

# Multi-faceted assessment of structural correlations to superconducting properties of coated conductors for high field applications

Fumitake Kametani<sup>1,3</sup>, Aixia Xu<sup>1</sup>, Yan Xin<sup>2</sup>, Cade Watson<sup>1</sup>, Jonathan Lee<sup>1</sup>, Jeseok Bang<sup>1</sup>, Jan Jaroszynski<sup>2</sup>, Dima Abraimov<sup>1</sup>, David Larbalestier<sup>1,3,4</sup>

<sup>1</sup> Applied Superconductivity Center, National High Magnetic Field Laboratory, Florida State University, FL, USA

<sup>2</sup> National High Magnetic Field Laboratory, Florida State University, FL, USA

<sup>3</sup> Department of Mechanical Engineering, FAMU-FSU College of Engineering, Florida State University, FL, USA

<sup>4</sup> Department of Materials Science & Engineering, FAMU-FSU College of Engineering, Florida State University, FL, USA



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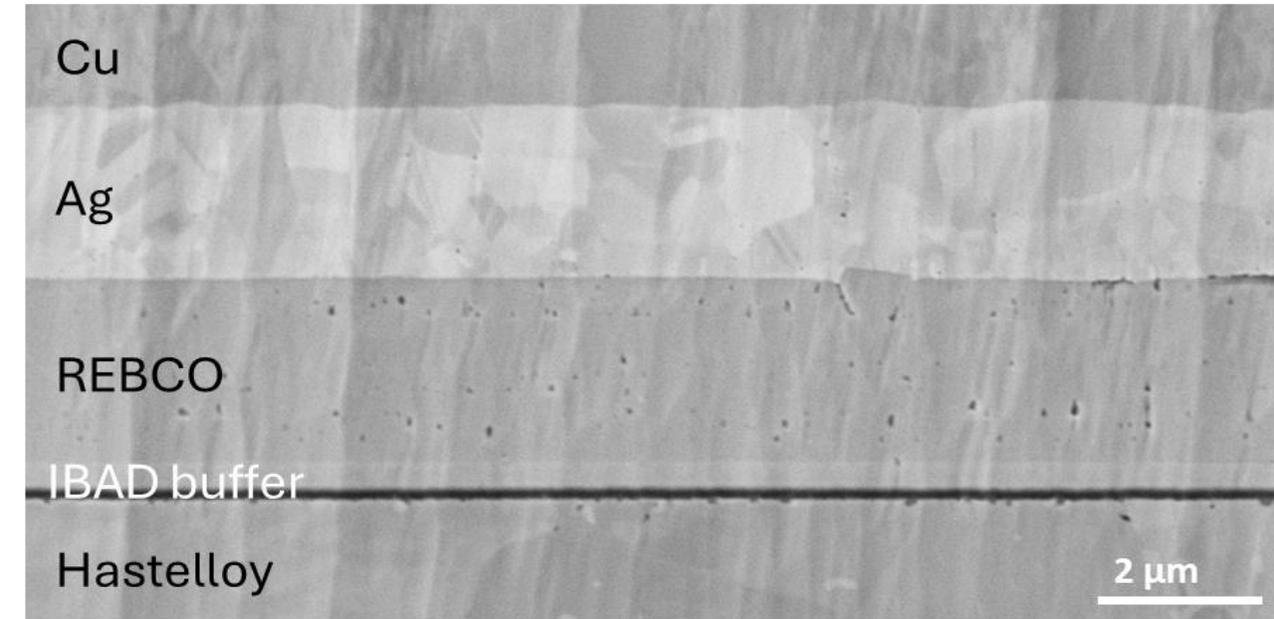
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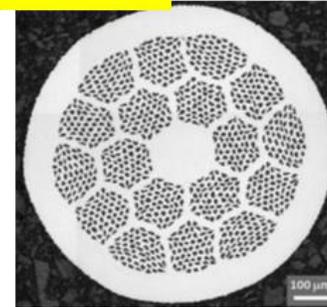
**FSU**

# Comparison of transverse cross sections of magnet conductors

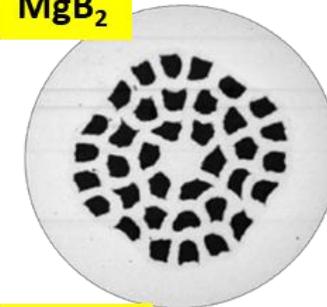
REBCO



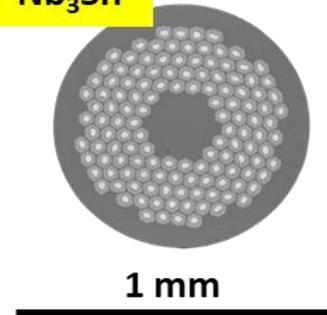
Bi-2212



MgB<sub>2</sub>



Nb<sub>3</sub>Sn

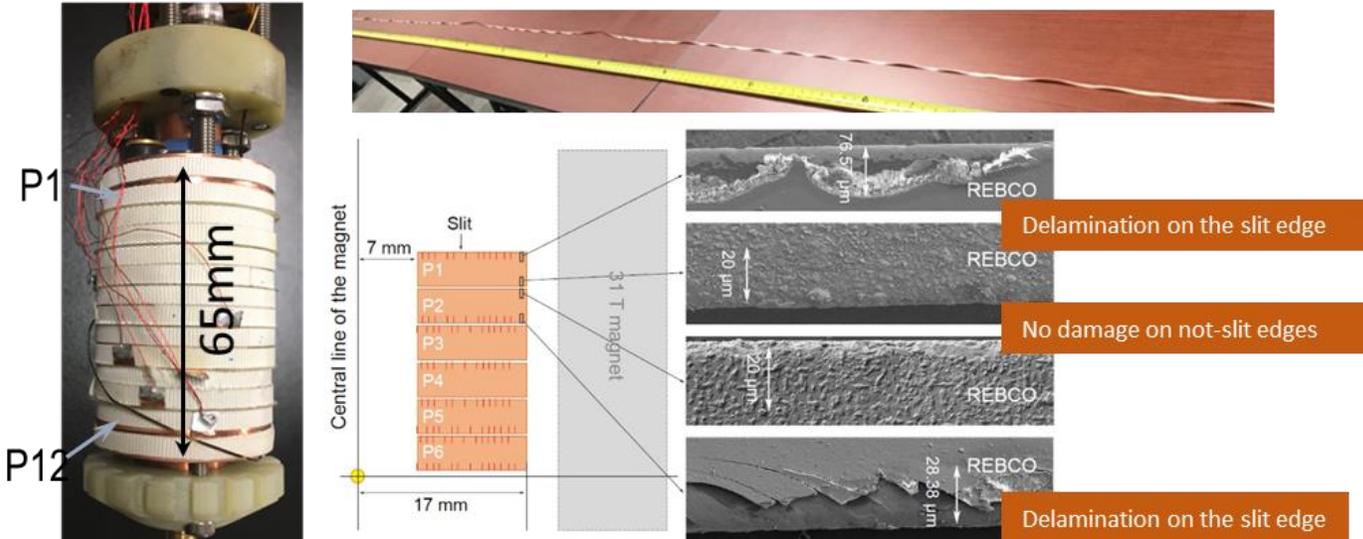


- REBCO is unique as a conductor!
  - REBCO is a nominally rectangular 4 mm (+/-? mm) wide, ~50-70 μm thick ribbon built on a strong Hastelloy
  - Soft Ag (~3 μm) and Cu (~5 μm) are then sputtered (Ag) or plated (Cu) to provide protection and stabilization
  - React-and-wind
- Bi-2212, MgB<sub>2</sub> and Nb<sub>3</sub>Sn are all round wires
  - Wind-and react: The magnet builders are responsible for final heat treatment

# REBCO challenges for becoming the true magnet-ready conductor

- REBCO coated conductors are the critical component for high field magnet technologies as extensively defined in MagSci 2024 and US Academy of Sciences 2024 Report
- The potential of REBCO as the high field conductor is clear
  - $J_e$  is sufficiently high and the conductor yield strength is high
  - 7 manufacturers globally (including the new US vendor HTSI)
- Present challenges of REBCO conductor to be fully pervasive to the magnet technology and other transformative technologies
  - **REBCO CCs is not the cartoon**
  - Need several orders of magnitude larger production
  - An order of magnitude cost reduction
- REBCO coated conductor R&D must be based on the real needs of magnet builders (pull), not from the materials science (push)
  - **Needs comprehensive property assessment of conductors**

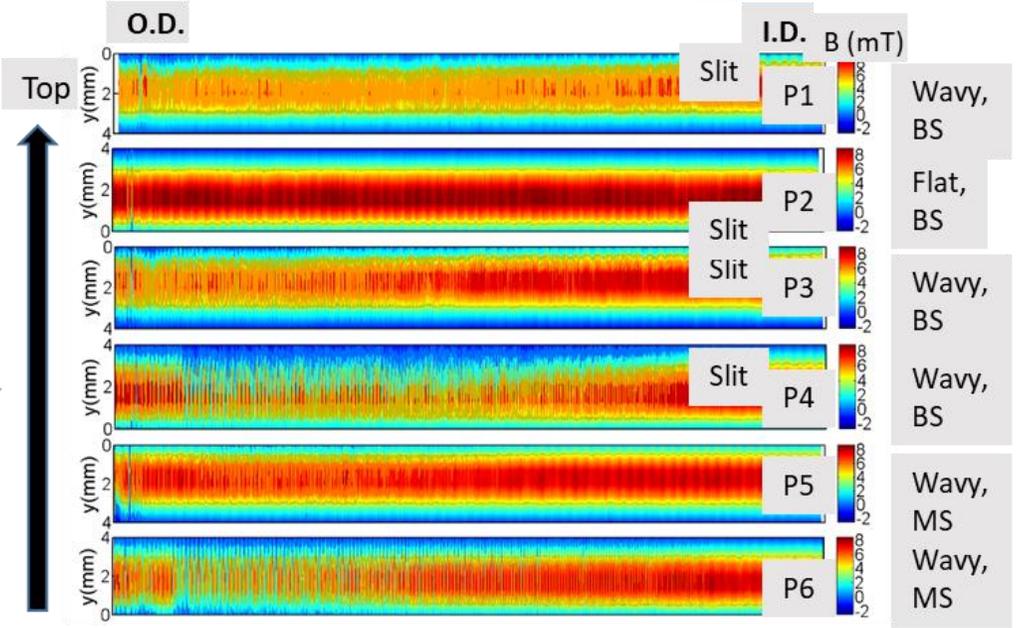
# Large conductor anisotropy of REBCO induces the unique challenges for the high field magnets



Heavy damage

No damage

Heavy damage

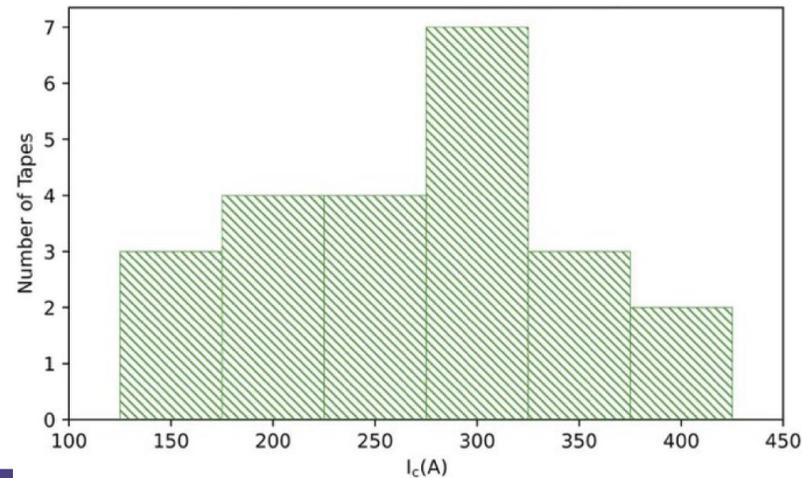
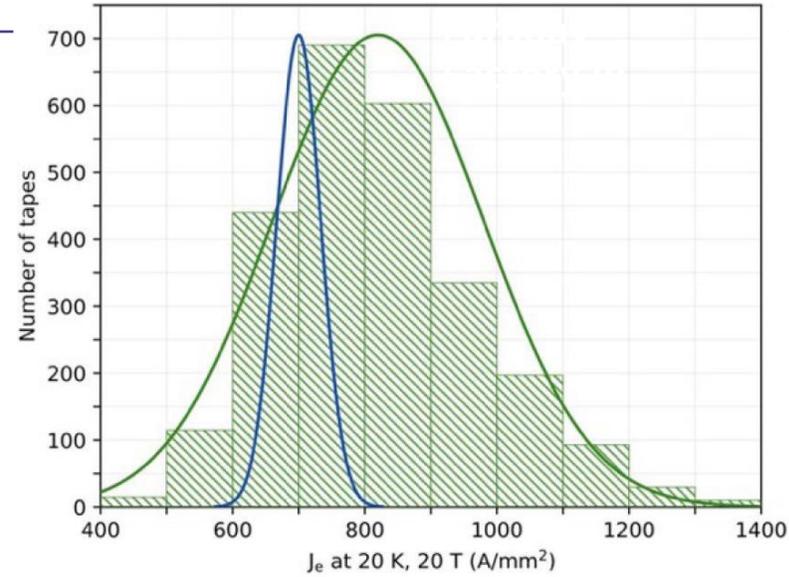


Degraded edge matches the plastically deformed edge.

- Little Big Coil 3 achieved 45.5 T total field inside the 31 T NHMFL resistive magnet.
- Evident plastic rippling was seen in several pancakes after unwinding (No damage was seen in any conductor before ramping the field).
- Large (30-50%) screening current enhanced stress values exceeding 1 GPa were calculated for the end windings that were most damaged.
- Plastic rippling was only seen in pancakes where the slit edge faced outwards.

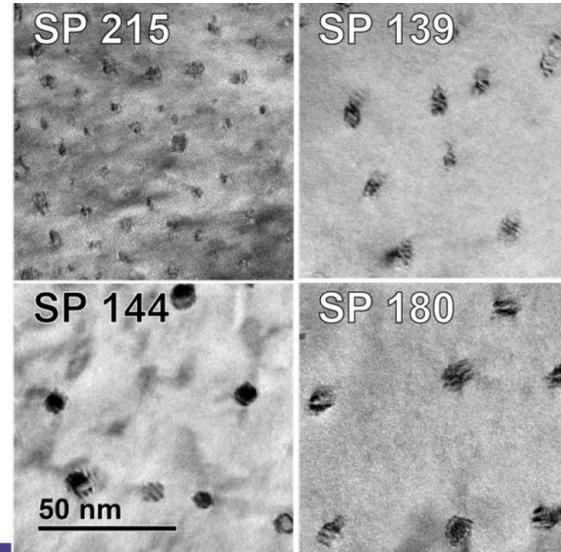
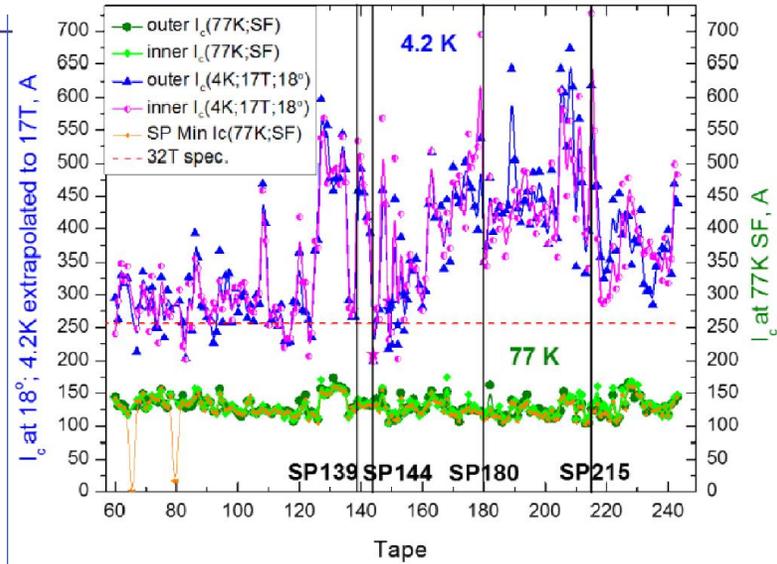
S. Hahn et al., Nature (2020)  
P. Hu et al., SUST (2021)

# Broad distribution of overall current density $J_e$ between the conductors



- Some manufacturer openly admits the large  $J_e$  distribution at 20 K, 20 T
- Maglab internal conductor testing shows the similar variability in other vendor's tapes
- Such a large property distribution drives up the production cost at manufacturers and the testing cost at the end users.

Lee and Petrykin, CCA, 2023  
Abraimov, Maglab report

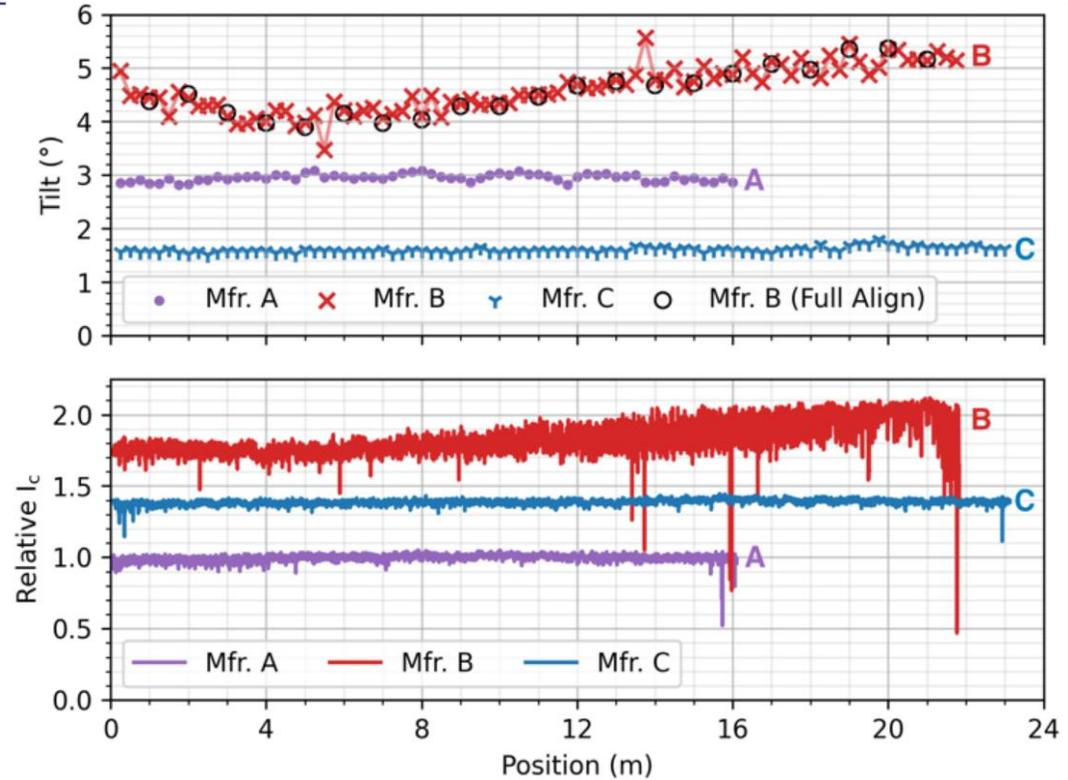
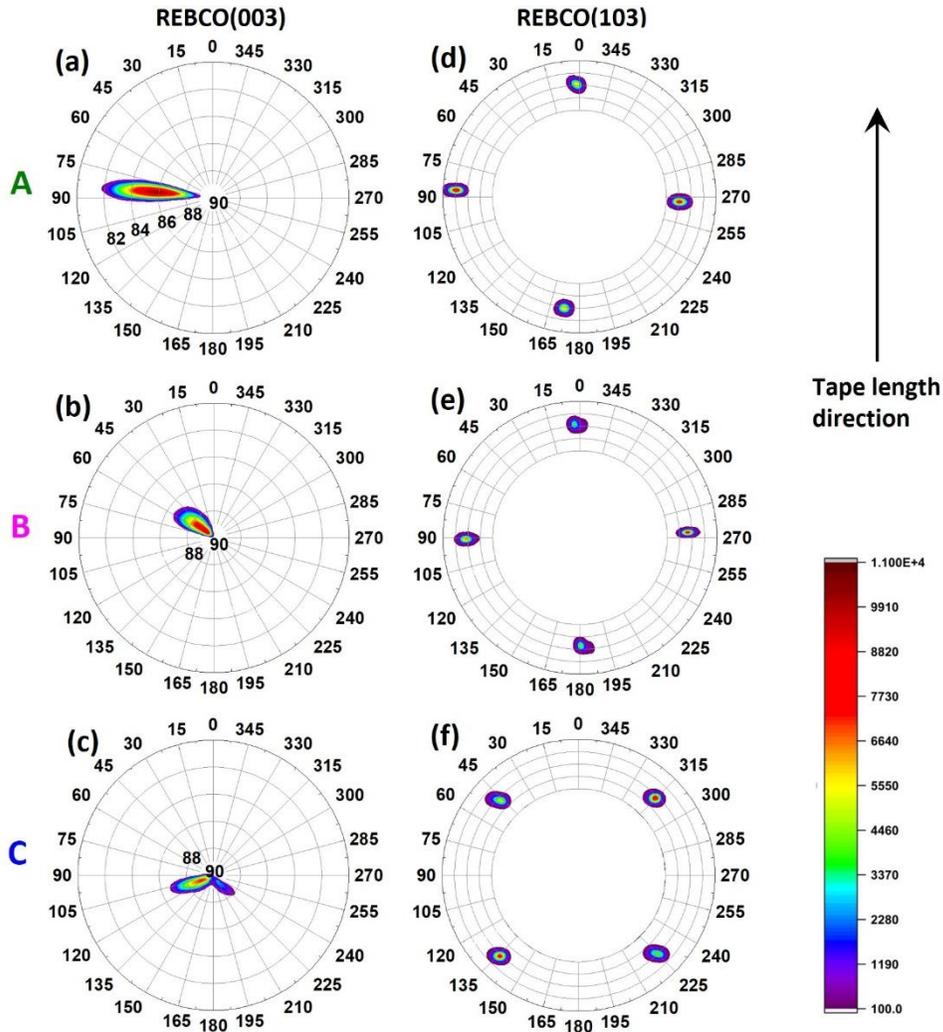


- The REBCO manufacturers don't always realize such large variability by 77 K  $I_c$  testing before delivery
- The  $I_c/J_e/J_c$  distribution at low T, high H comes from the large variability in the pinning nanostructure between the production batches and along the same piece length

Data acquired by D. Abraimov

Francis *et al.*, *SUST* **33**, 044011 (2020)

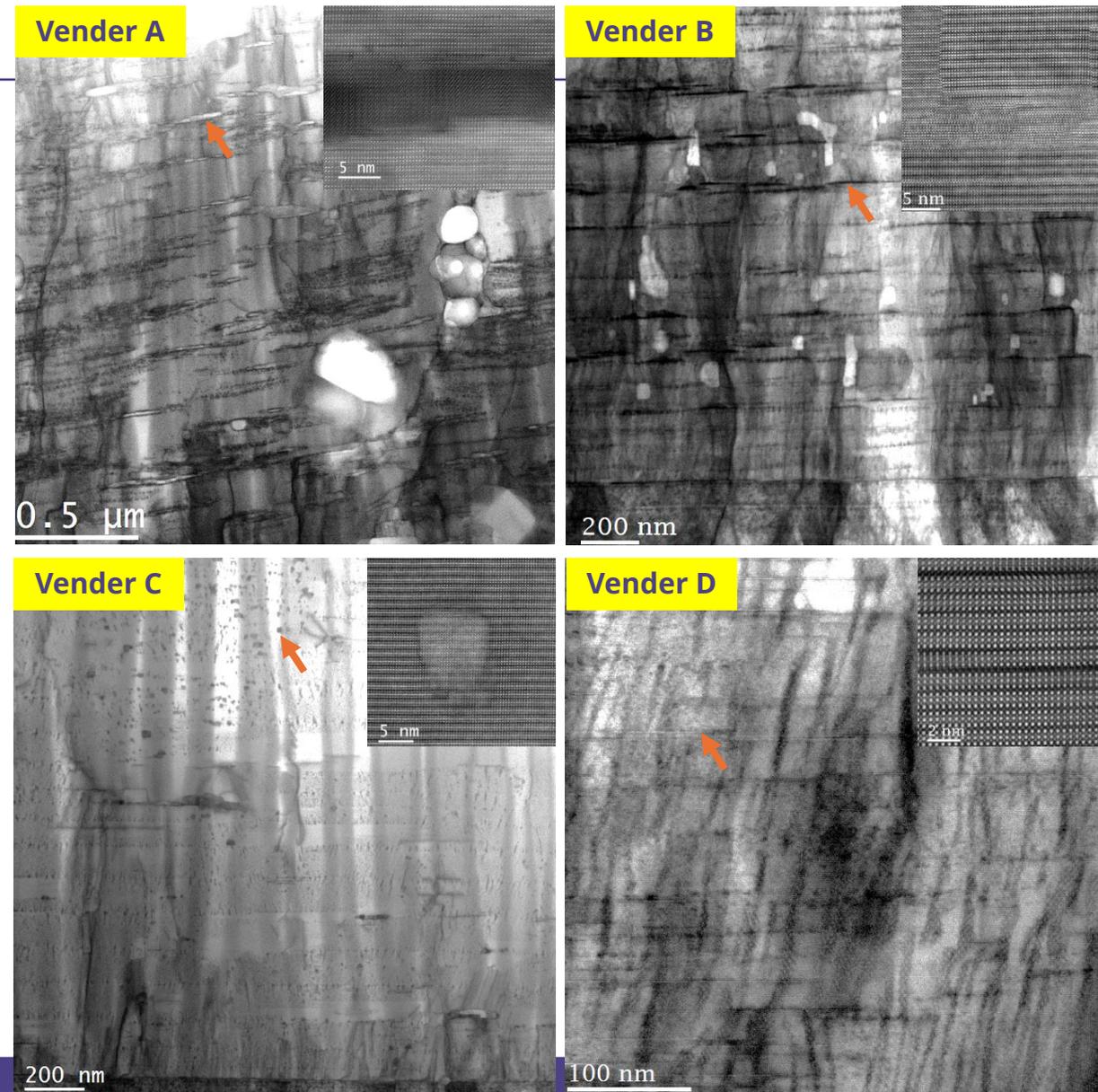
# Manufacturers' variation in the REBCO ab-plane tilt can affect the coil/magnet design



- $J_c$  can differ >50 % by 2-3 deg. off from the  $J_c(\theta)$  peak
- Recent XRD analysis shows that the ab-plane tilt varies easily more than 2-3 between the tapes



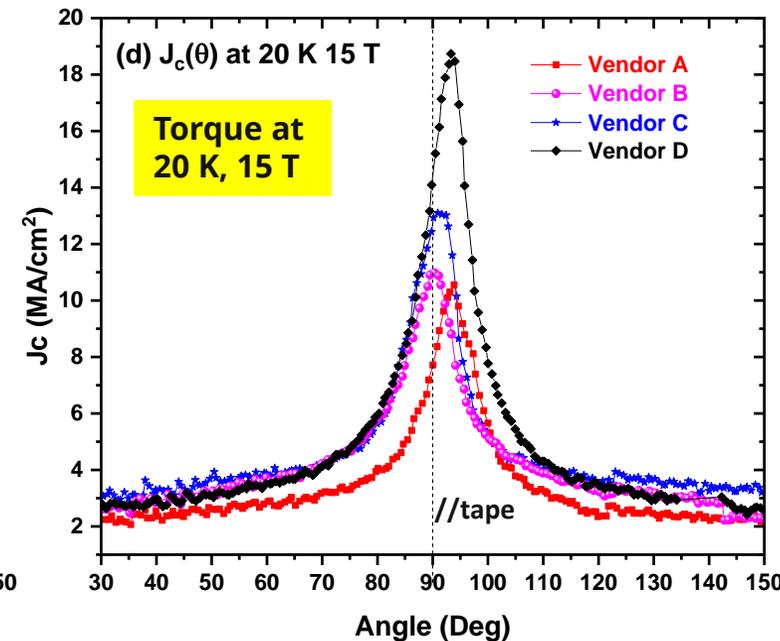
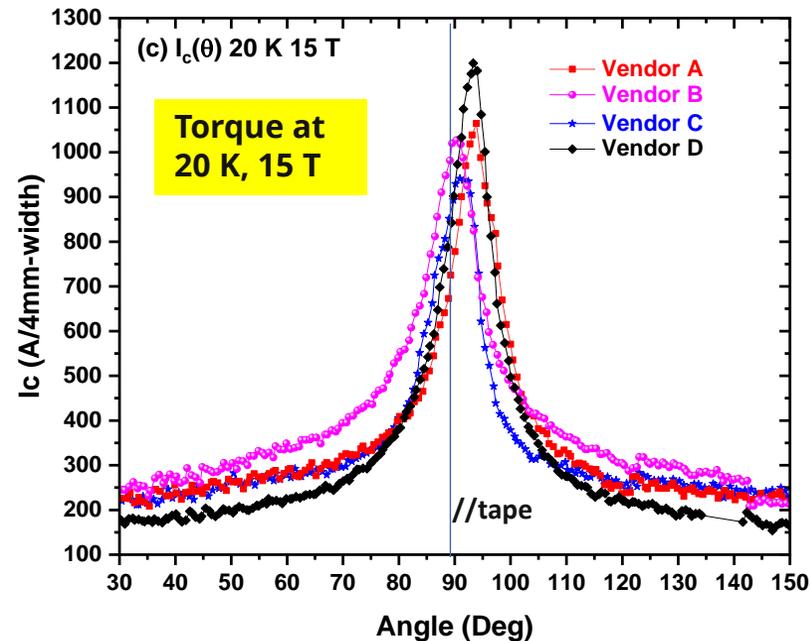
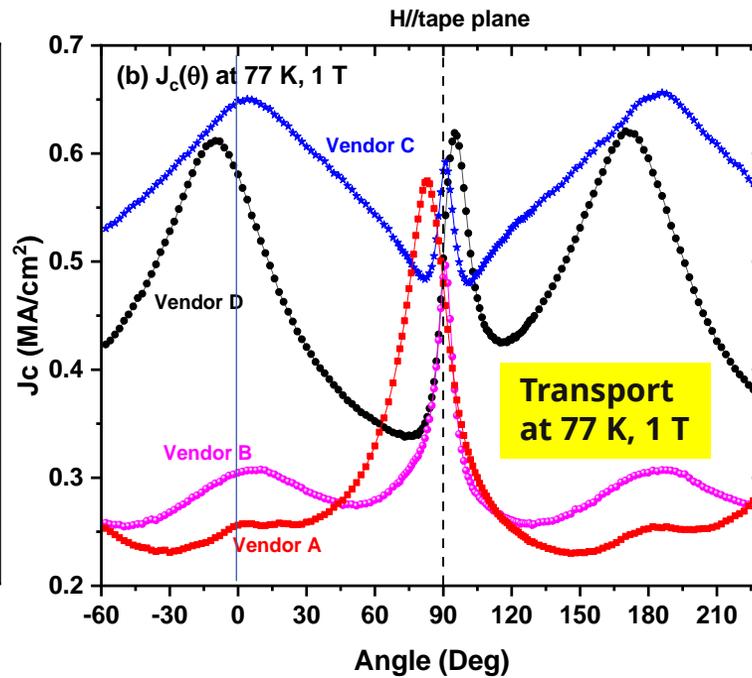
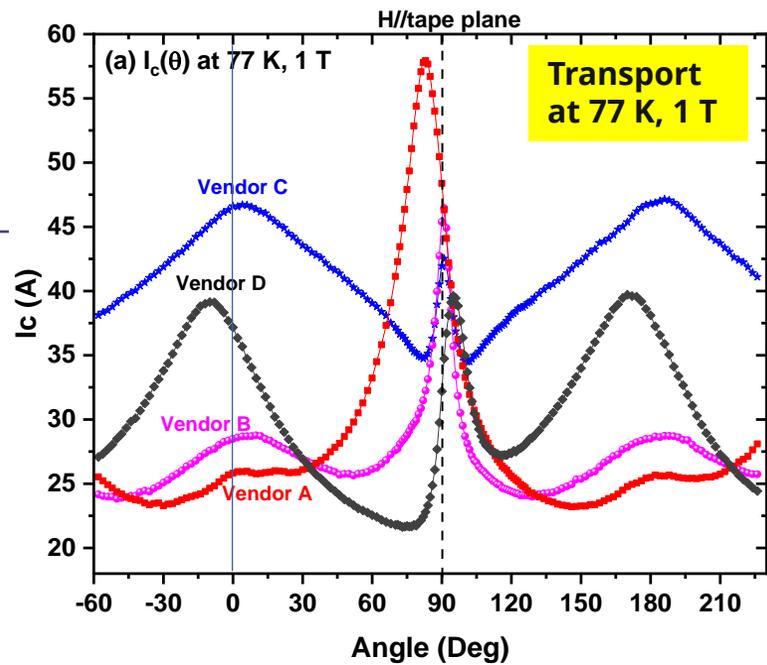
# Recently the pinning nanostructure of many vendors has become less 'nanorods'



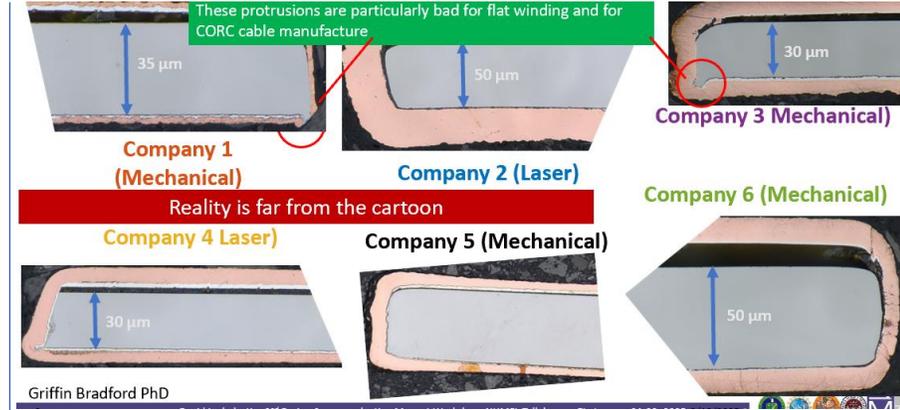
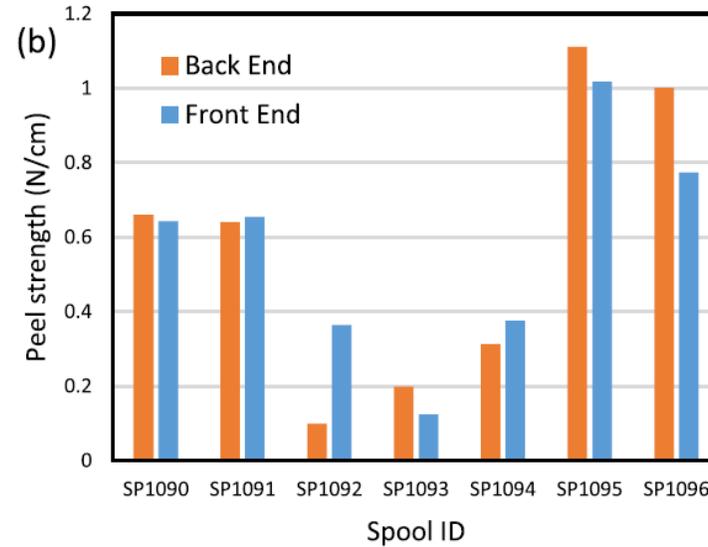
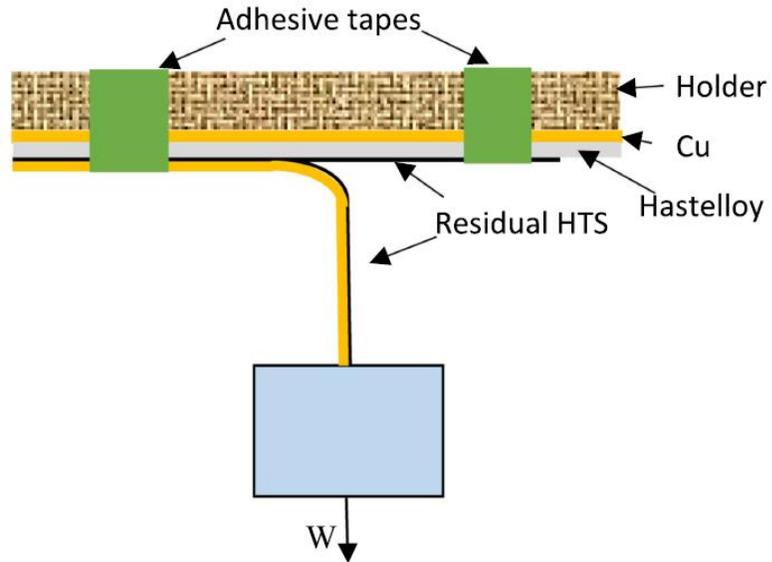
- Previously, major REBCO vendors used to use the nanorods as a strong pinning
  - $\text{BaZrO}_3$ ,  $\text{BaHfO}_3$ , etc
- But many vendors now are shifting to the nano precipitates as a pin
  - By design, and/or as a consequence of recent production scale up
  - Vender A, B and C incorporate nano-precipitates and high density of threading dislocations
  - But the distribution of nano precipitates is different between A, B and C
  - Vender D still has the high density of nanorods, but also stacking faults //ab

# How does the pinning nanostructure variation appear for $I_c/J_c$ at 77 K and 20 K?

- Different pinning nanostructures result in large variation of  $I_c/J_c(\theta)$  at 77 K, 1 T both at  $H // ab$  and  $//c$ 
  - The density and direction of nano-precipitates, nanorods and/or dislocations well correlates at 77 K
- Such a pinning difference becomes unrecognizable at 20 K, 15 T
  - $I_c(\theta)$  difference between the vendors is <50 % off from  $H//ab$ , <30 % near  $H//ab$
  - But  $J_c(\theta)$  is >80 % at  $H//ab$
  - Variation of FWHM of  $J_c$  at  $H//ab$  is critical for magnet use

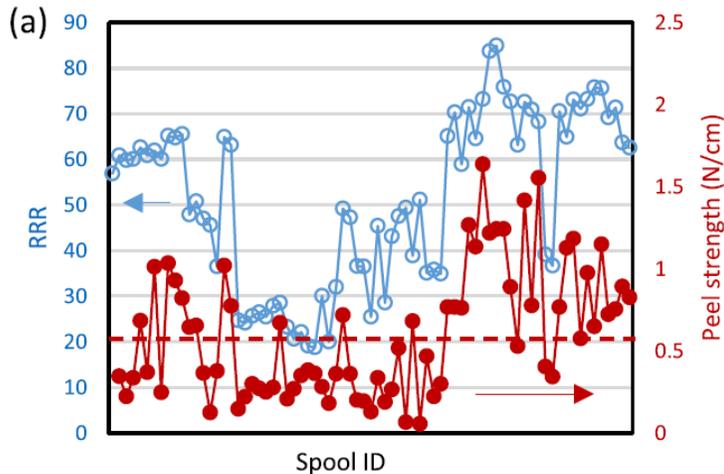


# Variation of delamination strength can be rooted on multi-scale structural causes (1)



J. Lu et al., *IEEE Trans. Appl. Supercond.*, **35**, 8400105 (2025)

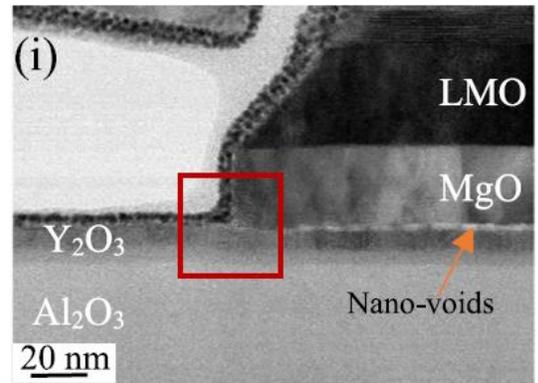
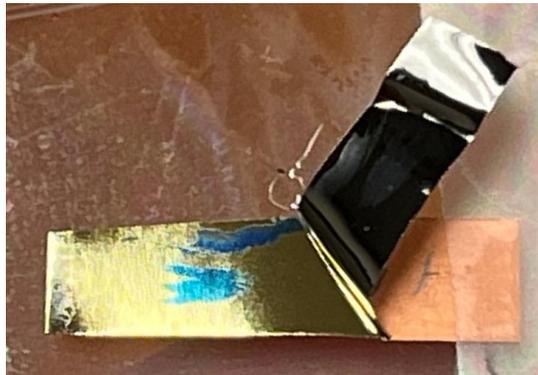
G. Bradford, FSU PhD Thesis (2025)



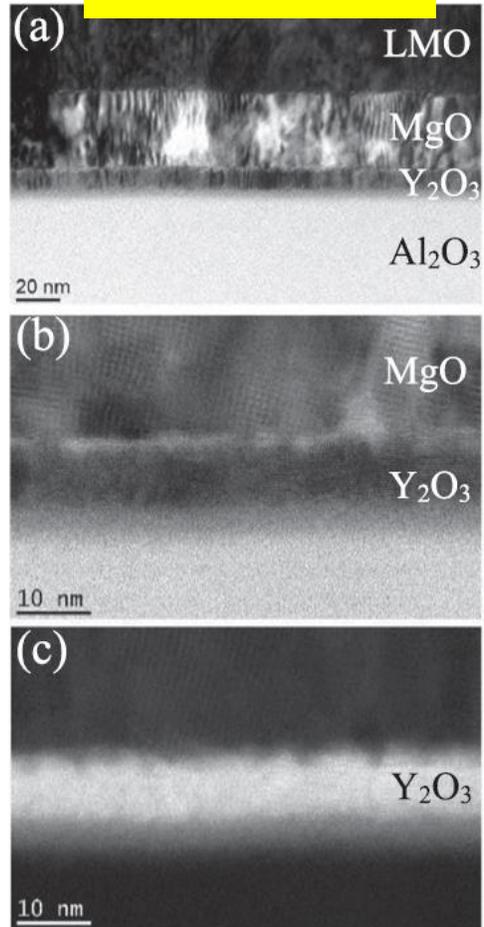
- Cu around the tape edges is variable between the vendors

- Peel strength strongly varies between the spool ID
- The Cu layer appears to play a significant role
  - RRR of the Cu layer correlates the peel strength
  - The grain size of Cu affects the stiffness of Cu layer?

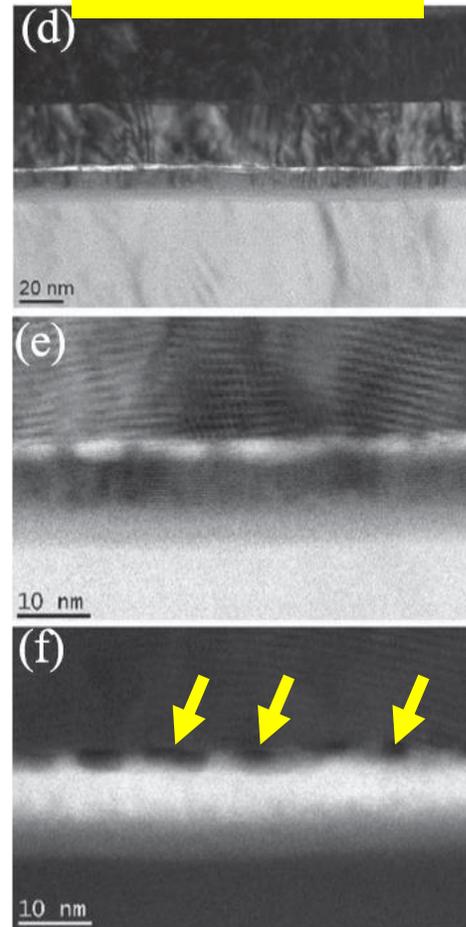
# Variation of delamination strength can be rooted on multi-scale structural causes (2)



Normal delamination



Weak delamination



- The propagation of delamination may also depend on the adhesion strength of IBAD layers
  - Recent TEM reveal that the array of nano porosity is present at the  $Y_2O_3/MgO$  interface in a weakly delaminated REBCO tape
- Comprehensive microstructural correlations are needed to fully understand the delamination in REBCO coated conductors

Y. Xin et al., *IEEE Trans. Appl. Supercond.*, **35**, 6601405 (2025)

# Conclusions

- REBCO possesses the largest  $J_c$ ,  $H_{irr}$  and T field, but is the highly geometrically anisotropic, single filament thin ribbon form
- Currently REBCO coated conductors are not interchangeable
  - As a result, each REBCO coil/magnet is generally designed from the ground up, yet replaceable
  - There are still large variations in the pinning, crystallographic properties, and a large  $I_c/J_c$  variability within the same manufacturers and between the manufacturers
- It is important to access the differences and their structural causes at a wide range of scales
  - Each vendor has a specific tilt angle of REBCO ab-plane, with which  $J_c$  becomes highest especially at 20 K or lower and high fields
  - REBCO pinning has become less ‘nanorods’ and more ‘nano precipitates’
    - Nevertheless,  $J_c(\theta)$  at 77 K of some vendors still shows a strong peak at  $H//c$  in addition to  $H//ab$
    - However, at 20 K, 15 T, such a large variation of pinning becomes less recognizable
    - Yet  $J_c$  at  $H//ab$  still shows variations and FWHM of  $J_c$  peak also vary
  - Delamination strength needs to be addressed and compared between the vendors
    - The Cu layers play a significant role for delamination strength
    - Also, the nanostructural integrity of IBAD buffers might cause additional variation of delamination strength

# Acknowledgement

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