SuperPower 2G HTS Wire
for Electrical and Magnet Applications

CERN Visit – Geneva, Switzerland
May 4, 2010
Drew Hazleton – Principal Engineer, HTS Applications
Traute Lehner – Sr. Director of Marketing
Agenda

• Company overview
• Manufacturing and R&D update
• HTS device demonstration project
• Product / service portfolio
SuperPower – History

- Established 2000 as subsidiary of Intermagnetics General Corporation
- Vision: develop 2G HTS wire for Energy Industry
  - Created new technology to leapfrog 1G technology
  - Original business plan: first mover to address enormous market
    - Intermagnetics/Philips + Government invested over $100M
- 2000-2010: from R&D group to acknowledged technology leader
  - Very significant IP portfolio; world-class technology team
  - Industry firsts: pilot production, largest wire delivery, first in-grid 1G power cable; first 2G device
- Philips Electronics acquired Intermagnetics in 2006
  - Business plan adjusted to develop customer-driven focus
  - Open many new, near-term market opportunities/applications
  - On track to be broad commercializer of 2G HTS technology
SuperPower – The Company

- Headquarters and manufacturing operation - Schenectady, NY
- Research & Development – Houston, TX
- 60+ employees
  - Recognized experts from around the world

Schenectady, NY

Houston, TX

SuperPower Confidential
Company organized for success
Pilot Manufacturing line established since 2006
Schenectady, NY - Headquarters + Manufacturing Operations

Strong and concentrated emphasis on manufacture of high quality, long length 2G HTS wire to satisfy market demand
Customer-responsive manufacturing operation

<table>
<thead>
<tr>
<th>Increasing annual capacity:</th>
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<tbody>
<tr>
<td>2010: 250 km</td>
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<tr>
<td>2011: 500 km</td>
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<tr>
<td>2012-2015: will expand based on market demand, up to 2500 km</td>
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<table>
<thead>
<tr>
<th>Improving manufacturing efficiency &amp; effectiveness:</th>
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<tbody>
<tr>
<td>Yield</td>
</tr>
<tr>
<td>Throughput</td>
</tr>
<tr>
<td>Quality assurance</td>
</tr>
<tr>
<td>On-time delivery</td>
</tr>
<tr>
<td>Cost improvement</td>
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<table>
<thead>
<tr>
<th>Product engineering/application support</th>
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<tbody>
<tr>
<td>Quality certification</td>
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<tr>
<td>New product</td>
</tr>
<tr>
<td>Customer technical support</td>
</tr>
<tr>
<td>Coil design/engineering and fabrication</td>
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</tbody>
</table>
2G wire research facilities at U. Houston

Strong and concentrated emphasis on technology development
R&D thrusts to meet application requirements

<table>
<thead>
<tr>
<th>Major R&amp;D areas</th>
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<tbody>
<tr>
<td><strong>Superior production wire performance</strong></td>
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<tr>
<td>High Ic</td>
</tr>
<tr>
<td>High in-field performance over wide temperature and angular range</td>
</tr>
<tr>
<td>Low ac loss</td>
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<tr>
<td>Multifunctional stabilizers</td>
</tr>
<tr>
<td><strong>Low cost product</strong></td>
</tr>
<tr>
<td>Higher yield (simplicity: simpler process, fewer layers, on-line monitoring)</td>
</tr>
<tr>
<td>Lean use of materials (more efficient conversion of raw materials to film)</td>
</tr>
<tr>
<td>Fewer process steps</td>
</tr>
<tr>
<td><strong>High production capacity</strong></td>
</tr>
<tr>
<td>Fewer process steps</td>
</tr>
<tr>
<td>Thinner layers</td>
</tr>
<tr>
<td>Better conversion efficiency</td>
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</table>
2G HTS provides unparalleled power density and weight savings for diverse commercial applications.

Sources: BCC Research, Internal
SuperPower Focus: 2G HTS Wire, Coils

- Development and manufacture of second-generation (2G) high-temperature superconductor (HTS) WIRE
  - Suitable for a wide variety of applications: research, energy, military, defense, industrial, transportation, high energy physics, medical, space
- Design and fabrication of COILS based on 2G HTS wire
- Engineering services
superior performance.

powerful technology.

2G HTS Wire Technology and Manufacturing at SuperPower
Technical approaches for 2G HTS wires

- SuperPower® 2G wire is based on high throughput IBAD MgO and MOCVD processes
- High throughput is critical for low cost 2G wire and to minimize capital investment
- Electroplating for copper stabilization in production process. Developing other stabilization techniques for process and materials to address various application needs

<table>
<thead>
<tr>
<th>Substrate /Buffer</th>
<th>HTS</th>
<th>Stabilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBAD-MgO</td>
<td>MOCVD</td>
<td>Electroplating</td>
</tr>
<tr>
<td>IBAD GZO</td>
<td>PLD</td>
<td>Bonding</td>
</tr>
<tr>
<td>IBAD YSZ</td>
<td>MOD</td>
<td></td>
</tr>
<tr>
<td>RABiTS</td>
<td>Evaporation</td>
<td></td>
</tr>
<tr>
<td>ISD</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Hermetic seal
- Thin profile
- Round edges

20μm Cu

1μm HTS (epitaxial)

2μm Ag

Buffer stack

< 0.1 mm
Key performance metrics of 2G HTS for applications

- Long length production at high throughput
- High $I_c$
- In-field performance
- Mechanical strength
- Other performance parameters: stability, ac loss, joints and insulation
Longer length *and* higher $I_c$ from 2005 to 2009!

- 600+ m lengths with $I_c > 300$ A/cm
- 1000+ m lengths with $I_c > 250$ A/cm
- 2009 World Record: 300,330 A-m
Higher $I_c$: Advancing towards 1000 A conductor

Over 1 m length,

$I_c = 976$ A = $813$ A/cm = $320$ A/4 mm

Using production buffer tapes

$I_c$: 80-100 A for today’s standard product
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 $I_c (77 \text{ K}, 0 \text{T}) = 100 \text{ A/4 mm}$ (surr. copper stabilized, (SmY)BCO) and scaling factors measured by D. Larbalestier, et al at FSU and E. Barzi, et al. of Fermi Lab.
HTS coil performance is often determined by anisotropy in field dependence.

Plots for illustration only

- High flux density at small angles (Near B//ab)
- Medium flux density at intermediate angle (20-30 deg)
- Low flux density at high angle (B//c)
2008: Zr doping was demonstrated in MOCVD to achieve dramatic in-field performance improvements

- 97% increase in minimum $I_c$ to 186 A/cm corresponds to $J_e$ of 28,500 A/cm$^2$ (no copper)
- 85% increase in $I_c$ ($B \perp$ tape) to 229 A/cm corresponds to $J_e$ of 35,200 A/cm$^2$ (no copper)

In 2009, Zr-doping chemistry successfully transferred to production line

Selvamanickam, Xie and Dackow, 2009 DOE HTS Program Review

Data from Y. Zhang, M. Paranthaman, A. Goyal, ORNL
Nano-defect sources for bi-directional pinning

HREM of nanorod

Horizontal (Gd,Y)\(_2\)O\(_3\) nano cluster

Vertical BZO Nanorod

TEM by F. Kametani (TEM) and D. Larbalestier, FSU
In-field performance enhancement also seen at higher fields

![Graph showing the relationship between magnetic field (T) and critical current density (Ic, A/cm) for three different materials: 3.5 micron SmYBaCuO, 2.8 micron GdYBaCuO, and 3.3 micron Zr:GdYBCO. The graph is labeled with '77K B // c'.]
In-field performance of production wire: Zr:(GdY)BCO vs. GdBCO

Magnetometer data provided by L. Civale, et al., of LANL
Enhanced pinning in Zr-doped MOCVD wires even at 4 K in high fields

- Higher $J_c$ in Zr-doped wires even without a peak at $B \parallel c$ at 4.2 K
- Broader peak at $B \parallel a-b$ in Zr-doped wire at 4.2 K
Benefit of Zr-doped wires realized in coil: improved performance

<table>
<thead>
<tr>
<th>Coil properties</th>
<th>With Zr-doped wire</th>
<th>With undoped wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil ID</td>
<td>21 mm (clear)</td>
<td>9.5 mm (clear)</td>
</tr>
<tr>
<td>Winding ID</td>
<td>28.6 mm</td>
<td>19.1 mm</td>
</tr>
<tr>
<td># turns</td>
<td>~2664</td>
<td>~2772</td>
</tr>
<tr>
<td>2G wire used</td>
<td>~480 m</td>
<td>~462 m</td>
</tr>
<tr>
<td>Wire I_c</td>
<td>72 to 97 A</td>
<td>72 to 82 A</td>
</tr>
<tr>
<td>Coil constant (mT/A)</td>
<td>41.9</td>
<td>44.4</td>
</tr>
<tr>
<td>Field generated at 77 K</td>
<td>0.95 T</td>
<td>0.73 T</td>
</tr>
</tbody>
</table>
Benefit of Zr-doped wires realized in coil: material saving

<table>
<thead>
<tr>
<th>Coil properties</th>
<th>With Zr-doped wire</th>
<th>With undoped wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil ID</td>
<td>21 mm (clear)</td>
<td>12.7 mm (clear)</td>
</tr>
<tr>
<td>Winding ID</td>
<td>28.6 mm</td>
<td>19.1 mm</td>
</tr>
<tr>
<td># turns</td>
<td>2688</td>
<td>3696</td>
</tr>
<tr>
<td>2G wire used</td>
<td>~ 480 m</td>
<td>~ 600 m</td>
</tr>
<tr>
<td>Wire I&lt;sub&gt;c&lt;/sub&gt;</td>
<td>90 to 101 A</td>
<td>120 to 180 A</td>
</tr>
<tr>
<td>Coil constant (mT/A)</td>
<td>42.2</td>
<td>51.8</td>
</tr>
<tr>
<td>Field generated at 65 K</td>
<td>2.5 T</td>
<td>2.49 T</td>
</tr>
</tbody>
</table>

Same level of high-field coil performance can be achieved with Zr-doped wire with less zero-field 77 K I<sub>c</sub>, less wire and larger bore.
SuperPower® 2G HTS wire has superior mechanical strength

77K Yield Stress 970 MPa
Strain at yield 0.92%

Superpower 4mm Wide 2G-HTS Tape
Stress-Strain Curves at Room Temperature and 77K
Tape ID # M3-383-1-BS504-569M

Data from R. Holtz, NRL
SuperPower® 2G HTS wire tolerates high axial stress up to 700 MPa

- $I_c$ drops by up to 10% reversibly under peak stress up to 700 MPa (about 0.6% strain)
- Above 700 MPa (0.6% strain) $I_c$ degrades irreversibly
- $N$-value does not change with peak stress up to 700 MPa
- $N$-value degrades irreversibly coincident with irreversible $I_c$ degradation
- Define $\sigma_{IcRL}(\varepsilon_{IcRL}) = “Ic Reversibility Limit” = Peak monotonic stress (strain) for $>98\%$ reversibility of $I_c$
- $\sigma_{IcRL}(\varepsilon_{IcRL}) = 700$ MPa (0.6%)

Data from R. Holtz, NRL
SuperPower® 2G HTS wire has larger operating stress-strain window compared to other conductors
Multifilamentary 2G HTS tapes for low ac loss applications

• Filamentization of 2G HTS tapes is desired for low ac loss applications.

• So far, there is no proven technique to repeatedly create high quality multifilamentary 2G tapes. Also, adds substantial cost.

5-filament tape, 4 mm wide (produced up to 15 m)

32-filament tape, 4 mm wide (difficult to make even 1 m lengths)
Market-driven products – delivering Innovation Technology Roadmap

Mission: develop technology for high-performance wire, custom-driven wire architectures, high efficiency processes & high production capacity

<table>
<thead>
<tr>
<th></th>
<th>Now</th>
<th>2 years</th>
<th>5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical current at 77 K (A)</td>
<td>80</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>Critical current (65 K, 3 T) (A)</td>
<td>30</td>
<td>90</td>
<td>260</td>
</tr>
<tr>
<td>Critical current (30 K, 5 T) (A)</td>
<td>120</td>
<td>350</td>
<td>1000</td>
</tr>
<tr>
<td>AC loss (W/m)</td>
<td>1.5</td>
<td>0.3</td>
<td>0.05</td>
</tr>
</tbody>
</table>

4 mm

Same performance as LTS wire in 3T MR system, but at 30K instead of 4K!

30 times less heat load
Insulated Wire Option

- Customer-driven demand for insulated wire
- In-house fabrication of insulated wire now in use for both 4 and 12 mm wide wire
- Tests show no breakdown at 1000 V with 0.0025 mm polyimide film before potting
SuperPower application programs

- DOE/NYSERDA - Albany HTS Cable project
- DOE/EPRI/NYSERDA - MFCL and SFCL programs
- ONR Generator program
- DOE HTS Transformer
- DOE Smart Grid Demonstration Program - FCL Transformer
- High field magnet coils
Albany Cable Project - Program Overview

- 350m long - 34.5kV - 800A_{rms} - 48MVA
- Cold dielectric, 3 phases-in-1 cryostat, stranded copper core design
- Two Phases – Phase I - 320m + 30m BSCCO
  - Phase II - 30m BSCCO replaced by 30m YBCO cable

<table>
<thead>
<tr>
<th>SuperPower Inc.</th>
<th>Project Manager; Site infrastructure, Manufacture of 2G HTS wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>nationalgrid</td>
<td>Host utility, conventional cable &amp; system protection, system impact studies</td>
</tr>
<tr>
<td>SUMITOMO ELECTRIC</td>
<td>Design, build, install, and test the HTS cable, terminations, &amp; joint</td>
</tr>
<tr>
<td>Linde</td>
<td>Design, construct and operate the Cryogenic Refrigeration System, and provide overall cable remote monitoring and utility interface</td>
</tr>
<tr>
<td>NYSERDA, U.S. DEPARTMENT OF ENERGY</td>
<td>Supported by Federal (DOE) and NY State (NYSERDA) Funds</td>
</tr>
</tbody>
</table>
Site Location

Phase I: BSCCO

Phase II: 30m YBCO
YBCO cable - critical current measurement

Sample: 3 meter 3-Core

- $I_c$ (Conductor) = Approx. 2660 – 2820A (DC, 77K, 1uV/cm)
- $I_c$ (Shield) = Approx. 2400 – 2500A (DC, 77K, 1uV/cm)

Very good match between test results and design values
AC Loss Measurement

Sample: 2.5 meter single core
Current loading: go & return through conductor and shield
Measuring: Lock-in amplifier with electrical 4 terminals

0.34 W/m/phase @ 800 Arms
Slightly better result than the 1 meter test sample core
Replacement of 30 meter Section with YBCO Cable (Phase II)

Joint Re-assemble (BSCCO-YBCO)

30m cable Installation

Termination Re-assemble
2G conductor for SFCL shows consistent, excellent performance

- Fast response time

<table>
<thead>
<tr>
<th>High-power SFCL test</th>
<th>2G</th>
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<tbody>
<tr>
<td>• Prospective current</td>
<td>90 kA*</td>
</tr>
<tr>
<td>• Limited current</td>
<td>32 kA</td>
</tr>
<tr>
<td>• Peak current through element</td>
<td>3 kA</td>
</tr>
<tr>
<td>• Response time</td>
<td>&lt; 1 ms</td>
</tr>
<tr>
<td>• Element quality range</td>
<td>Narrow</td>
</tr>
</tbody>
</table>

Quench speed around 0.5 ms

- Response time
- Peak current through element
- Limited current
- Prospective current
- Element quality range
2007 – First high field insert coil demonstrated

Wire:
Dimensions: 4 mm wide x 95 microns thick
Substrate: 50 micron Hastelloy
HTS: ~1 micron YBCO
Stabilizer: ~2 micron Ag on YBCO
~20 microns of SCS per side
Tape Ic: 72 – 82 A, 77 K, sf

Coil Winding
Double pancake construction
Dry wound (no epoxy)
Kapton polyimide insulation (co-wound)
Overbanding: 316 Stainless Steel

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
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<tbody>
<tr>
<td>Coefficient</td>
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</table>

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Width</td>
<td>4 mm</td>
</tr>
<tr>
<td>Wire Thickness</td>
<td>95 microns</td>
</tr>
<tr>
<td>Substrate</td>
<td>50 micron Hastelloy</td>
</tr>
<tr>
<td>HTS Thickness</td>
<td>~1 micron YBCO</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>~2 micron Ag on YBCO ~20 microns of SCS per side</td>
</tr>
<tr>
<td>Tc</td>
<td>72 – 82 A, 77 K, sf</td>
</tr>
<tr>
<td>Coefficient</td>
<td></td>
</tr>
<tr>
<td>Coefficient</td>
<td></td>
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Coil ID: 9.5 mm (clear)
Winding ID: 19.1 mm
Winding OD: ~87 mm
Coil Height: ~51.6 mm
# of Pancakes: 12 (6 x double)
2G tape used: ~462 m
# of turns: ~2772
Coil Je: ~1.569 A/mm² per A
Coil constant: ~44.4 mT/A
World Record High Field Coil – 26.8 T at 4.2 K

- Demonstration of world record high field 2G superconducting magnet
  - 26.8 T in background field of 19 T at 4.2 K
  - 9.81 T in self field at 4.2 K
  - Magnet coil constructed with 462 m of 4 mm wide SuperPower 2G HTS Wire™
  - In collaboration with NHMFL at Florida State University
High field insert coil achieved record performance

**Peak hoop stress ~ 215 MPa, well below tape limit**

![Graph showing peak hoop stress and central field vs. current.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>4.2 K Coil Ic @ Ic - self field</td>
<td>221 A</td>
</tr>
<tr>
<td>4.2 K Amp Turns @ Ic - self field</td>
<td>612,612</td>
</tr>
<tr>
<td>4.2 K Je @ Ic, self field</td>
<td>346.7 A/mm²</td>
</tr>
<tr>
<td>4.2 K Peak Radial Field @ Ic, self field</td>
<td>3.2 T</td>
</tr>
<tr>
<td>4.2 K Central field – self field</td>
<td>9.81 T</td>
</tr>
<tr>
<td>4.2 K Coil Ic @ 19 T background (axial)</td>
<td>175 A</td>
</tr>
<tr>
<td>4.2 K Amp Turns @ Ic – 19 T background (axial)</td>
<td>485,100</td>
</tr>
<tr>
<td>4.2 K Je @ Ic, 19 T background (axial)</td>
<td>274.6 A/mm²</td>
</tr>
<tr>
<td>4.2 K Peak Radial Field @ Ic, 19 T bkgd (axial)</td>
<td>2.7 T</td>
</tr>
<tr>
<td>4.2 K Central Field – 19 T background (axial)</td>
<td>26.8 T</td>
</tr>
</tbody>
</table>
2009: New coil tested in NHMFL facilities that provide up to 19.89T axial background field

Insert coil tested in NHMFL’s unique, 20-tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet

2G HF Insert Coil Showing Terminals, Overbanding and Partial Support Structure. Flange OD is 139.7 mm.
2009 - High field insert coil achieves new world record performance at 4.2 K

Coil Performance vs Applied Field

- Coil Ic
- Bo-total
- Bz-peak
- Br-peak

- 27.4 T in 20 T background
- 10.4 T self field
Current lead applications: 2G HTS offers distinct advantages

- “Standard” SCS4050 performs better than conventional vapor cooled leads above 100 mm length
- Non-Cu SF grades perform better than 1G Ag-Au leads
- Ag-Au is an option for 2G leads
2G HTS wire for power transfer applications

- Power cables can be adapted for either ac or dc power transfer applications

- ROEBEL cable is alternative configuration for power transfer applications
Product Portfolio

• Enabling commercial solutions
  – High strength substrate
  – Low ac loss
  – 2D uniformity
  – High Ic
  – Light weight, small footprint
  – High engineering current density (“packing factor”)
  – Coil design & engineering services
SuperPower 2G HTS Wire Types

• SuperPower is offering long lengths of robust, high-performance wire for sale in several configurations, including variations of width, substrate thickness, copper stabilizer, and insulation

• Our standard configurations include
  – Surround Copper Stabilizer: SCS3050, SCS4050, SCS6050, SCS12050
    • Width: 3 mm, 4 mm, 6 mm and 12 mm
    • Substrate thickness: 50 micron
  – Stabilizer Free: SF3050, SF4050, SF6050, SF12050, SF12100
    • Width: 3 mm, 4 mm, 6 mm and 12 mm
    • Substrate thickness: 50 or 100 micron
  – Insulated wire: SCS4050-i, SCS6050-i, SCS12050-i
    • Width: 4 mm, 6 mm and 12 mm
    • Variable overlap or butt-wrap available

• Other custom configurations are available on request