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superior performance. powerful technology.

SuperPower 2G HTS Conductor

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WAMHTS-1
Hamburg, Germany
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FURUKAWA ELECTRIC GROUP

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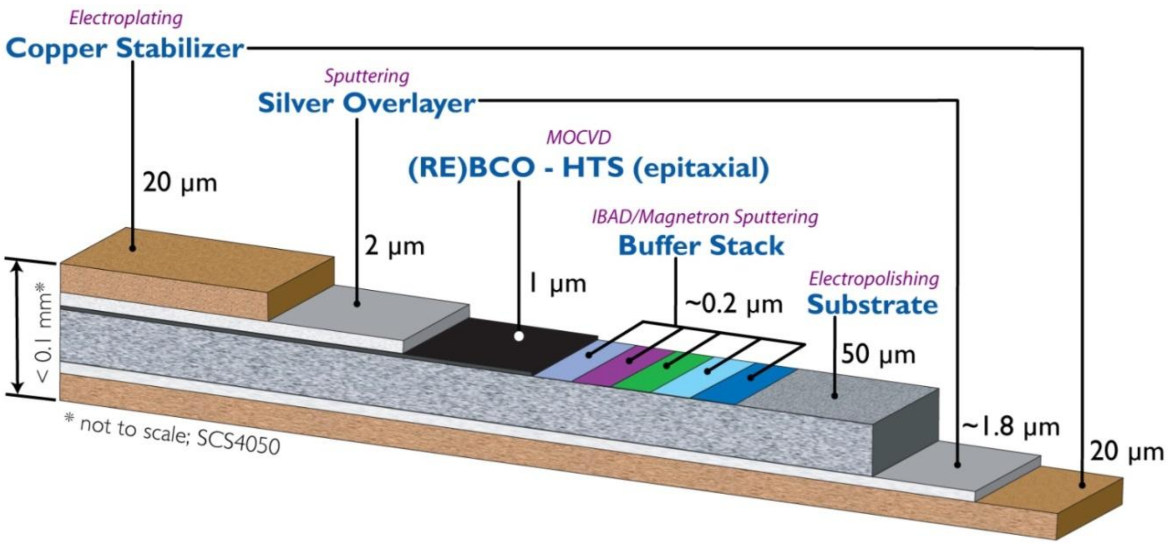
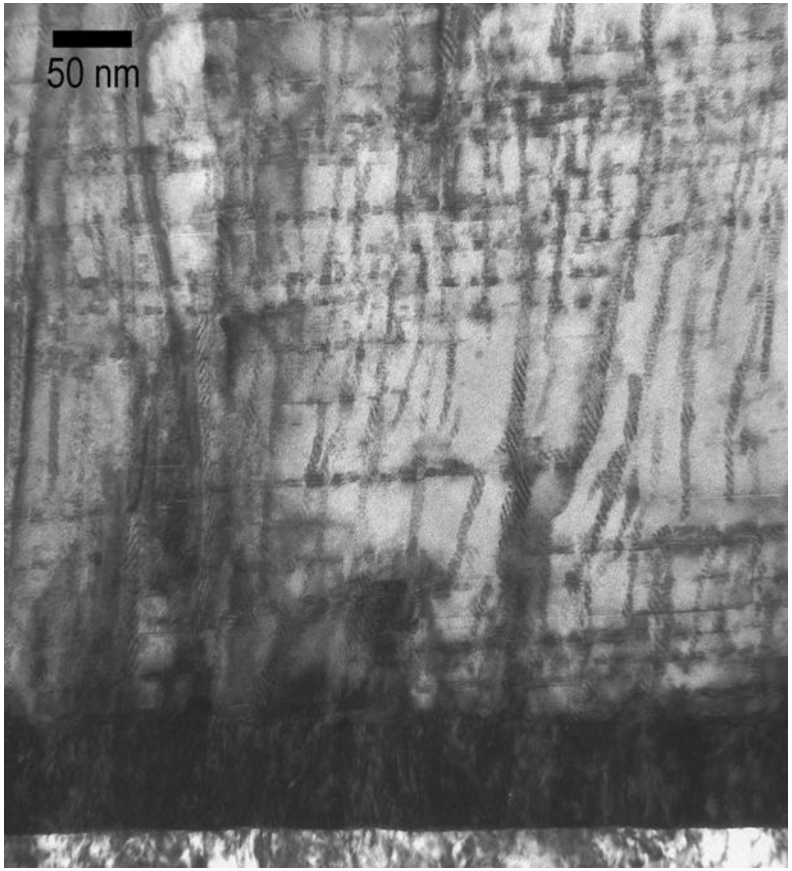
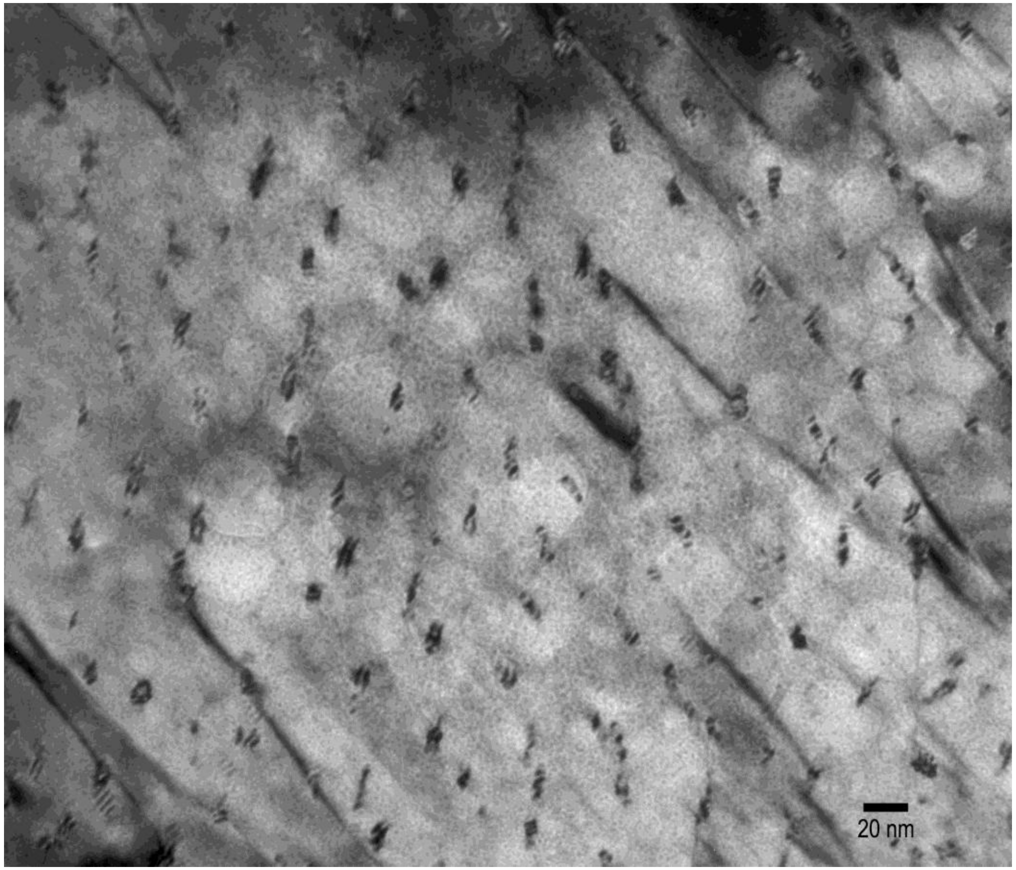
SuperPower's ReBCO superconductor with artificial pinning structure provides a solution for demanding applications



- 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

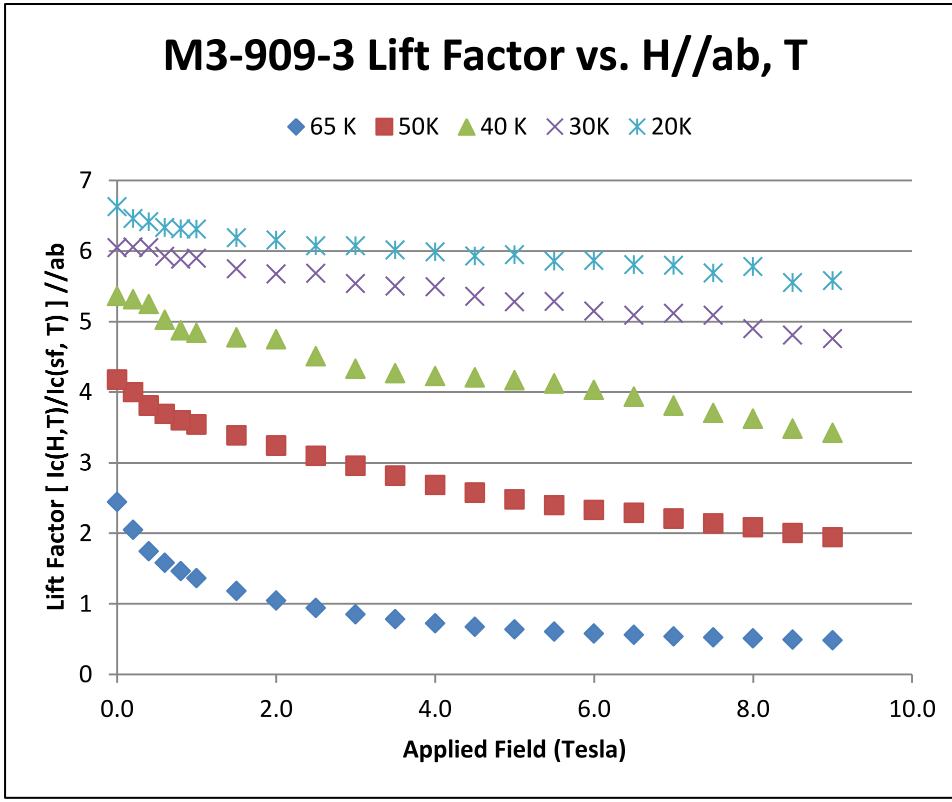
Microstructure of production MOCVD HTS wires with standard 7.5% Zr doping

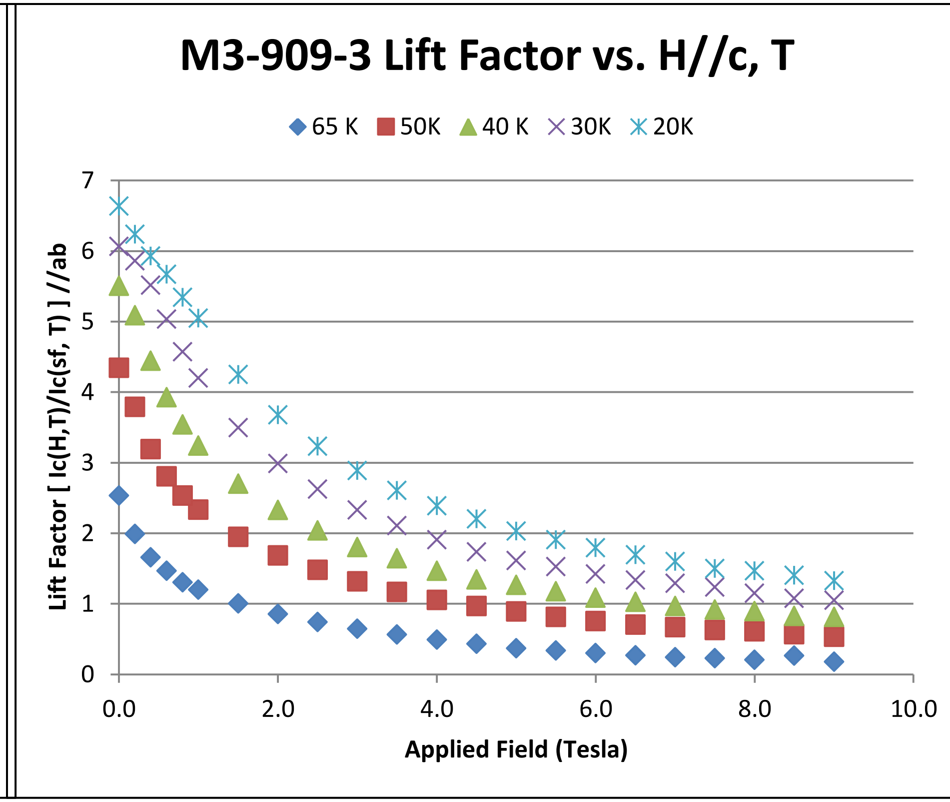




5 nm sized, few hundred nanometer long BZO nanocolumns with ~ 35 nm spacing created during in situ MOCVD process with 7.5% Zr

$I_c(B,T,\Phi)$ characterization is critical to understanding the impacts of processing on operational performance

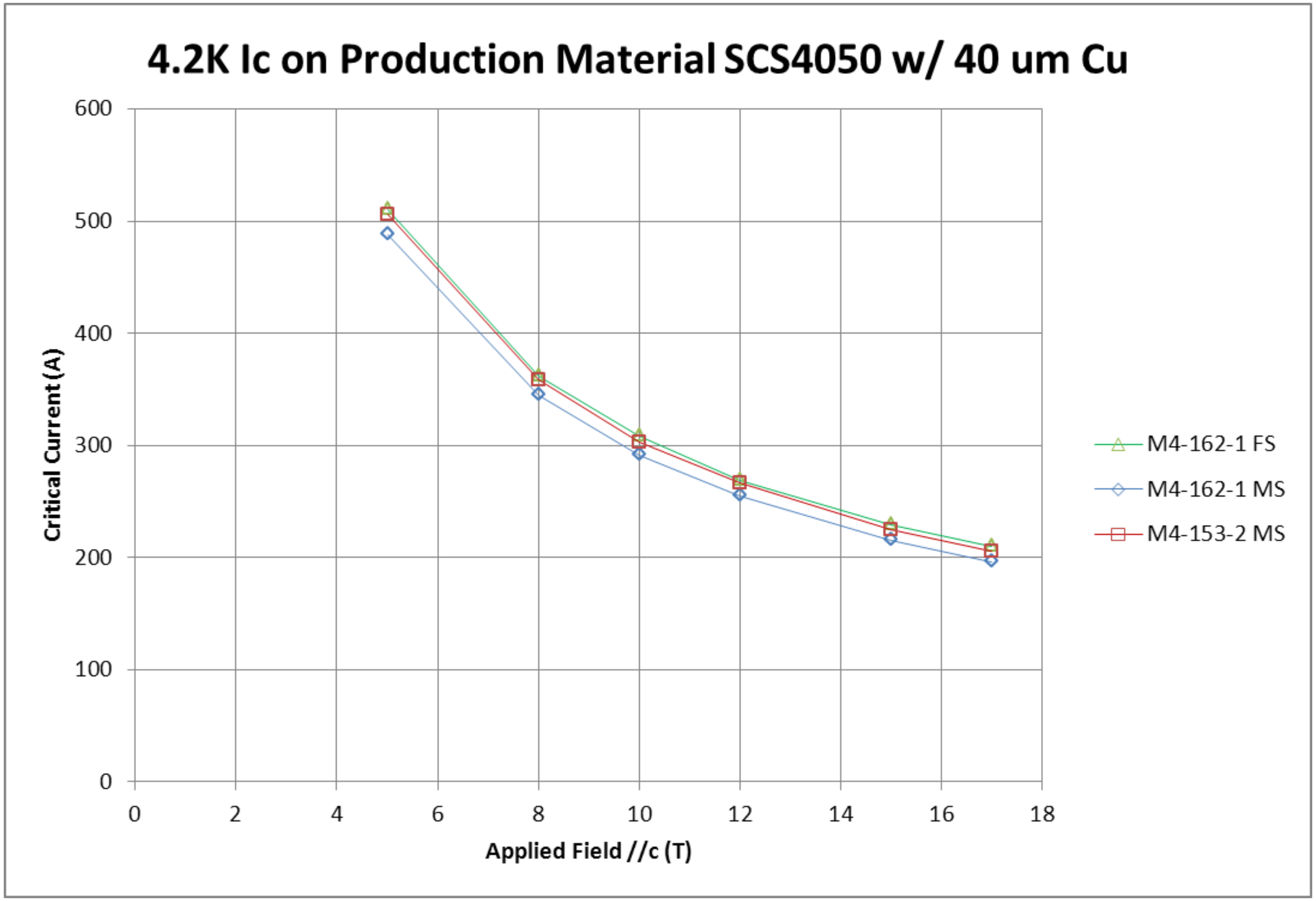




Measurements made at the University of Houston

- 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 $I_{op}/_{Ic}$ ratio inside coil body, and design quench protection.

4.2 K Ic data on recent production material



Measured at FEC/Nikko

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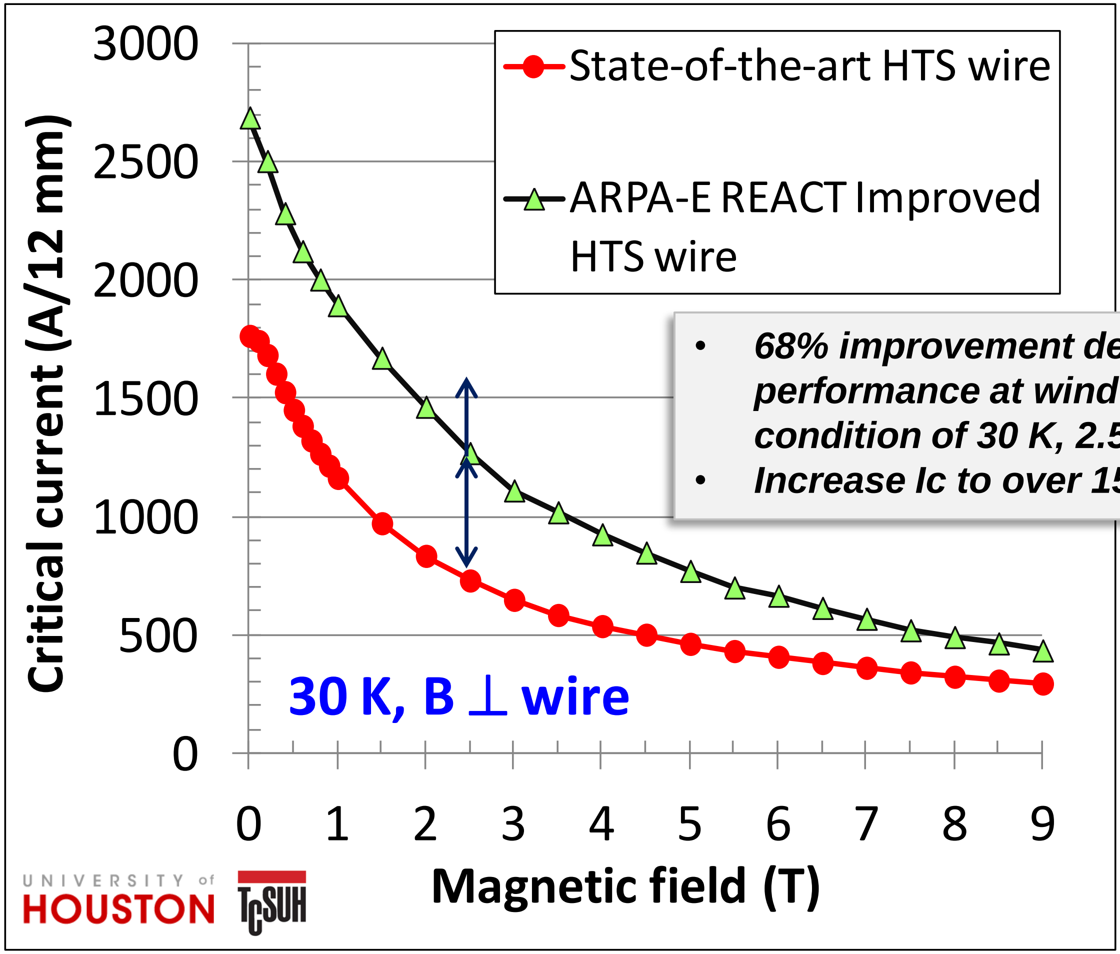
Technology development programs are focused on next level of product improvements …



- Increase base Ic
- Increase lift factor
- Increase wire strength
- Reduce ac losses

- *68% improvement demonstrated in wire performance at wind generator operating condition of 30 K, 2.5 T*
- *Increase Ic to over 1500A (demo in mid 2014)*

Structured, well-timed process for transfer of these advancements into production (by end of 2014)

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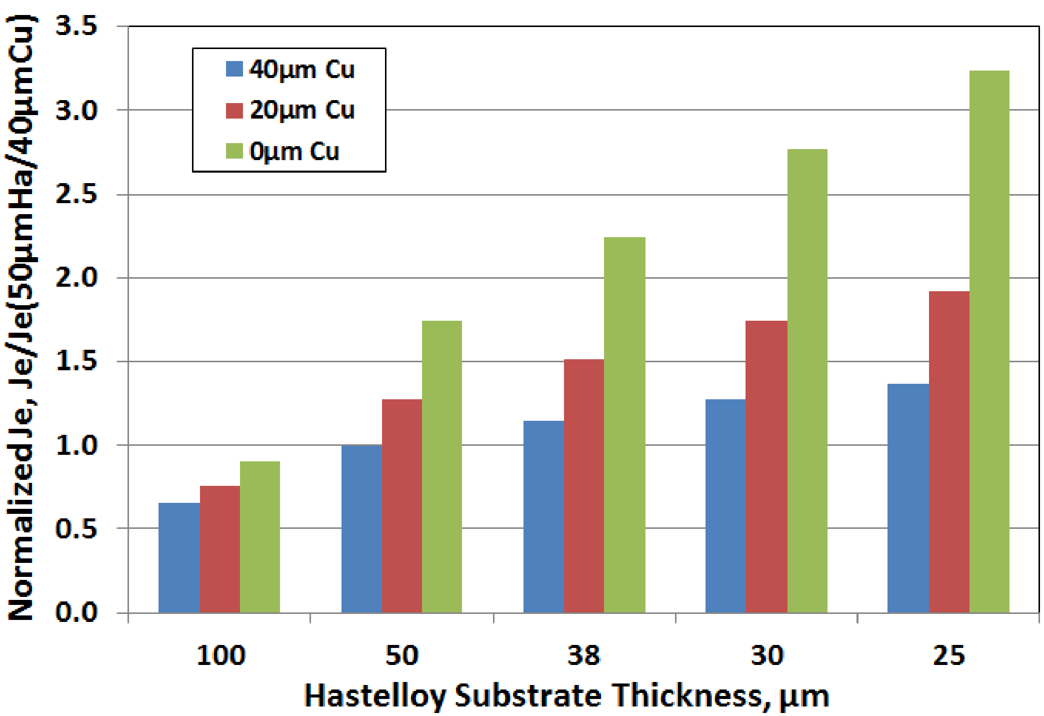
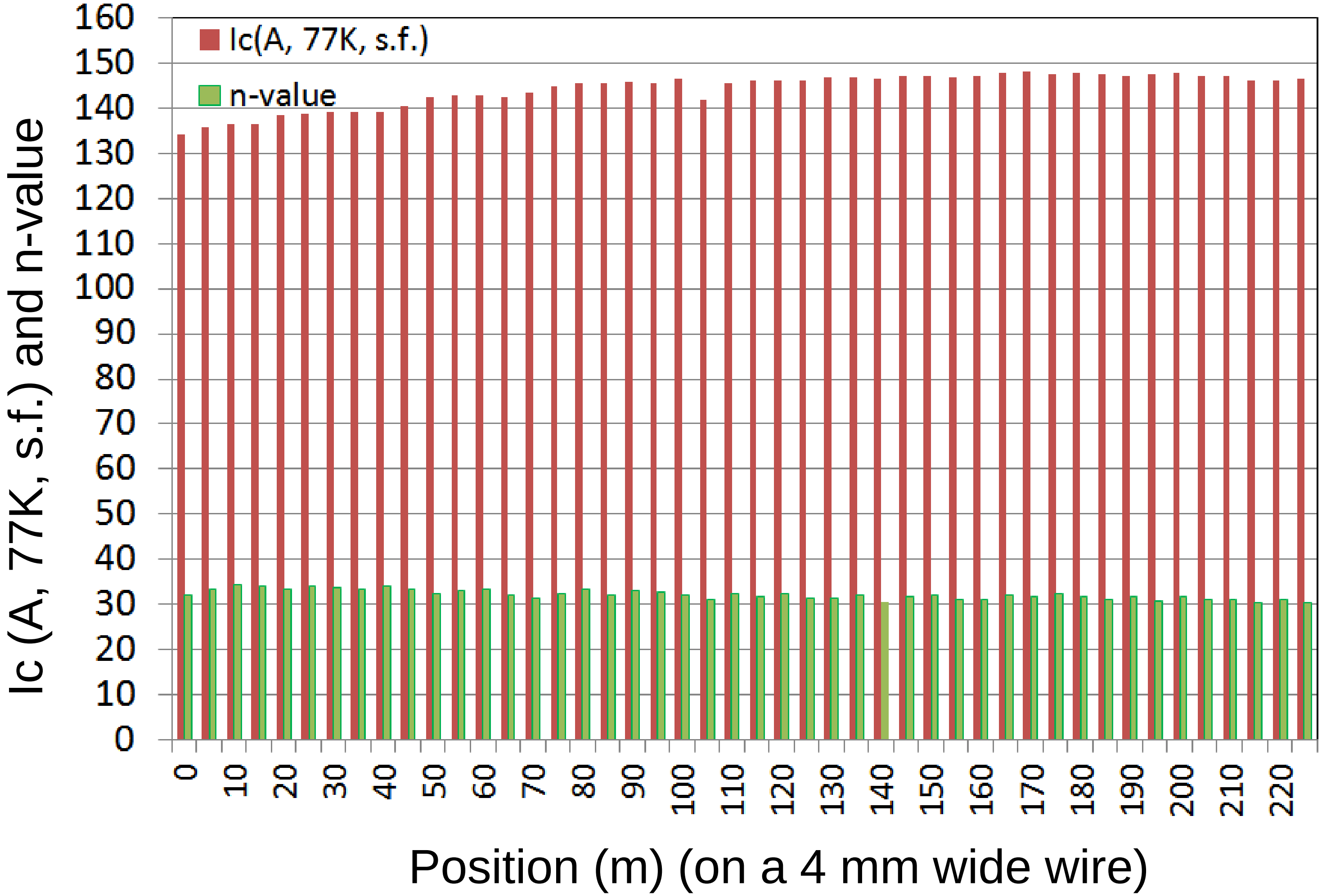
Thinner substrates offer improved current density while still providing strong mechanical support

- Current 2G HTS production material based on either 50 or 100μm Hastelloy® C276 substrate
  - For standard Cu thickness of 40μm total, the conductor thickness of current production 2G HTS conductor is ~ 0.095mm.
- Thinner Hastelloy® C276 of 25, 30 and 38μm thicknesses are being evaluated
  - For standard Cu thickness of 40μm total on a 25μm Hastelloy® C276 substrate, conductor thickness is reduced to ~70μm
  - This implies a 36% increase in current density
- Available second half of 2014

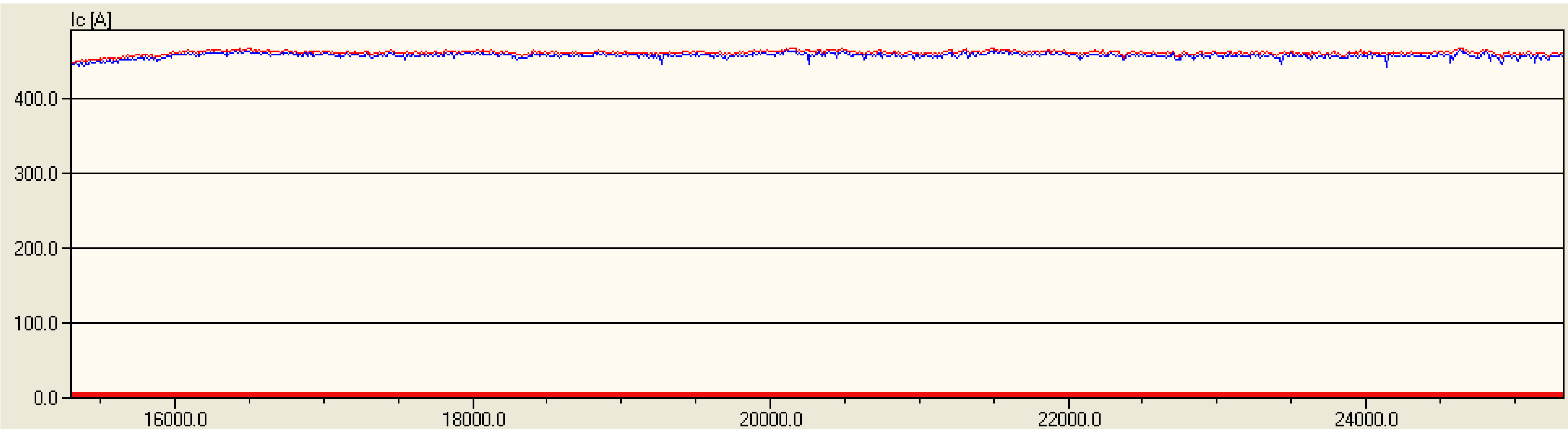


Baseline is 40 micron thick copper stabilizer

I_c uniformity along length (four-probe transport measurement)



I_c uniformity along length (TapeStar)



Position (cm) (on a 12 mm wide wire)

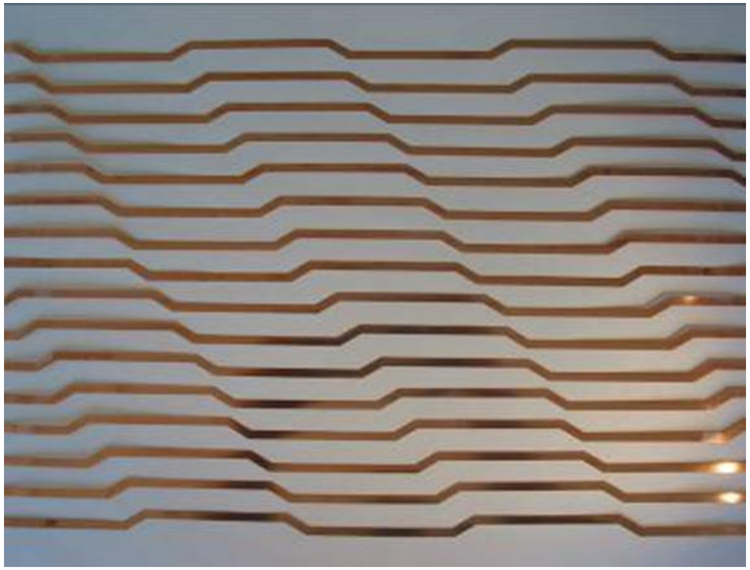
- Magnetic, non-contact measurement
- High spacial resolution, high speed, reel-to-reel
- Monitoring I_c at multiple production points after MOCVD
- Capability of quantitative 2D uniformity inspection

SuperPower 2G HTS conductor has been successfully demonstrated in ROEBEL cables

- ROEBEL Cable
  - KIT
  - General Cable

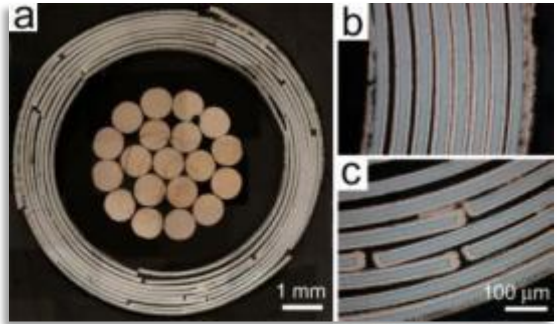
- Typically punched from 12 mm wide strips
  - Measured for 2D uniformity using TapeStar

- In the future, we may be able to deposit onto a pre-cut shape
  - There are no inherent process limitations to doing this



SuperPower 2G HTS conductor is adaptable for use in many demanding cable architectures.

- Various wire architectures under development by world wide customers to develop high current conductors for use in low inductance magnets
- Cable on Round Core (CORC)
  - Advanced Conductor Technologies
  - Thinner substrates will further enable this architecture
- Stacked cables
  - MIT, others
- Clad conductors (SP)
  - Increase strand currents
  - Customize properties for tailored applications (i.e. FCL-XFR)



Courtesy: Advanced Conductor Technologies

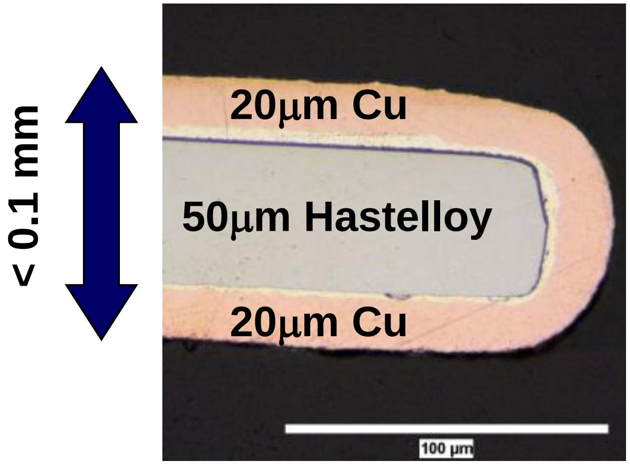
Capability for bonded conductors has been developed [higher amperage, specialty applications (FCL)]

- 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

Copper stabilization can be tailored to meet application requirements

- Copper stabilization typically added by electro-deposition
  - 10 μm to 120 μm total thickness

- Alternatively, copper stabilization can be clad to the superconductor to provide thicker stabilization
  - Laminates up to 1 mm thick have been clad to the 2G HTS
  - Alternates to copper can be clad (copper alloys, stainless steel)



SCS4050 w/ 40 μm Cu

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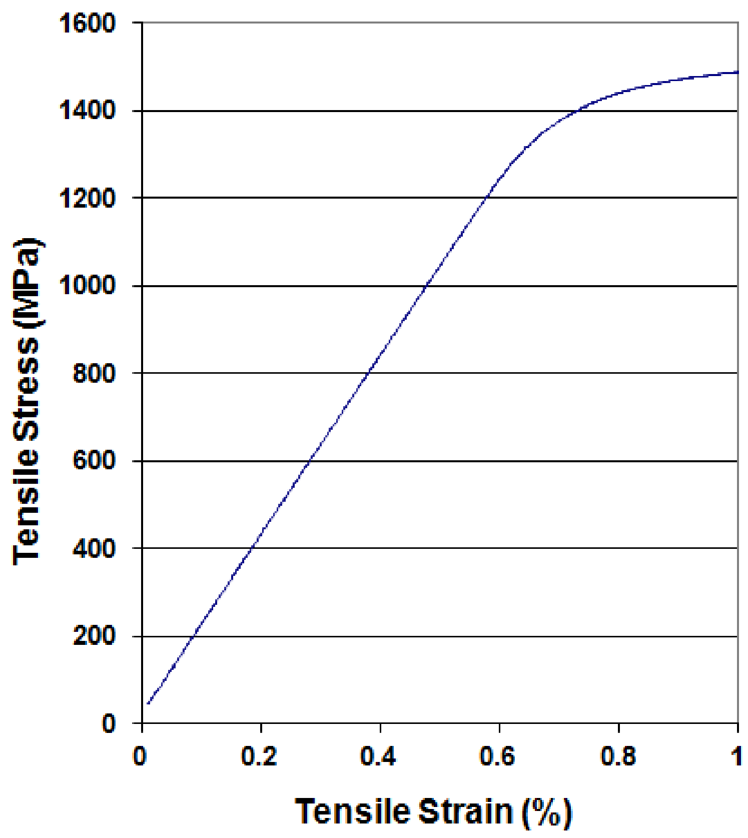
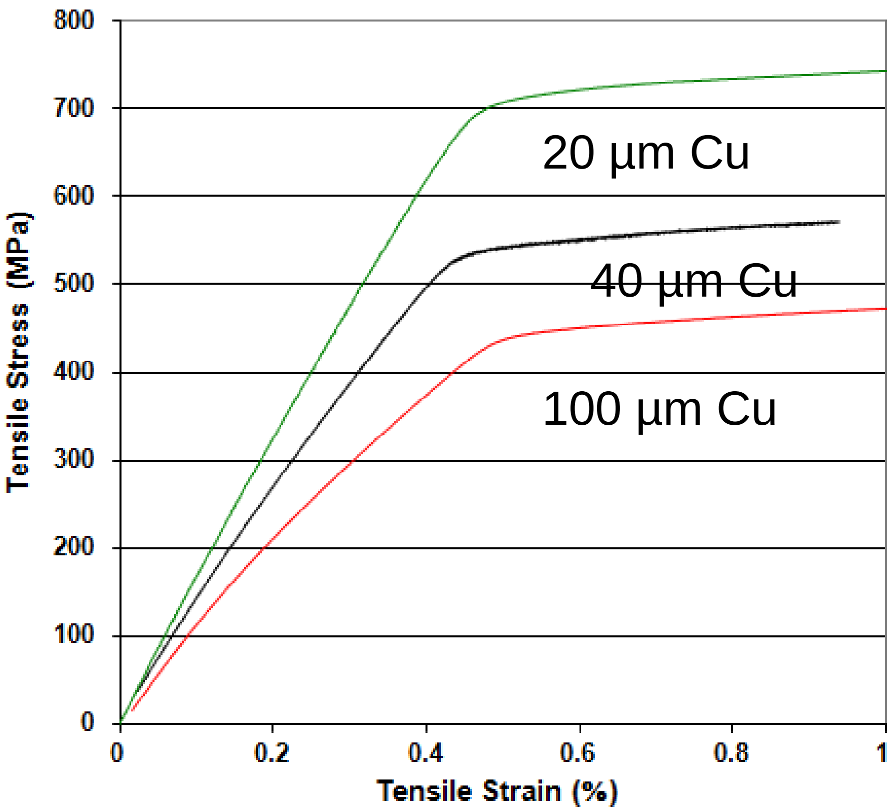
Tensile strength predominately determined by substrate

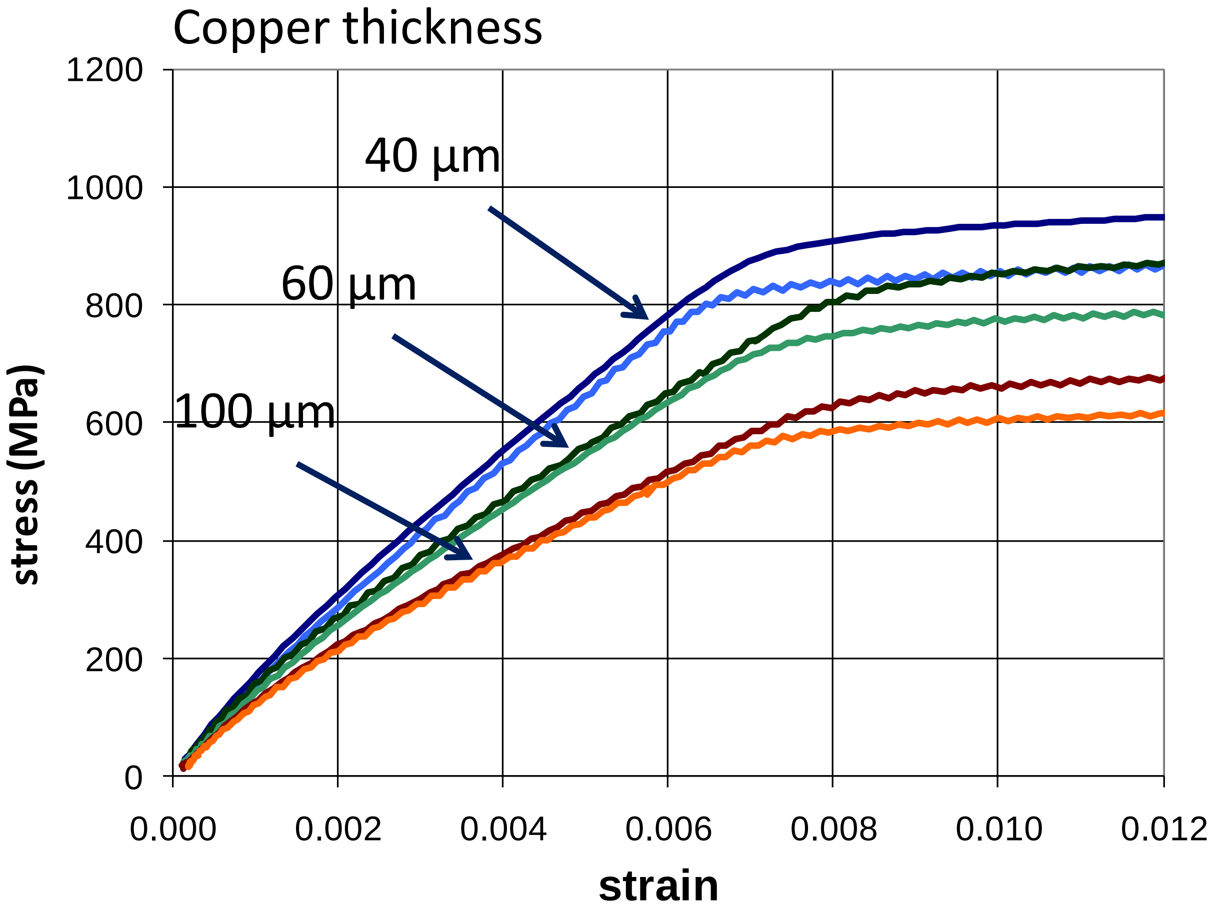


Tensile stress-strain relationship of as-polished Hastelloy substrate (room temperature)



Tensile stress-strain relationship of SCS4050 wires with different Cu stabilizer thickness (room temperature)

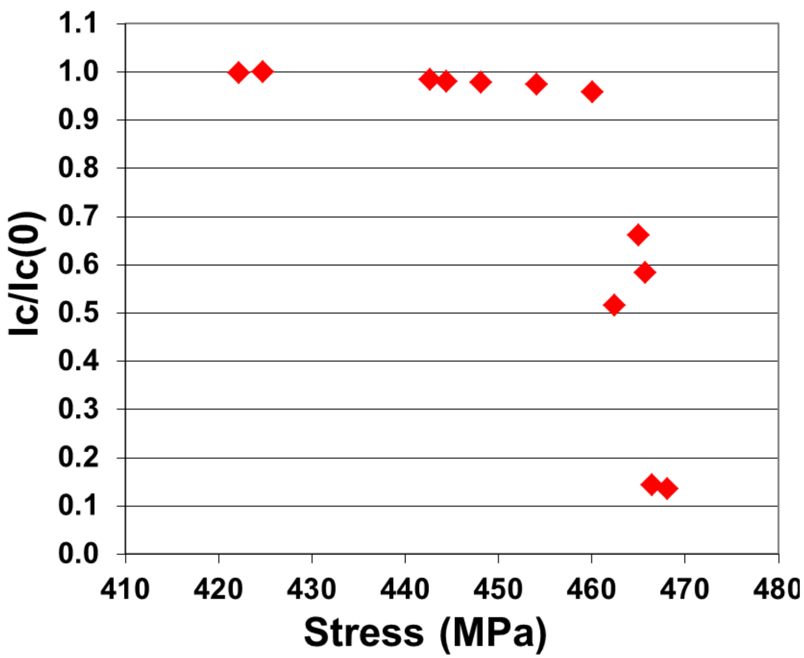
Conductor Stress-Strain at 77K and 4 K with Various Copper Thickness



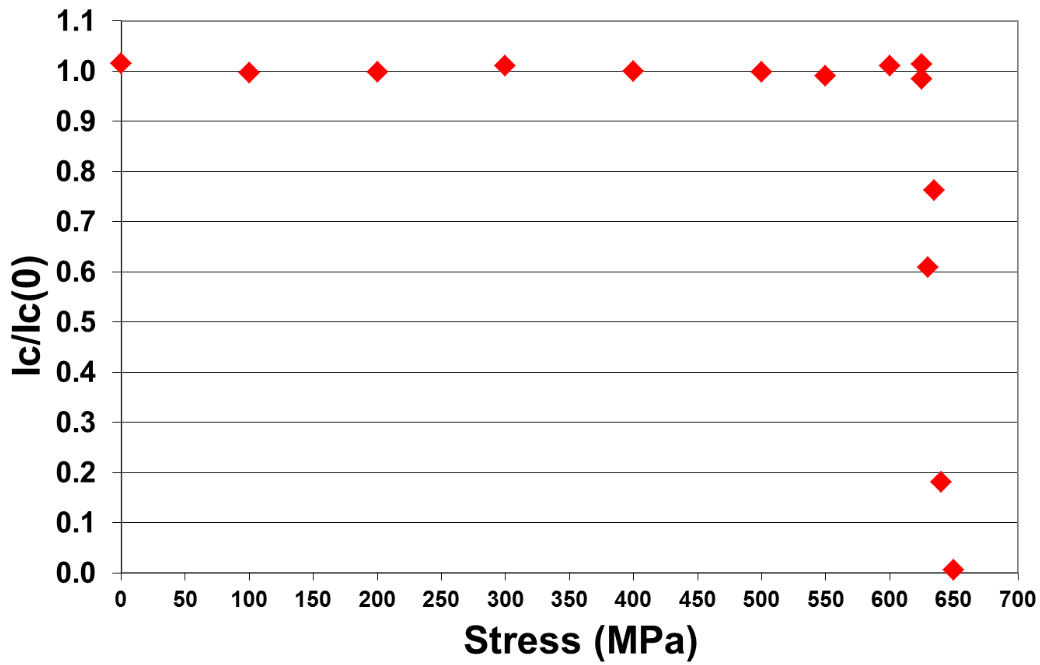
Significant softening of the stress-strain curve with added copper due to reduced modulus and yielding of the copper.

Tensile test of wires with SCS

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



M3-914-1 (100µm Cu)
Stress limit ≈ 460MPa

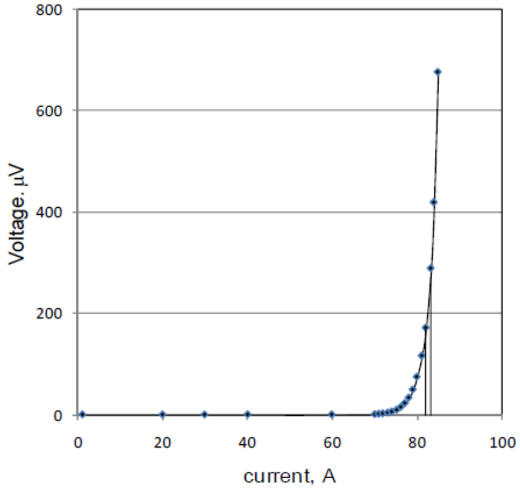


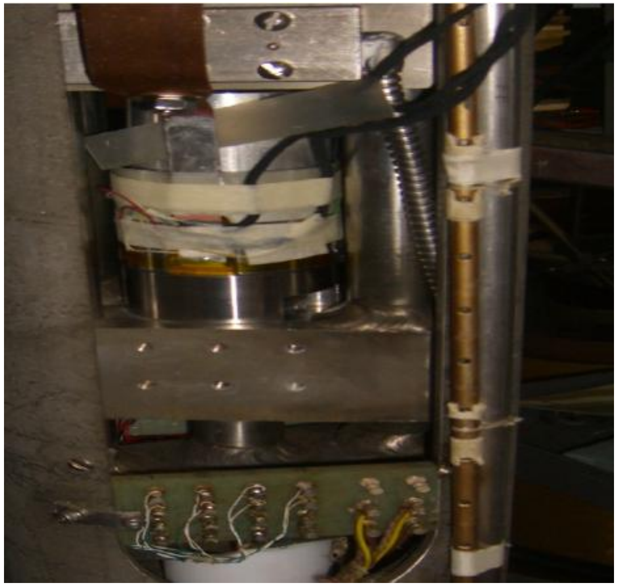
M3-861-2 (40µm Cu)
Stress limit ≈ 620MPa

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





Compressive Ic test setup (LN2 testing)

Summary of Ic data on coil sections

Section	Critical Current	"n" value
1	79.3A	32
2	80.8A	34
3	81.5A	32
4	79.1A	32
5	79.2A	32
6	81.3A	31

WB Sampson et al, Proceedings of 2011 Particle Accelerator Conference, New York, NY TUP169

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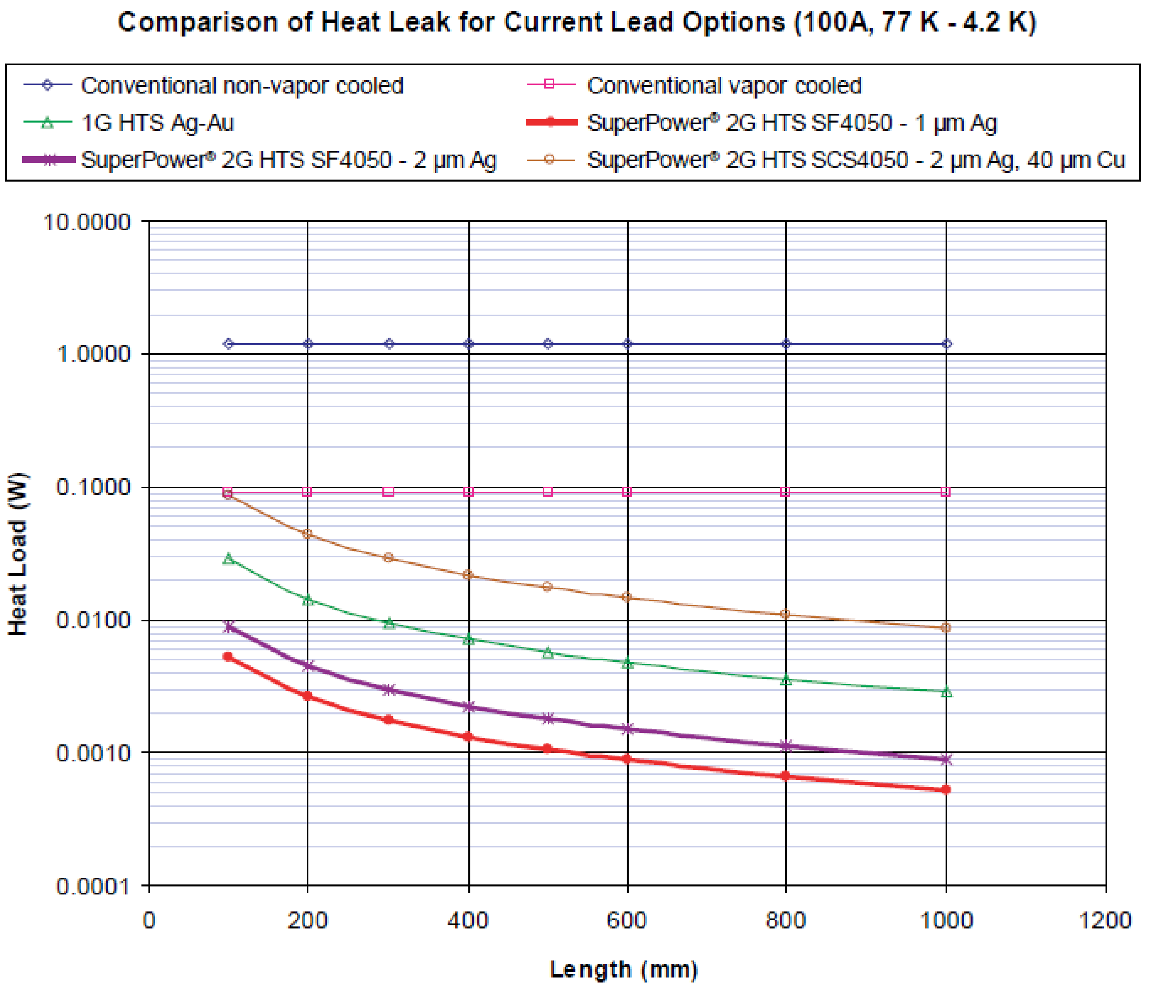
2G HTS offer low heat leak in current lead applications

- Eliminate I2R heat load
- Can be tailored to meet your target heat loads
- New configurations becoming available
  - Ag alloy
  - Bonded



Property	Current	Future (2/5 yrs)
Width range (mm)	2-12 (2,3,4,6,8,12)	2-12 / 2-12, others?
Production length (m)	800-1200	1200 / 2000
Unit piece lengths (m)	100 – 250	500 / 1000
Substrate	Hastelloy® C276	Hastelloy® C276, others?
Buffers	5 layer stack w/IBAD MgO	5 layer stack w/IBAD MgO, other?
REBCO thickness (μm)	1 - 2	2 - 5
Copper thickness (μm)	10 – 120 (total) plating Up to 1mm by lamination	5 – 120 (total) plating Up to 1 mm by lamination
Ic range (A/cm)	250 – 420 (77K, sf) 450 – 600 (4.2K, 15T//c)	350 – 800 (77K, sf) 1000 – 2500 (4.2K, 15T//c)
Jc range (A/mm^2)	350 @ 135A (77K, sf) 605 @ 230A (4.2K, 15T//c) SCS4050, 40 μm Cu	800 @ 240A (77K, sf) 2400 @ 725A (4.2K, 15T//c) SCS3050, 40 μm Cu
Critical current variation	< 10% std dev (spec)	< 5% std dev (spec)
Maximum stress/strain (tensile)	> 550 MPA, > 0.5% SCS4050, 40 μm Cu	> 550 MPA, >0.5% SCS3050, 40 μm Cu
Maximum stress/strain (comp)	> 80 MPA w/o failure – limit TBD	TBD

Pricing

- Pricing will be driven down on two fronts
  - Improved manufacturing
    - Better yields
    - Reduced costs on scale up
  - Improved performance
    - Higher baseline Ic (77K, sf)
      - Thicker HTS films
      - Better quality HTS films
    - Improved lift factor at operating conditions
      - Next generation AP with 2x or more improvement over current pinning
      - Demonstrated in samples, moving into production later this year
- The resulting price – performance ratio ($/kA-m) will continue to drop over the next years by factors of 2-4.

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 it 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
- We are open to exploring "out-of-the-box" configurations

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For more information on SuperPower, please visit us at: www.superpower-inc.com

e-mail: info@superpower-inc.com

SuperPower Inc. is a world leading developer and producer of second-generation high-temperature superconducting (2G HTS) wire, providing enormous advantages over conventional conductors of electric power - high efficiency, smart grid compatible, clean, green, safe and secure.