Second Generation HTS Wire for Electric Power Applications


2009 KEPRI-EPRI Joint Superconductivity Conference, Nov 16-19, Daejeon, South Korea
SuperPower develops advanced 2G HTS technology and manufactures commercial wires

**Surround Copper Stabilizer**: by electroplating; electric stability, hermetic seal. Solder temperature up to 250 °C. Minimal non-HTS edges

**HTS layer** (biaxially aligned): by MOCVD, high dep. rate + large dep. zone area ➔ high throughput

**Buffer stack**: IBAD-MgO based, biaxial texture formation with ~ 10 nm film ➔ high throughput; wide range of substrate selection

**Substrate**: High-strength, thin, flexible, highly resistive and non magnetic ➔ high J_c, low ac loss
IBAD-MgO-based MOCVD 2G HTS wire is produced in kilometer lengths

- Minimum current \( I_c \) = 282 A/cm-w over 1065 m
- 2009 new world record: \( I_c \times \text{Length} = 300,330 \) A-m
Albany HTS Cable Project

- 350m long - 34.5kV - 800A$_{\text{rms}}$ - 48MVA
- Cold dielectric, 3 phases-in-1 cryostat, stranded copper core design
- Cooled with subcooled, pressurized LN2 operating at ~ 69K
- Two Phases – Phase I - 320m + 30m BSCCO
  – Phase II - 30m BSCCO replaced by 30m YBCO cable

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

**DC $I_c$ test results**

Cable $I_c$ (DC) measurement at commissioning of Phase II – Results match Phase I performance

**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

*Phase II in operation for 3 months in 2008 with satisfactory performance*
Excellent in-field performance makes a wide range of real-world applications possible

High Temp, Low Fields:
- Cable
- SFCL
- Transformer
- Motor/generator
- Plasma Confinement
- Xtal growth magnet
- Magnetic separation

Medium Temp, Medium Fields:
- Motor/generator
- 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) and scaling factors measured by D. Larbalestier, et al at FSU and E. Barzi, et al. of Fermi Lab.
2008: Zr doping was demonstrated in MOCVD to achieve dramatic improvements in in-field performance

- 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)

- 67% increase in minimum $I_c$ to 267 A/cm corresponds to $J_e$ of 41,000 A/cm$^2$ (no copper)
- 88% increase in $I_c$ ($B \perp$ tape) to 340 A/cm corresponds to $J_e$ of 52,300 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
KEPRI-EPRI Joint Superconductivity Conference – November 16-18, 2009
Two coils made with Zr-doped 2G wire

Identical size, same quantity of Zr-doped wire with similar critical current performance at 77 K, zero field.

<table>
<thead>
<tr>
<th></th>
<th>Coil -1</th>
<th>Coil - 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coil ID</strong></td>
<td>21 mm (clear)</td>
<td>21 mm (clear)</td>
</tr>
<tr>
<td><strong>Winding ID</strong></td>
<td>28.6 mm</td>
<td>28.6 mm</td>
</tr>
<tr>
<td><strong>Winding OD</strong></td>
<td>~ 87 mm</td>
<td>~ 84 mm</td>
</tr>
<tr>
<td><strong>Coil Height</strong></td>
<td>~ 56.7 mm</td>
<td>~ 57.8 mm</td>
</tr>
<tr>
<td><strong># of Pancakes</strong></td>
<td>12 (6 x double)</td>
<td>12 (6 x double)</td>
</tr>
<tr>
<td><strong>2G wire used</strong></td>
<td>~ 480 m</td>
<td>~ 480 m</td>
</tr>
<tr>
<td><strong># of turns</strong></td>
<td>~ 2664</td>
<td>~ 2688</td>
</tr>
<tr>
<td><strong>Coil Je</strong></td>
<td>~ 163.5 A/mm² @ 100A</td>
<td>~ 167.9 A/mm² @ 100A</td>
</tr>
<tr>
<td><strong>Coil constant</strong></td>
<td>41.9 mT/A</td>
<td>42.2 mT/A</td>
</tr>
<tr>
<td><strong>Tape Ic (77 K, sf)</strong></td>
<td>72 to 97 A</td>
<td>90 to 101 A</td>
</tr>
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</table>

Repeatable enhanced coil performance demonstrated with Zr-doped 2G wire
Zr doping provides enhanced performance in nitrogen cooling

- 30% higher field in coils with made with Zr-doped chemistry
- 2008 and 2009 coils have larger winding I.D. and lower coil constant
2009 high field insert coil achieves record performance

Insert coil tested in NHMFL’s unique, 20 T, 20 cm wide-bore, Bitter magnet

<table>
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<tr>
<th></th>
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<th>Coefficient of Friction</th>
<th>12.7 mm (clear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding ID</td>
<td>19.1 mm</td>
<td>19.1 mm</td>
<td></td>
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<tr>
<td>Winding OD</td>
<td>~ 84 mm</td>
<td>~ 84 mm</td>
<td></td>
</tr>
<tr>
<td>Coil Height</td>
<td>~ 73.6 mm</td>
<td>~ 73.6 mm</td>
<td></td>
</tr>
<tr>
<td># of Pancakes</td>
<td>16 (8 x double)</td>
<td>16 (8 x double)</td>
<td></td>
</tr>
<tr>
<td>2G wire used</td>
<td>~ 600 m</td>
<td>~ 600 m</td>
<td></td>
</tr>
<tr>
<td># of turns</td>
<td>~ 3696</td>
<td>~ 3696</td>
<td></td>
</tr>
<tr>
<td>Coil J_e</td>
<td>~155.3 A/mm^2 @ 100A</td>
<td>~155.3 A/mm^2 @ 100A</td>
<td></td>
</tr>
<tr>
<td>Coil constant</td>
<td>~ 51.8 mT/A</td>
<td>~ 51.8 mT/A</td>
<td></td>
</tr>
<tr>
<td>Wire I_c (77 K, sf)</td>
<td>120 A – 180 A</td>
<td>120 A – 180 A</td>
<td>(non Zr-doping)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>77</th>
<th>65</th>
<th>4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central field – self field (T)</td>
<td>1.39</td>
<td>2.49</td>
<td>10.4</td>
</tr>
<tr>
<td>Total Central Field – in background field (axial) (T)</td>
<td>1.93</td>
<td>4.60</td>
<td>27.4</td>
</tr>
<tr>
<td>With Background field (T)</td>
<td>1.0</td>
<td>3.0</td>
<td>19.89</td>
</tr>
</tbody>
</table>
HTS generator project

- Funded by US Office of Naval Research (ONR)
- Target operation: 36.5 MVA
- Partners: SuperPower, Baldor Electric, General Dynamics-Electric Boat, Naval Surface Warfare Center (Philadelphia), Naval Research Lab, Oak Ridge National Lab
- Current Phase: Conceptual design / risk reduction studies
  - Smaller / lighter weight tradeoff studies vs. efficiency vs. cost
  - HTS windings development
  - Rotor / stator design / development
  - Fabrication of test articles
2G HTS coil for thermal cycle testing at NRL

- Model Coil 1: ~ 250 mm x 150 mm
- 250 m of 4 mm wide 2G HTS wire
NRL test results: Quench stability

(b) Typical voltage-time curves for the same HTS coil. For each value of current, the voltage is monitored for some period of time to determine if it is stable. The highest current at which the voltage exhibits long term stability is designated the quench instability limit current.

Data from R. Holtz, NRL
Proof of concept - 2G conductor for SFCL shows consistent, excellent performance

- 12 elements, 40 cm long with four 2G wires in parallel per element

<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>

**Fast response time**

Quench speed around 0.5 ms
SFCL modular system design – components integration

Module Design Specification and Criteria

- **2G tape** – $J_c$, $J/cm$/tape, RUL Arms/tape, mechanical, thermal and electrical properties

- **Shunt Coils** – $Z_{sh} = R_{sh} + jX_{sh}$, $X/R$ ratio, EM force withstand, thermal and electrical properties, connectors, size, weight, over-banding, ease of assembly and manufacturability

- **HTS assembly** – Tape per element, RUL per element, element energy capability, connectors, size, cooling orientation, failure mechanisms and mitigation, losses and their effects on cryogenics design

- **HV design** – LN2 and GN2 design stress criteria, spacing between tapes, elements and modules, stress shield dimensions, using solid barriers or not, bushings and assembly integration, assembly supporting structure (post insulators), overall assembly to cryostat spacing and integration

- **Cryogenics** – LN2 flow control, LN2 and GN2 interface, pressurizing, safety issues, thermal handling of fault and steady state losses

Complete Transmission / Distribution System Design Boundaries

- Instrumentation, control and condition monitoring of SFCL system

- **Systems issues** – SFCL device testing, systems study and utility interfaces
Test conditions evaluated:

- 2 SFCL tapes configurations ("standard" and new configuration) are evaluated with 2 types of modules
- Follows AEP sequence
- Module current scalable in multiples of 500 A peak
- Module voltage scalable from 400 V - 1 kV peak
- Prospective fault currents scalable from 5 - 10 kA peak
RUL vs. Fault Duration / Occurrence.
Summary

- SuperPower routinely produces 2G HTS wire in a manufacturing line. New 2009 world record performance of $I_c \times L = 300,330$ A-m achieved in km long wires.

- Albany Cable Project – World’s first in-grid 2G HTS device demonstrated the suitability of SuperPower® 2G wire for power cable and low ac loss.

- In-field performance enhancement at all field angles achieved via Zr-doping; technology has been transferred into production line.

- High-field coils with consistently improved performance demonstrated with SuperPower® 2G wire. Self field was increased from 0.73 Tesla to above 1 T at 77 K and more than 2 T at 65 K. At 4.2 K, maximum fields of 10.4 T and 27.4 T were achieved in self-field and with 19.9 T background, respectively.

- Model coils for HTS generator fabricated and demonstrated reliable performance.

- Proof-of-concept for resistive 2G SFCL demonstrated. Developed generalized SFCL module specification:
  - Module current scalable in multiples of 500 A peak
  - Module voltage scalable from 400 V - 1 kV peak
  - Prospective fault currents scalable from 5 - 10 kA peak
Questions?

Thank you for your interest!

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

or e-mail: info@superpower-inc.com