Insulation system for high temperature superconductor cables

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**Motivation**
- High-current capacity cables formed from ReBCO coated conductors are being developed for
  - Compact, high-field, next-generation fusion devices, with envisioned peak field 20 T ~ 22 T
  - Potential LHC high energy upgrade, with envisioned peak field 16 T ~ 20 T
  - Both applications subject conductor and coil to high dose radiation
- Present generation, coated conductor tapes sometimes delaminate following epoxy impregnation
  - Likely due to epoxy cure shrinkage or thermal contraction mismatch
  - May be an inherent feature of coated conductors
  - Need to prevent delamination to enable large-scale coil fabrication

**Objectives**
- Develop simple, repeatable, low cost screening procedure to test ReBCO cable insulations
  - Testing performed before and after application of cable insulation
  - Tested in liquid nitrogen
  - Slit-tape, trapped flux configuration
    - No current leads or lead breakouts to contend with
    - Minimal current transfer or redistribution, to increase repeatability
- Development of two-part insulation scheme
  - Barrier insulation followed by epoxy impregnation
  - Materials selected based on known or likely radiation resistance
  - Emphasis on cable rather than strand insulation scheme

**Coil assembly sequence**
- Slit-tape coil formed using 29 laser-slit, Ag-plated SuperPower tape
- AISI 1018 Iron pole pieces used to concentrate magnetic flux
- Conductor stack installed in water-jet-machined aluminum support plates
- Complete coil

**Test facility**
- Background field magnet with 2” x 7.25” rectangular bore
- 2 T peak field
- Background field magnet suspended below lab floor
- Coil sample placed in wooden cryostat
- Cooling by liquid nitrogen transfer into cryostat

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Superconductor</th>
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</thead>
<tbody>
<tr>
<td>Near-term</td>
<td>(10^5 \text{ Gy} \times 50 \text{ Mpa} ) (shear strength)</td>
</tr>
<tr>
<td></td>
<td>1,000 A/mm² (12 T, 4.2 K)</td>
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<tr>
<td></td>
<td>(3 \times 10^{10} \text{ Ppm} )</td>
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<tr>
<td>Long-term</td>
<td>(10^6 \text{ Gy} \times 500 \text{ Mpa} ) (shear strength)</td>
</tr>
<tr>
<td></td>
<td>1,000 A/mm² (12 T, 77 K)</td>
</tr>
<tr>
<td></td>
<td>1.5 \times 10^{13} \text{ Ppm}</td>
</tr>
</tbody>
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Barrier Insulation Evaluation

- Applied to cable (not strands)
- Initial work with PTFE/FEP shrink tube
  - Inadequate radiation stability for fusion applications
  - Not compatible with slit-tape configuration
  - 350°C shrink temperature incompatible with ReBCO conductor processing
- Selection of heat-shrink polyimide tape
  - Free of acrylic adhesives (known radiation sensitivity)
  - High dielectric strength
  - Achieves 8% shrink after 30 minutes at 150°C, compatible with ReBCO thermal requirements
  - Conforms to and tightly compresses conductor stack when applied with high initial tension
  - Applicable to arbitrary length cables
  - Effectively precludes resin flow inside of wrap
- Tensile testing of polyimide tape performed following irradiation in MIT nuclear reactor

Early trial on stacked copper cable: insulated with polyimide shrink tape (left) and potted with CTD-101G (right). Undamaged after repeated slow immersion in liquid nitrogen.

Potting Resin Evaluation

- Two resin systems considered:
  - CTD-101K – developed for and used in fusion magnets, low viscosity, long pot life
  - CTD-101G – similar formulation but with fillers to improve thermal conductivity and reduce shrinkage
  - CTD-101G selected following evaluation screening
- Short beam shear strength testing performed following irradiation at MIT nuclear reactor, on resin/S2-glass laminate specimens made using each resin candidate

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (K)</th>
<th>Tensile Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
<th>Strain to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>101G</td>
<td>77</td>
<td>96.1</td>
<td>19.12</td>
<td>0.51%</td>
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<tr>
<td>101G</td>
<td>295</td>
<td>38.5</td>
<td>11.43</td>
<td>0.32%</td>
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<tr>
<td>101K</td>
<td>77</td>
<td>74.7</td>
<td>6.98</td>
<td>1.11%</td>
</tr>
<tr>
<td>101K</td>
<td>295</td>
<td>45.4</td>
<td>4.03</td>
<td>1.22%</td>
</tr>
</tbody>
</table>

Negligible difference in laminate shear strength following irradiation to 4x10^{22} n/m^2 (4x ITER limit)
**Insulation Application**

- Process development from conductor surrogate to ReBCO stacked-tape conductor
- 50 \( \mu \text{m} \) thick Inconel strip for initial conductor trials
- 26 ReBCO tapes with 20 \( \mu \text{m} \) thick copper plate for first samples, to simulate likely magnet conductor
- 29 ReBCO tapes with 2 \( \mu \text{m} \) thick silver plate for final samples, to minimize laser-slitting artifact
- Polyimide tape applied and shrunk at 150° C for 30 minutes, inside aluminum formers
- Silicone sheet gasket applied to aluminum former to pot first coil half. Cure schedule: 3hr ramp to 110° C; 5hr soak @ 110° C; 1.5hr ramp to 135° C; 1.5hr soak @ 135° C; 2hr cool-down to 22° C.
- Silicone sheet gasket installed between aluminum formers to pot second half of coil using same cure schedule.

**Electromagnetic Modeling**

- High-fidelity, 3D COMSOL model of test arrangement
  - Cable current related to magnetic flux density measured by Hall probes on sample surface
  - Cable critical current related to magnetic field distribution over cable cross-section
  - Match between expected and measured cable critical current

Assumed variation in 77 K lift factors for SuperPower advanced pinning HTS tapes as a function of magnetic flux density (left), and magnetic field orientation relative to the broad face of the HTS layer (0.3 T data shown at right), based on measurements reported by Takayasu (ASC-2014)
Test Results

- Two-component electrical insulation developed and successfully applied to ReBCO cables
  - Polyimide shrink tape to consolidate cable and act as barrier to resin penetration
  - High thermal conductivity, low shrinkage CTD-101G resin as potting compound
  - ~20% degradation observed for cable sample with copper-plated ReBCO conductors due to slight resin infiltration within polyimide layer
  - No detectable degradation in cable sample with silver-plated ReBCO conductors at $I_c = 1800$ A

Conclusions

- Simple, low-cost cable insulation screening test developed
  - Test performed before and after application of cable insulation
  - Test evaluation based on high-fidelity 3D COMSOL model of setup
  - Good agreement between predicted and measured results
- Development of two-part cable insulation scheme
  - Polyimide barrier insulation followed by epoxy impregnation using CTD-101G
  - Materials selected based on known or likely radiation resistance
  - Compatible with large-scale continuous processing
  - Effective prevention of critical current degradation when properly applied
- Preliminary assessment of radiation resistance performed
  - Polyimide barrier insulation retains high tensile strength following irradiation
  - Negligible difference between CTD-101K and CTD-101G composite shear strengths following irradiation

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