superior performance. powerful technology.

Key performance of 2G HTS wire for coil applications

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Outline

• SuperPower Inc. - company profile
• Wire architecture, manufacturing, and specification
• Wire performance - important to coil applications
  – in-field performance
  – mechanical strength
  – splice resistance and strength
• Making reliable coils
• Summary
SuperPower Inc. formed in 2000 to develop and produce 2G HTS wire

- Intermagnetics (IGC) spins off from GE in 1971
  - Supplying LTS magnets for highly successful MRI business (Philips Electronics and others)
- Early focus on HTS begins at IGC in 1987
  - Development of first generation (1G) HTS (BSCCO) wire
  - Early device demonstrations (transformer, fault current controller) with 1G wire
  - Realization of superiority of 2G HTS materials – first to transition
- Multiple factors predict enormous market potential for 2G HTS-based electric power systems: increasing demand, aging infrastructure, deregulation
2006-2012 The Philips years

• IGC acquired by Philips Electronics in 2006 for MRI magnet business
• Six years to build value – leading supplier of 2G HTS wire
  – Buildup of strong R&D, manufacturing, and marketing team
  – R&D focusing on wire performance improvements
  – Strategic Research Agreement with the Univ. of Houston – TcSUH
  – Transition to pilot-scale manufacturing
• Market and customer oriented
  – Exploration of wide range of commercial markets – energy focus and beyond
  – Buildup of broad global customer base
A new strategic owner steps up

- Furukawa Electric acquired SuperPower in February 2012
  - Adding the world leader in 2G HTS to Furukawa’s long history in LTS
  - Focus on long-term sustainability in an evolving market
  - Concentration on continuous manufacturing improvements over established baseline capabilities
  - Steady expansion of production capacity to meet market requirements
Architecture of SuperPower’s 2G HTS wire

- Substrate (Hastelloy® C-276) provides mechanical strength, electropolished surface for subsequent layer growth
- IBAD-MgO provides template for growing epitaxial buffer layers
- Buffer layers provide:
  - Diffusion barrier between substrate and REBCO
  - Lattice match with REBCO
- REBCO layer – optimized composition with nanosized BZO & RE$_2$O$_3$ flux pinning sites for high in-field Ic at all field orientations
- Ag layer – provides good current transfer to HTS layer and facilitates oxygen diffusion during oxygenation annealing
- Cu layer – provides stabilization (parallel path for current) during operation and quench conditions
2G HTS wire manufacturing at SuperPower

- Automated processes, in-situ material characterization
- Reel-to-reel systems
- High throughput, fast processes
- Modular and scalable systems

Substrate electro-polishing  IBAD-MgO  REBCO layer MOCVD
2G HTS wire manufacturing at SuperPower

• Quality assurance throughout processes
• Rigorous testing, product certification with each delivery
• Continuous improvement in processing and wire performance
• Technical support to customers
2G HTS standard wire specifications

<table>
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<tr>
<th>Spec</th>
<th>SC3050</th>
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<td>11</td>
<td>25</td>
<td>mm</td>
<td>at room temperature</td>
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</table>

- **“SCS”** – Surrounded Copper Stabilizer’; **“SF”** – Stabilizer Free
- Two chemical formulations:
  - **AP** (Advanced Pinning) – for enhanced in-field performance for coil applications in motors, generators, SMES, high-field magnets, etc.
  - **CF** (Cable Formulation) – for cable and SFCL
- Variations in width, substrate thickness, stabilizer thickness, and insulation
  - Insulated wire: polyimide tape wrapped - 30% overlap or butt-wrap
2G HTS wire – a broad range of applications

- Much larger application potential lies beyond the capability of LTS wires, as well as MgB$_2$ and BSCCO wires
- Wide range of coil applications including generators & motors, SMES, flywheels, maglev, accelerators, insert magnets, transformers, MRI & NMR, induction heaters, bearings, etc.
- Requires sophisticated, engineered and cost-effective wires
- Requires performance in many aspects – electrical, mechanical, thermal, etc.

Adapted from B. Jensen et al.  
*J. Renewable & Sustainable Energy*  
Vol. 5, 023137 (2013)
Wire performance important to coil applications

• $I_c(B, T, \theta)$
  – engineering current density
  – field dependence
  – field orientation dependence
  – minimum $I_c(\theta)$

• Electromechanical properties (mechanical strength)
  – axial tensile (irreversible stress or strain limits)
  – transverse $(c$-axis$)$ tensile (along tape surface normal)
  – transverse $(c$-axis$)$ compressive (along tape surface normal)
  – transverse compressive (along width)
  – bending (with REBCO under compression or tension)
  – fatigue (in various stress states)

• Uniformity along length ($I_c$ and other attributes)

• Quench stability

• Splice
  – geometry
  – resistance (resistivity)
  – mechanical strength (tensile and bending)

Standards for 2G HTS wire characterization and testing are under development
### IEC Standards on Superconductivity (TC90)

(17 Publications, None on 2G HTS wire at this time)

<table>
<thead>
<tr>
<th>IEC</th>
<th>Description</th>
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<tbody>
<tr>
<td>IEC 61788-1</td>
<td>Critical current measurement - DC critical current of Nb-Ti composite superconductors</td>
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<td>IEC 61788-2</td>
<td>Critical current measurement - DC critical current of Nb3Sn composite superconductors</td>
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<td>IEC 61788-3</td>
<td>Critical current measurement - DC critical current of Ag- and/or Ag alloy-sheathed Bi-2212 and Bi-2223 oxide superconductors</td>
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<td>Residual resistance ratio measurement - Residual resistance ratio of Nb-Ti composite superconductors</td>
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<td>Matrix to superconductor volume ratio measurement - Copper to superconductor volume ratio of Cu/Nb-Ti composite</td>
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<td>IEC 61788-6</td>
<td>Mechanical properties measurement - Room temperature tensile test of Cu/Nb-Ti composite superconductors</td>
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<td>IEC 61788-7</td>
<td>Electronic characteristic measurements - Surface resistance of superconductors at microwave frequencies</td>
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<td>IEC 61788-8</td>
<td>AC loss measurements - Total AC loss measurement of round superconducting wires exposed to a transverse alternating magnetic field by a pickup coil method</td>
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<td>IEC 61788-9</td>
<td>Measurements for bulk high temperature superconductors - Trapped flux density of large grain oxide superconductors</td>
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<td>IEC 61788-10</td>
<td>Critical temperature measurement - Critical temperature of composite superconductors by a resistance method</td>
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<td>IEC 61788-11</td>
<td>Residual resistance ratio measurement - Residual resistance ratio of Nb3Sn composite superconductors</td>
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<td>IEC 61788-12</td>
<td>Matrix to superconductor volume ratio measurement - Copper to non-copper volume ratio of Nb3Sn composite superconducting</td>
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<td>IEC 61788-13</td>
<td>AC loss measurements - Magnetometer methods for hysteresis loss in Cu/Nb-Ti multifilamentary composites</td>
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<td>IEC 61788-14</td>
<td>Superconducting power devices - General requirements for characteristic tests of current leads designed for powering</td>
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<td>IEC 61788-15</td>
<td>Electronic characteristic measurements - Intrinsic surface impedance of superconductor films at microwave frequencies</td>
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<td>IEC 61788-16</td>
<td>Electronic characteristic measurements - Power-dependent surface resistance of superconductors at microwave frequencies</td>
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<td>IEC 61788-17</td>
<td>Electronic characteristic measurements - Local critical current density and its distribution in large-area superconducting films</td>
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</table>
In-field performance - key to coil applications

$I_c(B,T)/I_c$(self field, 77K) defined as Lift Factor

Cables, FCLs, transformers

Motors, generators

SMES
Lift factor of production wire

Lift Factor (2.5T, 30K, H//ab) = 5.6
Lift Factor (2.5T, 30K, H//c) = 2.6
Magnetic field orientation dependence of $J_c (I_c)$

- Results from electronic anisotropy and structural anisotropy
- Important to coil design
- Critical current density ($J_c$) given by force balance when pinning force = Lorentz force
- Nanoscale defects needed especially in the direction parallel to the $c$-axis to enhance flux pinning
- Zr doping effective to improve $J_c$ for $H//c$
Flux pinning enhancement via nanostructure engineering

- Techniques to introduce nanoscale defects into REBCO layer
  - Tailoring precursor composition (Zr content, RE substitution, RE:Ba:Cu ratio)
  - Optimized MOCVD deposition condition for the growth of nanostructure
  - BaZrO$_3$ and RE$_2$O$_3$ nanorods and nanoparticles
  - Controlled density, size, orientation & distribution
- Targeted wire performance for different applications (field and temperature)
- Zr doping results in significant enhancement in flux pinning for $H//c$, raising minimum $I_c$
- RE$_2$O$_3$ helps maintain high peak at $H//a$-$b$
ARPA-E REACT Program
- further improvement in in-field/low-T performance
  (Rare Earth Alternatives for Critical Technologies)

• Develop high performance, low-cost superconducting wires and coils for **wind turbine generators** that are lighter, more powerful, and more efficient

• Partnering between university, institution, and companies
  – University of Houston – project lead, wire improvements
  – SuperPower – wire manufacturer
  – 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 – device design

• Goal: four-fold improvement in lift factor (2.5T, 30K)
• Project started in January 2012
• Program period: 3 years
• Budget: $3.1 million
$I_c$ uniformity along length
(four-probe transport measurement)
$I_c$ uniformity along length (TapeStar)

Position (cm) (on a 12 mm wide wire)

- Magnetic, non-contact measurement
- High spacial resolution, high speed, reel-to-reel
- Monitoring $I_c$ at multiple production points after MOCVD
- Capability of quantitative 2D uniformity inspection
Mechanical strength of superconducting wires

- Longitudinal (axial) direction – static tensile, cyclic tensile
- Transverse direction (perpendicular to the surfaces) - static tensile, static compressive, cyclic tensile
- Transverse direction (parallel to the surfaces) – static compressive
- Peeling – complex and concentrated stress
- Bending – REBCO under tensile or compressive
Tensile strength of 2G HTS wire

• Stress-strain relationship under axial tensile load (at room temperature or operating temperature)
  - Basic mechanical behavior
• Electro-mechanical performance: effect of stress (strain) on $I_c$
  - $I_c$ measurement after applying stress at RT, compared with zero-stress critical current, $I_c(0)$
  - $I_c$ measurement while applying stress at a cryogenic temperature, e.g., 77K, compared with zero-stress critical current, $I_c(0)$
  - $I_c$ measurement after applying stress at a cryogenic temperature, e.g., 77K
  - Increase stress level while applying a constant current, e.g., at 95% of the zero-stress critical current, $I_c(0)$
• Tensile stress (strain) limit: critical stress (strain) above which $I_c$ drops below 95% of the zero-stress critical current, $I_c(0)$
• Tensile strength predominantly determined by the Hastelloy substrate, but affected by the copper stabilizer thickness
Tensile strength at room temperature

Effect of copper stabilizer thickness on stress-strain relationship at tension
Tensile strength - effect of stress on $I_c$

Relative $I_c$ vs. room temperature tensile stress for a 12mm wide wire with 100μm Cu stabilizer
Tensile strength at 4K and 77K
- Effect of copper stabilizer thickness

![Graph showing tensile strength at 4K and 77K](image-url)

4 K and 77 K data from NHMFL

Copper thickness

- 40 µm
- 60 µm
- 100 µm

stress (MPa)

strain
Bending test to determine minimum bending diameter

Relative $I_c$ vs. bending diameter for a 12mm wide wire with 100μm Cu

Compression

Tension

77K
Transverse compression perpendicular to surface

- Compression at room temperature, $I_c$ tested at 77 K
- No measurable degradation in critical current
Transverse (c-axis) tensile strength

- Stress builds up during coil winding, cooling, operation (mechanical, thermal, and magnetic) with tensile components perpendicular to wire surface
- Transverse (c-axis) tensile stress (more complicatedly, the peel stress, or cleavage stress) could cause wire delamination (either cohesive or adhesive)
- Various testing methods have been developed for the evaluation of wire strength against delamination
  - Anvil Test (NIST, SP, SRL-ISTEC, NHMFL w/\(I_c\))
  - Pin-Pull Test (SP)
  - Stud-Pull Test (Fujikura)
  - Cleavage Test (RIKEN w/\(I_c\))
  - Peel Test (SP)
  - Four Points Bending Test (SRL-ISTEC)
  - Double Cantilever Beam (DCB) Test (Kyoto University)
- Delamination behavior affected by mechanical properties of individual layers and the interfacial adhesion strength between adjacent layers
Peel strength – strength against delamination

- Peel test at various peeling angles (change in stress state at peeling tip), including 90°, 180° peel, or T-peel
- Peeling load vs displacement curve used for determination of peel strength (N/cm)
- Peeled surfaces analyzed for identifying weakest layer or interface
- Wire processing modification/optimization to achieve higher peel strength

![Peel test diagram](image)

![Graph](image)
Weakest layer (interface) varies with stress state

- 90° peel test
- 180° peel test

Optical images of peeled surfaces
Peel strength – strength against delamination

- Relationship observed between peel strength measured at different peeling angles, e.g., \( ps(90°) = 0.56ps(T) + 0.3 \)
Reliable splices – low resistance and high strength

- Splicing always required by real applications
- Splice properties are important conductor performance and have influences on dielectrics and cryogenics as well
- Low resistance and high electromechanical strength are basic requirements

- Contact resistivity at REBCO/Ag interface has an effect on splice resistance
- Splices fabricated via soldering at a temperature below 250°C
- Soldering temperature, pressure, duration time are important parameters
- \( I_c \) retained across the splices with no degradation through soldering
- Splice resistance \( R \leq 20 \, \text{n}\Omega \) and minimum bending diameter \( d \approx 25 \, \text{mm} \), for the lap joint geometry with a 10cm overlap length
- Splicing per customer request and each splice inspected
Splice resistance vs. overlap length

![Diagram](image_url)
Making reliable coils using 2G HTS wire
- coil winding techniques investigated

Epoxy
- Epoxy has strong effect on coil performance
  
Support
- Thermal coefficient consideration
  
Former Release
- Improvement found in coil stability
  
Insulation
- Alternative materials – stress relaxation & cooling
  
Co-winding
- Improved integrity and stability
  
Winding Tension
- Compactness and integrity

Mitigate stress and improve integrity & stability
Metal strip co-winding for high field magnet has been effectively used by many groups

- 1995, MIT/Sumitomo, SS co-winding, 1G HTS Bi2223
  - Generation of 24.0 T at 4.2 K and 23.4 T at 27 K with a high-temperature superconductor coil in a 22.54 T background field
    • \textit{APL}, 67, 1923, 1995

- 2003, NHMFL/OST, co-wind SS (28 \textmu m), 1G HTS Bi2212
  - Development of a 5T HTS Insert Magnet as Part of 25T Class Magnets

- 2011, MIT/FBML, co-wind Cu (0.2 mm with one side polyester) for REBCO, co-wind SS (50 um) for Bi-2223
  - A 1.3 GHz LTS/HTS NMR magnet – a progress report

- 2011, BNL, co-wind SS or Kapton (25 \textmu m), 2G HTS REBCO
  - High field HTS R&D solenoid for Muon Collider

- 2012, NHMFL, plain co-wind SS, 2G HTS REBCO
  - Design of a Superconducting 32 T magnet with REBCO high field coils
SS co-winding and partial epoxy winding

- **SS co-winding benefits**
  - Mechanical reinforcement
  - Less contained epoxy, improvement w/r to cool-down
  - Insulation may become stabilizer during transient/local quench
  - Increased thermal conductivity, compared to conventional insulation

- **SS co-winding impacts**
  - Ramping loss (low ramping rate, HTS larger thermal margin)
  - Current re-distribution during quench (may need modeling for large magnet)
  - Impact on current density

- **Partial epoxy impregnation offers positive results**
  - Side applied, epoxy partially penetrated into turns, 30-40% of epoxy coverage for 4 mm wide wire
  - Seals the coil, protects it from moisture
  - Mechanically fixes turn-turn and layer-layer
Summary

- 2G HTS wire provides advantages with higher current density and superior in-field performance for various coil applications
- SuperPower’s 2G HTS wire production grows steadily, meeting performance and volume requirements from different customers
- In-field performance (lift factor) and mechanical strength are among the key properties important to coil applications and being further improved with continuous R&D efforts
- Government-funded application development projects (e.g., SMES, FCL Transformer, and Wind Turbine Generator) are being pursued to demonstrate the technology and speed the adoption

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