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2G HTS Conductor Development at SuperPower for Magnet Applications

Drew Hazelton, Principal Engineer
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Acknowledgments

• Would like to acknowledge the contributions of my colleagues at SuperPower, in particular:

• Paul Brownsey
• Honghai Song
• Yifei Zhang

• Manufacturing and R&D teams
Outline

• **SuperPower 2G HTS conductor**
• Applications requirements
• Applications overview
• Conclusions
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
2G HTS Wire Specifications

- 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

<table>
<thead>
<tr>
<th>Spec</th>
<th>SCS3050</th>
<th>SF4050</th>
<th>SCS4050</th>
<th>SF6050</th>
<th>SCS6050</th>
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<th>SF12100</th>
<th>Unit</th>
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<td>100</td>
<td>150</td>
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<td>300</td>
<td>300</td>
<td>300</td>
<td>amp</td>
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<td>4</td>
<td>6</td>
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<td>12</td>
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<td>Total Wire Thickness</td>
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<td>&gt; 550</td>
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<td>&gt; 550</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
<td>MPa</td>
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<td>0.45%</td>
<td>0.45%</td>
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<td>0.45%</td>
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<td>11</td>
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<td>11</td>
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<td>mm</td>
<td>at room temperature</td>
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<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>
</tr>
</tbody>
</table>
Outline

- SuperPower 2G HTS conductor
- **Applications requirements**
- Applications overview
- Conclusions
Key performance requirements for HTS magnet applications

- High operating current density
- High operating currents – particularly for HEP applications
- Long piece length
- Uniform and consistent properties
- High mechanical strength
- Low ac losses
- Sufficient production capacity
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.
Improvements in in-field $I_c$ of Zr-doped conductors at intermediate temperatures

At 40K 3T, quantity of wire required for device is **reduced by HALF**, greatly improving the economics of the device.
Critical current vs. temperature and magnetic field of recent AP production material

Small cross-section of SuperPower2G HTS translates into high operational current density
Long piece lengths now routinely being manufactured

Example of >200 m 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 – IRL, KIT

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

![Graph showing stress-strain data for Copper thicknesses of 40, 60, and 100 µm. The graph includes data at 4 K and 77 K from NHMFL.](image)
SuperPower 2G HTS wire exhibits good fatigue strength

- Ic & N do not change under fatigue cycling if stress amplitude is below $s_{ICRL}$
- For stress > $s_{ICRL}$, Ic & N degrade with fatigue cycles
- Recommend a 98% reversible Ic retention as “failure” criterion

Data from Ron Holtz, NRL
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2G HTS is ready to serve a diverse range of applications

<table>
<thead>
<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>
<td>• Motors</td>
<td>• Maglev</td>
<td>• Induction heaters</td>
<td>• Current leads</td>
<td>• HF magnets</td>
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<td>• Motors</td>
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<td>• Space exploration</td>
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<td>• Directed energy weapons</td>
<td>• Rail engines</td>
<td>• Generators</td>
<td>• MRI</td>
<td>• SQUIDS</td>
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<tr>
<td>• Transformers, incl. FCL</td>
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<td>• Magnetic separation</td>
<td></td>
<td>• High energy physics</td>
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<tr>
<td>• Storage</td>
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<td>• Bearings</td>
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<td>– SMES</td>
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<td></td>
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<td>• Cell tower</td>
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<td>– Flywheels</td>
<td></td>
<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

Courtesy of SuperPower and Furukawa
2G HTS has been used in multiple high field insert coil demonstrations

SuperPower: 26.8 T, 27.4 T / 20 T
NHMFL: 33.8 T, 35.4 T / 31 T
BNL: various HF coils to 16 T (500 A/mm²)

Layer wound 2G insert for commercial customer

SP 26.8T

NHMFL 35.4T

BNL 2G HTS Coil
Successful winding techniques demonstrated

• Decoupling of former from winding has been demonstrated to be beneficial
  – Eliminates radial tensile stress on the 2G HTS windings
  – PET release layer incorporated at former:windings interface
  – Lower thermal expansion formers (Ti, controlled expansion glass-epoxy)

• Use of cowound stainless steel as “insulation” with partial epoxy application on coil sides
  – Mitigates impact of conductor dog boning
  – Mitigates radial tensile stress on the 2G HTS
  – Improves overall coil strength
  – Negative impact on coil current density
ARPA-E SMES development

- **Funding:** DoE ARPA-E $4.2 million (Total program = $5.25 million)
- **Project timeline:** 2011-2013
- **Partners:**
  - ABB, Inc.: project lead, power electronics
  - Brookhaven National Lab: SMES coil
  - SuperPower Inc.: 2G HTS wire, coil development
  - University of Houston, TcSUH: manufacturing improvements for wire cost reductions

- **Objective:** proof-of-concept of modular, scalable SMES system by integrating an advanced power conversion concept with superconducting magnet coil
  - 2 MJ class, 20 kW UHF SMES device
  - Field of up to 25 T at 4.2K
  - 2G HTS wire with high critical currents (~ 800 A) to drive down price/performance
  - Capable of flexible connection to medium voltage distribution networks at 15-36 kV

- **Relevance:**
  - High power and high energy storage in a compact device with cost advantages in material and system
  - Modular units for both long (hours) and short term (seconds) storage requirements to help load leveling on the grid being fed by variable renewable sources

Example of one of the pancake coils used in SMES magnet winding
Army Research Lab – SMES for Micro-Grid

- **Funding:** US Army Research Laboratory $4.2 M funded to date
- **Project timeline:** 3 yrs., 2012 - 2015
- **Partners:**
  - **SuperPower Inc:** project lead, 2G HTS wire, coil development
  - **Brookhaven National Lab:** SMES coil
  - **MTech Labs:** power electronics
  - **University of Houston, TcSUH:** low ac loss material development

- **Objective:** Build upon the developments achieved in the ARPA E-SMES project with HTS superconductors and adapt those developments to the Army’s tactical Microgrid application.
  - Model, design and fabricate a 2.5MJ tactical Microgrid SMES
  - Modify 2G HTS MJ ARPA E-SMES coil to meet the tactical Microgrid requirements
  - Develop robust quench protection and switching components
  - Investigate methods to reduce ac losses through superconductor tape design

- **Relevance:**
  - High power and high energy storage in a compact device enables a power solution for remote areas.
  - Build on ARPA E investment in SMES technology to provide a practical application in real world environments.
ARPA-E REACT (Rare earth alternatives for critical technologies) Program

Low-cost superconducting wire for future wind turbine generators

Partners:

*University of Houston* – project lead, wire improvements  
*SuperPower* – wire manufacture  
*NREL (National Renewable Energy Laboratory)* – impact evaluation of enhanced superconducting wire on overall system performance  
*Tai Yang Research Company* – coil fabrication and test  
*TECO Westinghouse Motor Company* – development of device design

**Budget:** $3.1 million  
**Program Period:** 3 years  
**Status:** project underway  
- work began January 2012
Significant improvement in lift factor at targeted operating conditions demonstrated
DoE Smart Grid SFCL transformer demonstration

- Funding: DoE Smart Grid Demo $10.7M (Total Program = $21.5M)
- Partners:
  - SuperPower (project lead)
  - SPX | Waukesha Electric
  - University of Houston
  - Southern California Edison
- Project objective:
  - Design, develop, manufacture and test SmartGrid-compatible SFCL Transformer
    - 28 MVA 3-phase FCL Medium Power Utility Transformer (69 kV / 12.47 kV class)
    - Testing on So. California Edison Smart Grid site in Irvine, CA – plan min 1 year of grid operation
  - First transformer to use significant amounts of 2G HTS wire
- Relevance:
  - Smaller footprint than conventional transformers, enabling existing substations to increase distribution capability without expanding into limited or expensive real estate

- Benefits
  - Greater efficiency
  - Smaller, lighter, potentially quieter
  - Safety: no oil for cooling
  - Can run indefinitely above rated power without affecting device life
- Add FCL feature ...
  - Compatibility with Smart Grid requirements
    - Incorporation of FCL feature to rapidly react to and limit surges at high power levels that can be handled by downstream equipment
      - 30-50% reduction of prospective fault current
      - Low ac loss conductor development at UH
Transformer winding and conductor development ongoing

- Practice low voltage winding for the FCL Transformer project using dummy conductor with proposed insulation scheme and coil geometry
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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 I\(_c\) even when joint is bent over 1” diameter and thermal cycled
  - Joint resistance ~ 40 nohm-cm\(^2\)
  - No issues with soldering to our 2G HTS Wire
- Manufacturing volume steadily increasing
Thank you for your attention