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2G HTS Coil Winding Technology Development at SuperPower

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SuperPower® 2G HTS wire: thin film deposition on robust, flexible substrate

- Automated processes
- Reel-to-reel systems
- High throughput, fast processes

- Modular and scalable systems
- Quality assurance throughout
- Rigorous testing, product certification with each delivery
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.
Key performance requirements for HTS magnet applications

- High operating current density
- High operating currents – particularly for HEP applications
- Long piece length
- Uniform and consistent properties
- High mechanical strength
- Low ac losses
- Sufficient production capacity
Critical current vs. temperature and magnetic field of recent AP production material

Small cross-section of SuperPower2G HTS translates into high operational current density

Measurements made at the University of Houston
Microstructure of production MOCVD HTS wires with standard 7.5% Zr doping

5 nm sized, few hundred nanometer long BZO nanocolumns with ~ 35 nm spacing created during in situ MOCVD process with 7.5% Zr
Long piece lengths now routinely being manufactured

Example of >200m piece length delivered to ARPA-E SMES project (Tapestar data)

- 12mm wide
- 65 micron Cu stabilizer
- 77K Ic ~ 400A
SuperPower 2G HTS wire has high tensile strength

See Y. Zhang’s presentation 2MOOr C2-05 on Wednesday for additional information
(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
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
Pros and cons of SS co-winding

• Pros
  – Mechanical reinforcement
  – Lower epoxy fraction resulting in lower radial thermal stress
  – Insulation becomes stabilizer during transient/local quench
  – Increased thermal conductivity compared to conventional insulation
  – Successfully used by many groups…MIT, BNL, NHMFL….

• Cons
  – Possible ramping loss (low ramping rate, HTS larger thermal margin)
  – Current re-distribution during quench needs further modeling and experiment (may be beneficial?)

• Partial epoxy impregnation of pancake coil windings
  – Side applied, epoxy partially penetrated into turns, 30=40% of epoxy coverage for 4 mm wide wire
  – Seals the coil
  – Mechanical fix turn-turn and layer-layer
  – Provides thermal link between cooling plates and windings
Control of windings critical during coil double pancake coil fabrication

Cowound stainless steel and 4 mm wide 2G HTS tapes

Lead out to conductor on storage spool for second pancake coil
Winding tension impacts residual coil stress in windings (hoop & radial)

- Be able to optimize winding induced tension in wound coils by changing winding tension
  - Back tension motor control, 10%, 20%, 30%, 40%, 50%, 60%, 70%
  - Winding tension 6.9 MPa, 13.8 MPa, 20.7 MPa, 27.6 MPa, 34.5 MPa, 41.4 MPa, 48.3 MPa,
Tension control and conductor positioning critical during winding
Coils with cowound stainless steel and partial epoxy application show excellent stability on thermal cycling
2G HTS has been successfully used in multiple high field insert coil demonstrations

SuperPower: 26.8 T, 27.4 T / 20 T
NHMFL: 33.8 T, 35.4 T / 31 T
BNL: various HF coils to 16 T (500 A/mm²)

Layer wound 2G insert for commercial customer
Continually improving large-scale production of robust, high-performance wire for coil applications

- High critical current:
  - 100A standard; 110-120+ A premium (4 mm width)
- Uniform critical current over long lengths: +/- 10% standard deviation
- Single piece lengths of 50-300 m (without splices); up to 1 km and longer with high quality splices
- Excellent joints & solderability:
  - No degradation in Ic even when joint is bent over 25mm diameter and thermal cycled
  - Joint resistance < 20 nano-ohms (100 mm lap joint)
  - No issues with soldering to our 2G HTS Wire
- Manufacturing volume steadily increasing
- Robust coils using SP 2G HTS have been built and successfully tested
Questions?

Thank you for your interest!

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

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