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Status of 2G HTS Wire for Electric Power Applications

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CIGRÉ SC D1 WG38 Workshop on High Temperature Superconductors (HTS) for Utility Applications
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Outline

• SuperPower 2G HTS conductor
• Electric power applications requirements
• Summary
SuperPower® 2G HTS wire: Thin film deposition on robust, flexible substrate

- Automated processes
- Reel-to-reel systems
- High throughput, fast processes

- Modular and scalable systems
- Quality assurance throughout
- Rigorous testing, product certification with each delivery
Each layer serves a function….

- Substrate (Hastelloy® C-276) provides mechanical strength, electropolished base for subsequent layer growth
- Buffer stack provides:
  - Diffusion barrier between substrate and superconductor
  - IBAD MgO layer provides texture template for growing aligned superconductor, necessary for high current density
  - Final buffer layer provides lattice match between buffer stack and superconductor
- HTS superconductor layer – (RE)BCO superconductor with BZO based pinning sites for high current carrying capability in background magnetic field.
- Ag layer – provides good current transfer to HTS layer while providing ready path oxygen diffusion during final anneal.
- Cu layer – provides stabilization (parallel path) during operation and quench conditions.
Microstructure of production MOCVD HTS wires with standard 7.5% Zr doping

5 nm sized, few hundred nanometer long BZO nanocolumns with ~ 35 nm spacing created during in situ MOCVD process with 7.5% Zr
2G HTS wire produced in manufacturing facility at SuperPower since 2006

- Substrate Electropolishing
- IBAD
- MOCVD
- Buffer Sputtering
# 2G HTS Wire Specifications

<table>
<thead>
<tr>
<th>Spec</th>
<th>SCS3050</th>
<th>SF4050</th>
<th>SCS4050</th>
<th>SF6050</th>
<th>SCS6050</th>
<th>SF12050</th>
<th>SCS12050</th>
<th>SF12100</th>
<th>Unit</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Minimum I&lt;sub&gt;c&lt;/sub&gt;</td>
<td>75</td>
<td>100</td>
<td>100</td>
<td>150</td>
<td>150</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>amp</td>
<td>measured by continuous direct current</td>
</tr>
<tr>
<td>Widths</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>mm</td>
<td></td>
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<tr>
<td>Total Wire Thickness</td>
<td>0.1</td>
<td>0.055</td>
<td>0.1</td>
<td>0.055</td>
<td>0.1</td>
<td>0.055</td>
<td>0.1</td>
<td>0.105</td>
<td>mm</td>
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<tr>
<td>Standard Copper Stabilizer Thickness</td>
<td>0.04</td>
<td>n/a</td>
<td>0.04</td>
<td>n/a</td>
<td>0.04</td>
<td>n/a</td>
<td>0.04</td>
<td>n/a</td>
<td>mm</td>
<td>surround stabilizer with rounded corners</td>
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<tr>
<td>Critical Tensile Stress</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>MPa</td>
<td>at 77K</td>
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<tr>
<td>Critical Axial Tensile Strain</td>
<td>0.45%</td>
<td>0.45%</td>
<td>0.45%</td>
<td>0.45%</td>
<td>0.45%</td>
<td>0.45%</td>
<td>0.45%</td>
<td>0.4%</td>
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<td>at 77K</td>
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<td>Critical Bend Diameter in Tension</td>
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<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>25</td>
<td>mm</td>
<td>at room temperature</td>
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<tr>
<td>Critical Bend Diameter in Compression</td>
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<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>25</td>
<td>mm</td>
<td>at room temperature</td>
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</table>

- Robust, high-performance wire; several architectures, incl. variations of width, substrate thickness, stabilizer, and insulation
  - Insulated wire: Kapton wrapped - 30% overlap or butt-wrap available
- Two chemical formulations:
  - AP (Advanced Pinning) – for enhanced in-field performance in motors, generators, transformers, SMES, high field magnets, etc.
  - CF (Cable Formulation) – for cable or FCL
Outline

• SuperPower 2G HTS conductor
• **Electric power applications requirements**
• Summary
2G HTS is ready to serve a diverse range of applications

<table>
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<tr>
<th>Energy</th>
<th>Defense</th>
<th>Transportation</th>
<th>Industrial</th>
<th>Medical</th>
<th>Science/Research</th>
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<tr>
<td>• FCL</td>
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<td>• Maglev</td>
<td>• Induction heaters</td>
<td>• Current leads</td>
<td>• HF magnets</td>
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<td>• Cable</td>
<td>• Cables</td>
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<td>• Motors</td>
<td>• NMR</td>
<td>• Space exploration</td>
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<tr>
<td>• Generators</td>
<td>• Directed energy</td>
<td>• Rail engines</td>
<td>• Generators</td>
<td>• MRI</td>
<td>• SQUIDS</td>
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<td>• Transformers, incl. FCL</td>
<td>• Weapons</td>
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<td>• Magnetic separation</td>
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<td>• High energy physics</td>
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<td>• Bearings</td>
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<td>– SMES</td>
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<td>• Cell tower</td>
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<td>– Flywheels</td>
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<td></td>
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<td>base station filters</td>
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</table>

Key:
- **Near-Term addressable:** 1-5 years
- **Mid-Term:** 3-7 years
- **Longer term:** 5-10 years

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Key performance requirements for electric power applications

- Long piece length
- Uniform and consistent properties
- High mechanical strength
- Low ac losses
- Sufficient production capacity
- High operating current density (magnets)
Excellent in-field performance makes a wide range of real-world applications possible

High Temp, Low Fields:
- Cable
- SFCL
- Transformer
- Motor/generator
- Propulsion motor
- Plasma confinement
- Crystal growth magnet
- Magnetic separation

Medium Temp, Medium Fields:
- Motor/generator
- Propulsion motor
- Plasma confinement
- Crystal growth magnet
- Magnetic separation
- Maglev
- SMES

Low Temp, High Fields:
- SMES
- High-field MRI
- High-field Insert
- NMR

\* $J_e$ is calculated based on $I_c$ (77 K, 0T) = 100 A/4 mm (surr. copper stabilized, (SmY)BCO) and scaling factors measured by D. Larbalestier, et al at FSU and E. Barzi, et al. of Fermi Lab.
Critical current vs. temperature and magnetic field of recent AP production material

Small cross-section of SuperPower2G HTS translates into high operational current density
Significant improvement in lift factor at targeted operating conditions for motor / generator demonstrated.
Long piece lengths now routinely being manufactured

Example of >200m piece length delivered to ARPA-E SMES project (Tapestar data)
- 12mm wide
- 65 micron Cu stabilizer
- 77K Ic ~ 400A
Alternative configurations for compact high amperage windings demonstrated

Compact cable – Advanced Conductor Technologies

ROEBEL cable – General Cable Superconductors, KIT

- Bonded conductors for kA class conductors
SuperPower 2G HTS wire has high tensile strength

Copper thickness

40 µm

60 µm

100 µm

4K and 77K data from NHMFL
Outline

- SuperPower 2G HTS conductor
- Electric power applications requirements
- **Summary**
SuperPower is driving price down on two fronts: Improving manufacturing process and increasing in-field performance

<table>
<thead>
<tr>
<th>Time</th>
<th>Standard Performance at 77 K, zero field*</th>
<th>Lift Factor at device operating condition (30K, 2T)</th>
<th>Performance at device operating condition</th>
<th>Average Wire price ($/m)</th>
<th>Wire price ($/kA-m) at device operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now</td>
<td>100 A</td>
<td>2</td>
<td>200 A</td>
<td>$ 45</td>
<td>$225</td>
</tr>
<tr>
<td>2 years</td>
<td>150 A</td>
<td>4</td>
<td>600 A</td>
<td>$ 40</td>
<td>$ 67</td>
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<tr>
<td>4 years</td>
<td>200 A</td>
<td>6</td>
<td>1200 A</td>
<td>$ 35</td>
<td>$ 30</td>
</tr>
</tbody>
</table>

* Based 4mm width

Improving wire performance is key to success
Continually improving large-scale production of robust, high-performance wire

- High critical current:
  - 100A standard; 110-140+ A premium (4 mm width)
- Uniform critical current over long lengths: +/- 10% standard deviation
- Single piece lengths of 50-300 m (without splices); up to 1 km and longer with high quality splices
- Excellent joints & solderability:
  - No degradation in Ic even when joint is bent over 1” diameter and thermal cycled
  - Joint resistance ~ 40 nohm-cm²
  - No issues with soldering to our 2G HTS Wire
- Manufacturing volume steadily increasing
Thank you for your attention!

- For further information, please visit  www.superpower-inc.com