high side-plates

Sample 3: identical cable,  
but not impregnated
Results: 1\textsuperscript{st} cable-type 10 - strand $l_p = 126$ mm SP cable

**Cable 2:** identical cable & impregnation but 3 mm side plates

![Image of cable and experimental setup]

![Graph showing critical current vs. transverse stress]

- Cable 1: 254 MPa
- Cable 2: 167 MPa
Results: 1<sup>st</sup> cable-type 10 - strand \( l_p = 126 \text{ mm} \) SP cable

**Cable 3:** identical but *not impregnated* (3 mm side plates)
Outline

- Introduction
- Experimental
- Results
- Conclusions & outlook

See also S. Otten et al. SUST 28 (2015) 065014
Conclusions & outlook

- **Transverse pressure tolerance impregnated Roebel promising**
  - 10-strand SP cable reproducibly meets Feather2 design goal (150MPa)
- **Residual issues with Araldite/glass-bead impregnation**

**Outlook:**

<table>
<thead>
<tr>
<th>Cable type</th>
<th># strands &amp; L_p</th>
<th>Tape</th>
<th>Impregnation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>10 (126mm)</td>
<td>SP</td>
<td>KIT</td>
</tr>
<tr>
<td>2.</td>
<td>15 (226mm)</td>
<td>SP</td>
<td>KIT</td>
</tr>
<tr>
<td>3.</td>
<td>15 (226mm)</td>
<td>SP</td>
<td>CERN</td>
</tr>
<tr>
<td>4.</td>
<td>15 (226mm)</td>
<td>BRUK</td>
<td>CERN</td>
</tr>
</tbody>
</table>

More at ASC 2016 …