Recent Developments in 2G HTS Coil Technology

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  – Ron Holtz
  – Supported through funding from the Office of Naval Research
2G HTS wire properties drive coil advancements

- SuperPower’s 2G HTS wire is based on high throughput IBAD MgO and MOCVD processes.
- Use of IBAD as buffer template provides us choice of any substrate.
- Advantages are:
  - high strength,
  - low ac loss (non-magnetic, high resistivity substrates) and
  - high engineering current density (ultra-thin substrates) – 2.66 A/mm² per A of operating current
2G HTS In-field performance improving with enhanced pinning

- In field performance vs. field angle drives coil design and performance
  - Critical region for coil is 15 – 30 degrees
    - Significant drop off in Ic
    - Relatively large field component
- New wire with enhanced pinning becoming available
Repeatable low resistance wire joints demonstrated

100 mm lap joint, face-to-face

**Typical 2G Tape Splice Resistance**

- Voltage (volts)
- Current (amps)

- **R = 148 nano-ohm**
- **77 K**
SuperPower® 2G HTS wire has superior mechanical strength

77K Yield Stress 970 MPa
Strain at yield 0.92%

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
Fatigue strength equivalent to $I_c$ reversibility limit

**Fatigue-Life at 77K**
Superpower 2G Tape ID M-383-1-BS-505-569
Tension-Tension Cyclic Loading at Stress Ratio (min/max) = 0.1

- **Mechanical Failures**: $I_c$ drops below 98%
- **Recommended Critical Stress for 100% $I_c$ Retention**
- **Runouts**: specimens that did not degrade either mechanically or electrically up to 100,000 cycles

Data from R. Holtz, NRL
SuperPower® 2G HTS wire has larger operating stress-strain window compared to other conductors.
2G HTS has favorable thermal expansion characteristics

![Graph showing thermal expansion characteristics of different materials](image-url)
Low ac loss multifilament wire becoming available

650 - 800 micron filaments & 100 - 125 micron trenches.
High field insert coil demonstrated

**Conductor:**
- **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 surround copper stabilizer per side
- **Wire 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

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<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Coil ID</strong></td>
<td>9.5 mm (clear)</td>
</tr>
<tr>
<td><strong>Winding ID</strong></td>
<td>19.1 mm</td>
</tr>
<tr>
<td><strong>Winding OD</strong></td>
<td>~87 mm</td>
</tr>
<tr>
<td><strong>Coil Height</strong></td>
<td>~51.6 mm</td>
</tr>
<tr>
<td><strong># of Pancakes</strong></td>
<td>12 (6 x double)</td>
</tr>
<tr>
<td><strong>2G tape used</strong></td>
<td>~462 m</td>
</tr>
<tr>
<td><strong># of turns</strong></td>
<td>~2772</td>
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<tr>
<td><strong>Coil Je</strong></td>
<td>~1.569 A/mm² per A</td>
</tr>
<tr>
<td><strong>Coil constant</strong></td>
<td>~44.4 mT/A</td>
</tr>
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</table>
NHMFL facilities provide 19T axial background field

Insert coil tested in NHMFL’s unique, 19-Tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet

2G HF Insert Coil Showing Terminals, Overbanding and Partial Support Structure. Flange OD is 127 mm.
High field insert coil achieves record performance for highest HTS field, highest magnetic field by a SC magnet

Peak hoop stress ~ 215 MPa, well below tape limit

<table>
<thead>
<tr>
<th></th>
<th>Ic of Tapes in Coil</th>
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<tbody>
<tr>
<td></td>
<td>72 A – 82 A (77K, sf)</td>
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<tr>
<td>4.2 K Coil Ic - self field</td>
<td>221 A</td>
</tr>
<tr>
<td>4.2 K Amp Turns @ Ic- self field</td>
<td>612,612</td>
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<tr>
<td>4.2 K Je @ Ic, self field</td>
<td>346.7 A/mm²</td>
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<tr>
<td>4.2K 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>
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<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>
Summary

• We have not reached the limit of 2G HTS wire capability
• 2G HTS wire with 50 micron Hastelloy substrate enables high winding pack Je
• 2G HTS wire is available in lengths and quantity to enable development in high field magnet design and construction
• 30 T (and beyond) is within our grasp……
Questions?

Thank you for your interest!

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

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