Progress in development of high-performance REBCO tapes and wires

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Acknowledgments

- R. Pratap, G. Majkic, E. Galstyan, M. Kochat, W. Luo, A. Ben Yahia, V. Mohan, R. Jain, S. Chen of University of Houston
- S. Kar and J. Sandra of AMPeers
- High-field measurements at LBNL by H. Highley, X. Wang, S. Prestemon
- Support for high-field measurements at NHMFL provided by J. Jaroszynski and D. Abraimov
- **Funding:** DOE Advanced Manufacturing Office, DOE Office High Energy Physics, DOE High Energy Physics SBIR
Outline

• Improving Performance of REBCO Tapes at 65 K, Low-fields
• Improving Performance of REBCO Tapes in High Magnetic Fields at 4.2K
• Development of In-line and Continuous Quality-Control Tools for High-yield Manufacturing
• Symmetric Tapes for round REBCO wires for high $J_e$ with diameter < 2 mm
• Bend tolerance and high-field performance of High $J_e$ STAR REBCO Wires
• Status and Next Steps
Two primary applications driving REBCO development

High Temperature, low-medium field
65K – 77K, 1 – 3 T

Next-generation Electric Machines
Magnets for Accelerators, Fusion
Improving Performance of REBCO Tapes at 65 K, Low-fields
Advanced HTS Wire Development in DOE-AMO Next-generation Electric Machines (NGEM) Program

<table>
<thead>
<tr>
<th></th>
<th>Prod. Tape now</th>
<th>AMO NGEM2 Target Tape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic @ 65 K, 1.5 T (A/cm)</td>
<td>340</td>
<td>1440</td>
</tr>
<tr>
<td>Tape quantity for 5.5 MW motor (km)</td>
<td>5.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Tape cost for 5.5 MW motor ($,(000))</td>
<td>236</td>
<td>26</td>
</tr>
<tr>
<td>% of motor cost</td>
<td>67%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Extending nanocolumn-engineered REBCO films from 1.7 to 5µm to meet goal
UH Advanced MOCVD system for high performance, low-cost, high-yield production

- New reactor to address all deficiencies of current production tools designs
  - 5µm thick films & 10X BZO density: Excellent control (0.1°C) of tape temperature by Direct Tape Heating and Direct Tape Temperature monitoring
  - 5X precursor-to-film conversion efficiency: Low volume, laminar flow reactor

Precursor-to-film conversion efficiency already increased 4X to 46% by Advanced MOCVD → 3X reduction in total tape cost
4.6 µm thick film deposited by Advanced MOCVD in a single pass with purely c-axis oriented REBCO

Previous 5 µm REBCO film by conventional MOCVD made in 5 passes

4-5 µm REBCO film by Advanced MOCVD in 1 pass

Routinely fabricating tapes with 4 – 5 µm thick films in single pass by Advanced MOCVD
Critical currents over 1600 A/12 mm achieved in thick films made by Advanced MOCVD

\(I_c^{sf} (77K) = 1611 \text{ A/12 mm} \)

\(J_c^{sf} (77K) = 2.92 \text{ MA/cm}^2\)
Well aligned BZO nanocolumns throughout 4.2 μm thick HTS films by Advanced MOCVD
Effect of film thickness on in-field critical current density of 5% Zr-doped tapes at 65 K

- At 65 K, 1.5 T (B || c-axis), $J_c = 2.6 - 3$ MA/cm$^2$ with all film thickness.
- In 4.8 µm film, $J_c = 3$ MA/cm$^2 = 1734$ A/12 mm (record high current).
  - $F_p \sim 87$ GN/m$^3$
Effect of Zr concentration on in-field critical current density of 4+ μm films at 65 K

5% Zr-doped films optimum below 5 T
15% Zr-doped films better above 5 T
**Effect of Zr concentration on in-field critical current density at 65 K**

![Graph showing critical current density vs. magnetic field](image)

- **Out-of-plane texture (°)**
  - 0% Zr: 0.9
  - 5% Zr: 1.1
  - 15% Zr: 1.4

- **In-plane texture (°)**
  - 0% Zr: 2.3
  - 5% Zr: 3.4
  - 15% Zr: 5.5

- **(GdY)BCO lattice constant (Å)**
  - 0% Zr: 11.68
  - 5% Zr: 11.73
  - 15% Zr: 11.75

- **(Ba – Zr)/Cu**
  - 0% Zr: 0.65
  - 5% Zr: 0.66
  - 15% Zr: 0.70

**Lattice parameter increase, texture deterioration in 15% Zr suppress \( J_c \) at 65 K, 0 T but near-constant \( J_c \) up to 6 T.**
Critical current > 1440 A/cm @ 65K, 1.5T – Met DOE Advanced Manufacturing Office milestone

5% Zr-added thick film REBCO tapes yield the best performance at 65 K, 1.5 T - 4.4X critical current of commercial REBCO tape
Improving Performance of REBCO Tapes in High Magnetic Fields at 4.2K
REBCO tapes for high fields at 4.2K-20 K for High Energy Accelerators and Compact Fusion Systems

HTS operating at 20+T enables 10X smaller fusion energy systems and compact high energy accelerators

Courtesy Commonwealth Fusion Systems
Effect of dopant concentration on in-field performance of 4+μm thick film tapes at 4.2 K

15% Zr-doped tapes superior at all fields above 2 T at 4.2 K
Influence of barium content at constant 15% Zr on tape performance at 4.2K,13T

Higher density of very fine BZO with increasing Ba → improved pinning
Too high Ba → degradation of REBCO texture, too high strain in REBCO
Influence of Ba content on self-field $J_c$ of 4+ µm 15% Zr-doped (Gd,Y)BCO

For Ba content < 2.1 → a-grains
For Ba content > 2.15 → degradation of in-plane texture
Transport $J_c$ of 4+ µm thick film with high BZO density comparable to 1 µm thick films

Similar $J_c$ in all tapes > 8 T at 4.2 K

Maximum pinning force of 4.2µm thick film REBCO tape = 1.86 TN/m³

Maximum pinning force of 1µm thick film REBCO tape = 1.76 TN/m³
Thick film 15% Zr REBCO tapes made by Advanced MOCVD exhibit very high $J_e$ at 4.2K

$J_e$ of UH REBCO @ 4.2 K, 15 T = 5200 A/mm²

5.4X Nb₃Sn @ 15 T

7X present commercial REBCO @ 15 T

Influence of Ba content on self-field $J_c$ of 4+ µm 15% Hf-doped (Gd,Y)BCO

<table>
<thead>
<tr>
<th>Ba content in precursor</th>
<th>Average (Ba-Hf)/Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.97</td>
<td>0.66</td>
</tr>
<tr>
<td>2.02</td>
<td>0.68</td>
</tr>
<tr>
<td>2.07</td>
<td>0.69</td>
</tr>
<tr>
<td>2.12</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Compared to 15% Zr-doped films, with increase in Ba content, no a-grains, no increase in c-lattice constant and no change in texture in 15% Hf-doped films.
Influence of Ba content on magnetization $J_c$ at 4.2 K, 13 T of 15% Hf-doped (Gd,Y)BCO

Wider compositional range available with 15% Hf doping for high $J_c$ at 4.2 K
Development of In-line and Continuous Quality-Control Tools for High-yield Manufacturing
Pilot-scale Advanced MOCVD built and commissioned for wire manufacturing
Compositional control of REBCO film important for high in-field $J_c$

Non-destructive method needed for rapid evaluation of REBCO film composition during manufacturing of long tapes
2D-XRD: Rapid non-destructive method to evaluate REBCO film composition

- Streaking of BZO (101) peak towards REBCO (103) peak
- C-axis lattice mismatch between REBCO and BZO decreases with increasing Ba/Cu composition
2D-XRD: Rapid non-destructive method to evaluate REBCO film composition

BZO (101) streak deviation angle good indicator of BZO nanocolumn size and film composition
Correlation between BZO (101) streak deviation angle and $I_c$ at 30 K, 3 T and 4.2 K, 13 T

In-line 2D-XRD in MOCVD manufacturing tool for real-time measurement of BZO streak deviation angle → to achieve consistent in-field performance.
In-line 2D XRD built and installed in pilot MOCVD tool for film monitoring & control
Key phases (REBCO, BZO, REO) identified in a single snapshot in in-line 2D XRD in pilot MOCVD tool.

Mapped variation in BZO (101) streak angle along tape length.

BZO (101) streak angle from in-line XRD predictive of tape performance.
Round REBCO Wires with Excellent Flexibility and High Engineering Current Densities
Bend strain-tolerant, round HTS wires needed for compact accelerator coils

Canted Cosine Theta (CCT) coil

**CCT coil requirements**

1. Round isotropic wire architecture
2. High $I_c$ with multi-strand geometry for low AC loss.
3. High tolerance to the bend strain.
4. $J_e = 540 \text{ A/mm}^2$ at 4.2 K, 21 T at 15 mm bend radius.


Physical review special topics—accelerators and beams 18, 103501 (2015)
Standard REBCO tapes fail at bend diameter < 2 mm

Standard REBCO tapes cannot be used to fabricate small diameter (< 2 mm) REBCO round wires needed for 15 mm bend radius requirement in CCT coils
Symmetric Tape Round (STAR) REBCO Wire for high $J_{e}$ with diameter $< 2$ mm

**Standard REBCO Tapes:**
- REBCO asymmetrically positioned far away from neutral plane

**Symmetric REBCO Tape:**
- Copper stabilizer primarily on REBCO side.
- REBCO positioned near geometric center.
- Minimizes the strains in the REBCO layer.

**Symmetric REBCO tapes used to make round REBCO wires on 0.8 and 1 mm diameter copper former**

Supercond. Sci. Technol. 3, 04LT01 (2018)*
Symmetric REBCO tapes retain > 95% $I_c$ even when bent to diameter of 0.8 mm

![Graph showing $I_c/|I_c|$ (Flat tape) (%) vs Bend diameter (mm)]
Caused by the progressive plastic deformation in the various layers.
Optimized copper thickness for different substrate thickness for use in STAR wires

$I_c$ retention for different Cu on REBCO side for 18 – 25 µm thick substrates

Optimum Cu on REBCO side for different substrate thickness

Copper thickness on substrate side in all tapes = 3 µm
STAR wires with $I_c > 600$ A at 77 K at 15 mm bend radius

- STAR wire (STAR # 2), 1.66 mm diameter
- REBCO STAR wire in straight form
- REBCO STAR wire at 15 mm bend radius

Bending properties of STAR wires

![Graphs showing bending properties of STAR wires with different currents and electric fields.](image-url)
STAR wires retain 90% of their $I_c$ even at a bend radius of 15 mm

<table>
<thead>
<tr>
<th>STAR #</th>
<th>$I_c$ (A) in straight form</th>
<th>$J_e$ (A/mm²) in straight form</th>
<th>$I_c$ (A) at 15 mm bend radius</th>
<th>$J_e$ (A/mm²) at 15 mm bend radius</th>
<th>Retention of $I_c$ (%) at 15 mm bend radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>518</td>
<td>215.8</td>
<td>506</td>
<td>210.8</td>
<td>97.7</td>
</tr>
<tr>
<td>2</td>
<td>482</td>
<td>223</td>
<td>450</td>
<td>208.3</td>
<td>93.4</td>
</tr>
<tr>
<td>3</td>
<td>516</td>
<td>227.5</td>
<td>482</td>
<td>212.5</td>
<td>93.4</td>
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<tr>
<td>4</td>
<td>&gt;600</td>
<td>NA</td>
<td>611</td>
<td>218.2</td>
<td>NA</td>
</tr>
<tr>
<td>5</td>
<td>&gt;600</td>
<td>NA</td>
<td>556</td>
<td>196.5</td>
<td>NA</td>
</tr>
</tbody>
</table>

Expected $J_e$ of REBCO STAR wire at 15 mm bend radius for AWG 20 Former
$J_e \sim 600 \text{ A/mm}^2$ at $20 \text{ T}$ in recent STAR wires

1.67 mm diameter STAR wire bent to a radius of 15 mm

At a bend radius of 15 mm, using REBCO tapes with 1.7µm thick films,
- 2018 STAR wire: 438 A/mm$^2$ at 20 T and 299 A/mm$^2$ at 31.2T
- 2019 STAR wire: 729 A/mm$^2$ at 15 T and 584 A/mm$^2$ at 20 T
10m long, 1.9 mm dia. STAR wires produced

Average $I_c = 476$ A at 77 K, self-field over 10 meters
Ongoing Improvements: Higher J_e with more tape layers on smaller dia (0.8 mm) former

6-layer STAR wire (1.0 mm former)

8-layer STAR wire (1.0 mm former)

20% reduction in former diameter leads to 11-12% reduction in final wire diameter and 15-19% increase in J_e at 77 K, self-field.

Ongoing Improvements: Symmetric Tapes with even thinner (10 µm) substrates

22 µm Hastelloy substrate

10 µm Hastelloy substrate

10 µm substrate tape (4 mm width)

$I_c = 114 \, A / 4 \, mm$
Status and Next Steps

- Advanced MOCVD developed for REBCO tapes with 5 µm thick films and fine-scale BZO nanocolumns high performance over 4.2 K – 65 K
  - $I_c \sim 1440$ A/cm at 65 K, 1.5 T (4.4X $I_c$ of commercial REBCO tape) 
    *(Met Department of Energy Advanced Manufacturing Office Program goal)*
  - $J_e \sim 5200$ A/mm² at 4.2 K, 15 T (5.4X best $J_e$ of Nb₃Sn, 7X commercial tape)
- In-line 2D XRD installed and used in pilot Advanced MOCVD system
  - BZO (101) streak angle predicts film composition and in-field performance
- Symmetric Tape Round (STAR) REBCO wire developed
  - $J_e = 584$ A/mm² at 4.2 K, 20 T at 15 mm bend radius
  - 10 m long, 1.9 diameter STAR wire with $I_c \sim 476$ A @ 77 K, self-field

**Next:**

- Scale up thick film, fine BZO tapes to 50 m lengths with high in-field $I_c$
  - use 2D-XRD for in-line QC for uniform and consistent in-field $I_c$
- Provide high-performance, lower-cost REBCO tapes for prototype demonstrations
- Scale up STAR wires to long lengths
- Increase $J_e$ of STAR wires > 1000 A/mm² at 4.2K, 20 T