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2G HTS Properties Beyond Critical Current

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*currently at MSU-FRIB
Outline

• SuperPower 2G HTS conductor architecture
• Critical current status
• Mechanical properties
  – General properties
  – Delamination
• FCL functionality
• Insulation
• Splices
• Closing remarks
Wire performance critical to practical applications

• $I_c(B, T, \theta)$
  – Temperature, magnetic field and field orientation dependence of $I_c$
  – Minimum $I_c$ at operating condition
• Mechanical properties (electromechanical performance)
  – Workability for fabrication into various devices
  – Irreversible stress or strain limits under various stress condition, in terms of $I_c$
• Uniformity along length ($I_c$ and other attributes)
• Thermal properties (thermal expansion coefficient and thermal conductivity)
• Quench stability (NZPV and MQE)
• Insulation (material and method)
• Splice
  – Resistance (resistivity)
  – Mechanical strength (tensile and bending)
SuperPower’s ReBCO superconductor with artificial pinning structure provides a solution for demanding applications

- Hastelloy® C276 substrate
  - high strength
  - high resistance
  - non-magnetic
- Buffer layers with IBAD-MgO
  - Diffusion barrier to metal substrate
  - Ideal lattice matching from substrate through ReBCO
- MOCVD grown ReBCO layer with BZO nanorods
  - Flux pinning sites for high in-field $I_c$
- Silver and copper stabilization
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.
$I_c(B,T,\Phi)$ characterization is critical to understanding the impacts of processing on operational performance.

- Lift factor, $I_c(B,T)/I_c(sf, 77K)$, particularly a full matrix of $I_c(B,T,\Phi)$ is in high demand.
- Frequently sought by coil/magnet design engineer, for various applications.
- Used to calculate local $I_{op}/I_c$ ratio inside coil body, and design quench protection.
$I_c$ 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
$I_c$ uniformity along length (four-probe transport measurement)
Tensile strength predominately determined by substrate

Tensile stress-strain relationship of as-polished Hastelloy substrate (room temperature)

Tensile stress-strain relationship of SCS4050 wires with different Cu stabilizer thickness (room temperature)
Conductor Stress-Strain at 77K and 4 K with Various Copper Thickness

Significant softening of the stress-strain curve with added copper due to reduced modulus and yielding of the copper.
Tensile strength - effect of stress on $I_c$

Normalized $I_c$ vs. room temperature tensile stress for a 12mm wide wire with $100\mu$m Cu stabilizer
Tensile test of wires with SCS

- Measurement of baseline data
- Effect of Cu/Hastelloy ratio

M3-914-1 (100µm Cu)
Stress limit \( \approx 460\text{MPa} \)

M3-861-2 (40µm Cu)
Stress limit \( \approx 620\text{MPa} \)
Axial compressive tests at BNL on pancake coil show no Ic degradation to at least 100 MPa

Pancake coil fabricated from 12mm wide SP 2G HTS

Typical Ic trace

Summary of Ic data on coil sections

<table>
<thead>
<tr>
<th>Section</th>
<th>Critical Current</th>
<th>“n” value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>79.3A</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>80.8A</td>
<td>34</td>
</tr>
<tr>
<td>3</td>
<td>81.5A</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>79.1A</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>79.2A</td>
<td>32</td>
</tr>
<tr>
<td>6</td>
<td>81.3A</td>
<td>31</td>
</tr>
</tbody>
</table>

WB Sampson et al, Proceedings of 2011 Particle Accelerator Conference, New York, NY TUP169
(RE)BCO coils can be subject to degradation under thermal cycling

Conclusions

(1) The critical current of epoxy impregnated circular coils wound using YBCO-coated conductors can be degraded in use.

(2) Degradation occurs if the cumulative radial stress developed due to winding, cool down and Lorentz force exceeds the critical transverse stress for the YBCO coated conductor, typically +10 MPa.

(3) The YBCO conductor is fractured at the interface between the buffer layer and the YBCO layer, or at the YBCO layer itself, causing cracks on the YBCO layer resulting in significant decline of the critical current.

• Takematsu et al., Physica C 674-677, 470, 2011
Delamination strength studied with peel test

90° peel test

T-peel test

Relationship between peel strength and processing conditions established
Successful winding techniques demonstrated to mitigate delamination issue

• 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)

• Alternative insulations/epoxy systems have been successfully demonstrated
  – PET shrink tube - NHMFL
  – Electrodeposited polyimide - Riken
  – Alternative epoxy system with filler - KIT

• Use of cowound stainless steel as “insulation” with partial epoxy application on coil sides
  – Mitigates radial tensile stress on the 2G HTS
  – Improves overall coil strength
  – Negative impact on coil current density
Stainless steel insulation, partial epoxy application on coil sides shows resistance to delamination

- Very thin layer of epoxy (transparent) after epoxy is cured
- Mechanical fix turn-turn and layer-layer
- Provides thermal link between optional cooling plates and windings
- Seals the coil

Five thermal cycles (77K), no degradation found

![Graph showing voltage (V) versus current (A) for different thermal cycles.](image)
Alternative epoxy for wet wound coils shows resistance to delamination

- Design of experiments on Araldite™ epoxy with Alumina
  - Epoxy (Araldite DBF): hardener (Araldite 951) = 10:1
- A fully wet wound coil
  - Conductor M3-919-2 BS, 566-576, 10 meter, 52 turns, ID=2”
  - No additional insulation except for the epoxy, PET release
    - Five thermal cycle, no degradation found

[C Barth et al, KIT, SuST. 26 (2013) 055007]
2G Conductor for SFCL Shows Consistent, Excellent Performance

- High-power SFCL test: 2G
- Prospective current: 90 kA*
- Limited current: 32 kA
- Peak current through element: 3 kA
- Response time: < 1 ms
- Element quality range: Uniform

Quench speed around 0.5 ms

*Limited to 32 kA due to limitations on the test setup.
Capability for bonded conductors being developed [higher amperage, specialty applications (FCL)]

• Bonded conductors offer the ability to achieve higher operating currents
  – LV windings of FCL transformer
  – HEP applications
  – High current bus applications
• Bonded conductors offer higher strength
  – FCL transformer fault currents
  – High field HEP applications with high force loadings
• Bonded conductors offer the ability to tailor application specific operating requirements, i.e. normal state resistance for a FCL transformer
Bonded conductors meet target normal state resistance while meeting mechanical strength targets for FCL transformer application.

- DOE SMART GRID Project
- 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
Insulation and other ongoing developments

• Additional wire insulation methods under development
  – Today: Kapton®/Polyimide wrapped (1-2 kV)
  – Other options under development: thinner profile, better coverage

• Additional wire architectures under development
  – Higher current carrying capability
    • Multi-layer combinations
    • Cable on Round Core (CORC)
    • Thinner substrates
  – Custom attributes
    • FCL – normal state resistance feature
Demanding requirements for ROEBEL cable for ac applications

- ROEBEL cable is a known approach to produce low ac loss, high current conductor/cable
- Conductor exposed to severe mechanical cutting at sharp angles

**ROEBEL cable made by KIT with SuperPower® 2G HTS Wire**

No failure, no delamination

Only 3% loss in current from conductor to ROEBEL cable

Cable engineering current density = 11,300 A/cm²
Terminal leads, joint, transition

- Terminals and leads are potential sources of damage in 2G HTS coils
- So their design, handling and fabrication are very critical
- Key points: Avoid kinking or over bending, making smooth transition with adequate support

Cu base for terminals and joints
(FLAT leading in and out)

Bridge joints between pancakes,
$R_{\text{tot}}=10^{-7}\Omega$

Smooth transition on inner crossover
Reliable splices – low resistance and high strength

- Splicing / terminations required in most 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 splices with no degradation through soldering
- Splice resistance $R \leq 20 \, \text{n} \Omega$ for the lap joint geometry with a 10cm overlap length

Bridge joints between pancakes, $R_{\text{tot}} = 10^{-7} \Omega$
Splice $I_c$ and resistance vs. bending diameter

- Lap joint (HTS-HTS) of SCS4050 tapes with 40 µm Cu stabilizer
- $R(\infty) = 6 \sim 20 \, n\Omega$ with 10 cm overlap length
- Bent at room temperature and $I_c$ measured at 77K
Closing remarks

- SuperPower 2G HTS conductor offers a flexible architecture to address the broad range of demanding applications requirements
- SuperPower is engaging major resources in improving its manufacturing capabilities to deliver a consistent, reliable, high quality 2G HTS product
  - Improved mechanical properties
  - Improved piece length / uniformity
  - Improved current density
  - Improved splice resistance
- Alternative conductor configurations are being developed to address customer specific requirements
  - Ag alloy
  - Bonded conductors