2G HTS Coil Technology Development at SuperPower Inc.

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Outline

• 2G HTS coil development
  – General conductor / coil mechanical performance
  – Challenges in epoxied coils
  – Develop alternative approaches in coil winding and post-wire-production
• An example: high quality 2G HTS pancake coil developments
  – Practices, winding, conductor splice, coil joint and testing
• Other coil-related areas
  – Layer wound coils, alternative insulation
• Conclusions
SuperPower’s wire exhibits robust mechanical properties

- Conductor mechanical properties can be characterized in three dimensions
  - \textit{ab} plane along the length
  - \textit{ab} plane along the width
  - Along the \textit{c}-axis direction, perpendicular to \textit{ab} plane
- Mechanical properties are a function of copper thickness and temperature

Conductor Stress-Strain at RT, 77K and 4 K with Various Copper Thickness

- 40 µm
- 60 µm
- 100 µm

Copper thickness vs. stress (MPa)

Data from NHMFL

Robust mechanical properties exhibited in 2G HTS coils along the width in \textit{ab} plane

- Mechanical properties in 3D
  - \textit{ab} plane along the length $\rightarrow$ Azimuthal direction
  - \textit{ab} plane along the width $\rightarrow$ axial direction ($z$ axis)
  - Along the $c$-axis direction, perpendicular to \textit{ab} plane $\rightarrow$ radial direction

W.B. Sampson \textit{et al.}, PAC11, NYC, March 28, 2011 (Brookhaven National Laboratory)

- Stress upon DPC coils up to 100 MPa, 77 K
- No observable change in critical current
- Repeat 100 times
Robust mechanical properties along c-axis (compressive)

- RT compression, Ic tested at 77 K
- No measurable degradation in critical current
Challenge: reported degradation (Ic reduction) in epoxy impregnated 2G HTS coils

Reported degradation in wet (epoxied) coil → weak mechanical properties along c-axis
- Takematsu et al., Physica C 674-677, 470, 2010
- Yanagisawa et al., Physica C 471, 480, 2011

Some reported solutions
- Thin wall (~20 μm) cryogenically compatible polyester shrink tube.
  - U. Trociewitz et al. APL 99, 202506, 2011
- Generation of 24 T at 4.2K with 2G HTS insert, impregnated with Paraffin
Addressing the degradation issue in epoxied coils

**Approach #1:**
Develop coil winding techniques to tolerate lower peel strength conductor (focus of this presentation)

**Approach #2:**
Stronger wires, higher c-axis strength from 2G HTS wire production
C-axis peel strength test used at SuperPower to guide conductor performance in coils

- Degradation in some epoxied coils also observed at SuperPower
- Phenomenon: $I_c$ drops in thermal cycles from RT to 77 K
- Peel strength of 2G HTS tape is a good indicator of conductor performance in epoxied coils


T-peel test on 2G HTS wire

- Load vs displacement curves
- Peel strength is reliable and sensitive method
Good correlation between c-axis peel strength result and epoxied coil performance

- Correlation between c-axis adhesion (peel) strength and coil performance
  - 50 cm cut for peel test
  - All the rest wound into wet wind epoxied coil
  - $I_c$ test in three thermal cycles (three $I_c$ run in each cycle)
Multiple coil fabrication approaches evaluated for winding epoxied coils without degradation

- **Epoxy**: Epoxy change alone is not a solution

- **Former**: Material with less shrinkage ratio

- **Release**: Significant improvement found in coils

- **Insulation**: Alternative insulations

- **Co-winding**: Reduce weight ratio between epoxy/coil, unify epoxy distribution

**Winding Tech**
- Improved fixturing for winding control
- Mandrel design improvement
- Winding tension control (on-going)

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Siemens presented their positive results at EUCAS 2011 (M. Oomen et al, 2-LB-11)

NHMFL, MIT/FBML

MIT/FBML, NHMFL, BNL
Metal strip co-winding with HTS conductor for high field magnet has been effectively used by many groups

- 1995, MIT/Sumitomo, SS co-winding, 1G HTS Bi2223
  - Generation of 24.0 T at 4.2 K and 23.4 T at 27 K with a high-temperature superconductor coil in a 22.54 T background field
    - *APL, 67, 1923, 1995*
- 2003, NHMFL/OST, co-wind SS (28 μm), 1G HTS Bi2212
  - Development of a 5T HTS Insert Magnet as Part of 25T Class Magnets
- 2011, MIT/FBML, co-wind Cu (0.2 mm with one side polyester) for ReBCO, co-wind SS (50 um) for Bi-2223
  - A 1.3 GHz LTS/HTS NMR magnet – a progress report
- 2011, BNL, co-wind SS or Kapton (25 μm), 2G HTS ReBCO
  - High field HTS R&D soldenoid for Muon Collider
- 2012, NHMFL, plain co-wind SS, 2G HTS ReBCO
  - Superconducting 32 T magnet with ReBCO high field coils, NHMFL
Pros and cons of SS co-winding

• Pros
  – Mechanical reinforcement
  – Less contained epoxy, improvement w/r to cool-down
  – Insulation may become stabilizer during transient/local quench
  – Increased thermal conductivity, compared to conventional insulation

• Cons
  – Ramping loss (low ramping rate, HTS larger thermal margin)
  – Current re-distribution during quench (may need modeling for large magnet)
  – Impact on current density

❖ Partial epoxy impregnation offers positive results
  – Side applied, epoxy partially penetrated into turns, 30-40% of epoxy coverage for 4 mm wide wire
  – Seals the coil, protects it from moisture
  – Mechanically fixes turn-turn and layer-layer
Key technologies demonstrated in high quality pancake coil development

1. Release layer $\rightarrow$ decouple coil and former, reduce radial tensile stress
2. Metal strip co-winding$\rightarrow$ coil geometry quality, *very flat side wall*, which impacts magnet design & assembly
3. Partial epoxy impregnation $\rightarrow$ physical quality, no Ic drop after cool-down
4. Winding tension $\rightarrow$ alignment, reduce tensile stress during cool-down
DPC development process highlights

Multi-roller winding system. SS-cowinding.

Building former first is recommended. Wind the coil and then cut former is risky.

With internal crossover, winding the first PC, the other half conductor stored on another spool. Finishing.

Double pancake coil, Interleaf layer added.
In coil splice methodology fully developed

**Resistance vs Splice Length**

- Typical conductor splice resistance
- In coil splice
Typical double pancake coil testing

- Test procedure
  - Slow ramping is recommended
    - minimizes induced voltage
  - Ramp current, dynamic data
  - Hold current for 10 s, static data
  - Smaller step during transition, divider = 5
  - cooling, warm-up (slow)

- Use static data for Ic and n-value
  - Two DPC (1-2, 3-4)
  - bridge joint (2-3)
  - ETE voltage
Layer wound coil for high field insert

- 2G HTS ReBCO is prime candidate for high performance coils required for high magnetic field applications
- Layer wound coil technology being developed
- Layer wound, epoxied coils tend to be less susceptible to degradation on thermal cycling
Alternative insulation systems – promising solutions being evaluated

• In-situ insulation applied to 2G HTS tape

• Test coil, ID=50 mm, G10 former, release layer on former, Stycast 1266 epoxy, 4 thermal cycles, no degradation
• More test coils to be wound

• Insulation by VPI

• Test coil, ID=50 mm, G10 former, 124 turns, Stycast 1266 epoxy, 5 thermal cycles, no degradation
• More test coils to be studied
Conclusions

- Coil winding techniques in epoxied coils have been demonstrated that mitigate coil degradation on thermal cycling
  - An example of a successful DPC coil development
    - SS co-winding, epoxy side application
    - DPC coil winding
    - Developed a superconductor bridge joint between coils
    - Achieve good $I_c$ and $n$-value, no degradation found.
  - The effectiveness of the partial epoxy side application technique to mitigate degradation of epoxied coils has been demonstrated.
    - Dry wind $\rightarrow$, Partial wet wind (epoxy on coil edges) $\rightarrow$, Full epoxy coils (Wet wind, VPI) $\rightarrow$ under development
    - Coil geometries: Pancake $\rightarrow$, Layer wound $\rightarrow$, Racetracks $\rightarrow$ next
- Stronger conductor (high peel strength) being researched and developed