Powering of an HTS Dipole Insert-Magnet Operated Standalone in Helium Gas between 5 and 85K


Thu-Mo-Or31
Feather-M2.1-2 insert-magnet was constructed within the framework of WP10.3 of EuCARD2

One of the first HTS dipoles in the world

Actually this was just a practice coil with low performance tape

This talk is about the standalone cold testing of this magnet

Winding, Impregnation and Assembly I

- Ring 2 (OFHC Copper)
- Ring 1 (OFHC Copper)
- Ring 3 (OFHC Copper)
- Layer Jump (Glass Filled Nylon)
- Coil Winding
- Former (316L Stainless Steel)
- Current Lead Box A (Glass Filled Nylon)
- Current Lead Box B (Glass Filled Nylon)
- Insulation Sheet 1 (Nomex)
- Insulation Sheet 2.1 (G11)
- Insulation Sheet 2.2 (G11)
- Insulation Plate (G11)
- End-Plate (316L Stainless Steel)
- Spacer (Copper)
- Insulation Sheet 3 (G11)
- End Pole (Iron 99.9%)
- Central Pole (Iron 99.9%)
- Spacers (Copper)
- Roebel Cable (REBCO tape)
- End-Plate (316L Stainless Steel)
- Impregnated Dummy With CTD 101K
- Insulation Plate (G11)
- Current Lead Box B (Glass Filled Nylon)
Winding, Impregnation and Assembly II

- Impregnation Mould
- Impregnated Coil
- Insertion in Support Cylinder
Magnet ready for Testing
• Triple-R is defined between 10 and 273K
• Voltage only measured at 95 and 300K for a current of 6A

Just before the superconducting Transition 93 K
Transition was gradual due to large heat capacity

Conclusion:
**RRR = 20±5**
• 160% difference between critical current at 10 µV/m and quench current
To estimate the performance of the magnet, the load-line intersections were calculated.

Critical surface from Victoria University assumed perpendicular magnetic field.

Measured reference value at 77 K self-field 300 A per tape, 15 tapes in cable.

Conclusion:
- No noticeable degradation occurred in the cable during winding, impregnation, and assembly.
- This cable is not very suitable for use in a magnet. Much better performance on next magnet.
Superconducting Transition and Ramp-Rate

- Quench current increases when ramped fast
- Essentially we are skipping the drift regime
- Opposite result from LTS where coupling losses reduce the quench current
- HTS has much more margin and seems to be unaffected by coupling loss

**Conclusion**
- The drift region implies temporal effects with respect to the quench current
The N-values were determined by fitting the power law to the measured electric field versus current:

\[ E = E_0 \left( \frac{I}{I_c} \right)^N \]

In essence, it is the slope on a log-log plot near the critical current.

N-values are very low. Likely an effect of current sharing and joint resistance.

To be confirmed...
- Lower Copper Resistivity
- Favouring current sharing?
- Closer to Critical temperature?

There seems to be an optimum around 40+K.
Measured Current Decay during Dump

- Measured current decay is more similar to the numerical model with ICED than theoretical exponential decay.

- Conclusion
  - Part of the current is jumping into the ring when the protection is triggered: ICED works as expected.
Detecting the Onset of a Quench I (electric field)

- Drift in the electric field is a clear indication that the magnet is about to quench.
- If not ramped fast, the electric field starts drifting minutes ahead of time.
- Reduction of only 100 A results in immediate recovery!

**Conclusion**
- If this behaviour is also present in higher current density magnets this could be a viable method for protecting future HTS magnets.
Detecting the Onset of a Quench II (electric field)

**Conclusion**
- No unexpected quenches due to cracking of resin, flux jump, training etc.

- All quenches occur over an electric field of **200 µV/m**
- Only quenches due to exceeding critical current

**Electric field, 1 second before triggering of protection**

- Electric field at Quench 1 (18.5m coil)
Detecting the Onset of a Quench III (temperature sensors)

- Temperature drifts away before quench
- Having distributed temperature sensing (i.e. temperature map of the coil) should yield interesting results when magnet is in current sharing regime

- Conclusion
  - Onset of quench also visible on temperature sensors
Joint Resistances (fin-block)

- New type of joint used for first time: FinBlock
- Joint resistances were determined on the order of 10-20 nΩ at 4K
- Strong temperature dependence

Conclusion
- Fin-Block joints are acceptable

Looks like copper resistivity
Magnetic Measurements I (resistive effect)

- Magnetic field in aperture was measured using Hall effect sensors.
- Hall sensors were cross-calibrated with pick-up coils.

- The hysteresis (lagging behind) of the magnetic field with the transport current strongly depends on ramp-rate.
- This is likely the current induced in the copper ICED ring due to the time-changing magnetic field:
  - i.e. the ring tries to resist a change of magnetic field.
  - Actually appears as coupling due to its frequency dependence.

- More on this effect in EUCAS 2017 by Carlo Petrone.
To measure only steady state effects a staircase ramp was performed.

- The acceleration and deceleration of the power supply give interesting pearl necklace effect.
- Difference between ramping up and down is persistent current effect.
- Only 10 units variation, likely due to the alignment of the field by the iron.

**Conclusion**
- Only 10 units variation due to persistent currents.
- More on this in EUCAS 2017 by Carlo Petrone.
Conclusion

• The EUCARD2 Feather-M2.1-2 magnet with SuperOx cable assembled Sunam tapes was tested successfully.

• The results from the test are interesting and provide valuable insight in the use of HTS in an accelerator magnet.

• Detecting quenches minutes ahead of time may be possible.

• The performance of the magnet was relatively low due to the batch of (cheaper) low performance tape used.

• The next magnet Feather-M2.3-4 with Bruker tape has the potential of reaching very high currents/fields.

• The future looks bright for HTS.

<table>
<thead>
<tr>
<th>strand no.</th>
<th>77K/SF</th>
<th>Ic 4.2 K/ST</th>
<th>length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>98</td>
<td>3050</td>
<td>29.2</td>
</tr>
<tr>
<td>2</td>
<td>98</td>
<td>3050</td>
<td>29.2</td>
</tr>
<tr>
<td>3</td>
<td>98</td>
<td>3050</td>
<td>27.1</td>
</tr>
<tr>
<td>4</td>
<td>81</td>
<td>3100</td>
<td>29.2</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>3097</td>
<td>27.4</td>
</tr>
<tr>
<td>6</td>
<td>140</td>
<td>3237</td>
<td>28.3</td>
</tr>
<tr>
<td>7</td>
<td>146</td>
<td>2304</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>210</td>
<td>2935</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>140</td>
<td>3237</td>
<td>28.3</td>
</tr>
<tr>
<td>10</td>
<td>123</td>
<td>2709</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>140</td>
<td>3237</td>
<td>28.3</td>
</tr>
<tr>
<td>12</td>
<td>140</td>
<td>3237</td>
<td>28.6</td>
</tr>
<tr>
<td>13</td>
<td>210</td>
<td>2935</td>
<td>28</td>
</tr>
</tbody>
</table>

39 kA @ (4.2 K, 5 T, pp)  
Estimated: 18 kA @ (4.2 K, 20 T, pp)  
Woah...(=)
Thank You for your attention