superior performance. powerful technology.

2G HTS Wire for Demanding Applications and Continuous Improvement Plans

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Tuesday, September 17, 2013  •  EUCAS-2013, Genova, Italy
Acknowledgements

• We would like to acknowledge the contributions of the team at SuperPower as well as collaborators from around the world.

• In particular we would like to acknowledge the input from Toru Fukushima, Paul Brownsey, Honghai Song*, Yifei Zhang, Justin Waterman, Trudy Lehner, Hisaki Sakamoto, Ross McClure and Allan Knoll.

• The work presented here is supported in part from funding from the US DOE Smart Grid Program and ARPA-E.

*currently at MSU-FRIB
Engineering progress drives 2G HTS adoption

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HTS applications have a wide range of demanding performance characteristics

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Courtesy of SuperPower and Furukawa

Courtesy of Waukesha

Courtesy of Oswald
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)

Standards for 2G HTS wire property testing are under development
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
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)
Tensile strength - effect of stress on $I_c$

Normalized $I_c$ vs. room temperature tensile stress for a 12mm wide wire with 100μm Cu stabilizer
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
In-field critical current operating conditions vary by application.
In-field performance: Advantage of 2G HTS wire with flux pinning

Advanced MOCVD growth technology:
• Formation of dense & uniform nanorods
• Engineered growth properties
• Potential migration to new compositions

→ Enhanced Artificial Pinning Effect
→ Improved in-field critical current
→ SuperPower’s “AP wire” recipe

Nanorods with BaZrO
Pinned flux
Superconductive current flow
Increased Zr doping in ReBCO layer for improvement in critical current in the field

Lift factor performance tied to film composition and growth conditions

Precursor composition / Flow rate / Concentration / Chamber pressure, etc. etc.
$I_c(B, T, \Phi)$ characterization is critical to understanding the impacts of processing on operational performance.

Measurements made at the University of Houston

- 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.
IcBT measurement system being built for routine production sampling

**Target operating conditions**
- **Temperature**: 30K – 77K
- **Field**: 0 - 2T (65K)
  - Higher field operation at 4K
- **Field //c and //ab** (rotatable 0-225 deg)
- **Sample length in field**: min 25 mm
- **Maximum sample current**: 800-1200A
  - Full width samples to 4mm wide
- **Maximum coil current**: 400A
  - 2G HTS background coils
- Enables testing of production material in Schenectady (77K-30K, 0-2T) to evaluate consistency of lift factor.
Low temperature high field data being collected at multiple sources

- Internally at FEC’s Nikko facility in Japan (4 mm tape up to 17T)

- Collaborators / customers facilities
  - NHMFL (full tape, to 15T, YatesStar)
  - Tohoku University (through FEC, bridge samples, to 15T)
  - BNL (8T+)
  - Other international high field test sites
  - Customer facility (to 17T)

- This data will be correlated with processing conditions to better understand processing windows to result in more consistent uniform product.
$I_c$ uniformity along length (TapeStar)

- 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)
Engineering new wire innovations to address customer requests and meet application requirements

- Additional wire insulation methods
  - Today: Kapton®/Polyimide wrapped
  - 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)
    - Plus others …
  - 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
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
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 $R \leq 20 \text{n}$Ω for the lap joint geometry with a 10cm overlap length
• Splicing per customer request and each splice inspected
Splice $I_c$ and resistance vs. bending diameter

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

- 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 consistency of lift factor
  - Improved piece length
  - Improved current density
  - Improved uniformity
- Alternative conductor configurations are being developed to address customer demand