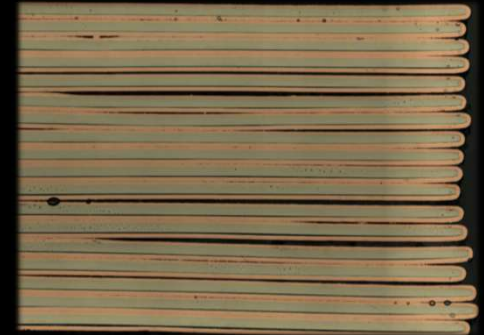
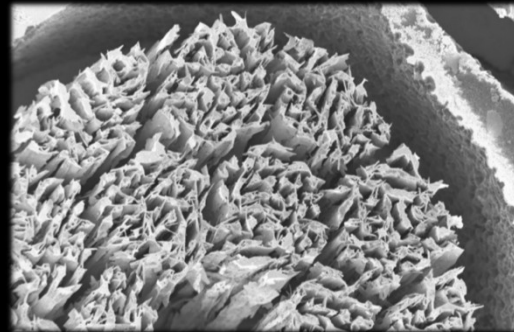


# Critical properties of HTS beyond critical current density to become **THE** material for **magnets**



**Anna Kario**

**CERN Experimental Physics, University of Twente**

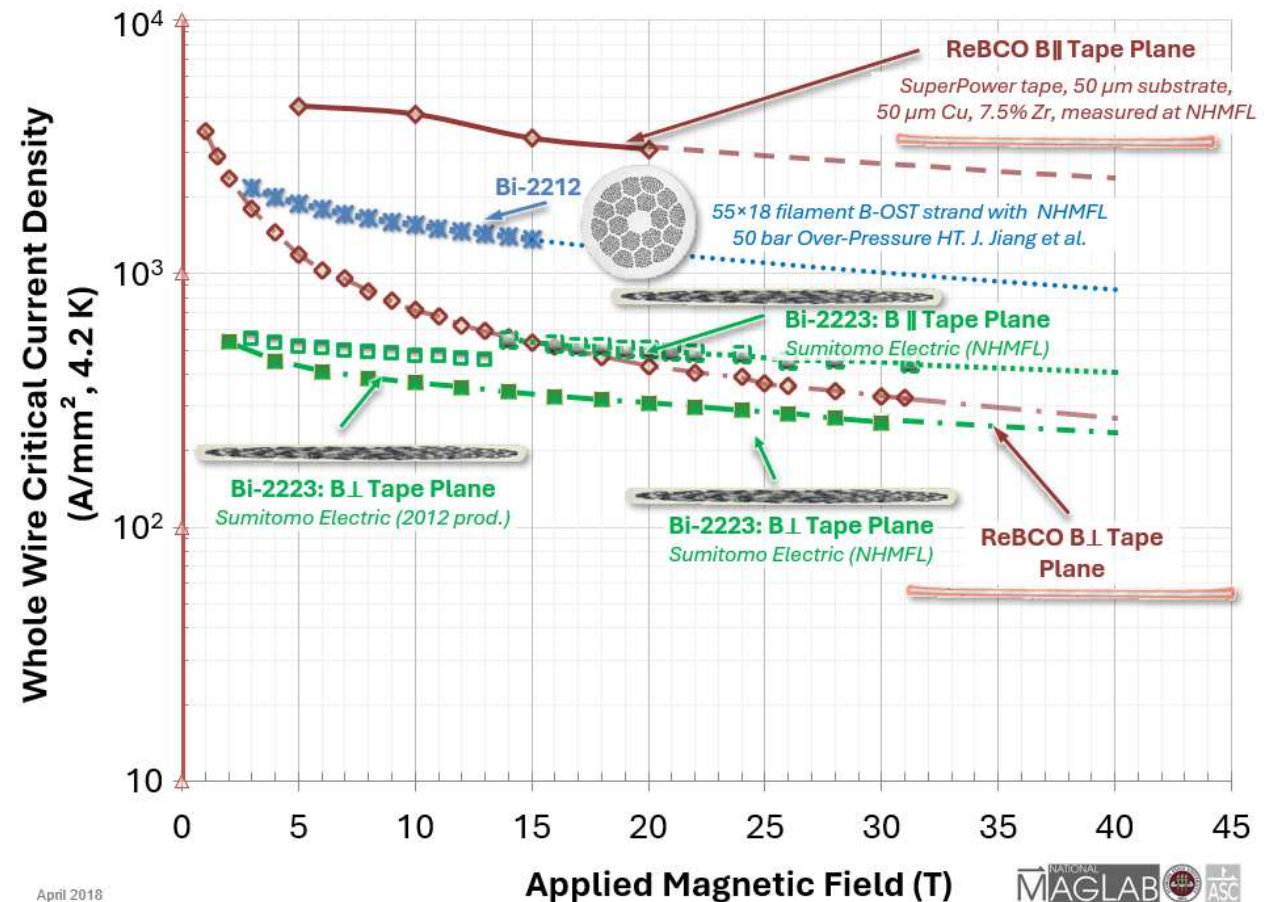
# Credits:



- Erik Hellstrom, Ulf Trociewitz (Applied Superconductivity Center, National High Magnetic Field Laboratory) News on Bi-2212 from USA
- Peng Gao (Institute of Plasma Physics, Chinese Academy of Sciences(ASIPP), Shengnan Zhang (Northwest Institute for Non-ferrous Metal Research ) and Xifeng Pan (CEO, Hefei Kuafu Superconducting Co.Ltd , Dr./Prof., Fujian Normal University) – News from China
- Arno Godeke (Senior Consulting for Superconductivity) BiSCCO ambassador
- Carmine Senatore and Celia Lucas Esparseil, Gianluca Vernassa (University of Geneva) newest  $J_c$  data and electromagnetic delamination of ReBCO
- Cynthia Annema (University of Twente) art of scientific drawings
- Jeroen van Nugteren (Little Beast Engineering) for lets finally build some magnets!
- Amalia Ballarino (CERN) woman HTS dinner discussion
- Alexander Molodyk (Faraday Group) chat about presents and future of ReBCO
- Kazumasa Iida (Nihon University), Matthias Mentink, Benoit Cure (EP R&D), Antonio della Corte (ENEA) for support
- David Larbalestier, Jeseok Bang, Jan Jaroszynski, Rastislav Ries (National High Magnetic Field Laboratory), LittleBigCoil-x

# Critical properties of HTS beyond critical current density to become **THE** material for **magnets**

- Production of the HTS
- Mechanism behind critical current density enhancement
- Mechanical strength of the HTS materials
- Stability of Bi-2223, Bi-2212 and ReBCO conductors



<https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots/>

# High Temperature Superconductor cooking

- **Bi-2223 tapes**
- **Bi-2212 wires**
- **ReBCO coated conductor**

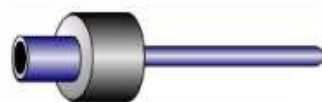


# Bi-2223 tape production route

1. Bi-2212 precursor powder into Ag tube



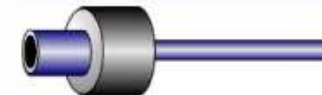
2. Drawing



3. Multifilamentary stacking



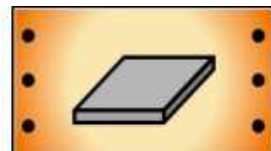
4. Drawing



5. Rolling

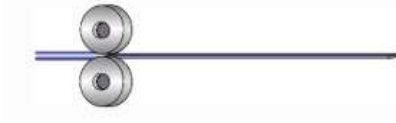


6. Sintering

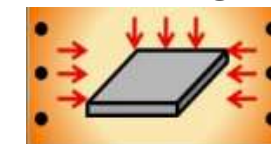


826°C/15h 7.5% O<sub>2</sub>

7. Rolling



8. Sintering



826°C/50h

Ken-ichi Sato et al., Japanese Journal of Applied Physics 51 (2012) 010006

- Traditional Powder-In-Tube technology
- Oxygen is released and absorbed during the reaction from the Bi-2212 precursor
- Silver matrix allowing oxygen diffusion
- Bi-2223:  $(\text{Bi,Pb})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+x}$  tapes made by rolling with intermediate heat-treatments

Sumitomo Electric

H & G

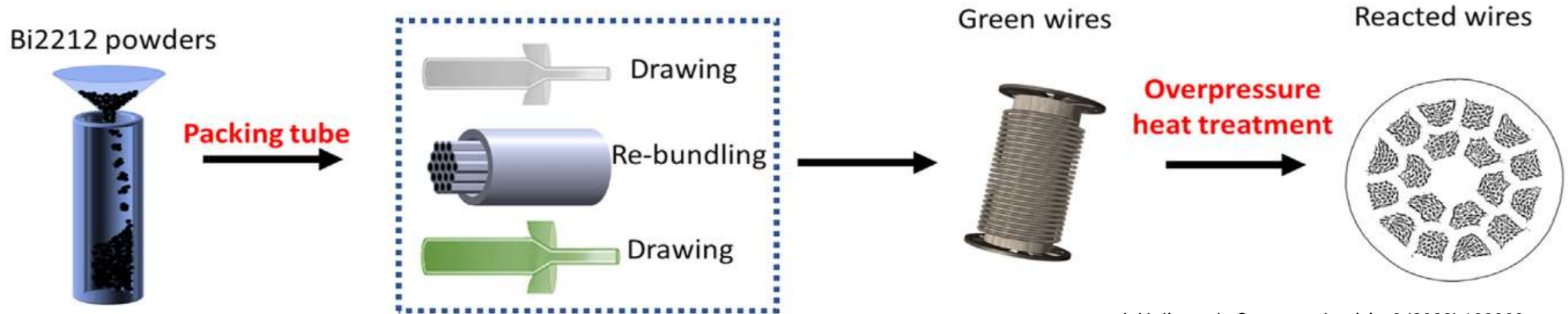


HT-NX



A. Godeke, Supercond. Sci. Technol. 36 (2023) 113001 (28pp)

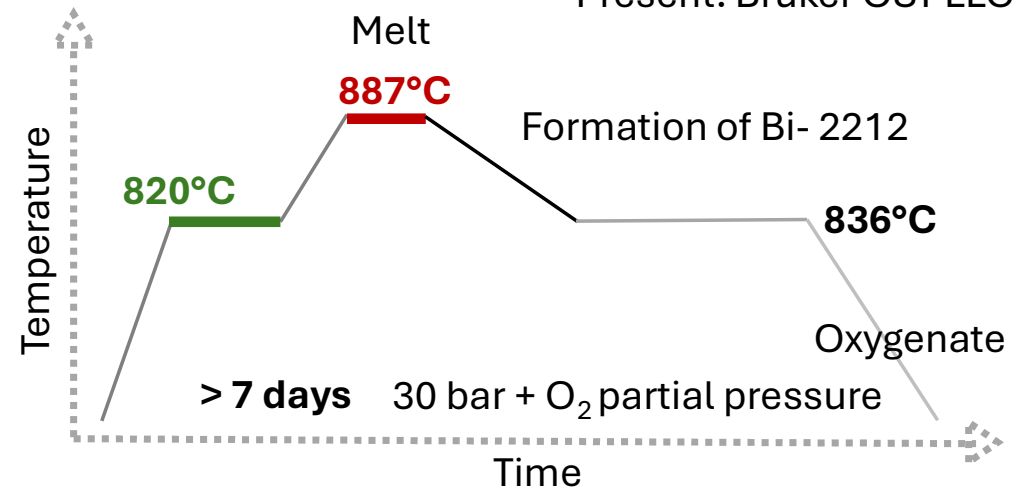
# Bi-2212 wire preparation method



L.H. Jin et al., Superconductivity 8 (2023) 100060

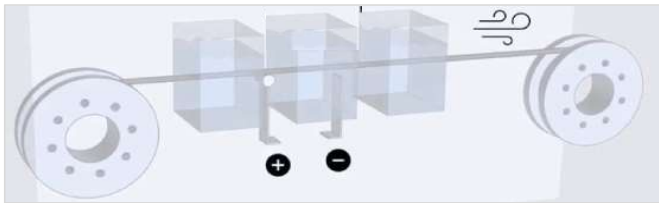
Future: WST, KAT  
Present: Bruker OST LLC

- Traditional Powder-In-Tube technology with Silver matrix allowing oxygen diffusion
- Bi-2212:  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$  wires made by drawing, re-bundling
- Heat treatment process: partial-melt, grain arrange solidifying within slow cool down
- Heat treatment at high pressure with partial oxygen pressure involved

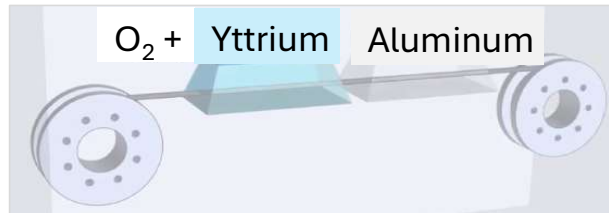


# ReBCO tape manufacturing

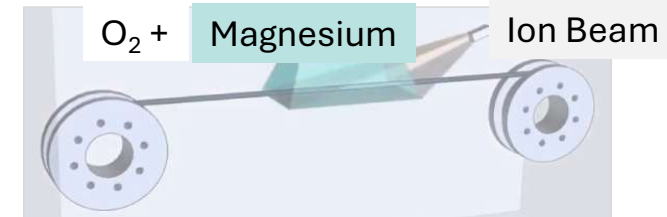
1. Hastelloy electropolishing



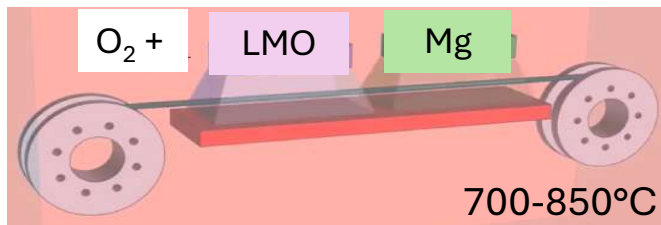
2. Magnetron sputtering  $Y_2O_3, Al_2O_3$



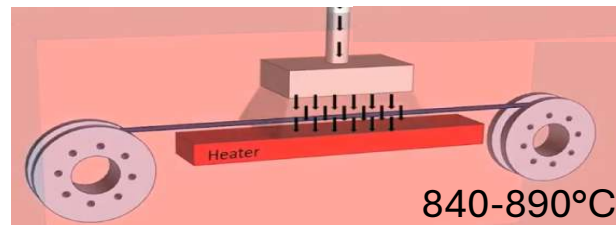
3. Ion Beam Assisted Deposition MgO



4. Magnetron Sputtering LMO



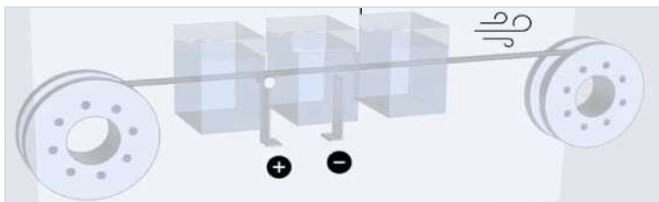
5. Metalorganic Chemical Vapor Deposition



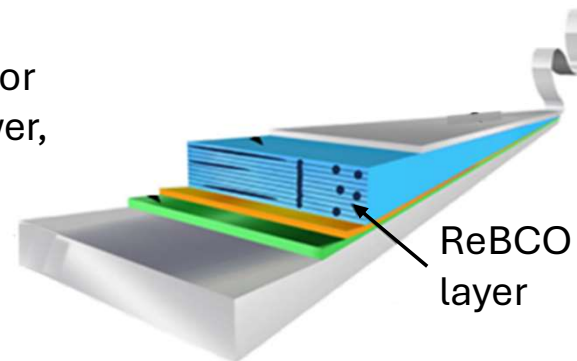
6. Magnetron Sputtering Ag



7. Electroplating Cu



Example for  
SuperPower,  
MOCVD



- L. García-Tabarés et al., <https://doi.org/10.1007/s40766-025-00071-6>
- Based on Renaissance Fusion video

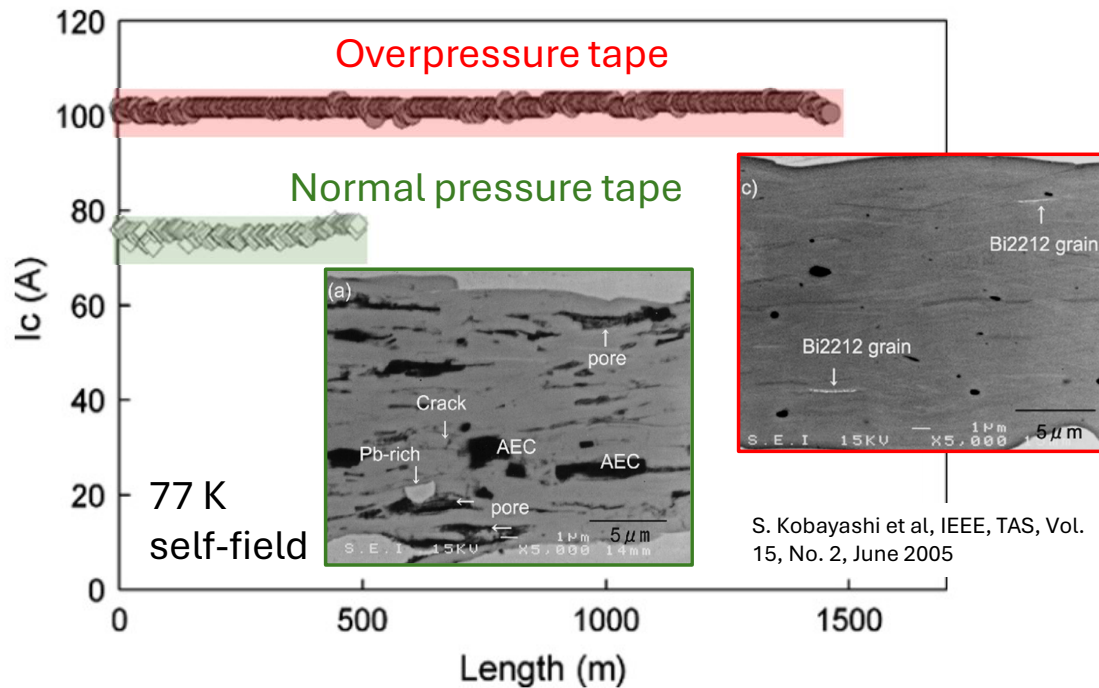
## Critical current density

- **Density in Bi-2223**
- **Density and grain boundaries in Bi-2212**
- **Deposition and pinning in ReBCO**

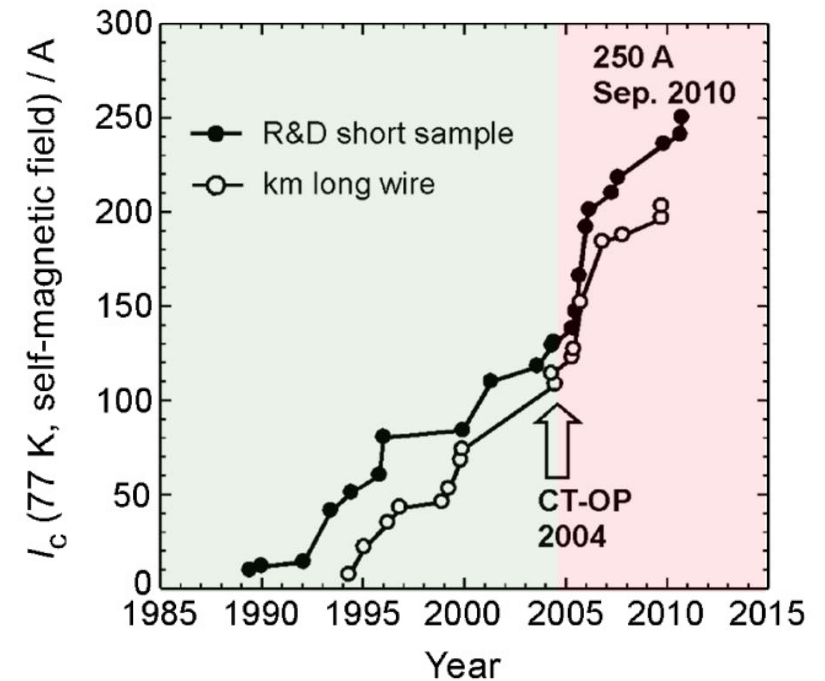


# Critical current in Bi-2223 depends on density

Critical current and microstructure before and after overpressure



Critical current enhancement over years

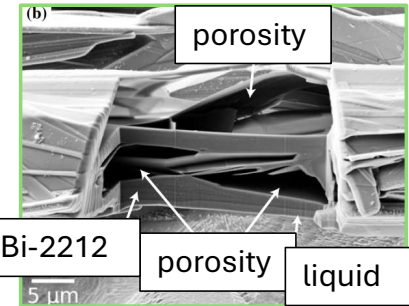
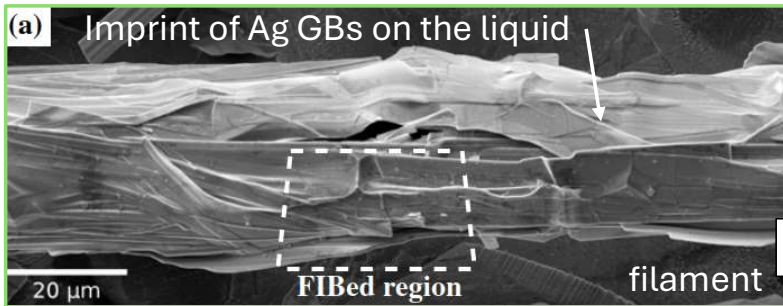
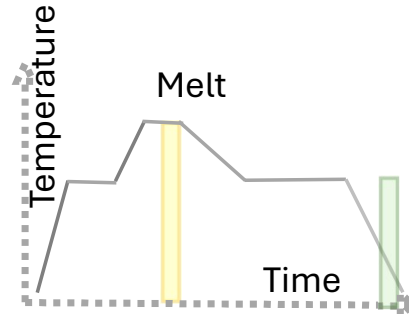
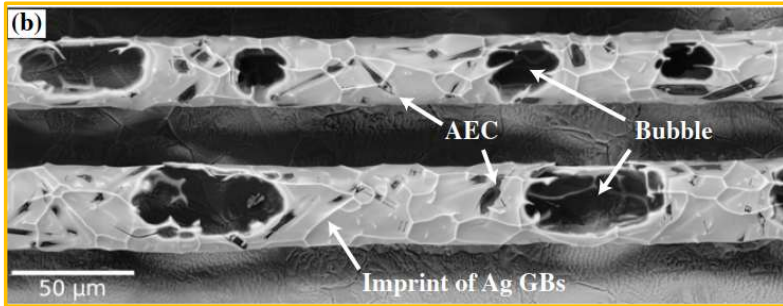


- Overpressure sintering at 30 MPa Bi-2223 tape enhanced  $I_c$  by more than 30%
- The relative density increased from 88% to 100% in overpressure sintered tapes, healing cracks and pores and resulting in homogeneous phase

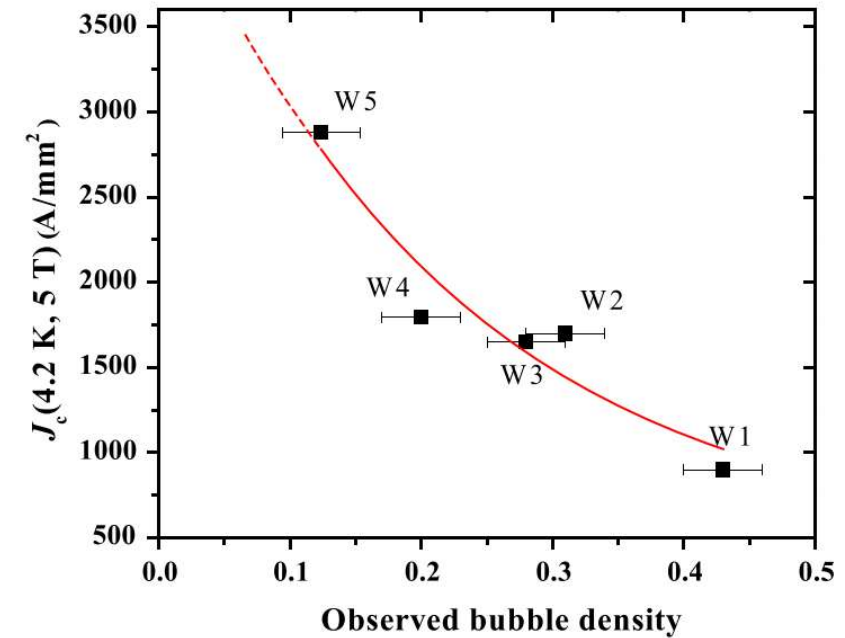


# Critical current in Bi-2212 depends on densification

SEM images of the Bi-2212 filaments



Critical current as a function of bubble density

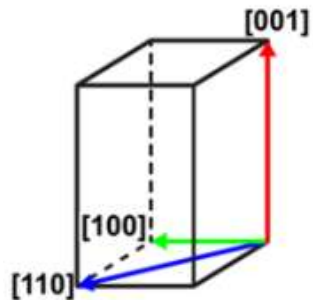


- Porosity in form of bubbles in Bi-2212 agglomerates in the melt state
- Bubbles are major current blocker in a powder-in-tube multifilamentary wires
- Densifying Bi-2212 wires by overpressure heat treatment enhance connectivity, which is controlling critical current density

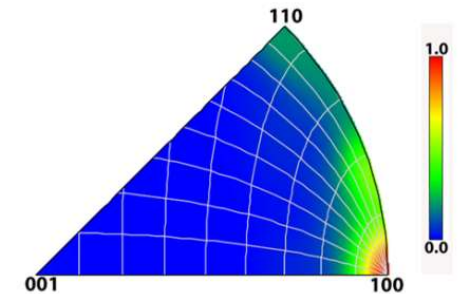
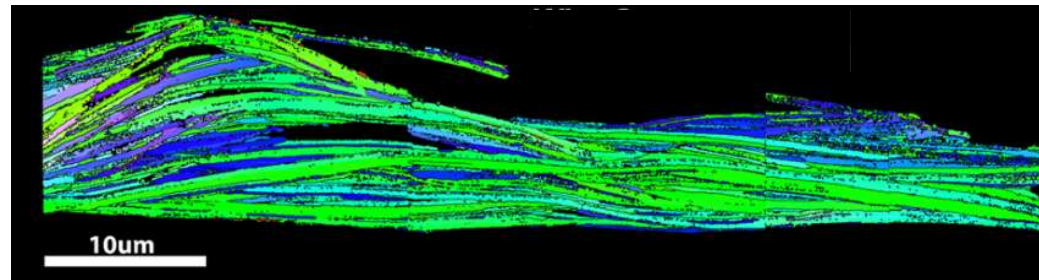
Bruker OST LLC wire

# Critical current in Bi-2212 depends on grain boundary cleanness

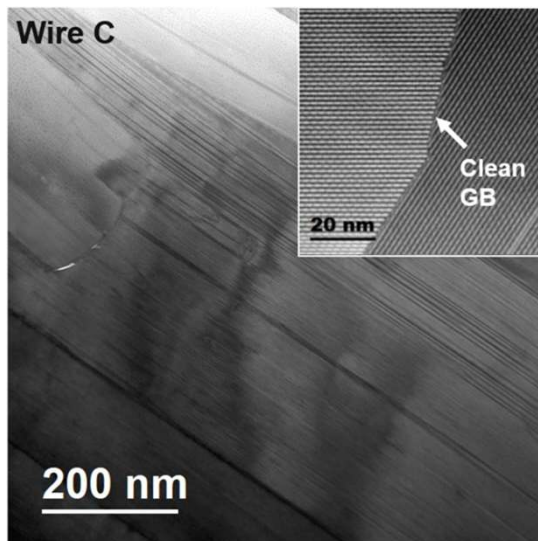
Bi-2212 unit cell



EBSD-OIM on the longitudinal cross-section



TEM image of grain boundary



- Grain boundaries disconnected by amorphous layers is a central cause of low critical current
- Clean grain boundaries are the primary factor for high critical current density
- Critical current density depends on quasi-biaxial texture within a small, not merged filament in Bi-2212
- Achieving the best wire performance is challenging because of the narrow heat treatment window, efforts to increase it are ongoing.

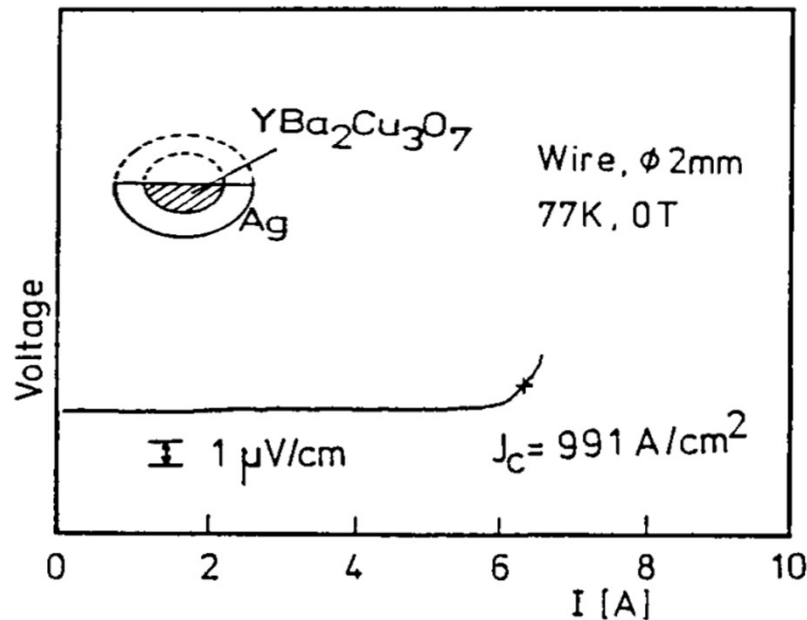
T A Oloye et al 2021 Supercond. Sci. Technol. 34 035018

Bruker OST LLC wire

Chiara Tarantini et al 2024 Supercond. Sci. Technol. 37 015021

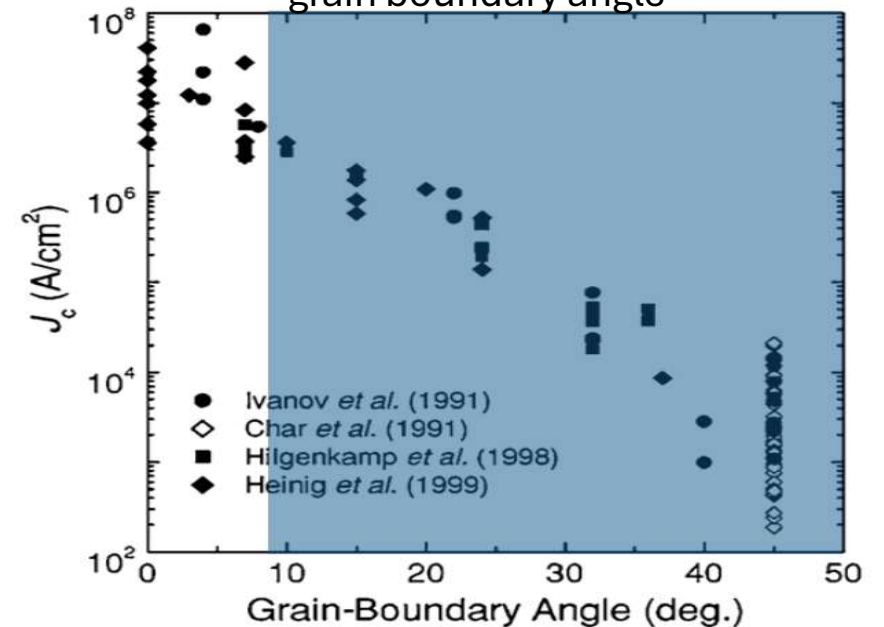
# Critical current in ReBCO depends on grain boundaries alignment

Critical current of the ReBCO round wire



Rene Flukiger et al, Physica C 153-155 (1988) 1574-1579

Critical current density as a function of the grain boundary angle

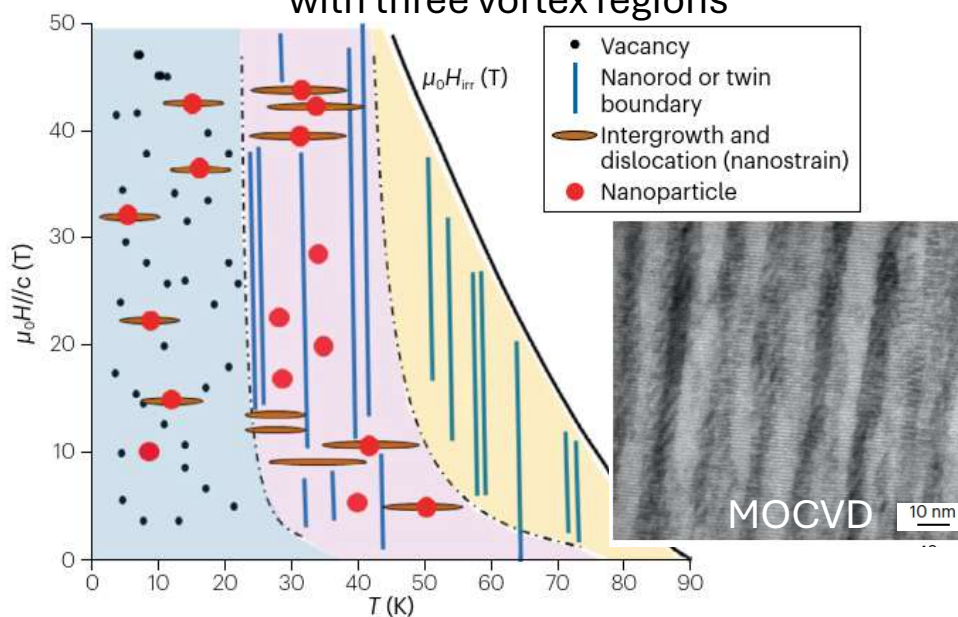


Hilgenkamp and Mannhart, RMP 74 (2002) 485

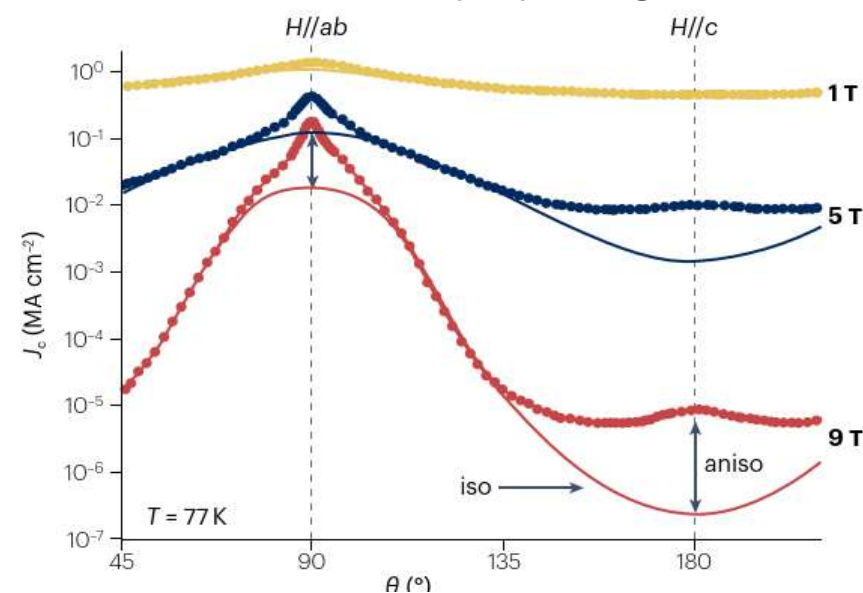
- For angles above 8-10 degrees, the  $J_c^{GB}$  is reduced by a factor >100!!!
- In order to get high  $J_c$  in the conductor, the c-axis texturing is not enough
- We do need also texturing in the ab plane = produce a km- length single crystal

# Critical current in ReBCO depends on pinning landscape

The magnetic field–temperature diagram ( $\mu_0 H // c$ ) with three vortex regions



Angular dependence of the  $J_c$  with isotropic and anisotropic pinning



- Each growth method uses specific process parameters resulting in different pinning
- Different shapes of pinning; point linear, planar and spherical defects serving at different temperature
- Pinning influencing nanostructures differ between films grown by parallel methods, but result in similar performance

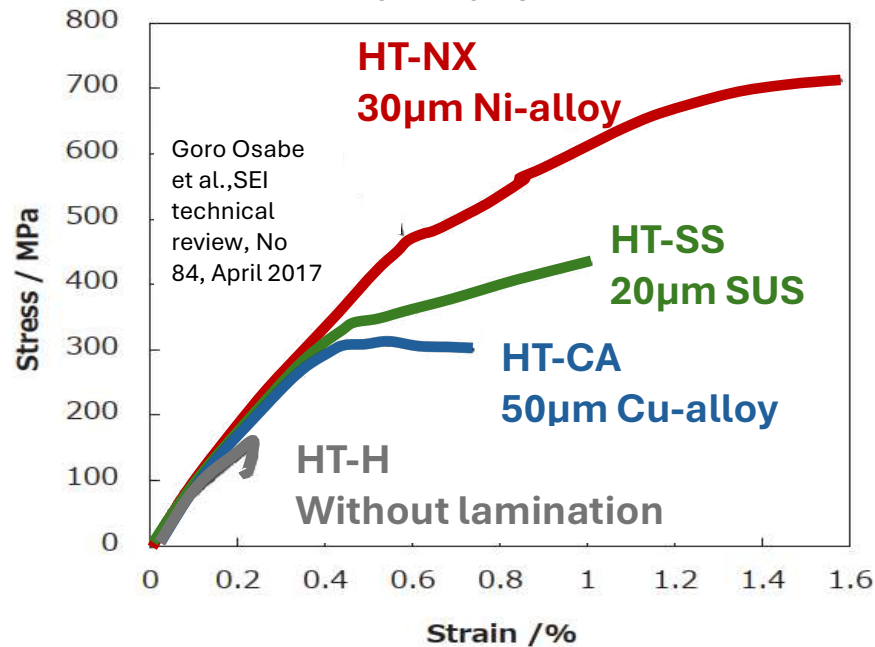
## Mechanical properties

- Lamination of Bi-2223
- Bi-2212
- Deposition stresses in ReBCO
- Complexity of ReBCO; tensile, transverse delamination, shear and fatigue

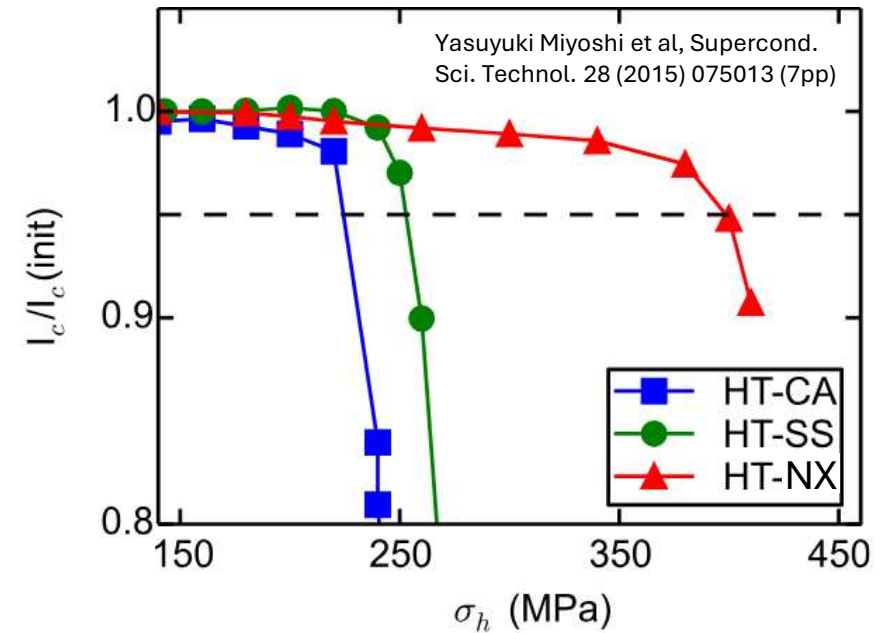


# Mechanical properties of Bi-2223 tape

Stress strain for Bi-2223 tapes with different lamination

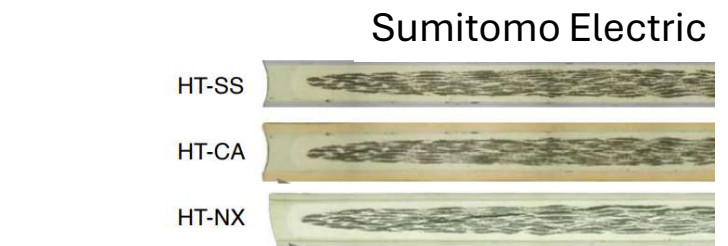


Normalized critical current as a function of hoop stress



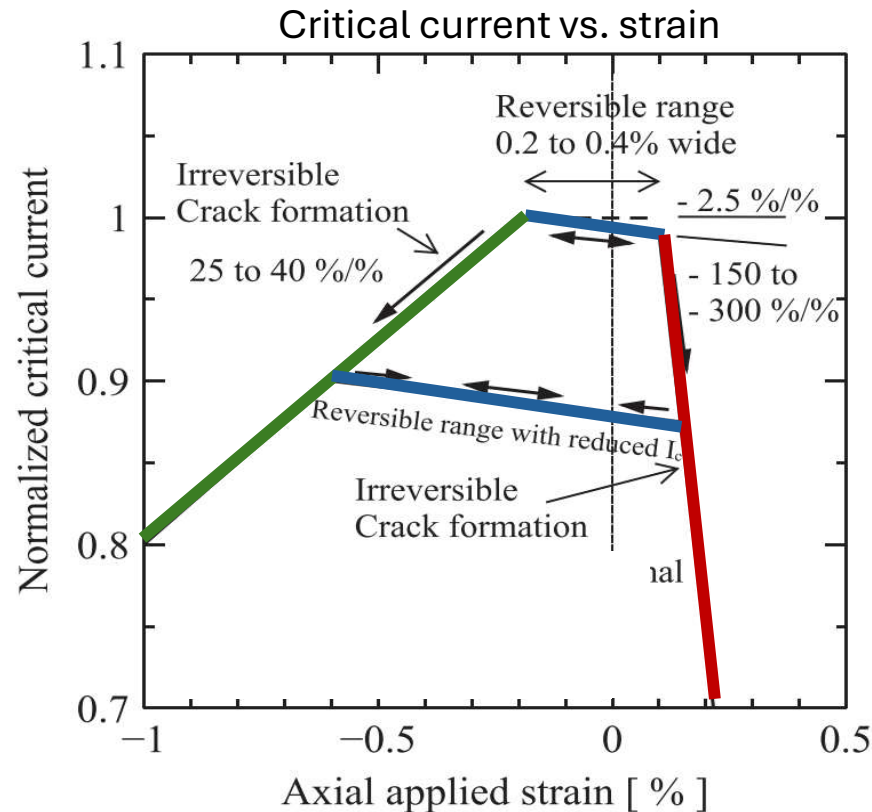
- Sumitomo Electric developed the extra high strength Type HT-NX tape, which achieves a critical tensile strength of 400 MPa at 77 K
- Degradations occur in the range of 400–420 MPa applied hoop stress
- In the next generation DI-BSCCO tapes the critical tensile stress reach 500 MPa at 77 K

Takayoshi Nakashima et al., IEEE, TAS, Vol. 25, No. 3, June 2015

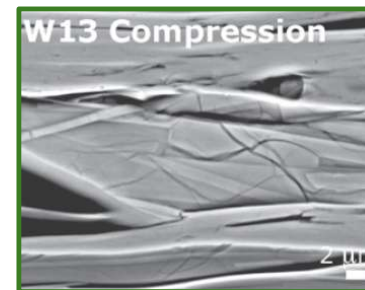
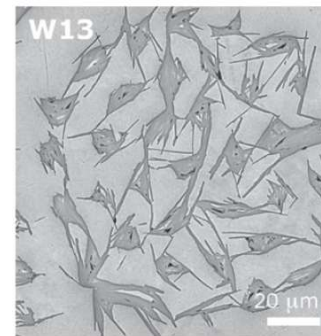


A. Godeke, Supercond. Sci. Technol. 36 (2023) 113001 (28pp)

# Mechanical properties of Bi-2212 wire



SEM images of the cross-section and longitudinal section

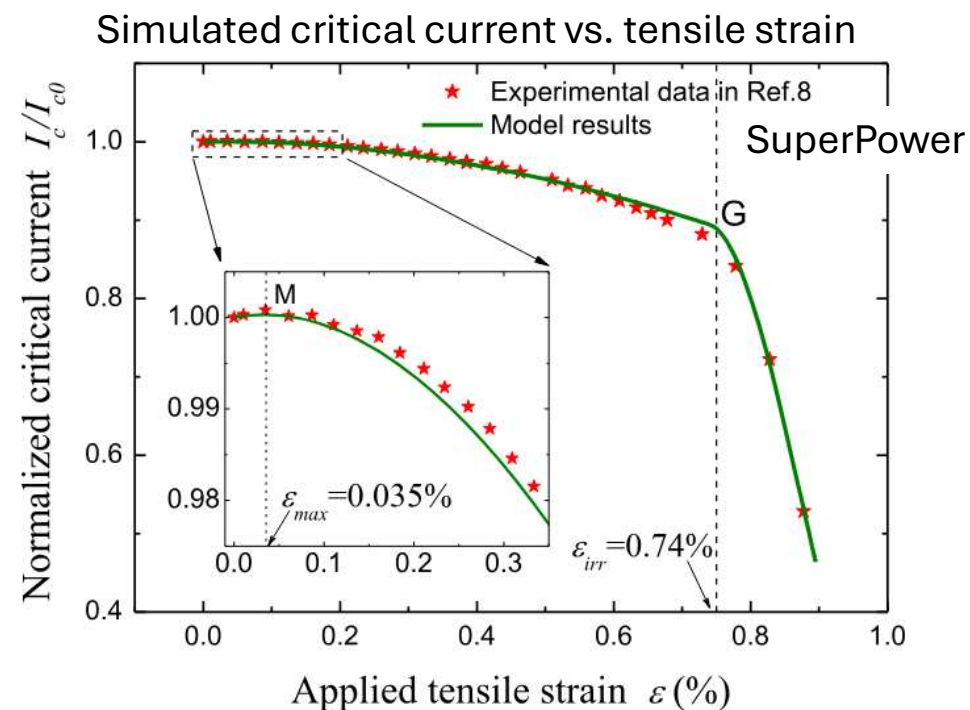
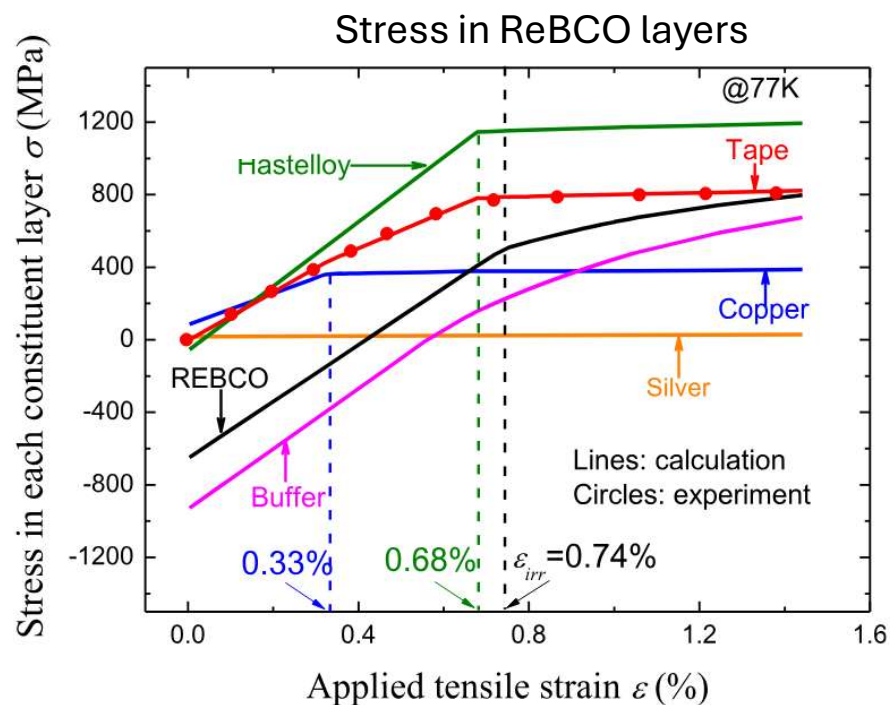


- Linear reversible range with 0.3% strain in porous wires do not improve with densification
- Critical current as function of strain is largely crack dominated
- Magnet design should compensate for the mechanical properties of Bi-2212

Bruker OST LLC wire

A Godeke et al 2015 Supercond. Sci. Technol. 28 032001

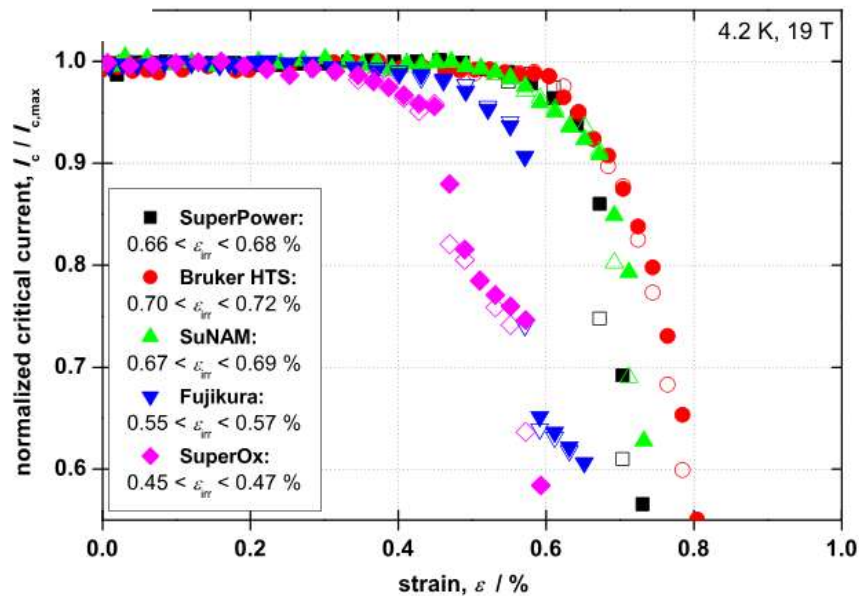
# Mechanical properties of ReBCO tape - stress in the layers



- Multilayer modeling method, taking into account all ReBCO layers, reproduce experimental data
- Non-zero thermal residual stress accumulated during fabrication and cooling exist in all the layers
- The critical current increase slightly and degrade sharply after reaching 0.74% irreversible strain

# Mechanical properties of ReBCO tape - tensile test

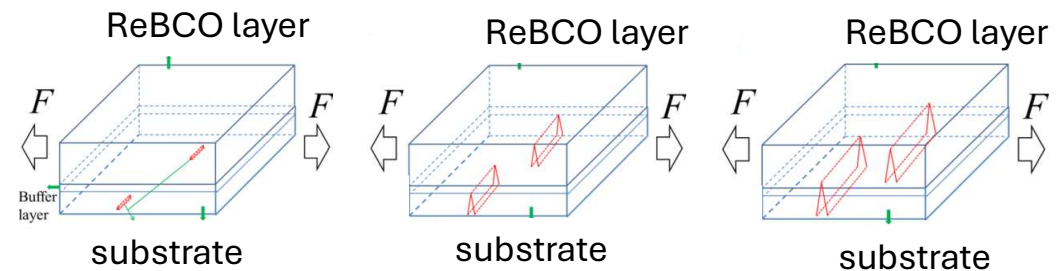
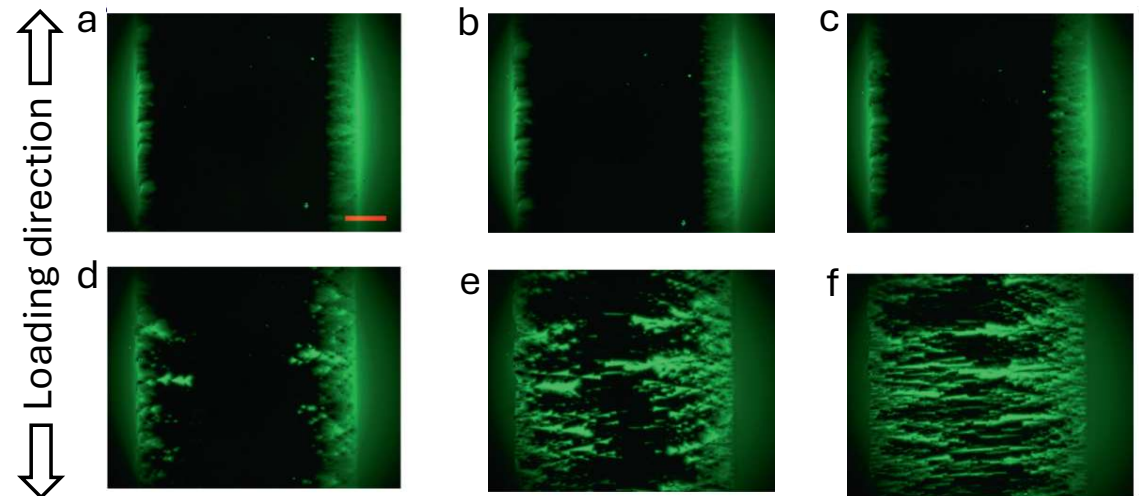
Normalized critical current vs. strain



C Barth et al 2015, Supercond. Sci. Technol. 28 045011

- Irreversible stress limits of all samples are in the 740-840 MPa range
- Degradation is caused by crack propagation with amorphous phase crack tip at level of the substrate

Magneto-Optical Imaging of ReBCO during tensile test

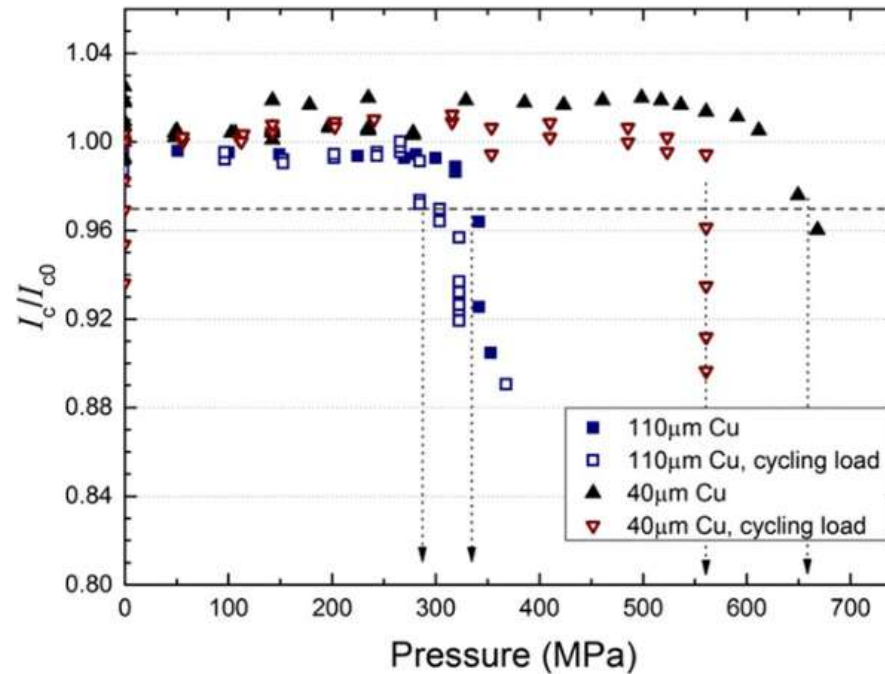


You-He Zhou et al., Nature Communications (2021), <https://doi.org/10.1038/s41467-021-23487-0>

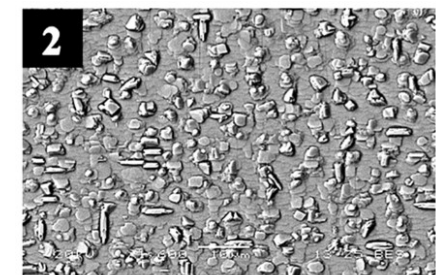
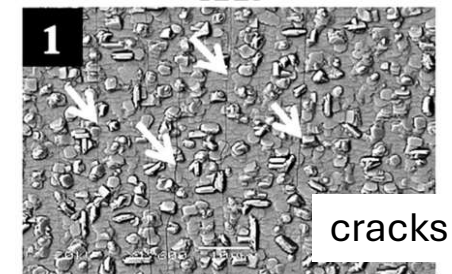
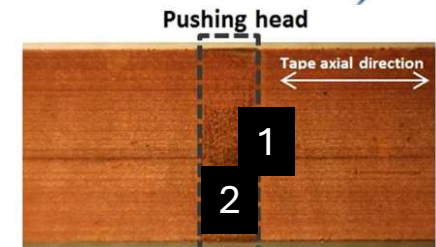
# Mechanical properties of ReBCO - transverse compressive

- Bare, flat ReBCO tape can sustain >700 MPa
- Tape is not ideally flat causing stress concentrations
- Adding soft copper is reducing the maximum pressure before degradation
- Transverse pressure is 550-650 MPa with 40  $\mu\text{m}$  copper thickness
- Only 300 MPa with 110  $\mu\text{m}$  copper thickness
- Cracks are visible at the edge of pressure area

Normalized critical current as a function of transverse load

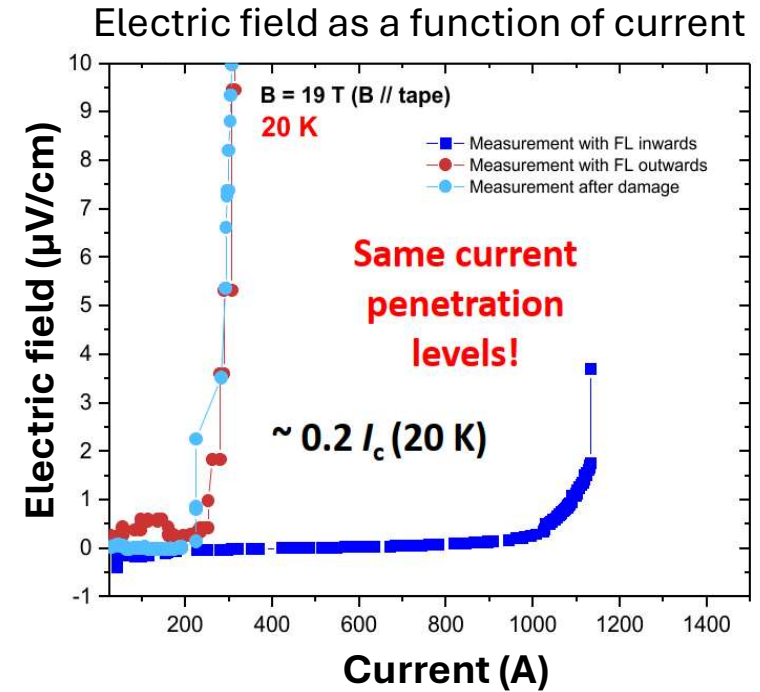
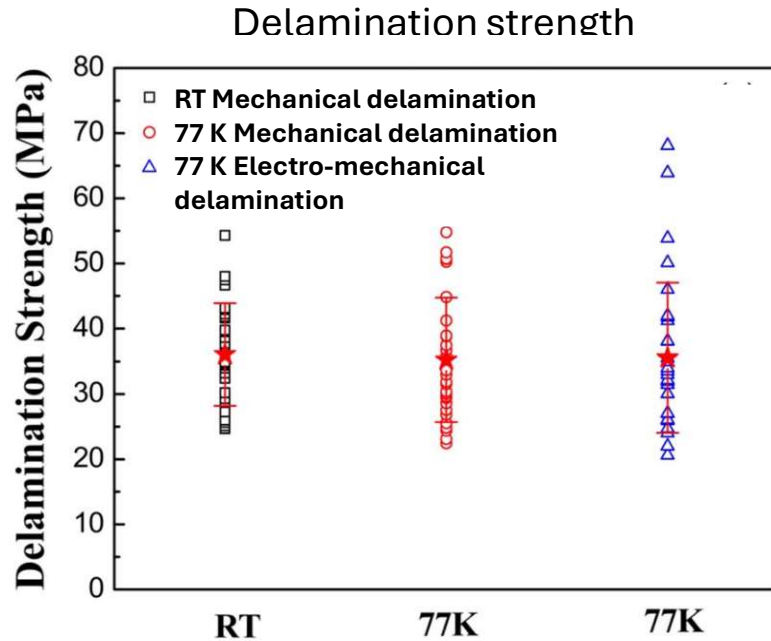


K Il'in et al 2015 Supercond. Sci. Technol. 28 055006

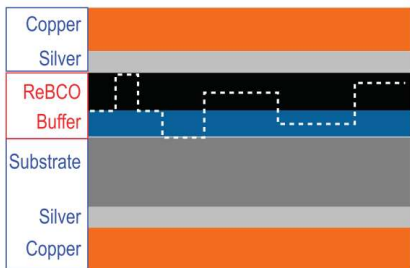


Microstructure observation after experiment, optical microscope with copper, SEM after etching

# Mechanical properties of ReBCO - delamination



Celia Lucas et al 2025  
Magnet Technology  
2025, Boston, USA



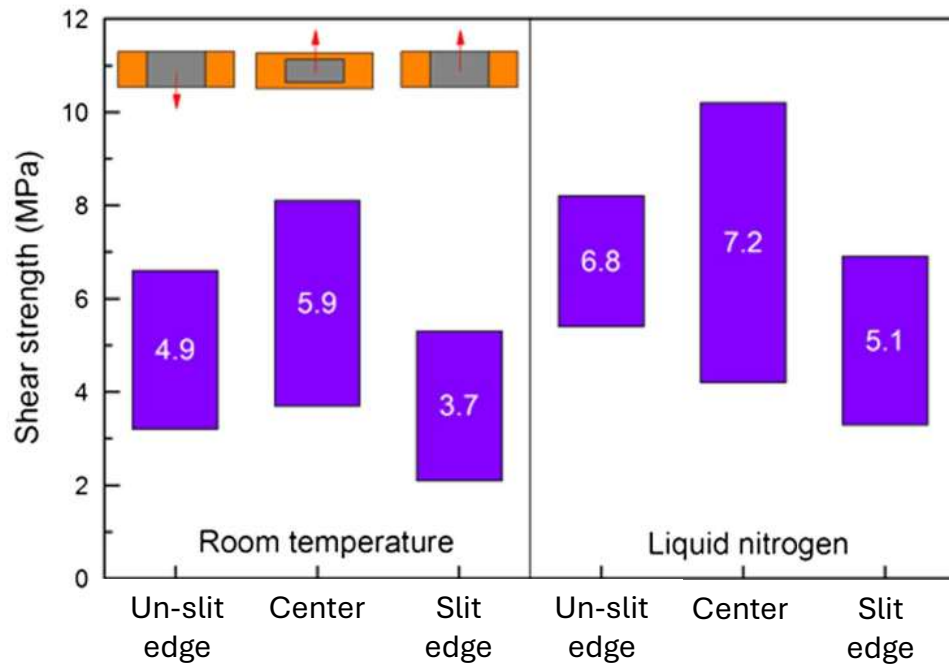
A schematic zigzag of delamination

Hyung-Seop Shin and Alking Gorospe 2014 Supercond. Sci. Technol. 27 025001

- Local tensile force in transverse direction leads to delamination and loss of critical current
- Delamination strength is between 5- 50 MPa depending on tape type, slitting edge or not and temperature

# Mechanical properties of ReBCO - shear

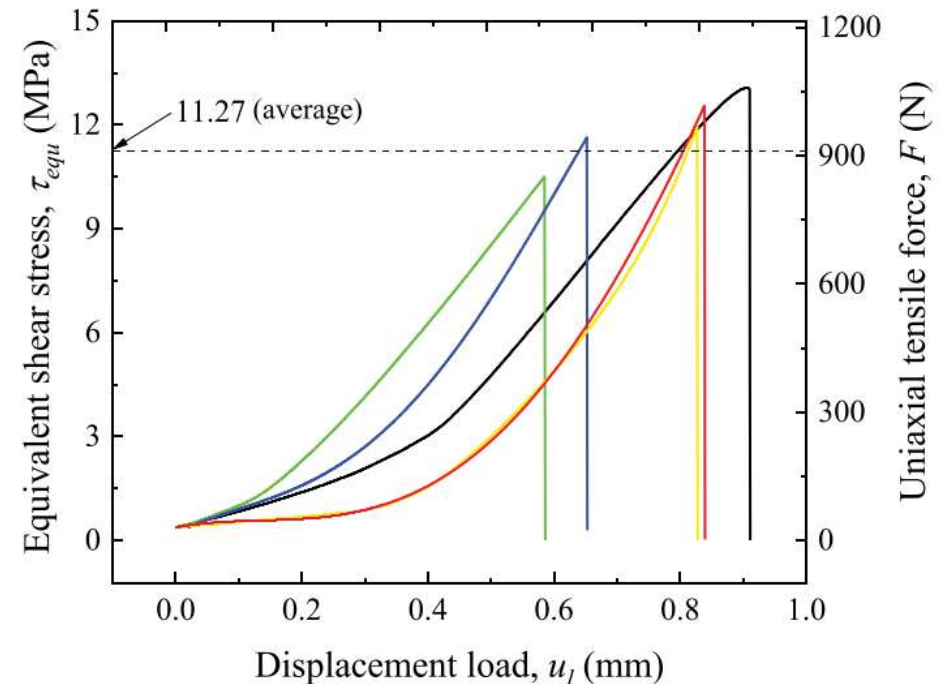
Shear strength for different tape area



- The averaged shear strength for the center of the tape is the highest, and the slit edge shows the lowest value

Liyuan Liu et al., IEEE, TAS, Vol. 26, No. 6, Sep. 2016

Shear stress as a function of displacement



- Delamination under shear load was the fracture within REBCO superconducting film, and a small portion of the buffer layers were peeled off

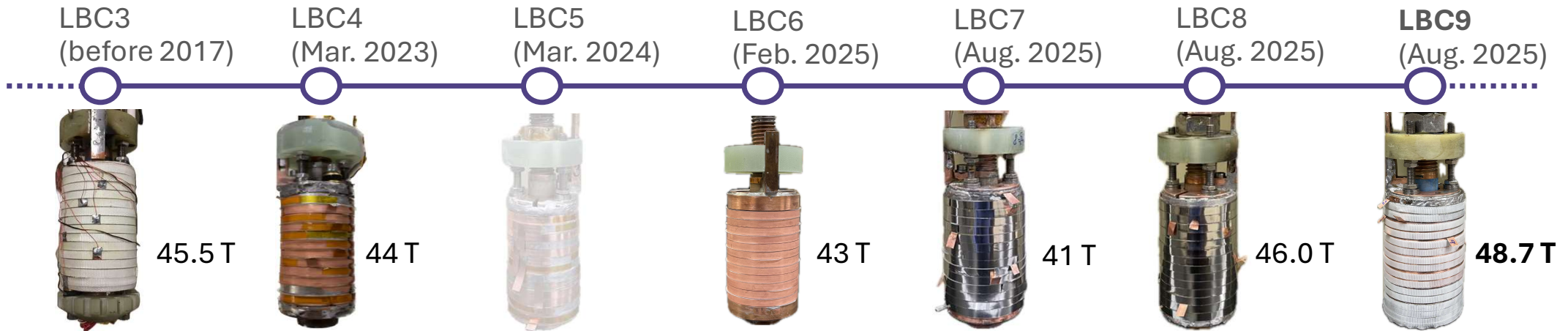
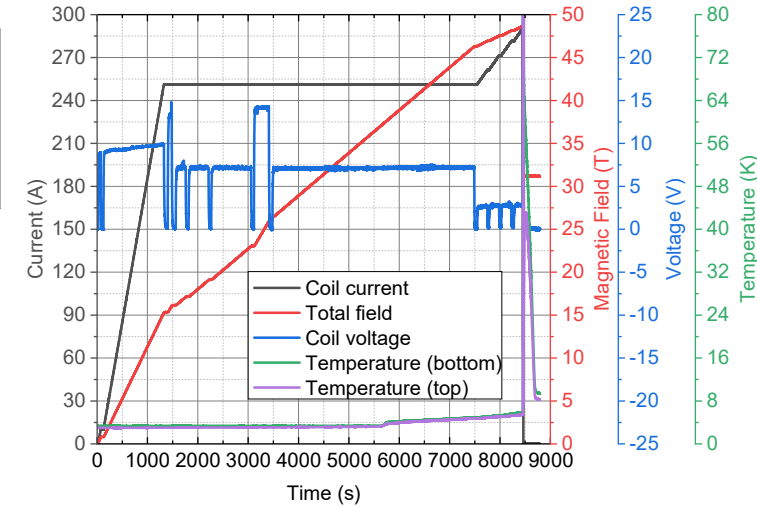
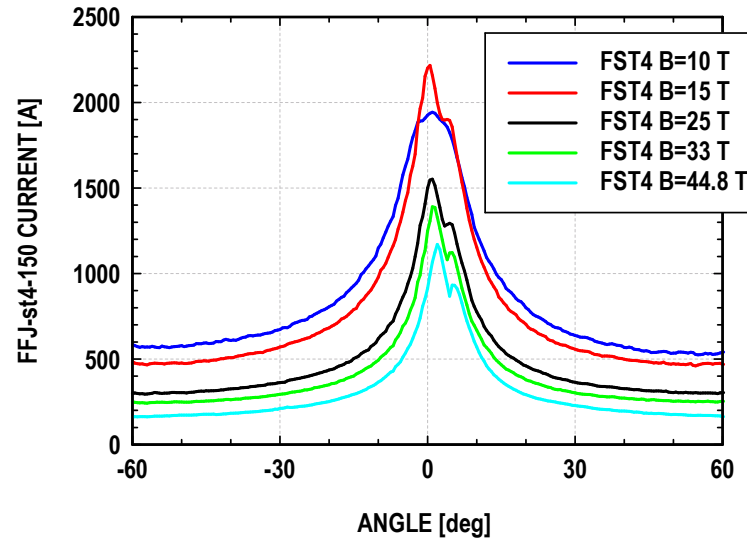
Peifeng Gao et al, IEEE, TAS, Vol. 32, No. 4, June 2022

# Electro-mechanical properties of ReBCO - LBC

## Little Big Coil 9

- Reached 48.7 T magnetic field in the center
- The quench at peak field, 290 A coil current, initiated by some dissipation at the outer joints
- Damage on outer joints due to screening current stress

Courtesy of: Jan Jaroszynski, Rastislav Ries, Jeseok Bang, David Labalastier



## Stability

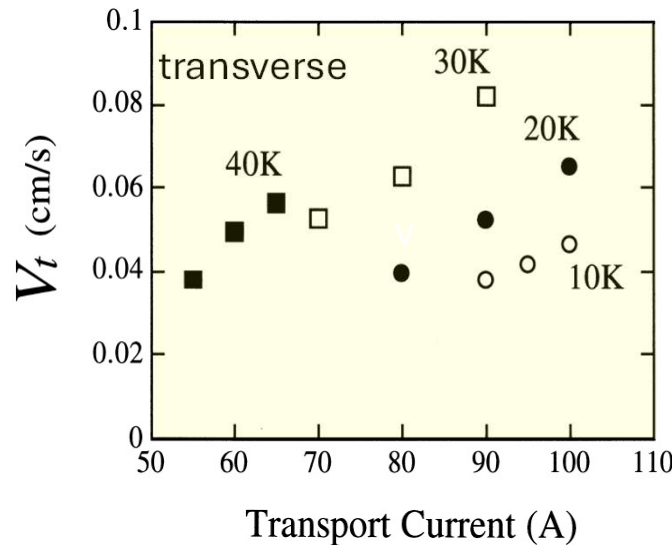
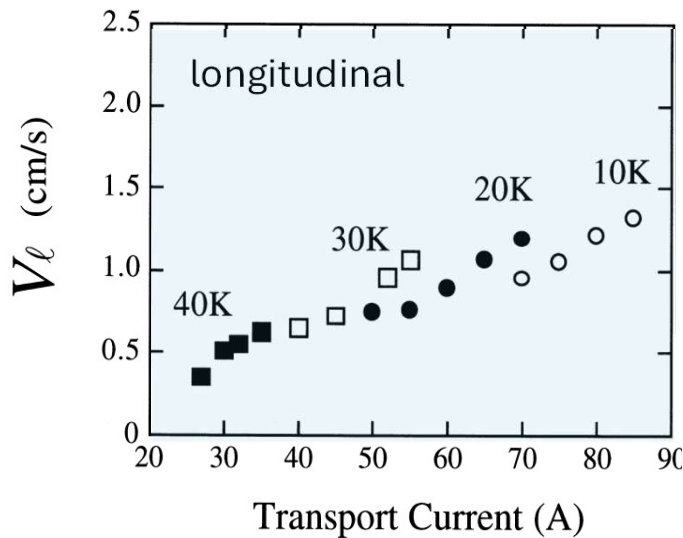
normal zone propagation  
minimum quench energy

- **Bi-2223**
- **Bi-2212**
- **ReBCO**

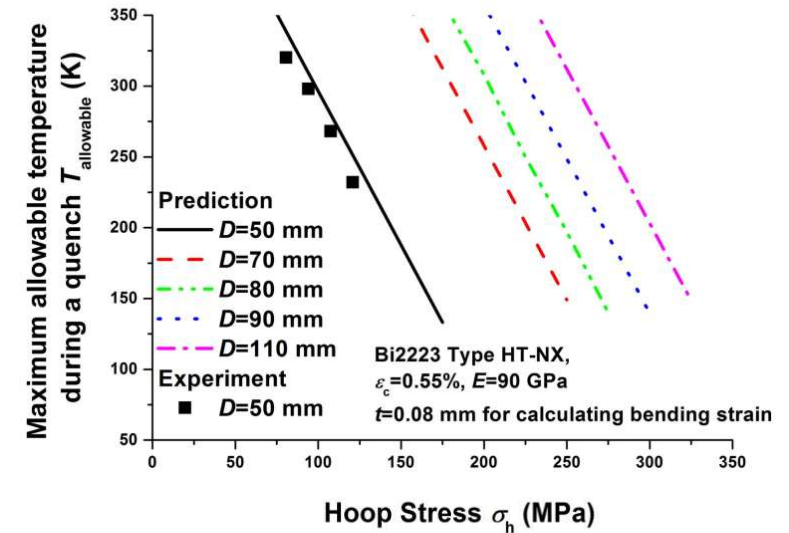


# Stability of Bi-2223 tapes

Normal zone propagation velocity



Maximum temperature vs. hoop stress



- The normal zone propagation velocity in the longitudinal direction is 0.5–2.0 cm/s
- The transverse direction velocity is 0.02–0.08 cm/s, which is 1–2 orders slower than longitudinal velocity

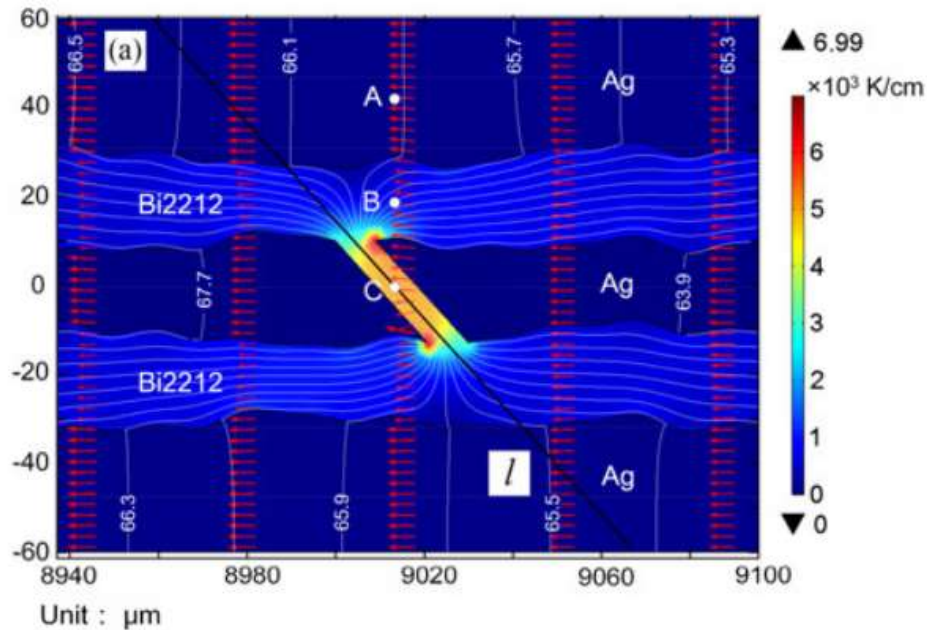
- Experimental results can be predicted using a simple strain analysis
- The conductor degrades permanently above allowable temperature

S.B. Kim et al., Cryogenics 38 (1998) 823–831

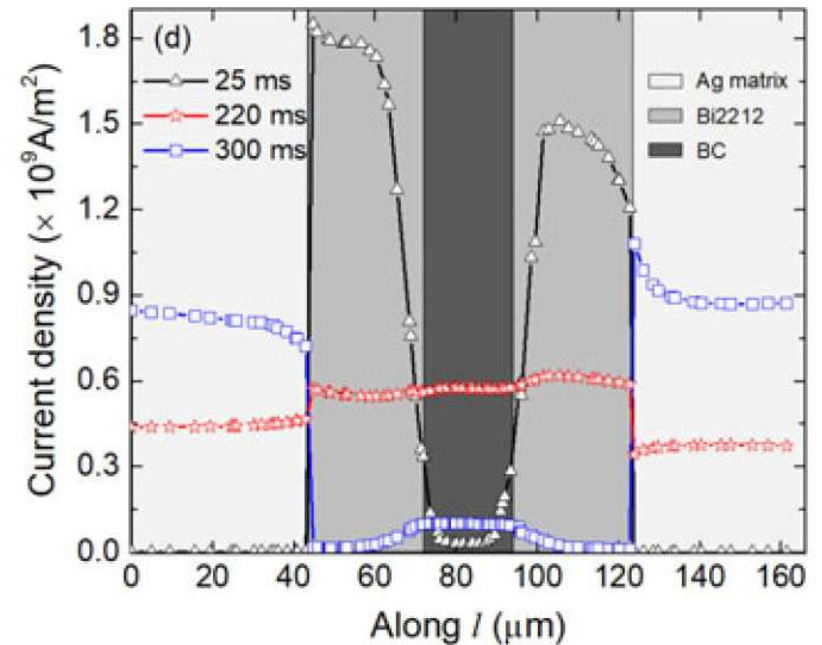
Tengming Shen et al 2018 Supercond. Sci. Technol. 31 015012

# Stability of Bi-2212 wire

Longitudinal section with bridge connection between two filaments

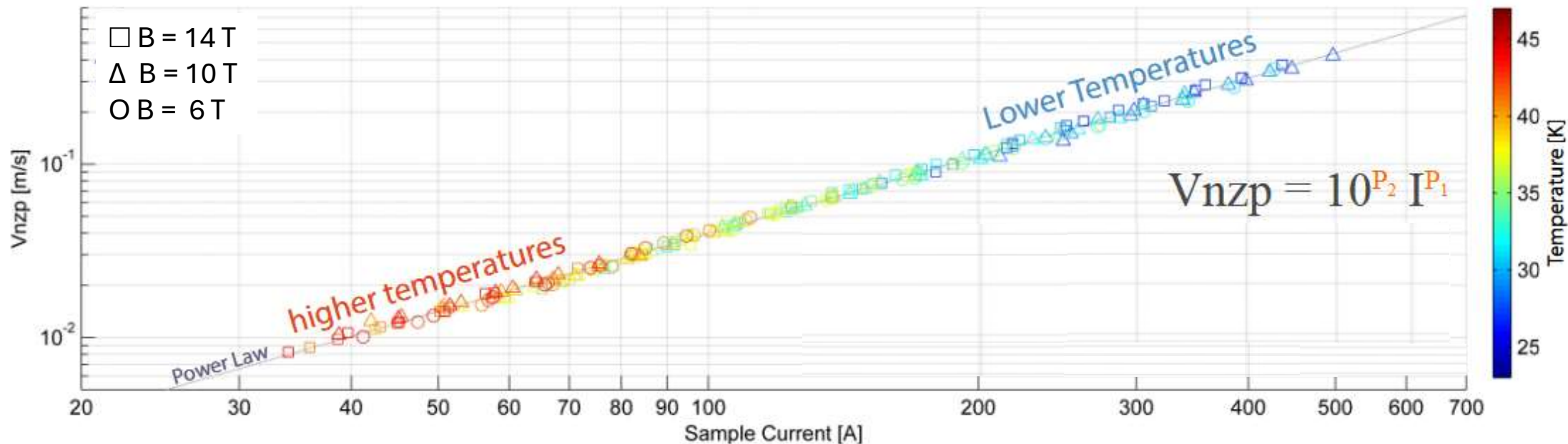


Current density distribution in an Ag matrix, Bi-2212 filaments and bridge connection



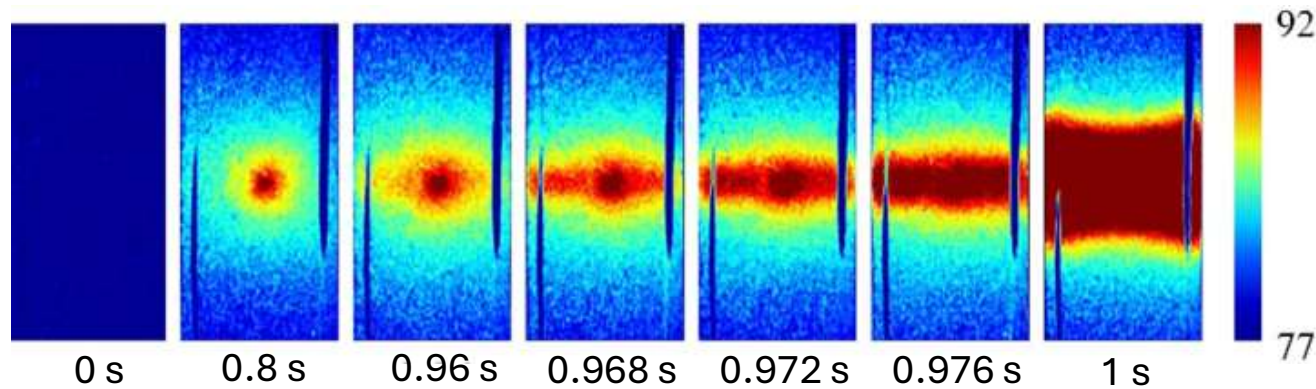
- Impact of the complex microstructure especially the bridge connection in the local region is very important
- The temperature gradient at the bridge connection sharply rises, results in inhomogeneous distribution of the thermal stress, as well as thermal and/or mechanical failure initiated at the local region

# Normal Zone Propagation Velocity of ReBCO tape



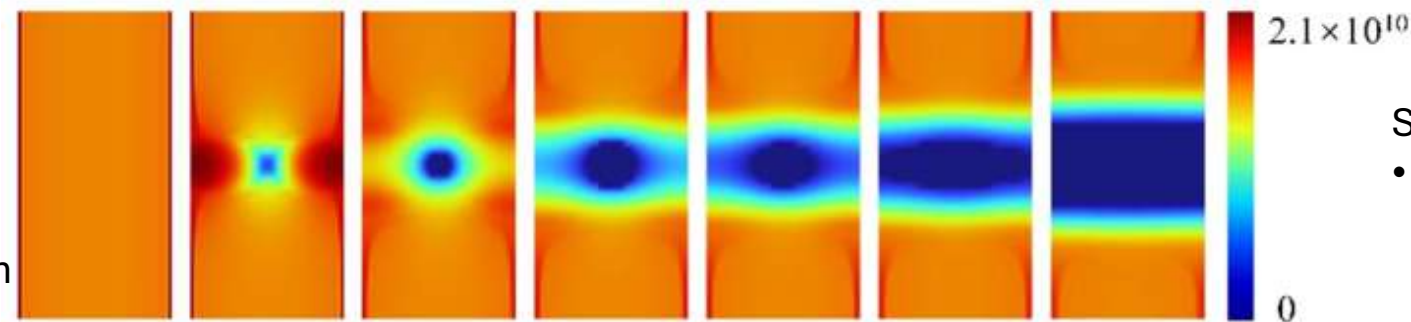
- Normal zone propagation velocity at all measured magnetic fields 6, 10 and 14 T and temperatures 23 to 47 K seems to depend only on the current through a simple power law relation
- Differences between model and measurements are caused by the inability to compensate correctly for the efficiency of the heater, which is unknown because the thermal resistance of the boundary between the heater and the tape is difficult to determine

# Quench propagation of ReBCO tape



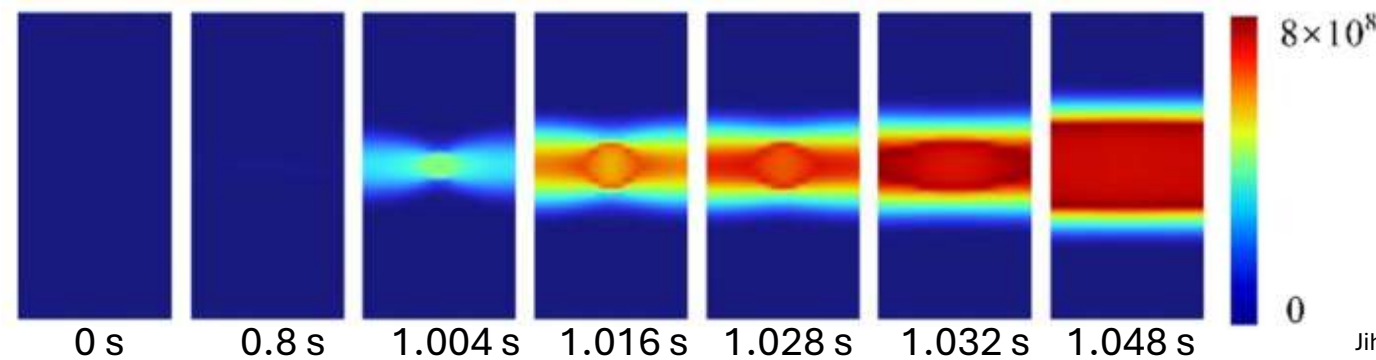
## Experimental results

- The surface temperature of the tape when a pulse heat source is applied at its center, with energy levels of 175 mJ



## Simulations

- Current density in the superconducting layer ( $A/m^2$ )

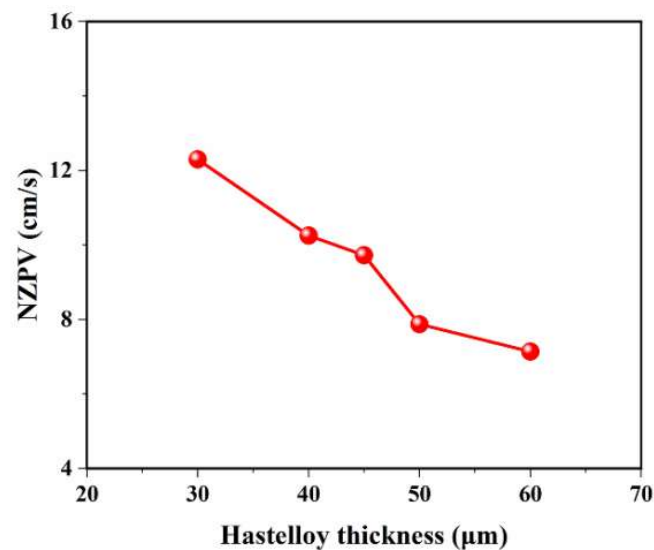
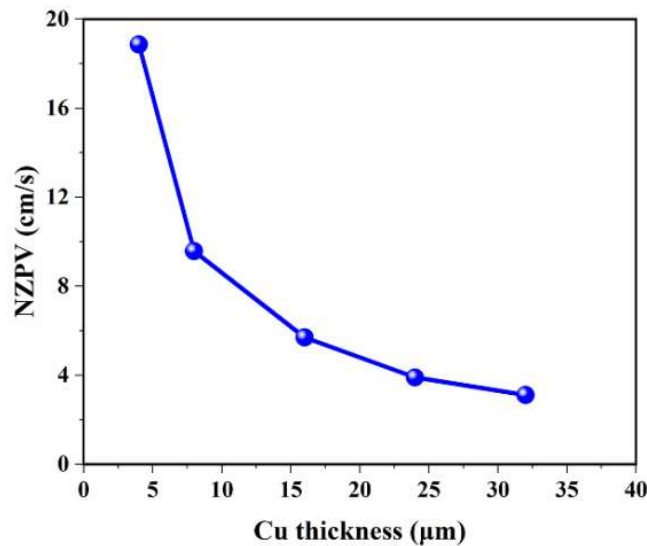


## Simulations

- Current density in the top copper layer ( $A/m^2$ )

# ReBCO – stability versus metal thickness

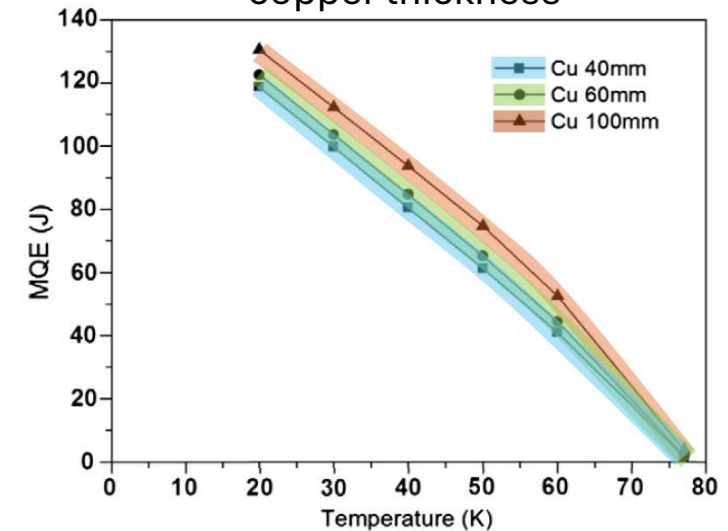
Normal zone propagation velocity as a function of copper and Hastelloy thickness



- Effect of copper layer and Hastelloy layer thickness on the NZPV
- The NZPV decreases as the copper layer thickness increase
- The NZPV decreases with increasing Hastelloy thickness

Jihua Deng et al 2025 Supercond. Sci. Technol. 38 055026

Minimum Quench Energy vs. copper thickness

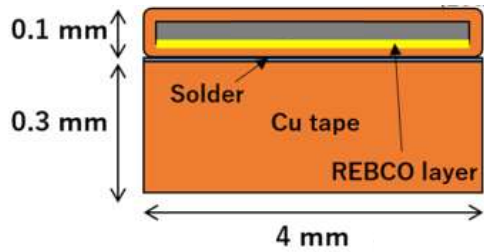


- MQE become large with decreasing operating temperature
- MQE decrease with decreasing copper thickness

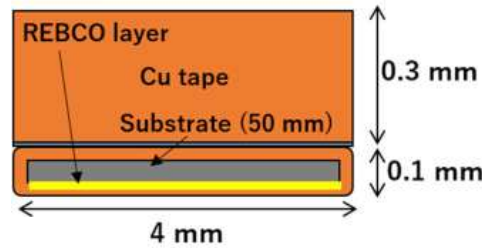
J.H. Bae et al., Physica C 470 (2010) 1880–1882

# ReBCO – NZPV increase

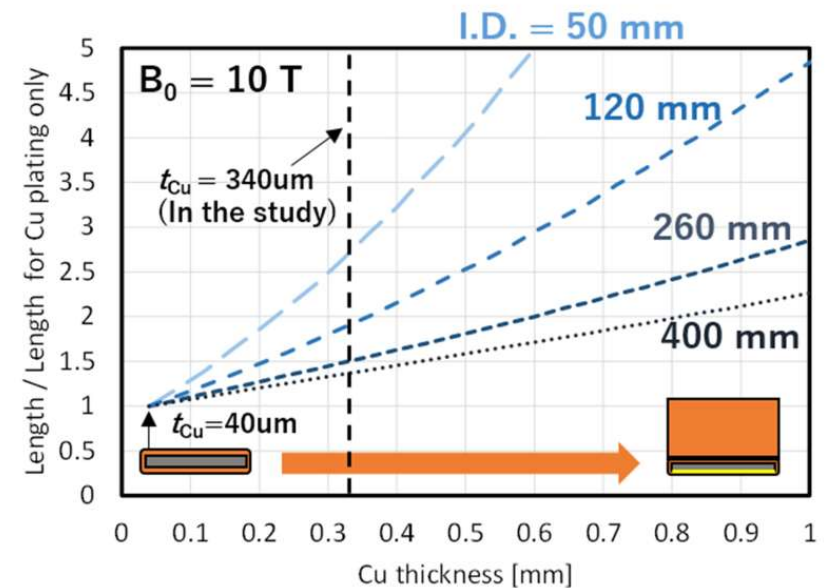
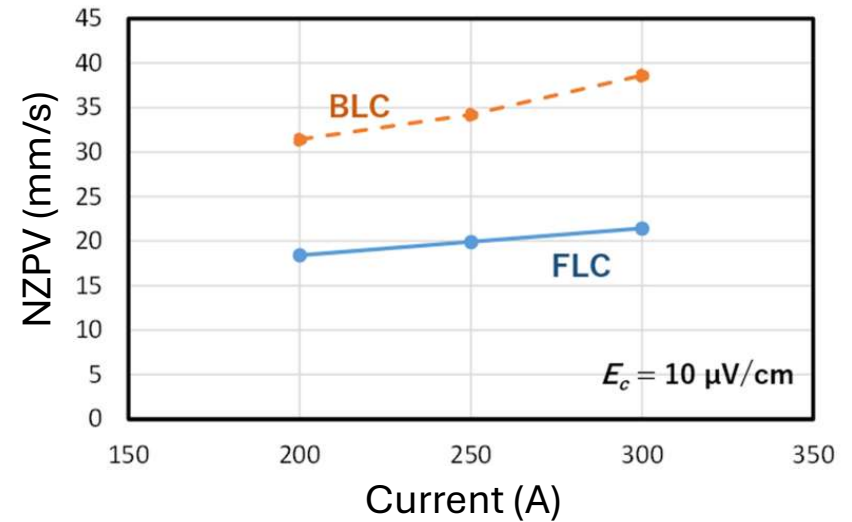
**Front side Laminated Conductor (FLC)**



**Back side Laminated Conductor (BLC)**



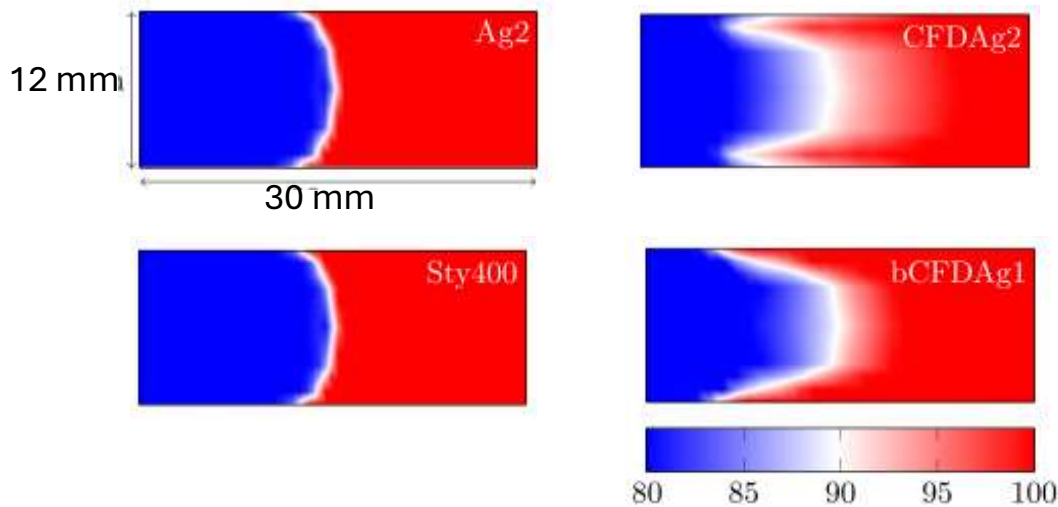
- The hotspot temperature was suppressed in both conductors regardless of the lamination on the front or back side
- We found that the NZPV of the back side (BLC) is faster which is beneficial for a quench protection
- The conductor with stabilisation was optimised for the conductor length and magnet needs



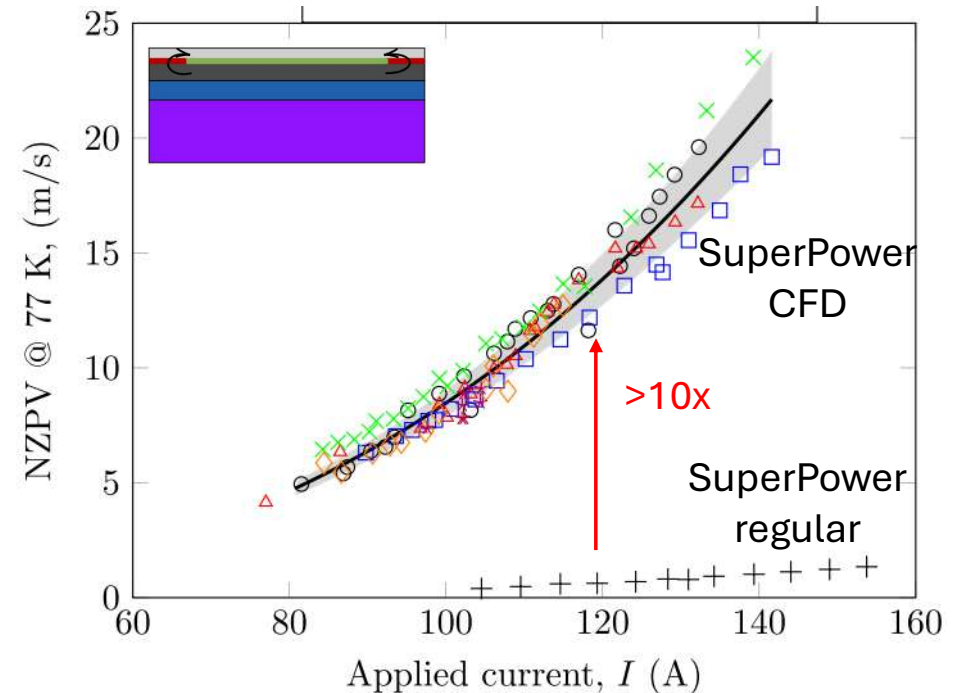
Shogo Muto et al., IEEE, TAS, Vol. 32, No. 6, September 2022

# ReBCO – Current Flow Diverter

Temperature in the ReBCO layer during normal zone propagation at 77 K



Reel-to-reel tape with current flow diverter



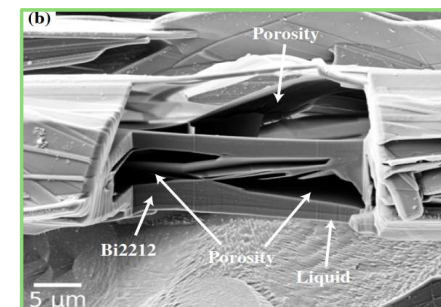
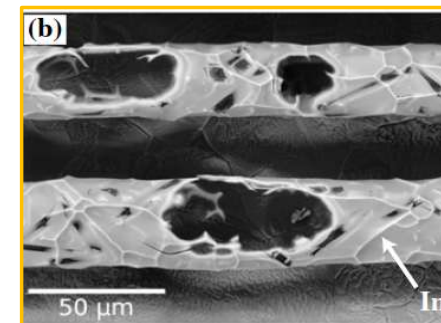
- ReBCO tape with a thin stabilizer, its high electrical resistance, low heat capacity and large  $\lambda d$  will lead to a large NZPV value
- Guide for tape manufacturers to consider different tape architectures when quench dynamics is a key issue

# Conclusions and Outlook

- Critical current is important, but for magnet design and manufacturing the predictable and consistent critical current work the best
- Please, limit work on increasing critical current of the tapes!
- Work on yield and consistent product from current, geometry, mechanical properties and stability point of view

## High Temperature Superconductors Cooking

- Bi-2223 tapes - reacted product, but not available now as commercial product
- Bi-2212 wires - increasing time of high temperature plateau needed, to make the coils heat treatment possible to realize
- ReBCO tapes - already reacted product, what do we need more!



# Conclusions and Outlook

## Mechanical properties

- Bi-2223 tapes - lamination of NX
- Bi-2212 wires - need to be compensated at magnet level
- ReBCO tapes - delamination, peel, shear

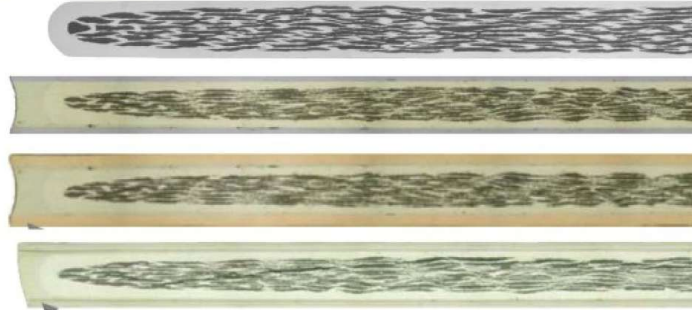
Sumitomo Electric

H & G

HT-SS

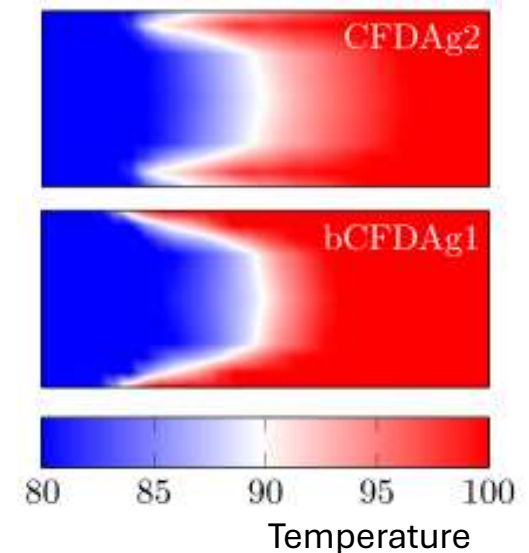
HT-CA

HT-NX



## Quench / stability

- Bi-2223 tapes - anisotropic quench propagation
- Bi-2212 wires - complexity due to interlinked filaments
- ReBCO tapes - playing with stabilizer and current flow diverter increase normal zone propagation velocity
- ReBCO tapes - non insulated coils solve the stability problem only for some applications (temperature, field)



# Conclusions and Outlook

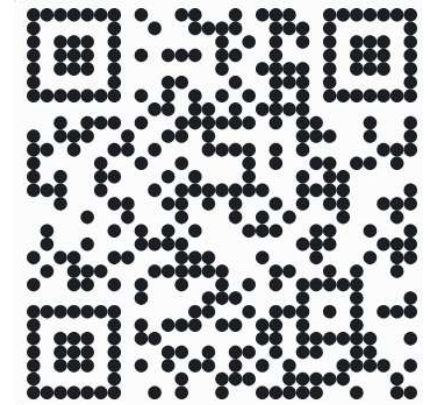
- Bi-2223 tapes - transferred to China, lets cross fingers for comparable to Sumitomo product soon
- Bi-2212 wires - expanding, companies in Asia are planning to sell wires commercially
- ReBCO tapes - lets fusion to progress and succeed, that other applications can profit from ReBCO tapes in the future



- In the meantime, lets work together, connecting experiments and simulations, work in collaboration with companies and with each other.

# Will you choose Bi-2212 or ReBCO material and why, when building an experimental magnet?

- A) Bi-2223, if it would be available commercially
- B) Bi-2212, because it is wind and react type of conductor
- C) Bi-2212 as it is round wire in kilometer length
- D) Bi-2212 as it is quasi multifilamentary wire with isotropic properties
- E) ReBCO, because it is reacted and wind type of tape
- F) ReBCO as it is mechanically strong material, beside delamination
- G) ReBCO as it is high critical current density compromised with challenges as anisotropy, aspect ratio and non-uniformities



<https://pe.app/a/questions/933328546>

# Will you choose Bi-2212 or ReBCO material and why, when building an experimental magnet?

Active

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