Status of REBCO coated conductors for high field applications

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Outline

• Superior in-field performance of heavily-doped REBCO
• Achieving consistency in in-field performance of HTS tapes
• Evaluation of consistency in low-temperature in-field performance based on 77 K measurements
• High $J_c$ tapes and isotropic round REBCO wires
3X improvement in in-field performance in the with increasing Zr content

- Critical current of 25% Zr-added tape at 30 K, 3 T, $B||c$
  $J_c = 20.1 \text{ MA/cm}^2$,
  Pinning force = 603 GN/m$^3$
- Lift factor at 30K, 3 T, $B||c \sim 6.4$
  (200% improvement!)

- Enabled by engineering a high density of nanoscale defects while maintaining high crystalline quality of the superconductor films
Very high pinning forces in 25%Zr-added tapes: above 1000 GN/m³ at 20 K!

- Maximum pinning force at 30 K: 698 GN/m³
- Maximum pinning force at 20 K: 1021 GN/m³

Very high critical currents in 2.2 μm thick 20% Zr-added tapes over a broad temperature range


<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>30 K, 3 T</th>
<th>40 K, 3 T</th>
<th>50 K, 3 T</th>
<th>65 K, 3 T</th>
<th>77 K, 3 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_c) (A/12 mm)</td>
<td>3963</td>
<td>2833</td>
<td>1881</td>
<td>805</td>
<td>184</td>
</tr>
<tr>
<td>(J_c) (MA/cm²)</td>
<td>15</td>
<td>10.1</td>
<td>7.1</td>
<td>3.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>
100 times high flux pinning force in heavily-doped REBCO tapes

Courtesy of T. Puig, EUCAS 2015
Achieving consistency in in-field performance of HTS tapes
Variability in in-field performance of REBCO tapes

\[ J_c (77 \text{ K}, 0 \text{ T}) \) (MA/cm²) \]

\[ J_c (30 \text{ K}, 2.5 \text{ T}) \) (MA/cm²) \]

\[ Jc \] at 77 K, 0 T needs to be between 2.4 and 3.8 MA/cm² at 77 K, 0 T for \( Jc > 15 \) MA/cm² at 30 K, 2.5 T


28 104003 (2015)
Inverse correlation between $J_c$ at 77 K, 0 T and lift factor at 30 K

$Lift \text{ factor at } 30 \text{ K, 2.5 T, } B \parallel \text{c}$

$J_c$ (77 K, 0 T) (MA/cm²)

$J_c < 3.2 \text{ MA/cm}^2$ at 77 K, 0 T needed for lift factor above 6 at 30 K, 2.5 T

Compositional control important for achieving high lift factor at 30 K

Lift factor > 4 at 30 K, 2.5 T for \((\text{Ba+Zr})/\text{Cu} > 0.69\)

$J_c$ at 77 K, 0 T decreases with increasing (Ba +Zr)/Cu beyond 0.69

For high $I_c$ at 30 K, 3 T, need a combination of good $I_c$ at 77 K, 0 T and a high lift factor at 30 K, 3 T

*Need to control (Ba+Zr)/Cu in REBCO film in a narrow range!*
$J_c$ at 77 K, 0 T of 25 mol.% Zr-added (Gd,Y)BCO tapes correlates well with $\Delta T_c$

Broader $T_c$ in tapes with high $(\text{Ba}+\text{Zr})/\text{Cu}$ indicates structural change
Found increase in c-axis lattice parameter with increasing (Ba+Zr)/Cu composition in tape.

As (Ba+Zr)/Cu content in the tape increases, the lattice parameter of the superconductor film increases towards that of BZO.
BZO lattice shrinks towards REBCO lattice with increasing (Ba+Zr)/Cu content
Transition to continuous-aligned nanocolumns at high (Ba+Zr)/Cu

(Ba+Zr/Cu) ↑ → REBCO lattice expands & BZO lattice shrinks to match each other → BZO nanocolumns become continuous

(Ba+Zr)/Cu = 0.675
Lift factor @ 30 K, 2.5 T = 3.85
$J_c$ (30 K, 2.5 T) = 11.86 MA/cm$^2$

(Ba+Zr)/Cu = 0.737
Lift factor @ 30 K, 2.5 T = 6.93
$J_c$ (30 K, 2.5 T) = 21.34 MA/cm$^2$
Correlation between c-axis lattice parameter and lift factor at 30 K, 3 T

Improvement in lift factor when c-axis lattice constant > 11.74 Å.
Use of in-line XRD system in pilot MOCVD tool

- For real-time monitoring of shift in c-axis lattice parameter as a tool to enable consistency in film quality for consistent in-field performance.
Use of in-line XRD system in pilot MOCVD tool

• For real-time monitoring of shift in c-axis lattice parameter as a tool to enable consistency in film quality for consistent in-field performance
C-axis peak shift method used in the in-line XRD system in MOCVD tool to discern variation in (Ba+Zr)/Cu
Control of film composition by MOCVD process temperature and oxygen flow rate

Lower deposition temperature and higher oxygen flow rates yields films with higher (Ba+Zr)/Cu ratio even when precursor composition is maintained the same.
Evaluation of consistency in low-temperature in-field performance based on 77 K measurements
Good correlation between $I_c$ at 77 K, 3 T at in-field $I_c$ at 30 K

$I_c$ at 77 K, 3 T at $B||c$ is good predictor of $I_c$ at 30 K, 3 T at $B||c$
Good correlation between $I_c$ at 77 K, 3 T and in-field $I_c$ at 30, 40, 50 and 65 K

Critical current measurements at 77 K, 3 T is a good Quality Assurance metric for in-field performance at lower temperatures

Magnetization measurements confirm good correlation between $I_c$ at 77 K, 3 T and at 4.2 K.
Transport measurements show decent correlation between $I_c$ at 77 K, 3 T and at 4.2 K, 20 T.
Reel-to-reel testing system to rapidly qualify consistency and uniformity of $I_c$ in a magnetic field of 3 T

Goal: To verify consistency and uniformity in in-field performance of long tapes and assess ability to control nanoscale defects in microstructure over tens of meters
Reel-to-reel testing system as a tool to qualify consistency and uniformity of in-field performance of HTS tapes

426 I-V curves at 77 K, 3 T every 5.7 cm of 26 m long tape

Standard deviation in $I_c$ at 77 K, 3 T ~ 4%
Standard deviation in n value at 77 K, 3 T ~ 9%
Higher Je tapes and Isotropic Round REBCO Wires
15%Zr & 20%Zr tape performance at 4.2K better than all wires even in field perpendicular to tape


UH data on 15%Zr tapes from APL Materials 2, 046111 (2014)
Additional improvements in $J_e$ with thinner tapes

- 3x $J_e$ improvement with 25% Zr addition
- Additional 2X $J_e$ improvement with 2X thicker film $\rightarrow J_e \sim 1700 \text{ A/mm}^2$ at 4.2 K, 20 T
- Yet another 2X $J_e$ improvement with $\frac{1}{2}$ thick tapes $\rightarrow$ 25 µm total tape thickness! (45 µm with Cu stabilizer) $\rightarrow J_e$ of 3000 A/mm² at 4.2 K, 20 T feasible!

**Ultrathin REBCO tapes can be wound on 0.51 mm diameter without Ic degradation!**

**Ultrathin REBCO tapes enable ultra-small diameter REBCO wires.**

1.6 mm diameter wire wound on 0.8 mm diameter core, with $I_c$ of 283 A
Excellent mechanical properties of round ultra-small diameter REBCO wire

3 cm bending diameter
Near isotropic in-field performance of round ultra-small diameter REBCO wire

Sample specification
- Single layer
- 18 mm long
- 1.1 mm former
- 1.2 mm O.D.

-93° to 35°
-77 K, 1 T, I_c = 9.2 A, 11.3% variation
-30 K, 3 T, I_c = 101 A, 8.2% variation

Far less angular dependence than flat REBCO tape (100% to 160%)
Summary

• Very high performance achieved in REBCO tapes by heavy doping.
  – $J_c > 20 \text{ MA/cm}^2$ at $30 \text{ K}$, $3 \text{ T}$ in 25% Zr-added tapes
  – $I_c \sim 4000 \text{ A/12 mm}$ at $30 \text{ K}$, $3 \text{ T}$ in 2.2 µm thick films
  – At $4.2 \text{ K}$, $21 \text{ T}$, $I_c = 663 \text{ A/4mm}$, $J_e = 1658 \text{ A/mm}^2$

• Understanding developed to address consistency in in-field performance.
  – As $(\text{Ba+Zr/Cu})$ increases $\rightarrow$ REBCO lattice expands & BZO lattice shrinks to match each other $\rightarrow$ BZO nanocolumns become continuous. High lift factors achieved with continuous BZO nanocolumns.
  – Since $\Delta T_c$ increases and $J_c$ at $77 \text{ K}$, $0 \text{ T}$ decreases with higher $(\text{Ba+Zr/Cu})$, need to maintain $(\text{Ba+Zr})/\text{Cu}$ composition in a narrow range
  – In-line XRD being developed for real-time monitoring of $(\text{Ba+Zr})/\text{Cu}$ composition and adjust process parameters to maintain in a narrow range

• Good correlation between $I_c$ at $77 \text{ K}$, $3 \text{ T}$ and $I_c$ at low temperatures down to $4.2 \text{ K}$ and high fields. Reel-to-reel in-field $I_c$ measurement system used to verify consistency in low-temperature in-field performance of long REBCO tapes

Consistent achievement of excellent performance in heavily-doped REBCO tapes open opportunities for HTS applications in high fields
Higher amount of a-axis grains contribute to lower $J_c$ at 77 K, 0 T in tapes with $(\text{Ba}+\text{Zr})/\text{Cu} < 0.69$
Degradation of REBCO in-plane texture for (Ba+Zr)/Cu > 0.8
Better control of BZO in Advanced MOCVD System; superior control for thick films too

BZO size mostly 3 nm
Half the size of BZO in tapes made in conventional MOCVD system

Thick films made with Advanced MOCVD system with no degradation in Jc

More details on Advanced MOCVD in next talk…