Recent progress on HTS conductors for high-field magnets: critical surface studies

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Outline

Activities on HTS for HEP magnets in EC programs
  • **R&D goals from FP7** [EuCARD² to h2020 ARIES]

Overview of the measurement campaign on R&D YBCO tapes from **BRUKER**
  • *Transport* \(I_c\) measurements up to 2 kA in variable temperature and at various orientations

Very recent tests on new high-performance REBCO tapes from **Fujikura and SuperOx**

Conclusions
Towards 20+ T dipoles: the call for HTS

Advances in R&D from FP7 EuCARD² to h2020 ARIES

EuCARD² has developed

- a HTS CONDUCTOR for accelerator dipoles (10 kA-class cable)

- a DIPOLE DEMONSTRATOR with accelerator quality (5 T, 40 mm bore)

Tests of the coils as stand alone and in-field are ongoing

van Nugteren et al., SuST 31 (2018) 06502


**ARIES** is building on the shoulders of **EuCARD²**

The objectives of **ARIES** are:

- **Set up a NEW process in BRUKER to:**
  - *Increase Jₑ by a factor 2 wrt EuCARD²*
  - From $Jₑ (4.2 \text{ K, } 20 \text{ T}) = 400-600 \text{ A/mm}^2$ to $Jₑ (4.2 \text{ K, } 20 \text{ T}) = 800-1200 \text{ A/mm}^2$

- **Produce in BRUKER some 600 m of tapes**

- **Use in a winding at CERN (very much like EuCARD²)**

- **Reduce the cost by a factor 2 in the production (at BRUKER)**

The partners:

- L. Rossi  
  *Task Leader*
- Th. Lecrevisse  
  *Deputy Task Leader*
- M. Dhallé
- C. Senatore
- U. Betz, A. Usoskin  
  *Industrial Partner*
Performance target for YBCO layer

How to get there?

- Increase the layer $J_c$ of YBCO
- Increase the thickness of YBCO
- Reduce the thickness of the substrate $100 \, \mu\text{m} \text{ SS} \rightarrow 50 \, \mu\text{m} \text{ SS}$

Double disordered YBCO
Usoskin et al., SuST 28 (2015) 114007

$J_e$ [A/mm$^2$] vs Magnetic field [T]

@4.2K, $B//c$
PROCESSING **50 µm** x 12 mm x 29 m HTS tape

- $I_c$ measurement from tape sample (start position) $I_c(77 \text{ K, s.f.}) = 174 \text{ A}$
- Average $I_c$ value from Hall-Probe-Measurement (TapeStar) of the 29 m long HTS tape $I_c(77 \text{ K, s.f.}) = 161 \text{ A}$
- 2 x $I_c$ drops detected in the range 23-25 m

**Courtesy of A. Usoskin, BHTS**
**ARIES project @ Bruker HTS**

**General appearance of HTS tapes with 50 µm SS substrates**

The new tapes reveal a strong curvature across the width (tape bow)

In the ABAD process biaxial texturing is achieved in a ~2 µm-thick YSZ layer (IBAD uses a thinner MgO layer)

Reduce the bow by depositing YSZ on the two sides of the tapes

Curvature does not exceed the critical one: no deterioration of $I_c$ is observed

*Courtesy of A. Usoskin, BHTS*
## Measurement campaign on the ARIES tapes

<table>
<thead>
<tr>
<th>Tape ID</th>
<th>Width</th>
<th>DD-YBCO thickness</th>
<th>Stabilizer</th>
<th>Orientation</th>
<th>Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q023</td>
<td>12 mm</td>
<td>1.95µm</td>
<td>2x 20µm Cu</td>
<td>90°</td>
<td>4.2K – 20K – 30K – 40K</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90°</td>
<td>4.2K – 20K – 30K</td>
</tr>
<tr>
<td>Q056</td>
<td>4 mm</td>
<td>1.78µm</td>
<td>2x 20µm Cu</td>
<td>90°</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0°</td>
<td>4.2K – 10K – 20K– 30K– 40K</td>
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<tr>
<td>Q064</td>
<td>12 mm</td>
<td>1.9-2.0µm</td>
<td>2x 20µm Cu</td>
<td>90°</td>
<td>4.2K – 10K – 20K– 30K– 40K</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0°</td>
<td>40K</td>
</tr>
<tr>
<td>Q065</td>
<td>12 mm</td>
<td>1.9-2.0µm</td>
<td>2x 7µm Cu</td>
<td>90°</td>
<td>4.2K</td>
</tr>
</tbody>
</table>

All Bruker tapes with the new 50µm-thick stainless steel substrate
Critical current tests up to 2 kA on 12mm tapes

Magnetic fields up to 19 T (21 T) and temperatures up to 40 K

- Possible to test long samples (> 120 mm) at various angles: $\theta = 0^\circ, 5^\circ, 7.5^\circ, 10^\circ$ and $90^\circ$

- Active stabilization of the sample temperature

C. Barth, M. Bonura, and CS, IEEE TASC 28 (2018) 9500206
Reproducibility of performance: $I_c(B, \theta = 90^\circ, T = 4.2\, K)$

The 4mm tape has a slightly lower decrease of $I_c$ with $B$

The maximum measured spread in $I_c$ is $\sim10\%$ (at 19 T)
Reducing the temperature by 10 K, \( J_e \) is increased by

- a factor 1.6 in **perpendicular orientation**
- a factor 1.7 in **parallel orientation**

*Exponential temperature dependence of \( I_c \) → CS et al., SuST 29 (2016) 014002*
**Engineering current density** $J_e(B, T=4 \, K)$

**Performance target**

Tape Q065-18 (with 2x 7$\mu$m Cu) reached **1150 A/mm$^2$** at 4.2 K, 19 T, 90°
Very recent high-performance REBCO tapes from Fujikura and SuperOx

<table>
<thead>
<tr>
<th>Tape ID</th>
<th>Width</th>
<th>REBCO thickness</th>
<th>Substrate/Stabilizer</th>
<th>Orientation</th>
<th>Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>FESC-SCH04(40)</td>
<td>4 mm</td>
<td>2.5 µm</td>
<td>50 µm Hastelloy 2x 40 µm Cu</td>
<td>90°</td>
<td>4.2K – 20K</td>
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<tr>
<td>19-0008</td>
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<td></td>
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</tr>
<tr>
<td>FESC-SCH04</td>
<td>4 mm</td>
<td>2.5 µm</td>
<td>50 µm Hastelloy 2x 20 µm Cu</td>
<td>Ongoing tests</td>
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<td>19-0007</td>
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<tr>
<td>#287-L</td>
<td>4 mm</td>
<td>3.1 µm</td>
<td>100 µm Hastelloy 2x 20 µm Cu</td>
<td>90°</td>
<td>4.2K – 20K</td>
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<tr>
<td>#337-R</td>
<td>4 mm</td>
<td>2.7 µm</td>
<td>40 µm Hastelloy 2x 5 µm Cu</td>
<td>90°</td>
<td>4.2K – 20K</td>
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</tbody>
</table>

New SuperOx tapes courtesy of Alexander MOLODYK

Fujikura tapes courtesy of Simon RICHARDSON and Masanori DAIBO
Engineering current density $J_e(B,T=4\text{ K})$

Comparison of 3 manufacturers

The REBCO layer is deposited by PLD for the three manufacturers

Fujikura FESC tape is based on EuBCO with BHO APC

SuperOx introduced a new composition, still undisclosed
Layer critical current density $J_c(B,T=4 \ K)$

Comparison of 3 manufacturers

At 4.2 K, 19 T the tapes do not differ significantly in terms of layer is $J_c$

All lie between 40 and 50 kA/mm$^2$
Towards HTS-based dipoles operating at $T > 1.9\,\text{K}$

**Diagram**

- **Q064-18, 2x 20μm Cu**
  - $I_c$ @ 1 μV/cm
  - $\theta = 90°$

**Graph**

- Engineering current density [A/mm$^2$] vs. Magnetic field [T]

- **LHC Nb-Ti wire @ 1.9 K**
- **HiLumi Nb$_3$Sn wire @ 1.9 K**
- **LHC dipole operating point**
- **HiLumi dipole operating point**

**Notes**

- **BRUKER tape Q064-18, 50μm stainless steel, 2x 20μm Cu, 2μm YBCO**
- **Engineering current density in perpendicular field orientation**
Summary

- High-$J_e$ HTS conductors are setting the grounds for accelerator magnets in the 20 T range

- The R&D tapes with thinner substrate (50 µm stainless steel) from exhibit very reproducible performance

- In spite of the tape shape, we got $J_e \approx 1150 \text{ A/mm}^2$ @ 4.2 K, 19 T

- Fujikura new tape with EuBCO + BHO, with $J_e \approx 1300 \text{ A/mm}^2$ @ 4.2 K, 19 T, is a commercial product

- SuperOx implemented a new composition and its new tape reached $J_e \approx 2000 \text{ A/mm}^2$ @ 4.2 K, 19 T and 1000 A/mm² @ 20 K, 19 T

- In light of the present results, should we target also accelerator magnets operating at higher temperatures?
Thank you for the attention!

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Performance overview (2016): $J_c(s.f., 77K)$ vs. $J_c^\perp(19T, 4.2K)$
Performance overview (2016): \( J_c(s.f., 77K) \) vs. \( J_c^\perp(19T, 4.2K) \)

Updated with the most recent results (2019)
Temperature dependence of $J_e$

Temperature scaling \[ J_e(B, T) = J_e(B, T = 0) \exp \left( -\frac{T}{T^*} \right) \Rightarrow \frac{J_e(B, T_1)}{J_e(B, T_2)} = \exp \left( \frac{T_1 - T_2}{T^*} \right) \]

$T^*$ ranges between 18 K and 29 K, with a maximum at 4 T
$I_c$ tests in gas flow

Active temperature stabilization

Q023 – 12 mm in perpendicular field

Sample temperature [K]

Current [A]

Voltage [µV]

Current [A]
**Q056-18**: 4 mm, 50 µm SS + 2x 20 µm Cu

- **T2290**: 100 µm SS + 2x 20 µm Cu
  - $E = 187$ GPa, $R_{p0.2} = 736$ MPa

- **Q056-18**: 50 µm SS + 2x 20 µm Cu
  - $E = 173$ GPa, $R_{p0.2} = 499$ MPa

<table>
<thead>
<tr>
<th>Material</th>
<th>RRR</th>
</tr>
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<tbody>
<tr>
<td>T2290</td>
<td>23</td>
</tr>
<tr>
<td>Q056-18</td>
<td>57</td>
</tr>
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</table>