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2G HTS Properties Beyond Critical Current

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FURUKAWA ELECTRIC GROUP

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**currently at MSU-FRIB*

Outline

- SuperPower 2G HTS conductor architecture
- Critical current status
- Mechanical properties
  - General properties
  - Delamination
- FCL functionality
- Insulation
- Splices
- Closing remarks

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)

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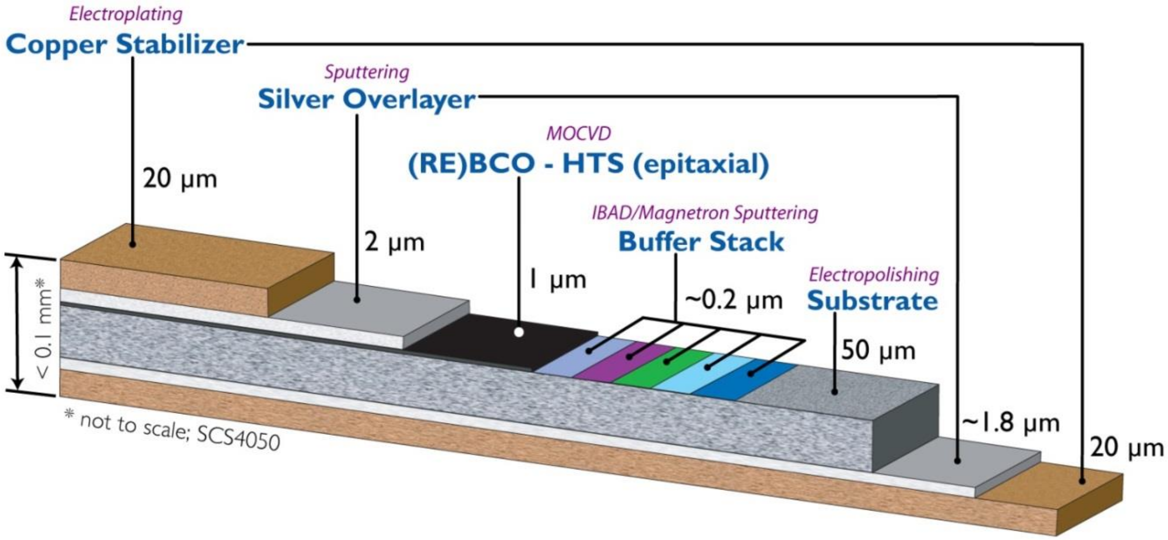
SuperPower's ReBCO superconductor with artificial pinning structure provides a solution for demanding applications

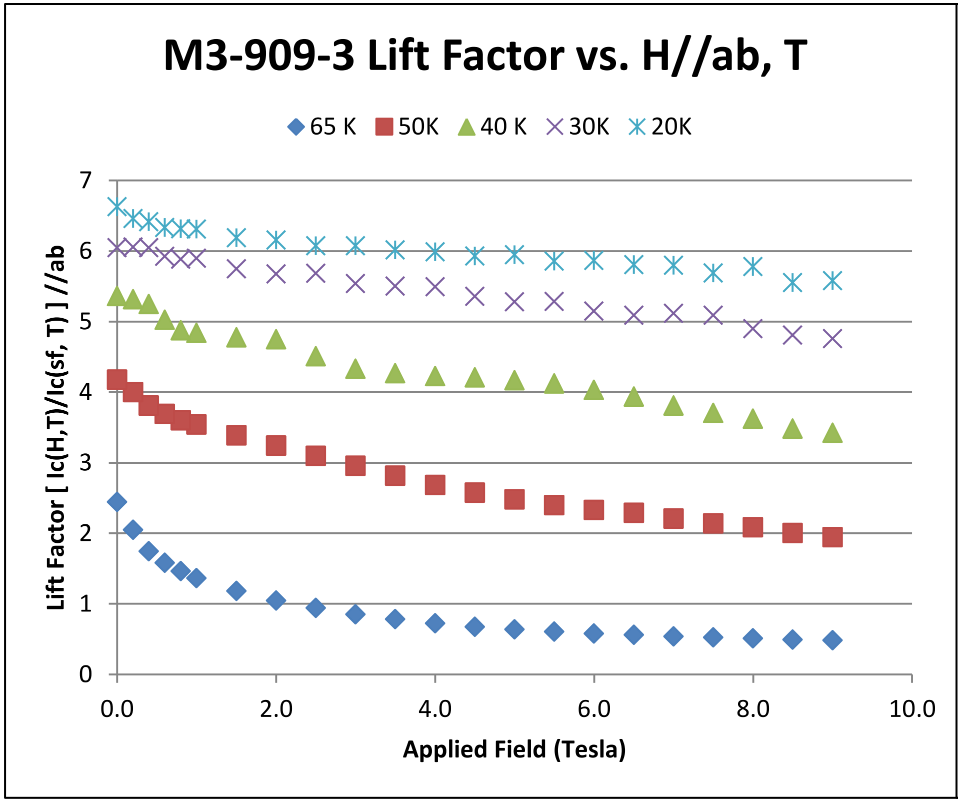


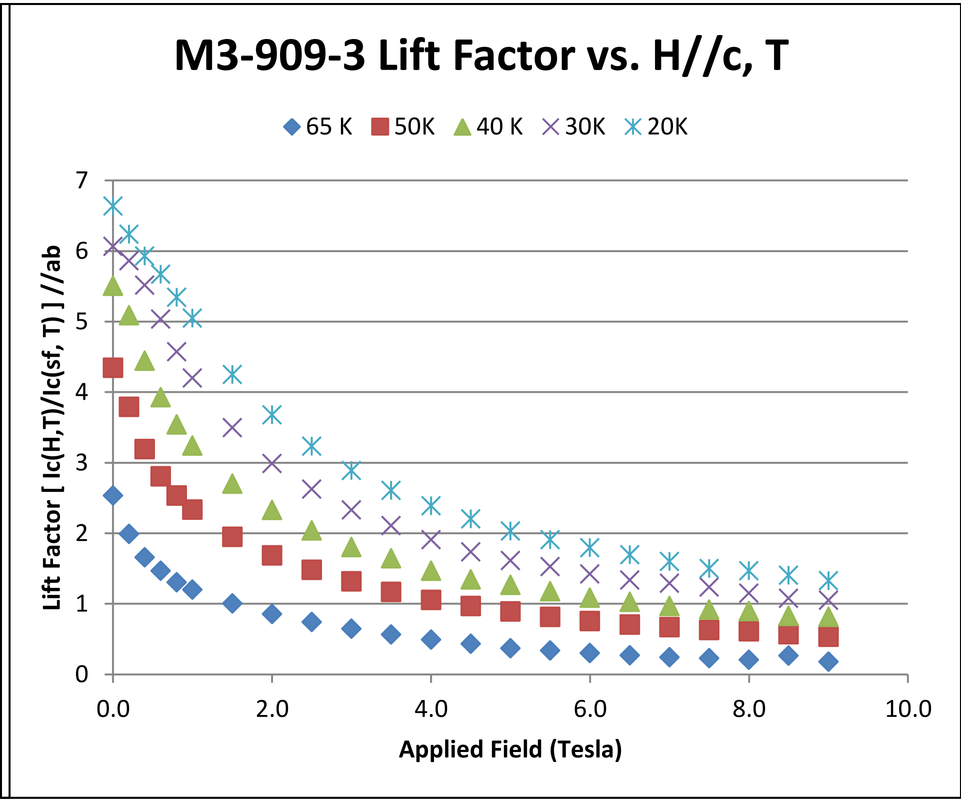
- Hastelloy® C276 substrate
  - high strength
  - high resistance
  - non-magnetic
- Buffer layers with IBAD-MgO
  - Diffusion barrier to metal substrate
  - Ideal lattice matching from substrate through ReBCO
- MOCVD grown ReBCO layer with BZO nanorods
  - Flux pinning sites for high in-field I_c
- Silver and copper stabilization

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.

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

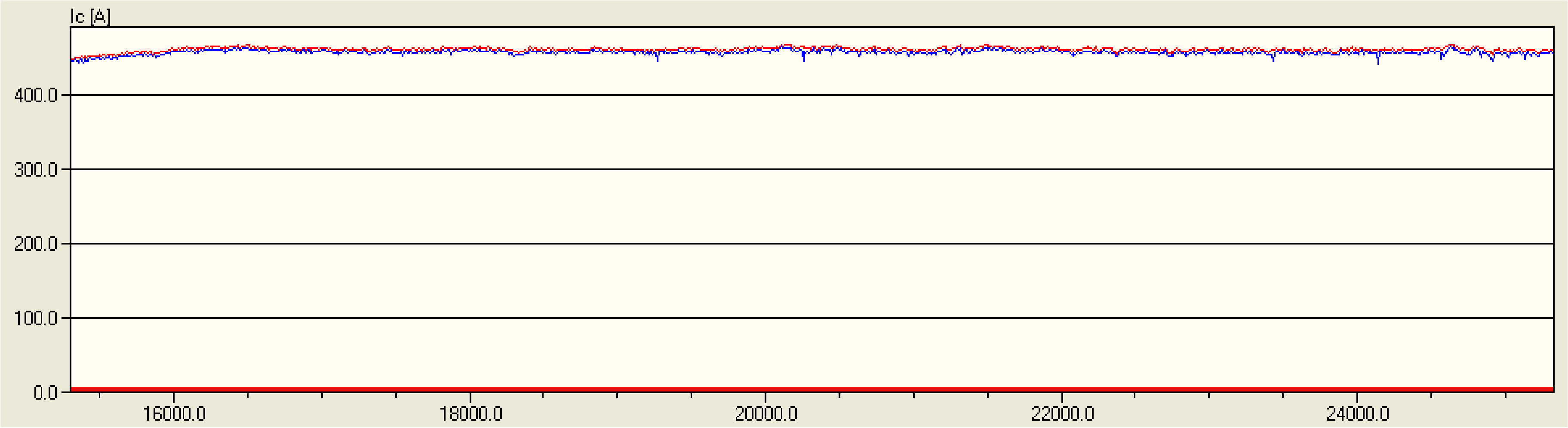




Measurements made at the University of Houston

- Lift factor, $I_c(B,T)/I_c(\text{sf, 77K})$, 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.

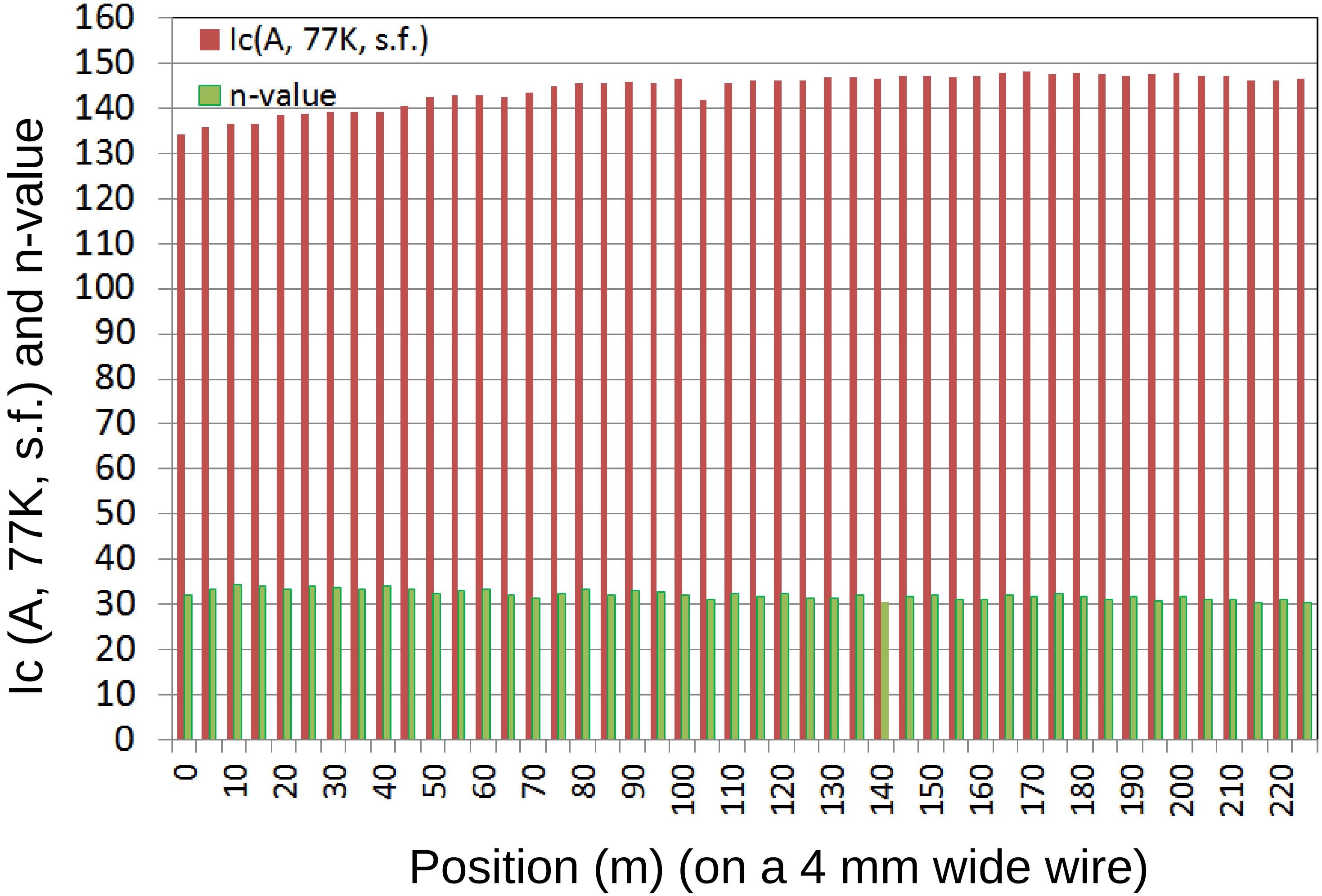
I_c uniformity along length (TapeStar)



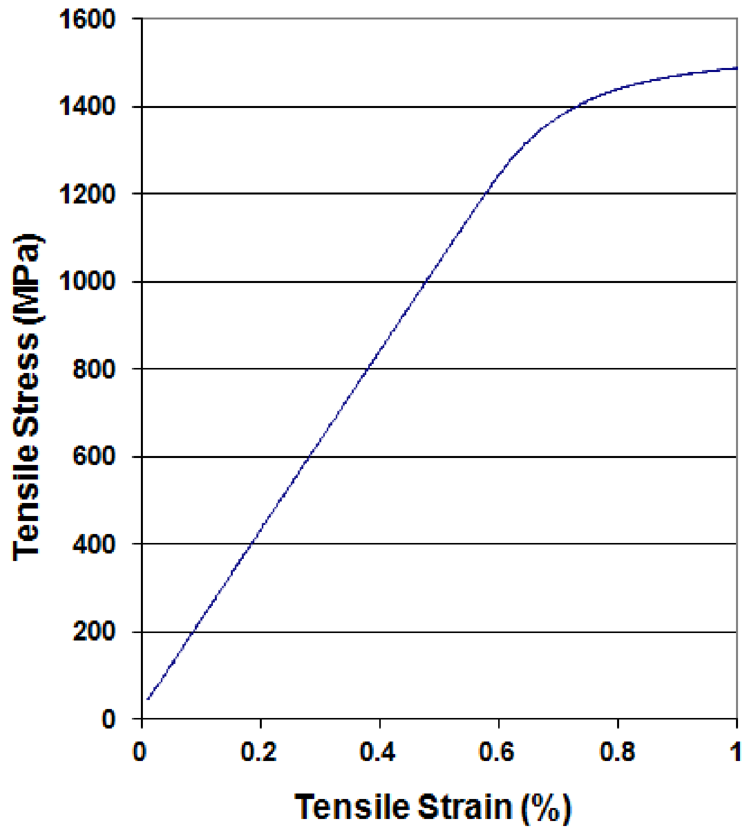
Position (cm) (on a 12 mm wide wire)

- 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

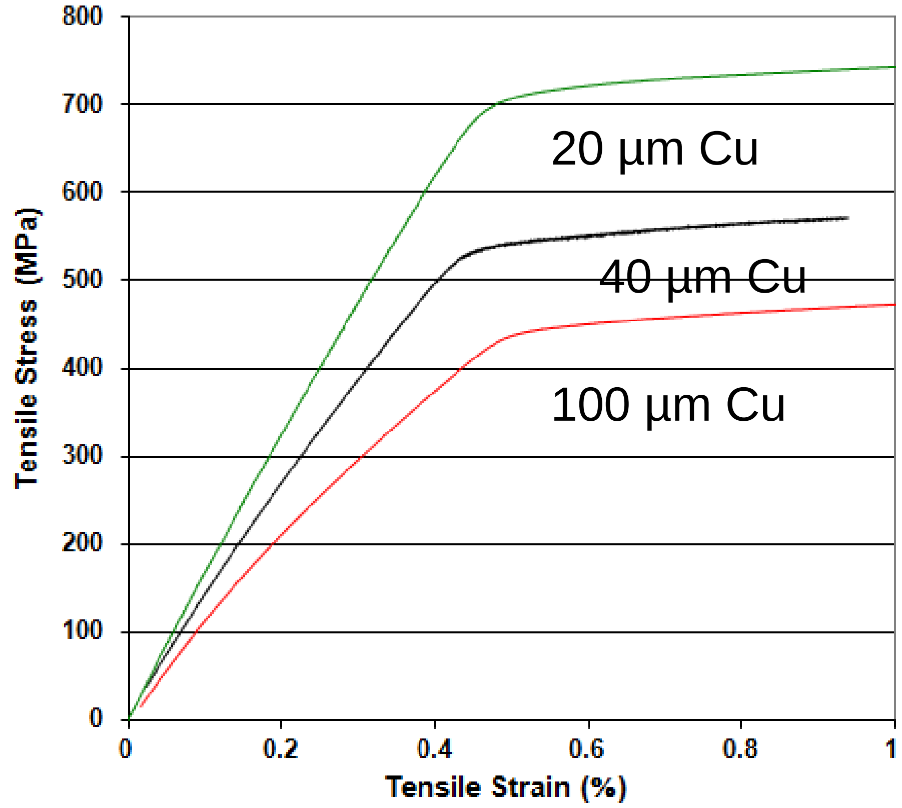
I_c uniformity along length (four-probe transport measurement)



Tensile strength predominately determined by substrate

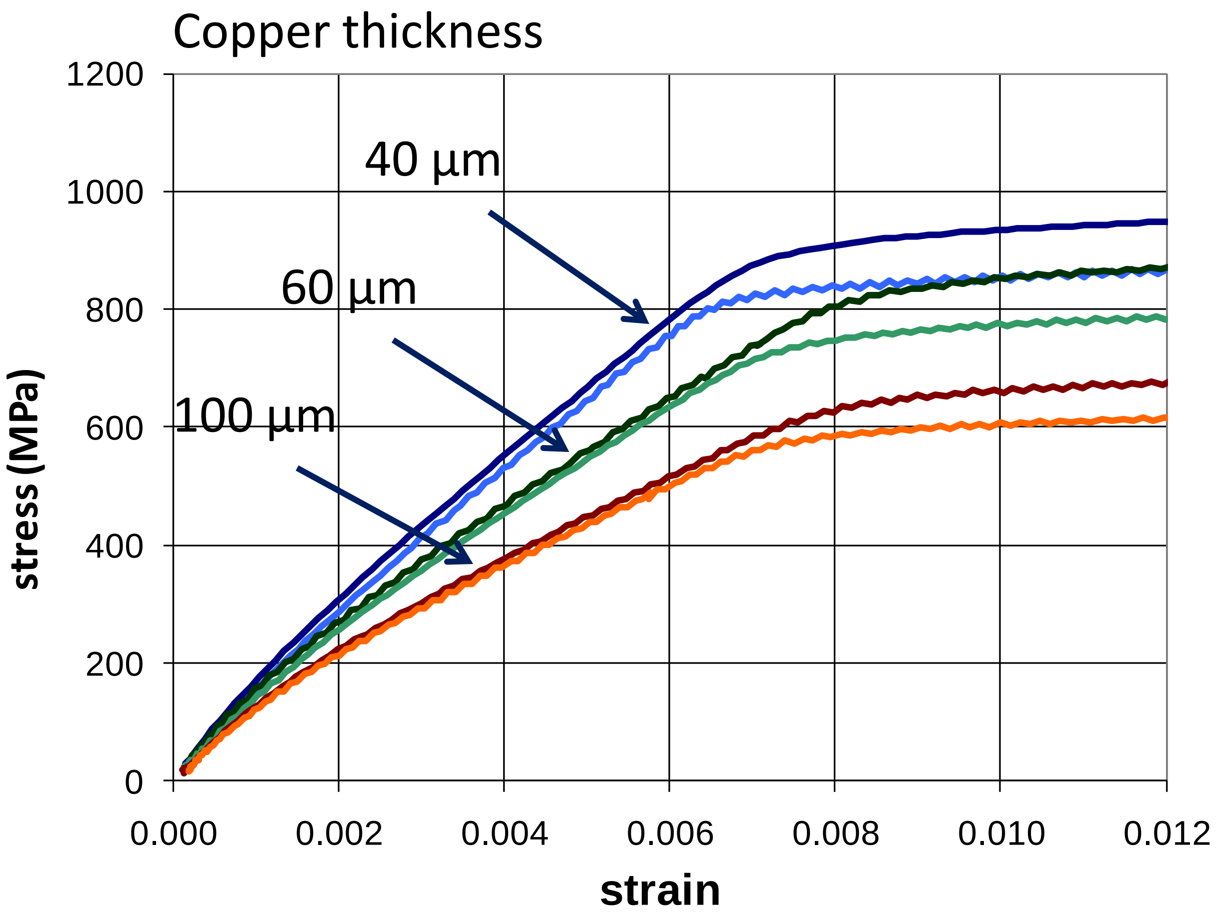


Tensile stress-strain relationship of as-polished Hastelloy substrate (room temperature)



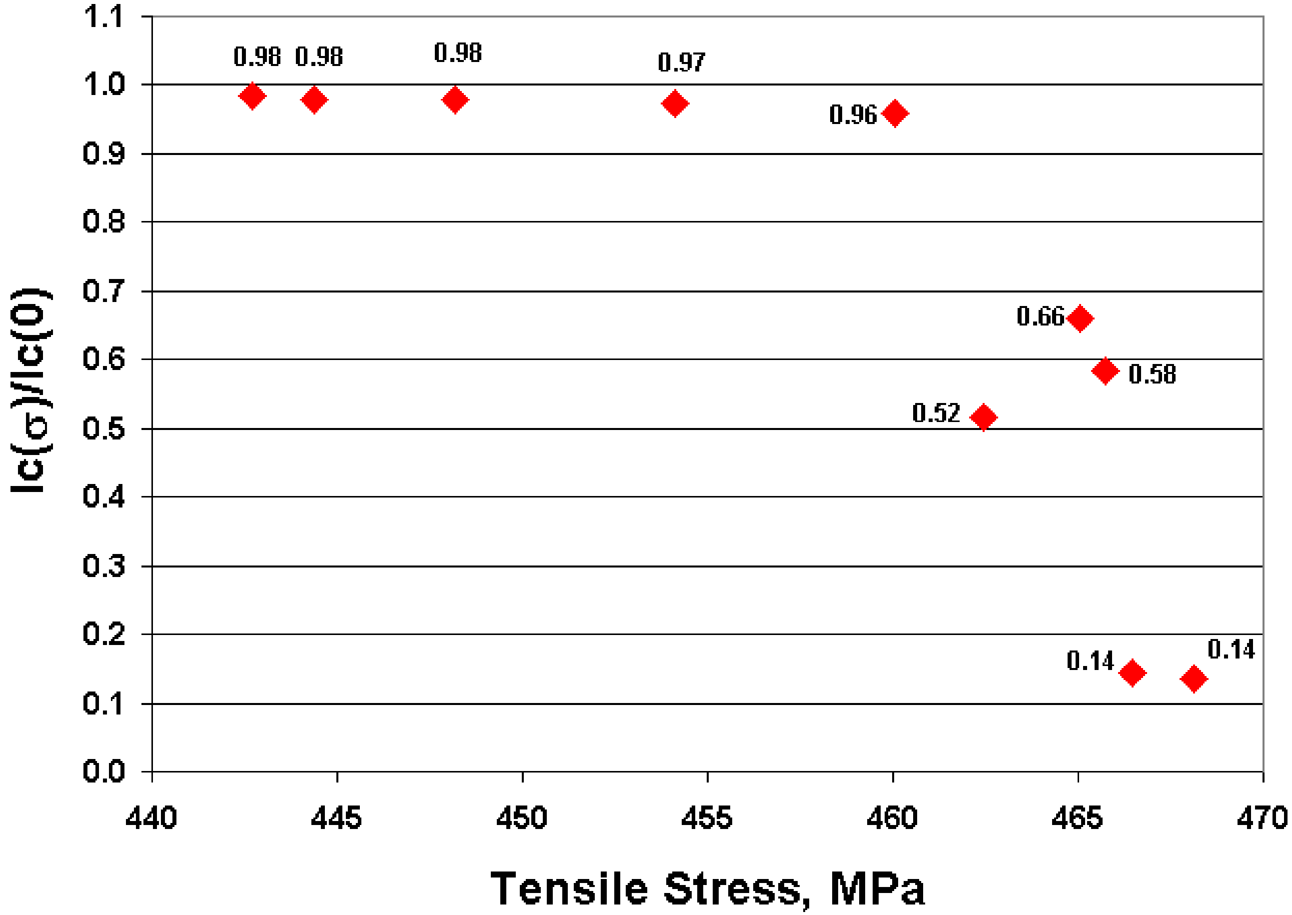
Tensile stress-strain relationship of SCS4050 wires with different Cu stabilizer thickness (room temperature)

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.

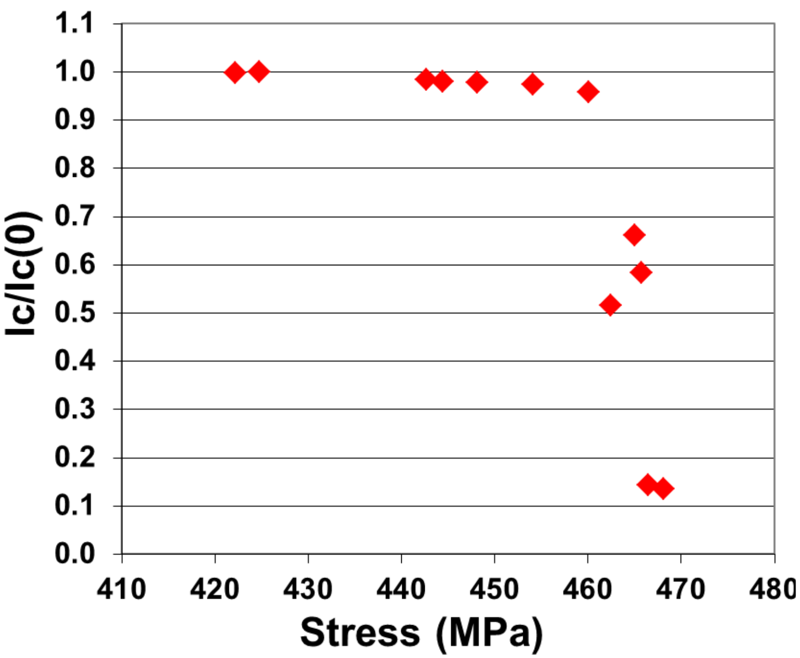
Tensile strength - effect of stress on I_c



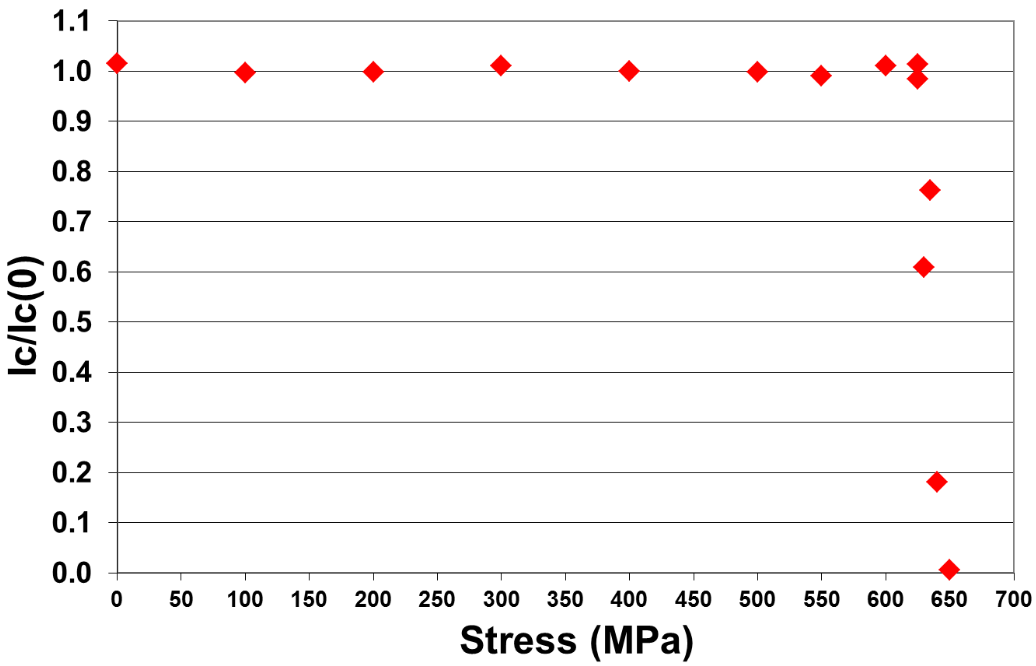
Normalized I_c vs. room temperature tensile stress for a 12mm wide wire with 100µm Cu stabilizer

Tensile test of wires with SCS

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



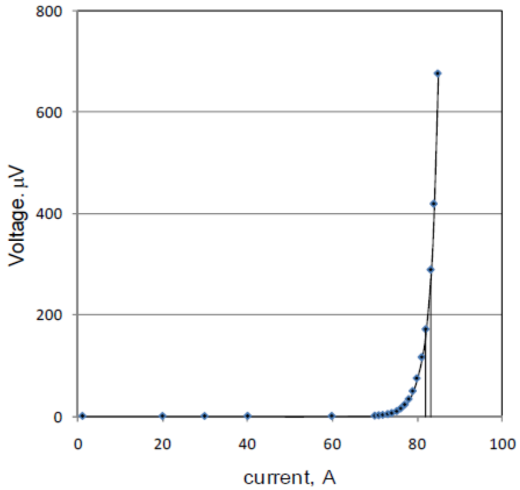
M3-914-1 (100µm Cu)
Stress limit ≈ 460MPa



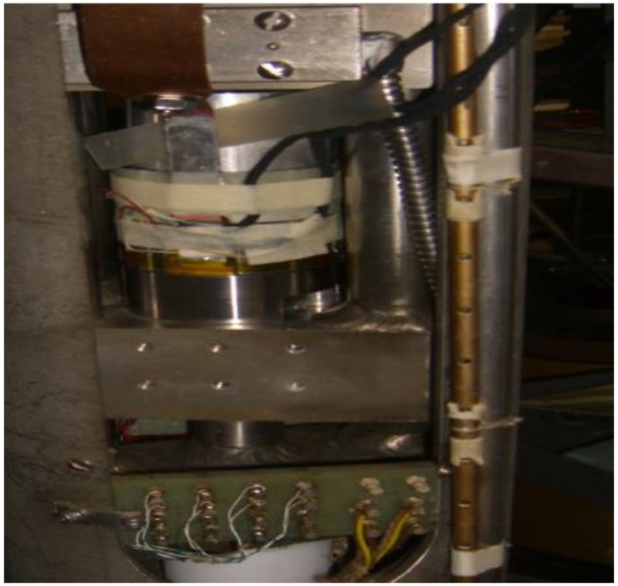
M3-861-2 (40µm Cu)
Stress limit ≈ 620MPa

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



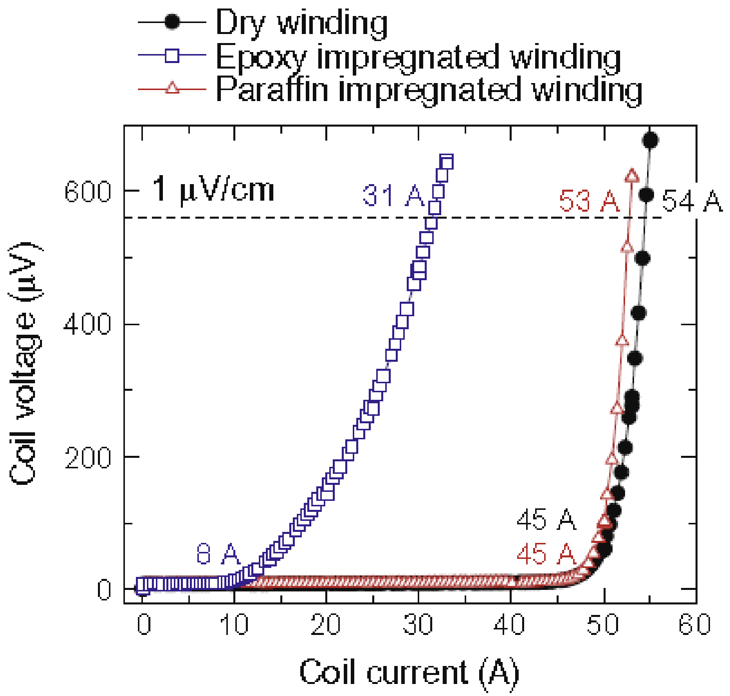
Compressive Ic test setup (LN2 testing)

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

(RE)BCO coils can be subject to degradation under thermal cycling



Conclusions

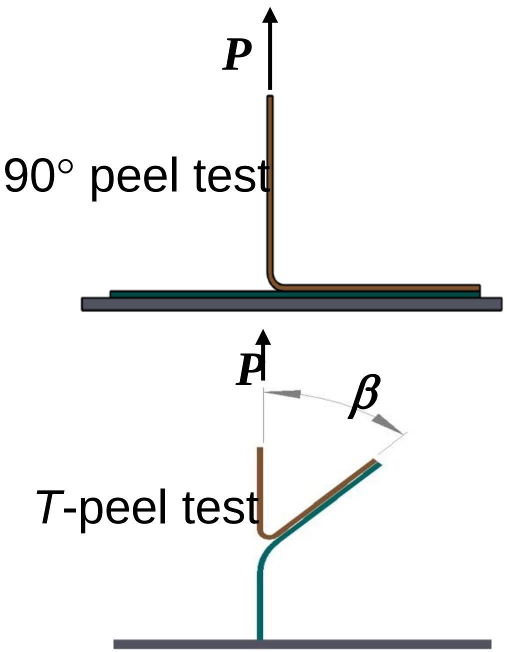
(1) The critical current of epoxy impregnated circular coils wound using YBCO-coated conductors can be degraded in use.

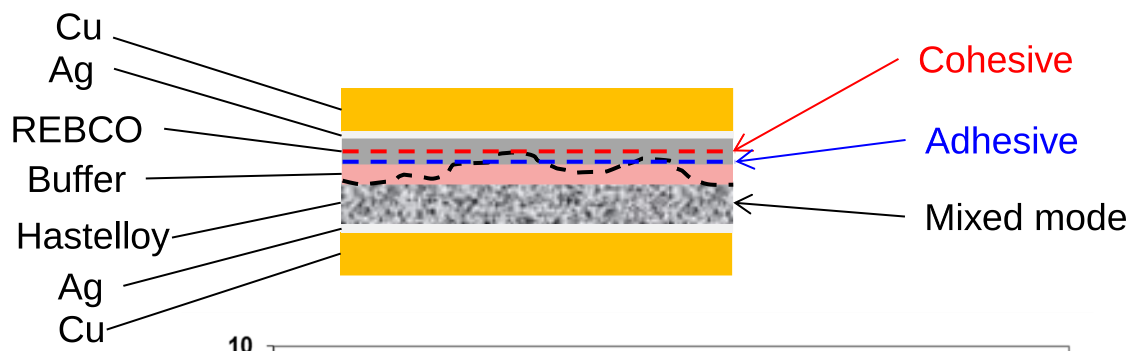
(2) Degradation occurs if the cumulative radial stress developed due to winding, cool down and Lorentz force exceeds the critical transverse stress for the YBCO coated conductor, typically +10 MPa.

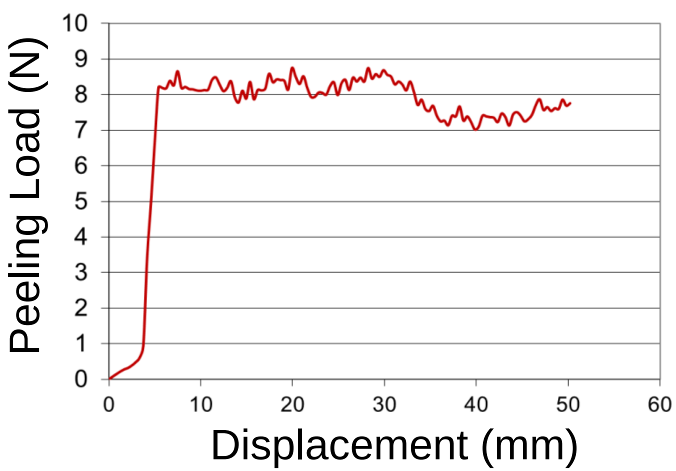
(3) The YBCO conductor is fractured at the interface between the buffer layer and the YBCO layer, or at the YBCO layer itself, causing cracks on the YBCO layer resulting in significant decline of the critical current.

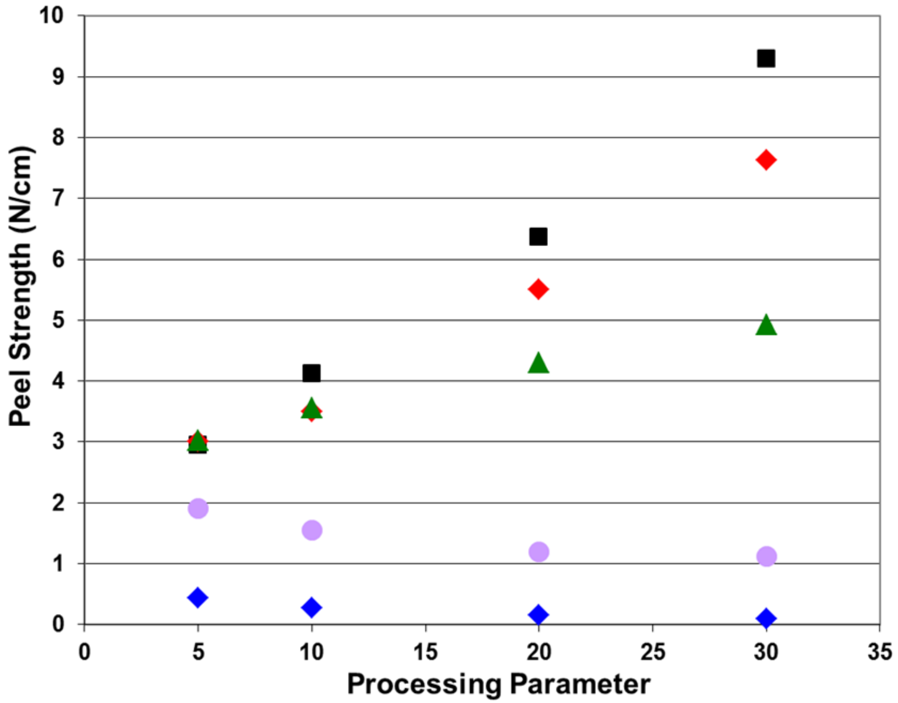
- Takematsu *et al.*, *Physica C* 674-677, 470, 2011

Delamination strength studied with peel test







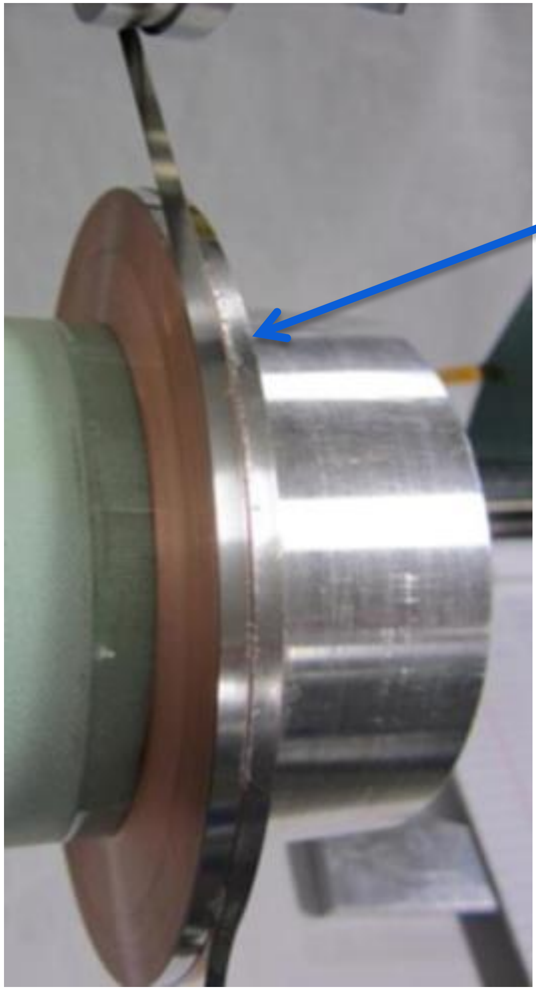


Relationship between peel strength and processing conditions established

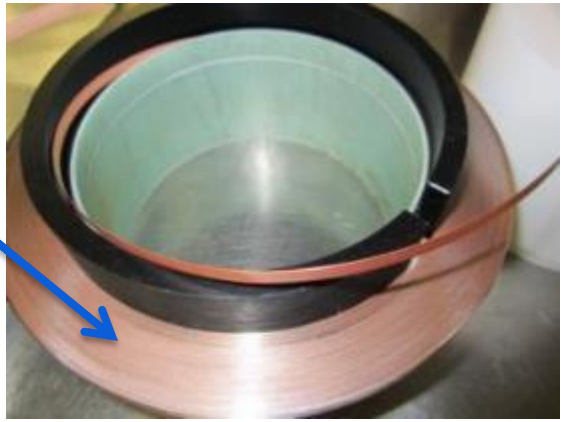
Successful winding techniques demonstrated to mitigate delamination issue

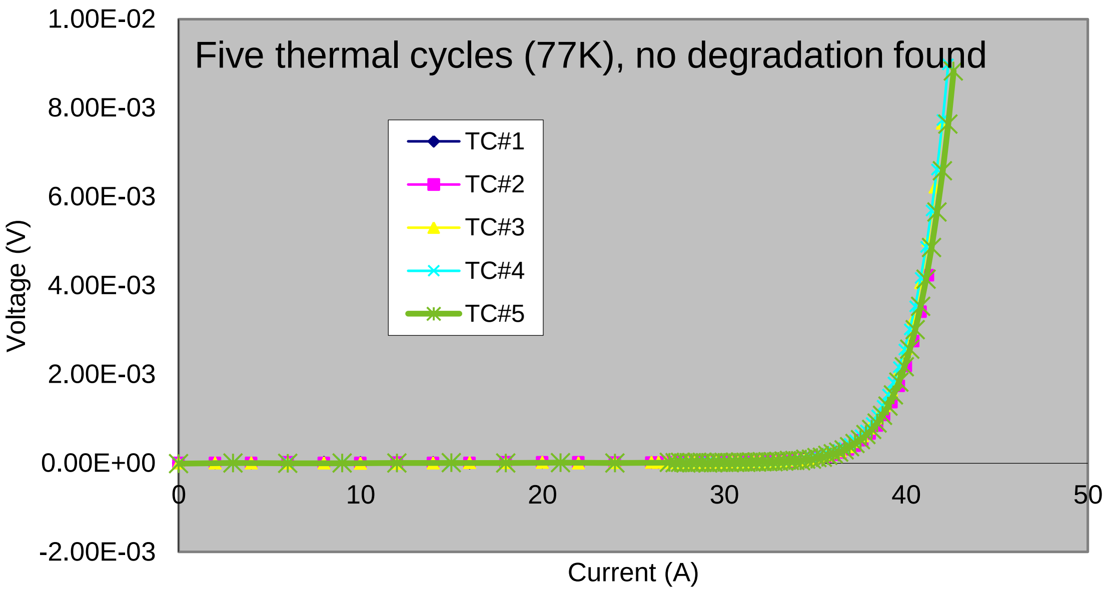
- Decoupling of former from winding has been demonstrated to be beneficial
  - Eliminates radial tensile stress on the 2G HTS windings
  - PET release layer incorporated at former:windings interface
  - Lower thermal expansion formers (Ti, controlled expansion glass-epoxy)
- Alternative insulations/epoxy 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





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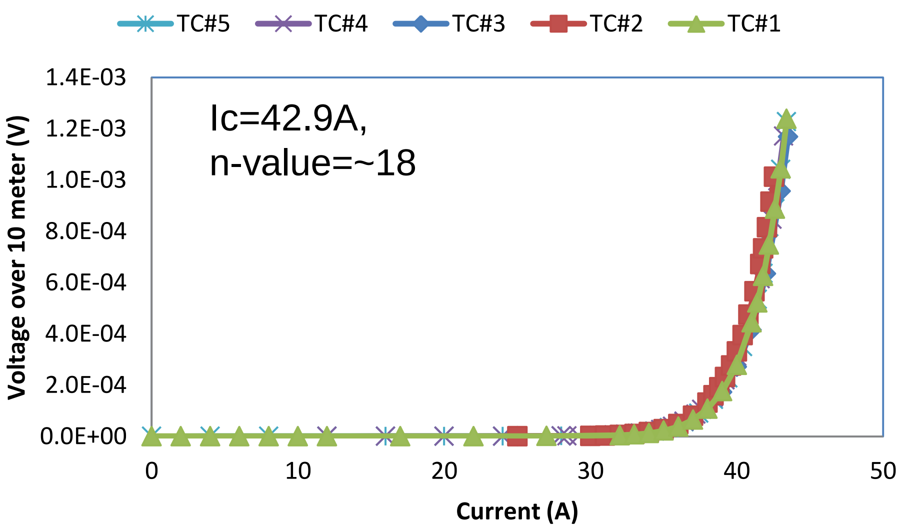
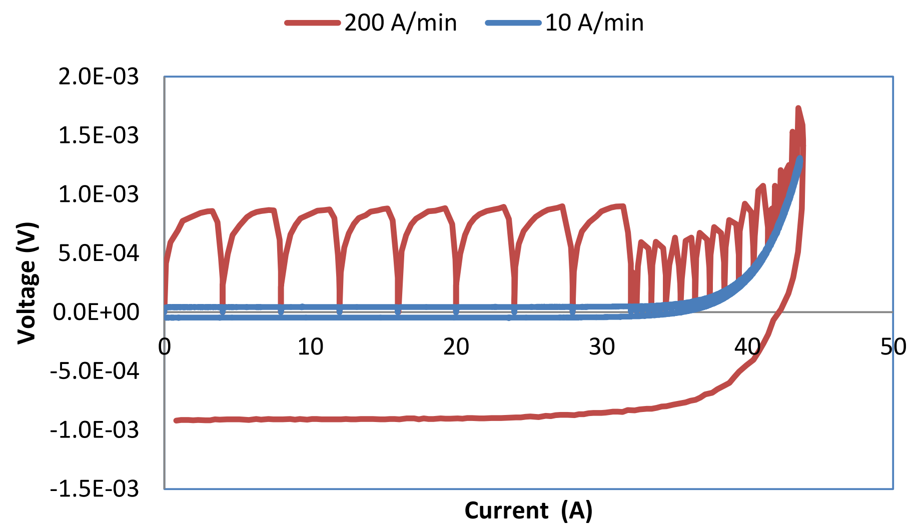
Alternative epoxy for wet wound coils shows resistance to delamination

- Design of experiments on Adraldite™ epoxy with Alumina
  - Epoxy (Araldite DBF): hardener (Araldite 951) = 10:1
- A fully wet wound coil
  - Conductor M3-919-2 BS, 566-576, 10 meter, 52 turns, ID=2''
  - No additional insulation except for the epoxy, PET release
    - Five thermal cycle, no degradation found

[C Barth *et al*, KIT, SuST. 26 (2013) 055007]



Five thermal cycles, no degradation

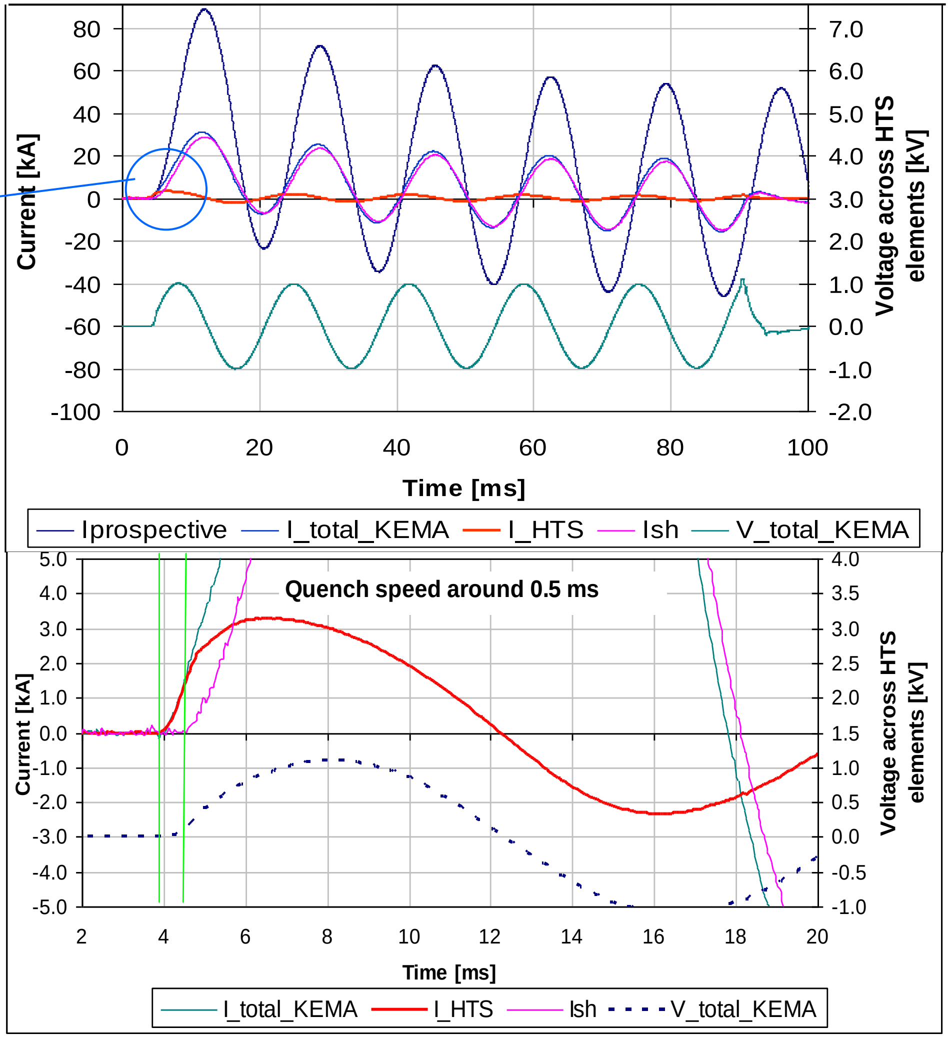


In TC#5, ramp rate comparison,
no difference in Ic and n-value, 42.9A/17.5

2G Conductor for SFCL Shows Consistent, Excellent Performance

Fast response time

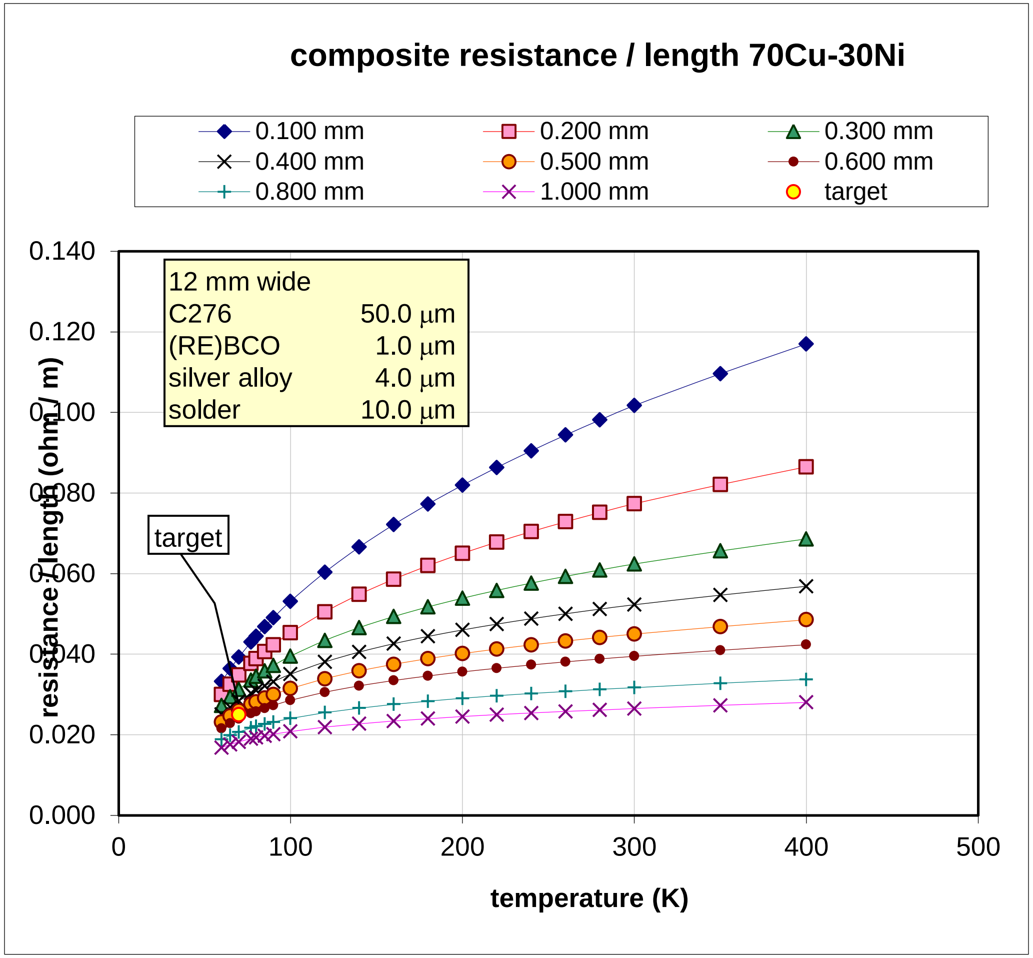
High-power SFCL test	2G
Prospective current	**90 kA***
Limited current	**32 kA**
Peak current through element	**3 kA**
Response time	**< 1 ms**
Element quality range	**Uniform**

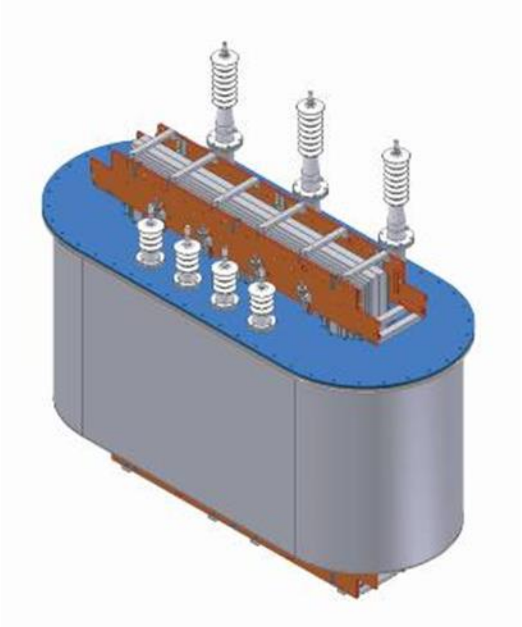


Capability for bonded conductors being developed [higher amperage, specialty applications (FCL)]

- 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

Bonded conductors meet target normal state resistance while meeting mechanical strength targets for FCL transformer application]



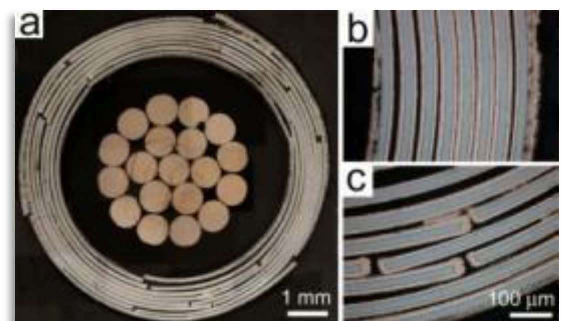


- DOE SMART GRID Project
- 28 MVA 3-phase FCL Medium Power Utility Transformer (69 kV / 12.47 kV class)
- Testing on So. California Edison Smart Grid site in Irvine, CA – plan min 1 year of grid operation

Insulation and other ongoing developments

- Additional wire insulation methods under development
  - Today: Kapton®/Polyimide wrapped (1-2 kV)
  - Other options under development: thinner profile, better coverage

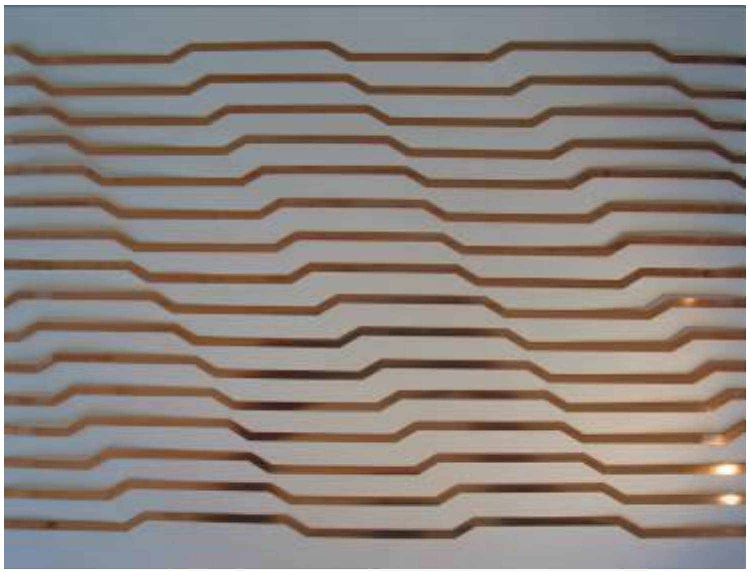
- Additional wire architectures under development
  - Higher current carrying capability
    - Multi-layer combinations
    - Cable on Round Core (CORC)
    - Thinner substrates
  - Custom attributes
    - FCL – normal state resistance feature



Courtesy: Advanced Conductor Technologies

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

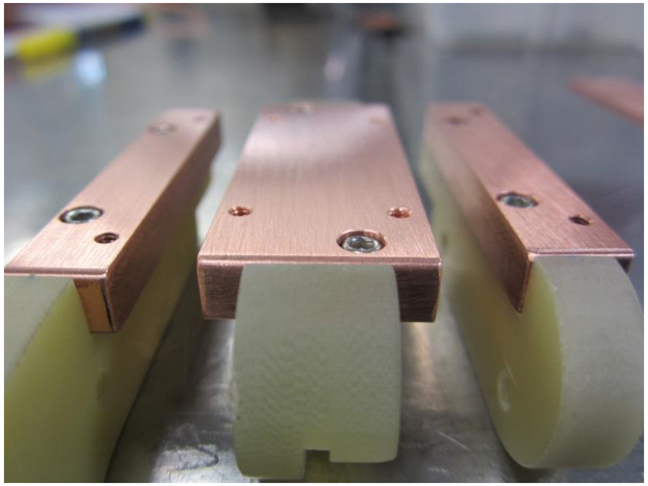
Karlsruhe Institute of Technology

No failure, no delamination

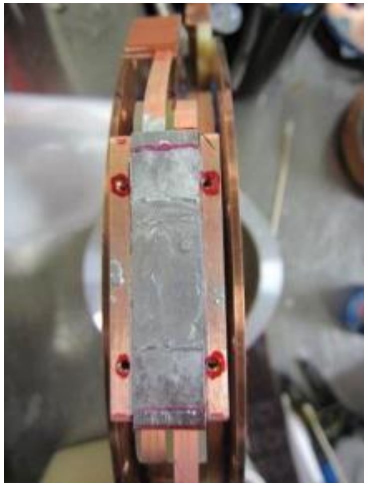
Only 3% loss in current from conductor to ROEBEL cable

Cable engineering current density = 11,300 A/cm^2

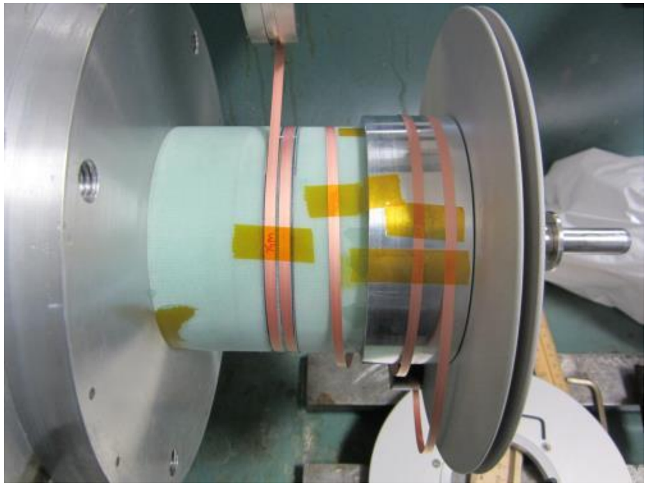
Terminal leads, joint, transition



Cu base for terminals and joints (FLAT leading in and out)



Bridge joints between pancakes, $R_{tot}=10^{-7}\Omega$



Smooth transition on inner crossover

- Terminals and leads are potential sources of damage in 2G HTS coils
- So their design, handling and fabrication are very critical
- Key points: Avoid kinking or over bending, making smooth transition with adequate support

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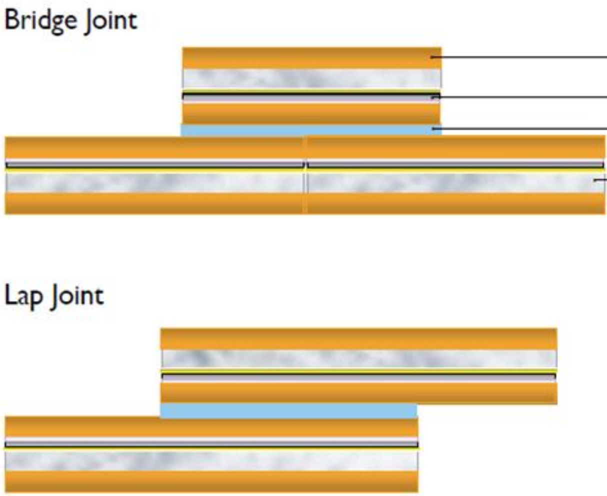
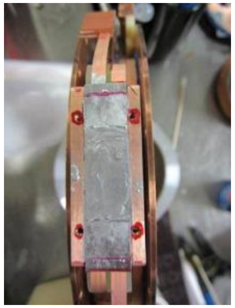
Reliable splices – low resistance and high strength

- 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

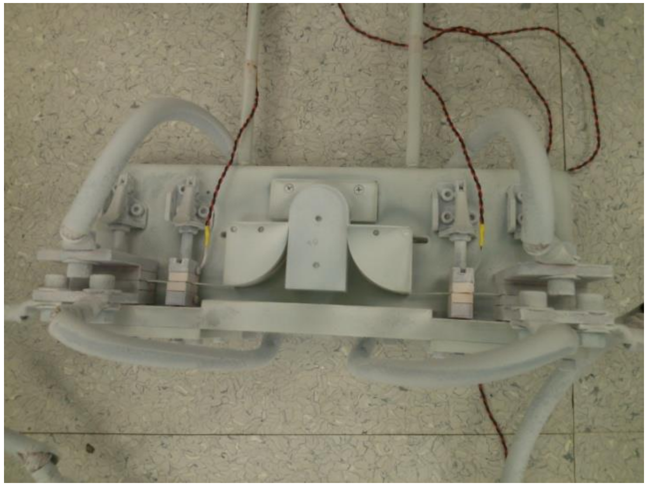


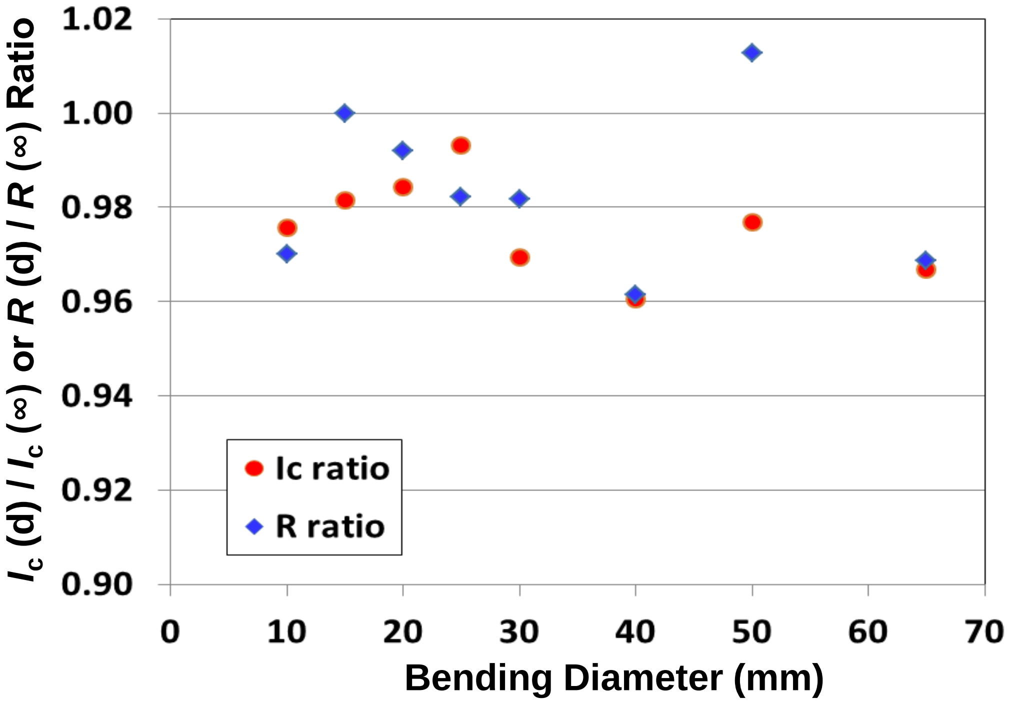


Bridge joints between pancakes, $R_{tot} = 10^{-7}\Omega$

- 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 ≤ 20 nΩ for the lap joint geometry with a 10cm overlap length

Splice I_c and resistance vs. bending diameter





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

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