Critical current retention of potted and unpotted REBCO Roebel cables with transverse pressure

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Introduction

• ReBCO Roebel cable
  • Fully transposed cable/ equivalent topology to Rutherford cable (with $R_c = \infty$)
  • High $J_e$
  • High bend tolerance

• Manufacturing facility at Robinson Research Institute, VUW (GCS – in transition, parent company sold)
  • Can use 10 mm or 12 mm ReEBCO tape to make strands
  • Can punch and wind long lengths
Introduction (cont)

- Pressure experiments reported here use 5/5 cable
- Geometry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>2 mm Cable</th>
<th>4.5 mm Cable</th>
<th>5 mm Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{TRANS}}$ ($=2L$)</td>
<td>Transposition length</td>
<td>90 mm</td>
<td>300 mm</td>
<td>300 mm</td>
</tr>
<tr>
<td>$W_R$</td>
<td>Strand width</td>
<td>2 mm</td>
<td>4.5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>$W_X$</td>
<td>Crossover width</td>
<td>1.7 mm</td>
<td>5.0 mm</td>
<td>6.0 mm</td>
</tr>
</tbody>
</table>
Background – transverse pressure issues

• Requirements ~150 MPa in a dipole magnet
• Pressure concentration due to Roebel shape

• The geometry of Roebel assembly concentrates pressure in non-trivial patterns [1].
  • The ‘blue’ areas are thicker
  • Shifts can concentrate stress further – not reported here

• Odd or even strand #s behave quite differently

Objectives

• Measure transverse pressure performance of unpotted Roebel cable
  • Previous results have been variable
  • Find critical pressure for irreversibility
    • Understand variability and mechanisms
  • Important for preparing coils pre-impregnation

• Improve pressure performance by encapsulation
  • Reproduce successful previous results (CERN, KIT, Twente) on our cable geometry
  • Find critical pressure
    • Understand variability and mechanisms
Experimental

• Planar face compression
  • Simulate effect of hoop stress
  • Pressure applied via hydraulic ram
  • Rotational coupling between ram and platen

• Liquid N$_2$ immersion

• Strand $I_c$ testing
  • Single strand energised
  • Incremental pressure increase
  • I-V curves were measured with cycling of pressure (pressure/release/pressure/...)
  • $I_c$ checked after each pressure cycle (@ $P=0$)
Roebel cable pressure test

- Point of initial irreversible $I_c$ degradation
  - Criteria $I_c$ changes by 1%

![Graph showing pressure test results for PR0009 Non-impregnated cable. The graph indicates that the pressure threshold for degradation is $P_{\text{threshold}} = 13.3$ MPa.]
Results: unpotted 5/5 cables

- $P_{\text{threshold}} = 4.2 - 34.2 \text{ MPa}$
- $n$-value more sensitive to damage than $I_c$
Evidence of pressure concentration

• After transverse pressure of 60 MPa was applied to 5/5 cables
  • Change in surface finish over part of surface
    • Seen as darker in picture
    • Light reflection more specular
  • Implies pressure concentration
Optical microscopy

- Stress concentration
- Buckling of strand
- Live strand

(1) Length 3447.32 μm
(2) Length 2927.75 μm
Stress concentration

• Concentrated pressure region
  • Overlapping edges

• Mitigation
  • Distribute the pressure evenly
  • Investigate cable impregnation
Epoxy impregnation

- Molded planar cable
  - Bisphenol-A epoxy resin system
    - Araldite CY5538 + HY5571
- $I_c$ degraded on cooldown
  - (but not further degradation)
  - Believed due to thermal mismatch
Matching CTE

• A mismatch of the coefficients of thermal expansion of the epoxy and the 2G wire
  • which causes mechanical degradation of HTS layer, is likely the cause of this failure.

• SiO2 / Epoxy composites
  • Closely match CTE of the Roebel cable strands.
  • Epoxy+SiO2-nanopowder (< 1 um) 46.5% Vf
    • Highest vol. fraction that still allows resin flow
    • American Elements SI-OX-02N-P.01UM
    • 1:1:3 resin: hardener: silica powder by weight

• Thermal cycling also investigated
46.5% $V_f \text{ SiO}_2$

- Good retention of $I_c$ at 46.5%.

Critical current retention after first cooling down of RC potted by epoxy+46.5% SiO$_2$

Number of studied RCs

Retained $I_c$ ratio

N 3

0 1 2 3 4 5

0.96 0.98 1.00 1.02 1.04
Pressure and thermal cycling

- $I_c$ retained with combined pressure and thermal cycling (to 100 MPa)
Pressure testing to irreversibility point

- Potted length 80 mm
Irreversibility point for tested cables

- Some evidence of mechanical damage
  - Cracks in epoxy
Conclusions

• Non-impregnated cable is susceptible to damage at low transverse pressures
  • Evidence for stress concentration (different from simple models)

• We can epoxy impregnate and retain $I_c$ with thermal and mechanical cycles

• Increase in irreversibility to 75 - 212 MPa
  • Variability may be due to non-optimised sample production