TechCon 2021 Virtual

64th Annual Technical Conference Proceedings Virtual Event: May 3 – 7, 2021
 ISSN 0737-5921, ISBN 978-1-878068-41-5

Roll-to-Roll Manufacturing of Thin Film Superconductor Tapes: Status, Challenges, and Opportunities

Venkat Selvamanickam, University of Houston, Houston, TX

Tremendous progress has been made in the past two decades in the development and roll-to-roll (R2R) manufacturing of thin film RE-Ba-Cu-O (REBCO, RE=rare-earth) superconductor tapes world-wide. Based on a unique biaxially-textured substrate/buffer architecture and epitaxial film growth, REBCO tapes have been demonstrated with high critical current densities over a wide range of temperatures – 4.2K to 77K. Using CVD, PVD and solution coating techniques, many companies worldwide are producing thin film REBCO tapes in lengths of several hundred meters with uniformly good critical currents. Additionally, through the introduction of Artificial Pinning Centers (APC) in form of nanoscale defects, the critical current densities of these tapes have been increased over 10-fold, resulting in pinning force levels 100 times that of the most-commonly used superconductor, Nb-Ti. The major challenges in largescale commercialization of thin film superconductor tapes are in their high cost and limited manufacturing throughput. Status, challenges and opportunities in R2R manufacturing of thin film superconductor tapes will be discussed in this presentation.

https://doi.org/10.14332/svc21.proc.0053

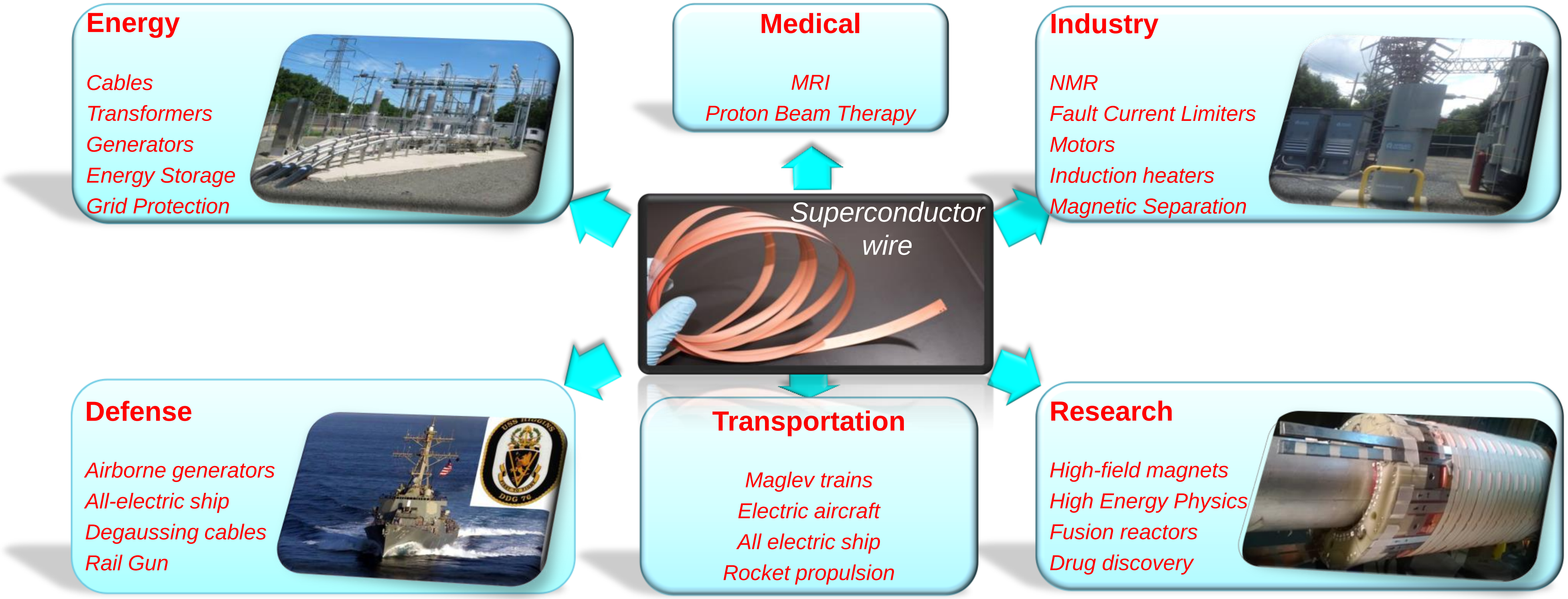
Outline

- Thin film HTS tape R2R manufacturing: Epitaxial thin films on flexible substrates
- Improving performance of RE-Ba-Cu-O (REBCO) tapes in high magnetic fields
- Advanced Metal Organic Chemical Vapor Deposition (MOCVD) for high-current REBCO tapes for high-field applications
- Development of in-line and continuous quality-control tools for high-yield manufacturing
- Opportunities in REBCO manufacturing

RE-Ba-Cu-O (REBCO) Thin Film Superconductor Tapes

REBCO superconductor tapes carry 300 – 600 times the current as a comparably-sized copper wire

REBCO High Temperature Superconductors can impact a broad range of industries



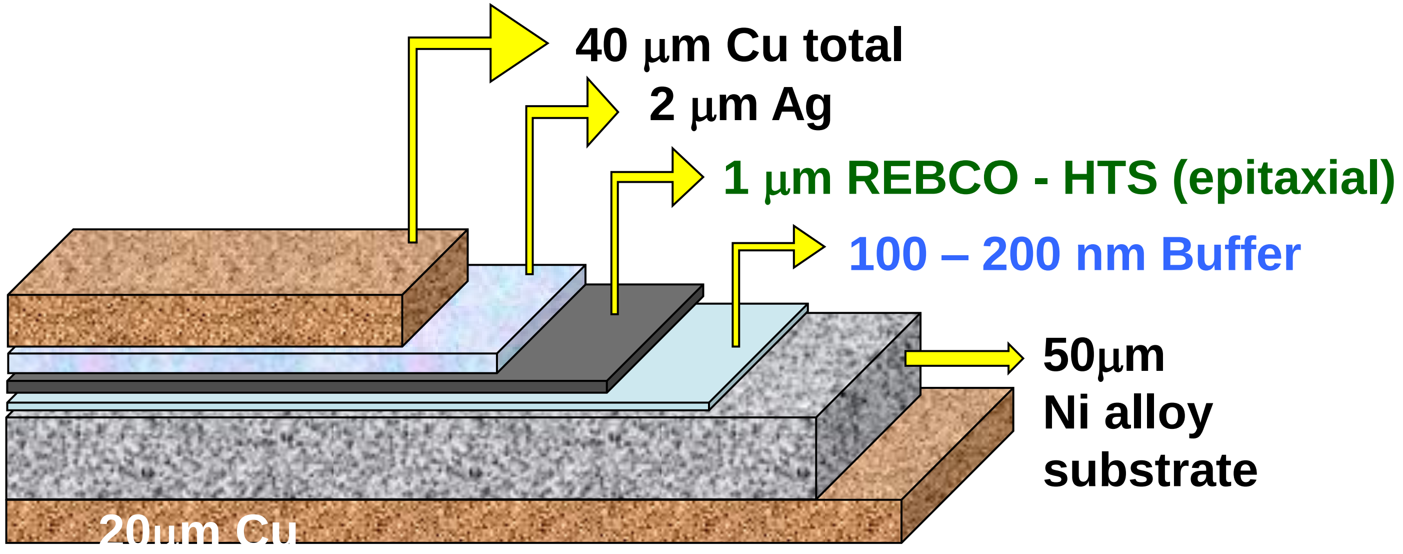
- Enhanced energy efficiency
- High power density
- Less CO_2 emission
- Better power quality

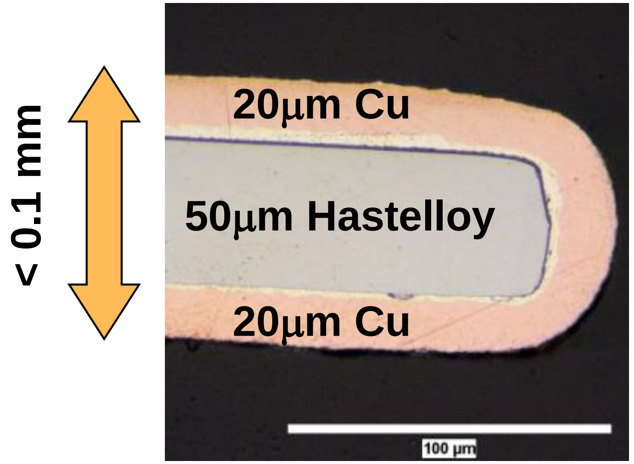
- Better security of electric power grid
- Medical Imaging
- High Speed Transportation
- Pharmaceutical – drug discovery

Thin film HTS tape R2R manufacturing: Epitaxial thin films on flexible substrates

REBCO HTS tape manufacturing approach

- REBCO tape is produced by thin film vacuum deposition on a flexible nickel alloy substrate in a continuous reel-to-reel process.
  - Only 1% of tape is the superconductor
  - ~ 97% is inexpensive nickel alloy and copper
  - Automated, reel-to-reel continuous manufacturing process



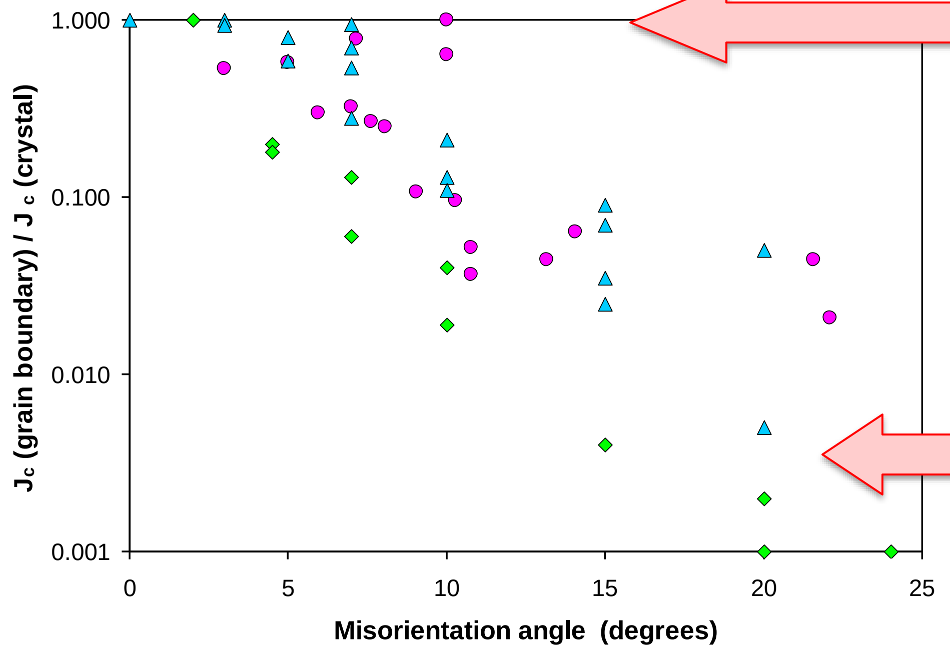


Fundamental challenge in thin film HTS tapes

Current density of epitaxial thin film of HTS on single crystal substrate ~ 5 MA/cm^2

Current density of thin film of HTS on polycrystalline substrate ~ 0.01 MA/cm^2

Grain-to-grain misorientation in a polycrystalline HTS thin film is responsible for low current density



Single crystal film current density

- D. Dimos, *et al.*, Phys. Rev. B **41**, 4038 (1990).
- N.F. Heinig, *et al.*, Appl. Phys. Lett. **69**, 577 (1996).
- D. T. Verebelyi, *et al.*, Appl. Phys. Lett. **76**, 1755 (2000).

Typical current density of HTS film on polycrystalline substrate

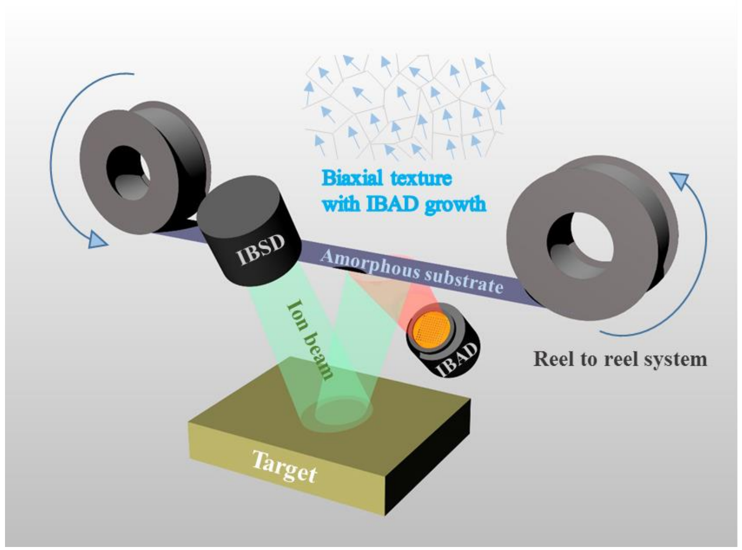
(data complied by S. Foltyn, LANL)

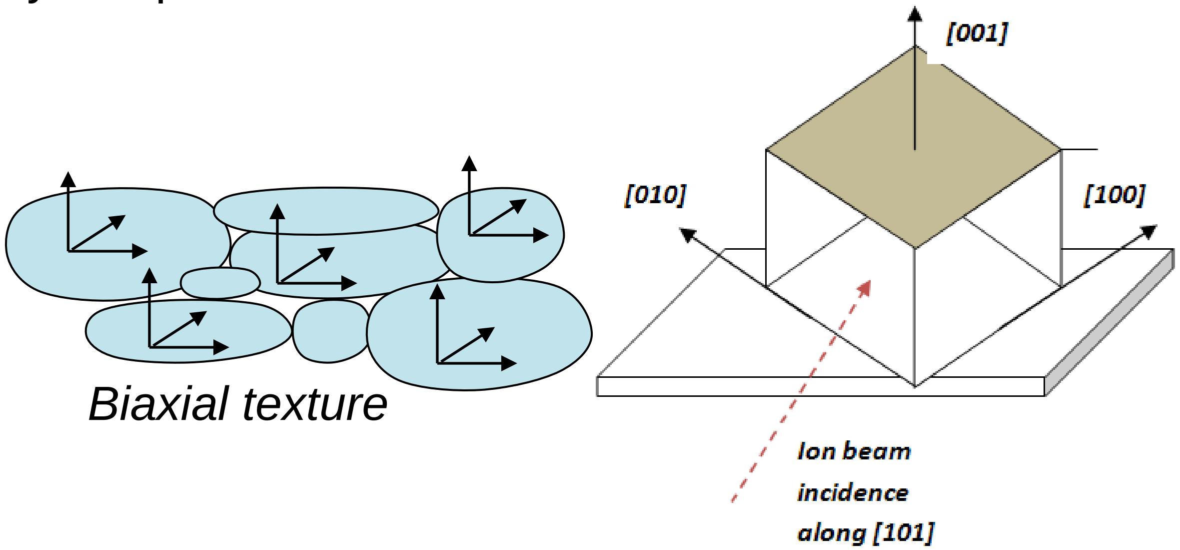
Cannot make kilometer lengths of HTS thin film tape on single crystal substrates.

Need a way to produce single crystalline like HTS thin films on practical, polycrystalline flexible substrates

Ion Beam Assisted Deposition (IBAD) – A technique to produce near single crystal films on polycrystalline or amorphous substrates

- Essentially, any substrate can be used – stainless steel, nickel alloys, glass, polymer …(room temperature process)
- Biaxial texture achieved in certain conditions of ion bombardment resulting in grain-to-grain misorientation in film plane of about 5 degrees !
- Only 10 nm of IBAD film is needed – very fast process !

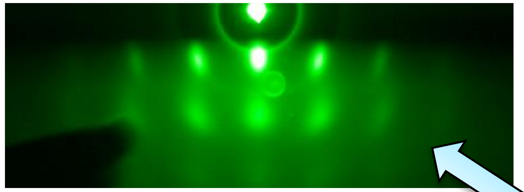




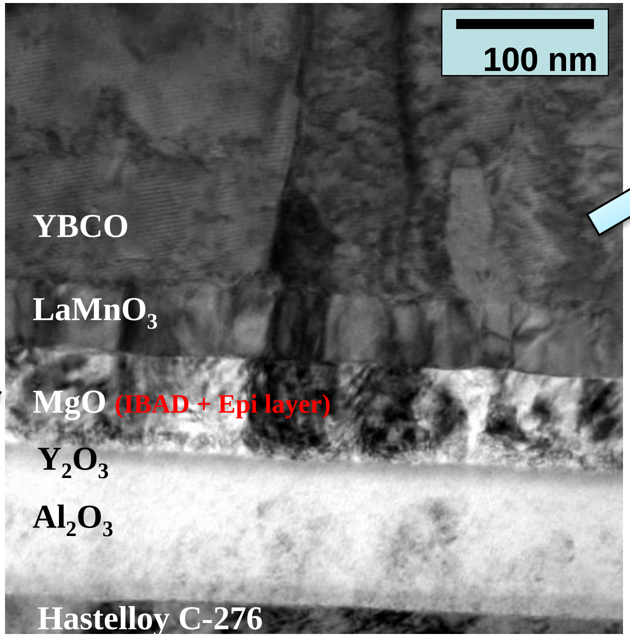
Grains in the IBAD film are arranged in a 3-dimensional aligned structure with grain-to-grain misorientation in any axis less than 5 degrees – essentially a near-single crystalline structure

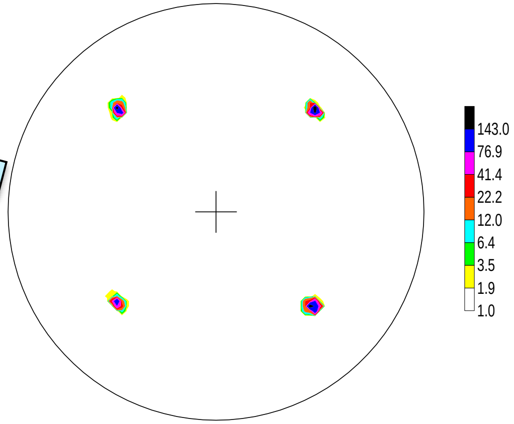
Epitaxial single crystalline-like films on polycrystalline or amorphous substrates based on IBAD

- A near single crystalline film is achieved by IBAD under specific conditions.
- Once a template is created, this near-single-crystalline structure can be transferred epitaxially to many other films.



Reflection High Energy Electron Diffraction of growing IBAD film showing biaxial texture development within a few nanometers



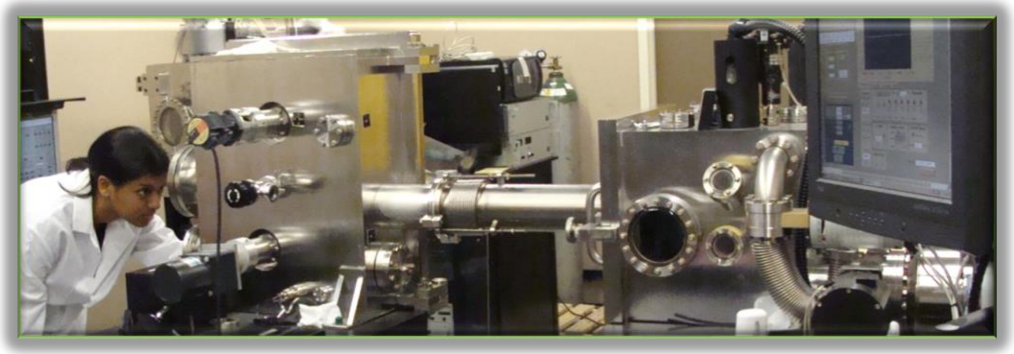


YBCO(113)

X-ray polefigure showing a high degree of biaxial texture in a superconducting $YBa_2Cu_3O_x$ film grown epitaxially on a IBAD MgO film even though the lattice mismatch is about 8%

Roll-to-roll deposition of IBAD-based templates and superconductors

Dual Ion Beam Sputter and Assist, Magnetron Sputtering, Metal Organic Chemical Vapor Deposition (MOCVD)

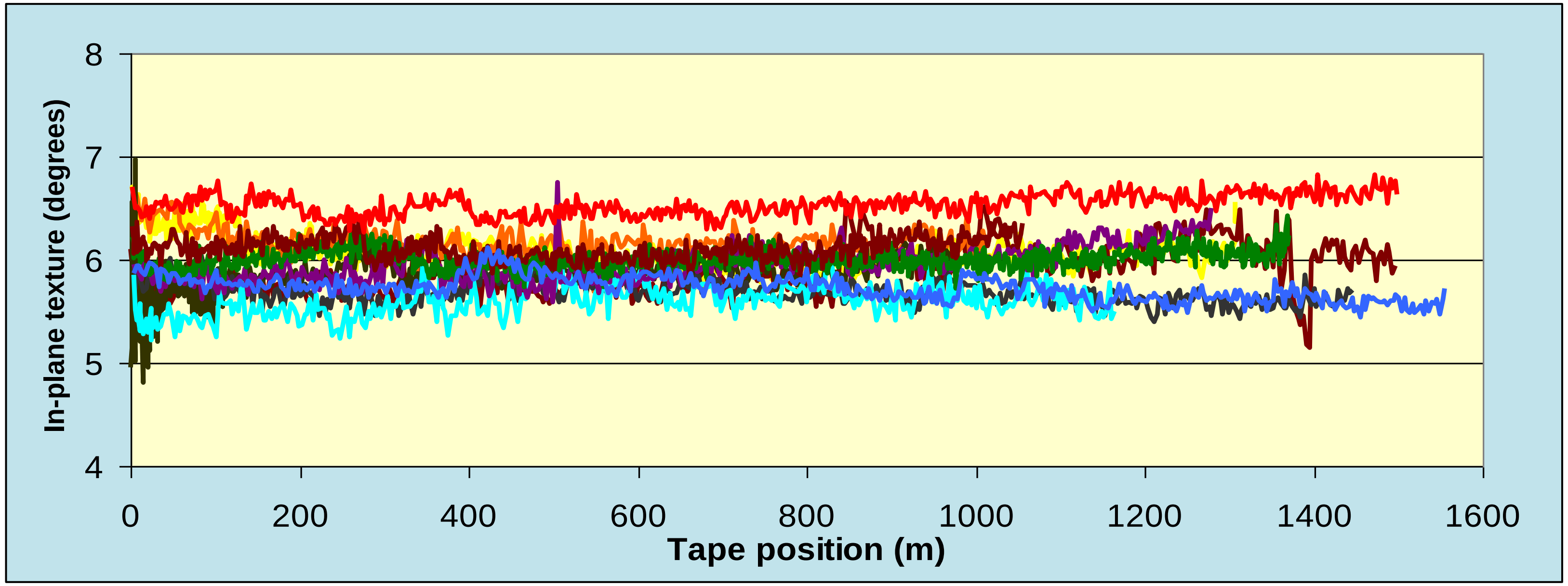


Immense challenge in scaling up 2G HTS tape fabrication from R&D to manufacturing

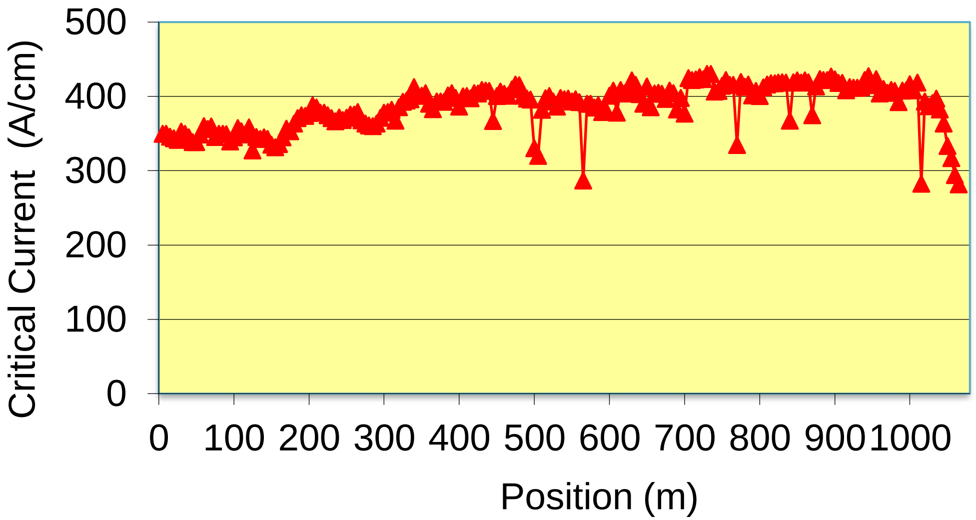
- **Epitaxial thin film growth over kilometer**
  - Never been accomplished in any material system
- **Uniform critical current over kilometer lengths**
  - Uniform stoichiometry of superconductor over kilometer lengths
  - Uniform thickness of 5-layer buffer stack without imperfections (porosity, scratches…) over a kilometer with buffer thickness as small as 7 nm
- **High-rate vapor deposition** of complex, multi-component films over 1 μm in thickness **over large deposition area**.
- **Stable deposition conditions over 40 hours** with temperature, precursor deposition uniformity over 100 cm × 15 cm deposition area

Numerous advances in materials science, processing, and equipment engineering were needed for scaling up to kilometers

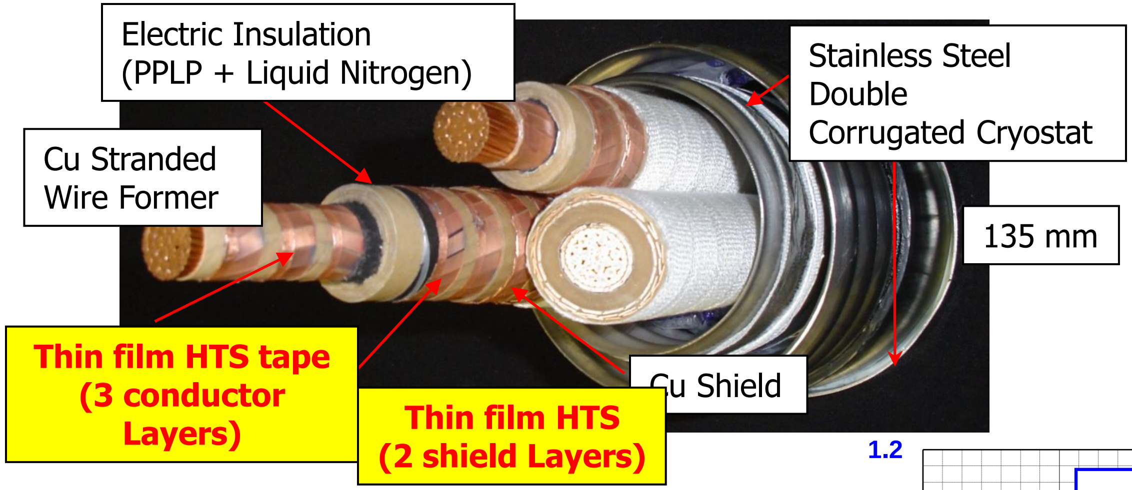
REBCO tapes manufactured in kilometer lengths

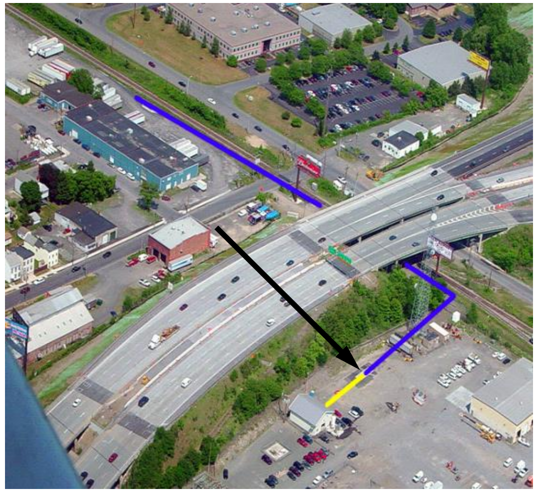


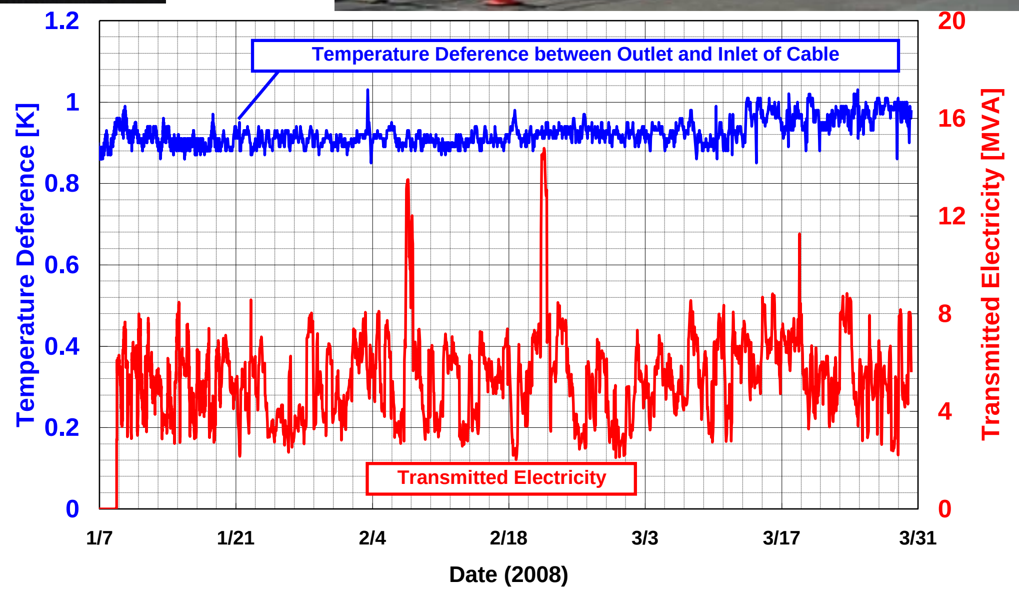
2G HTS tape is now routinely produced up to **kilometer lengths** with **400 times** the current carrying capacity of copper wire



Demonstration of the world's first device with REBCO thin film tape in a live power grid







350 m cable made with 30 m segment of 2G HTS thin film tape was energized in the grid in January 2008 & supplied power to 25,000 households in Albany, NY

Many more companies manufacturing REBCO tapes now

SuperPower Inc. A Furukawa Company

amsc

2006: Only the two (US) companies manufactured REBCO tapes

SuNAM — *Korea*

SuperOx — *Russia, Japan*

Fujikura — *Japan*

上海超导 SHANGHAI SUPERCONDUCTOR — *China*

THEVA — *Germany*

Shanghai Creative Superconductor Technologies Co., Ltd. — *China*

中国科学院苏州纳米技术与纳米仿生研究所 — *China*

BRUKER — *Germany*

deutsche nanoschicht — *Germany*

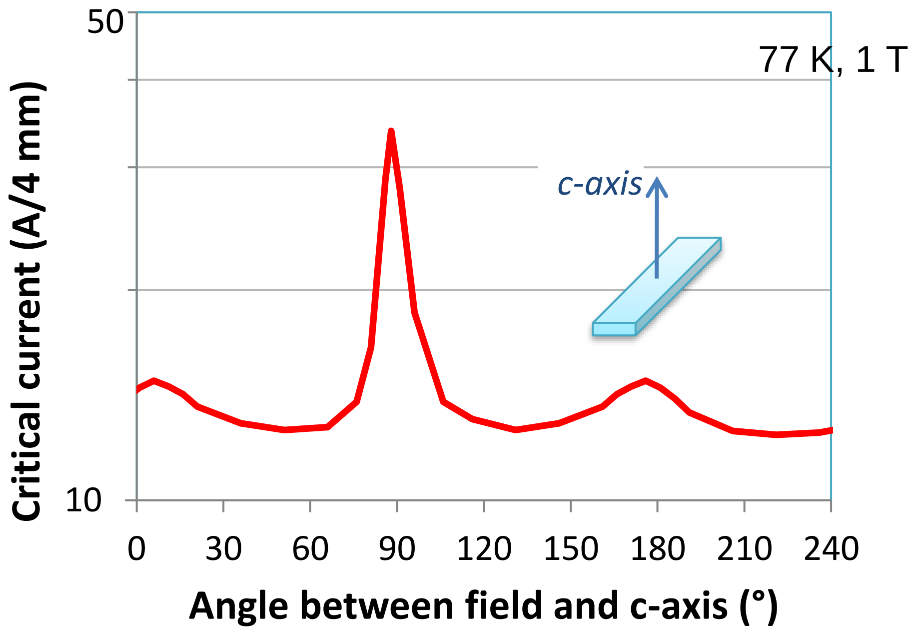
METOX — *USA*

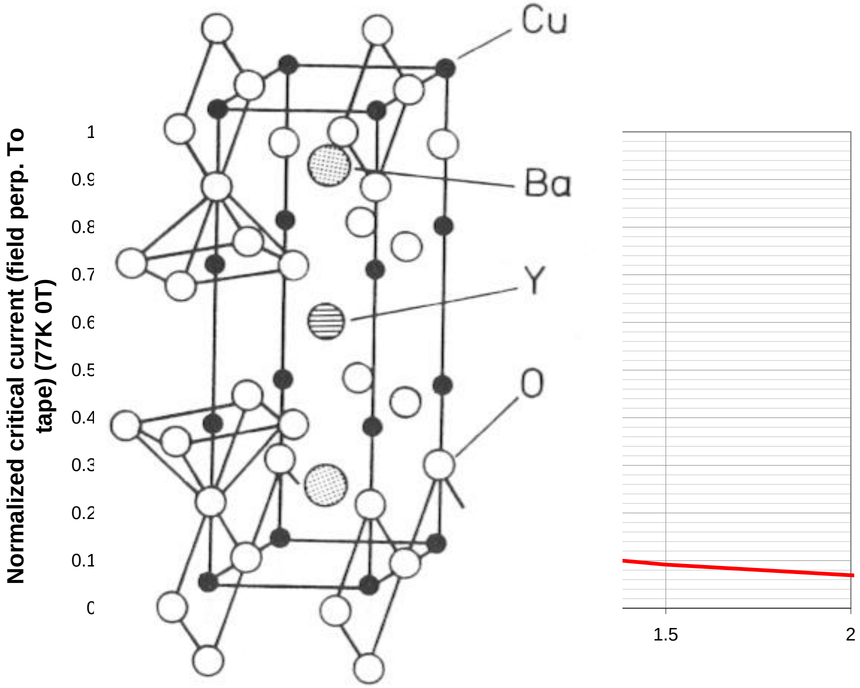
2020: 12 companies are manufacturing REBCO tapes!

Improving performance of REBCO tapes in high magnetic fields

Need to improve critical current of REBCO tapes in a magnetic field

- Even though HTS tapes have good critical current (I_c) at zero field, their performance reduces rapidly in an applied magnetic field at higher temperatures.
- Critical current of HTS tapes is anisotropic and the minimum current value limits use.



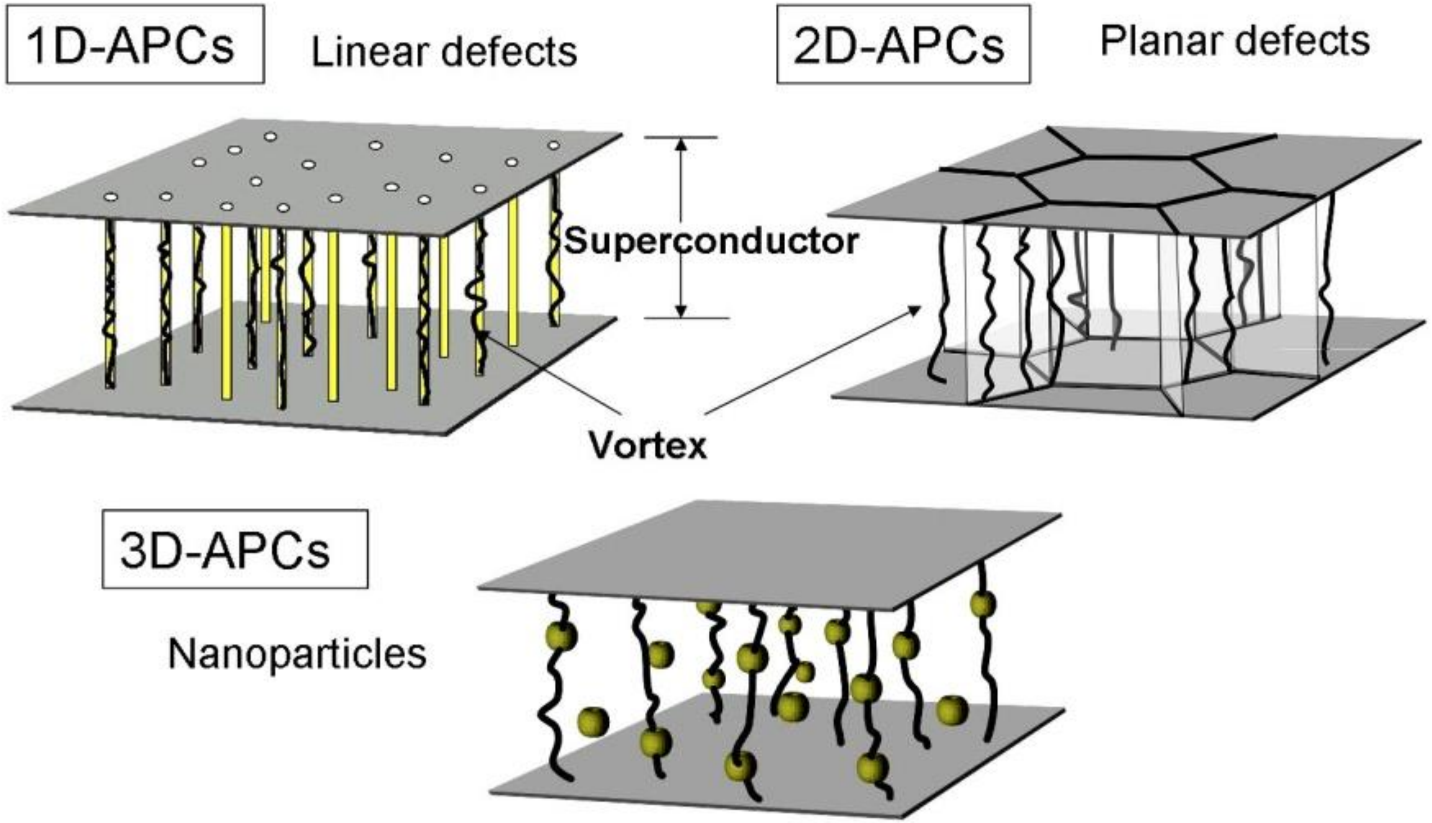


Nanoscale defect structures need to be introduced to achieve isotropic and strong flux pinning and thereby improve critical current of HTS tapes

AMI Advanced Manufacturing Institute
TcSUH

UNIVERSITY of HOUSTON

Nanoscale defects for pinning flux lines

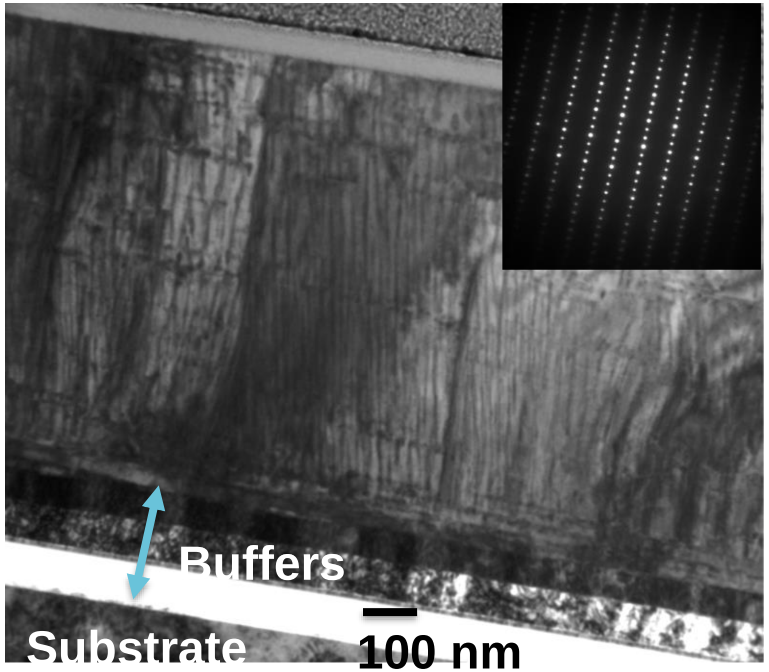


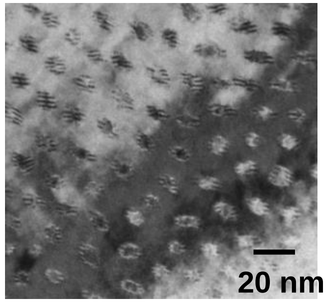
AMI Advanced Manufacturing Institute
TcSUH

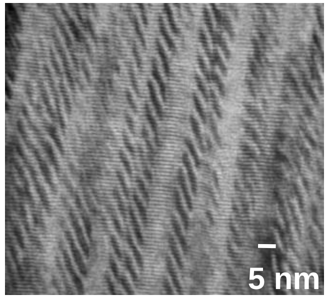
From Matsumoto

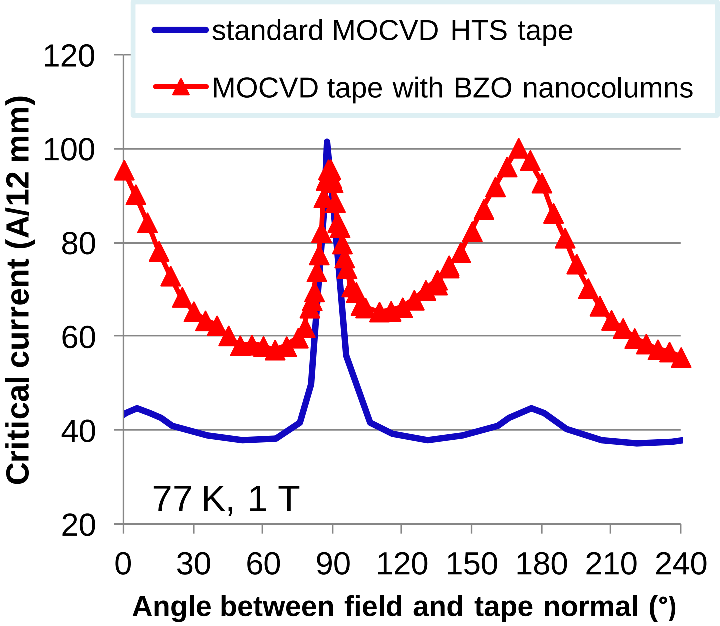
Improved pinning by Zr doping of REBCO tapes

- *5 nm sized, few hundred nanometer long $BaZrO_3$ (BZO) nanocolumns with ~ 35 nm spacing created during metal organic chemical vapor deposition (MOCVD)process with 7.5% Zr*
- Two-fold improvement in critical current at 77 K, 1 T achieved by **7.5%** Zr addition in MOCVD films





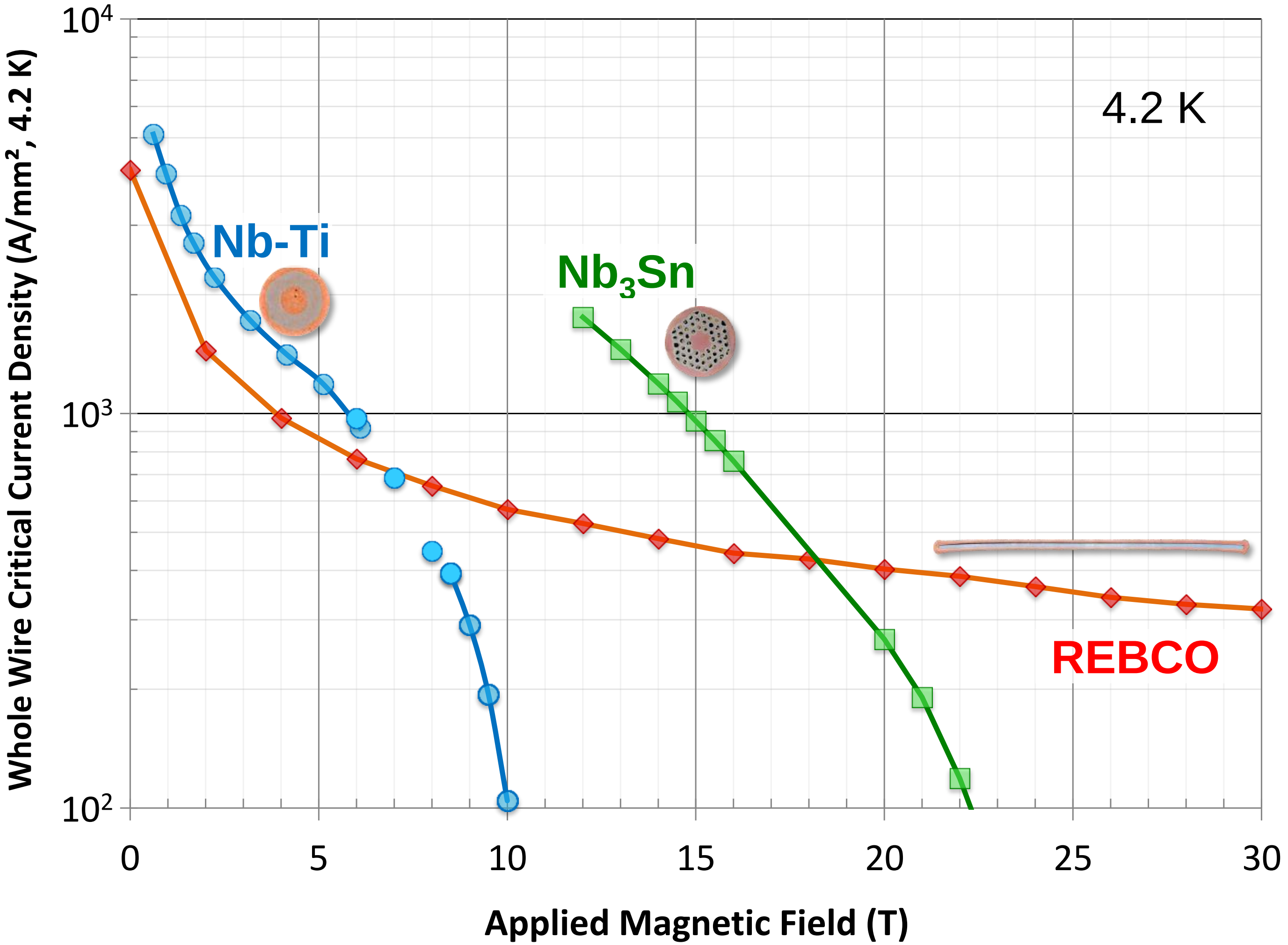




Process for improved in-field performance successfully transferred to manufacturing in industry – standard product in the last ten years

AMI Advanced Manufacturing Institute
TcSUH

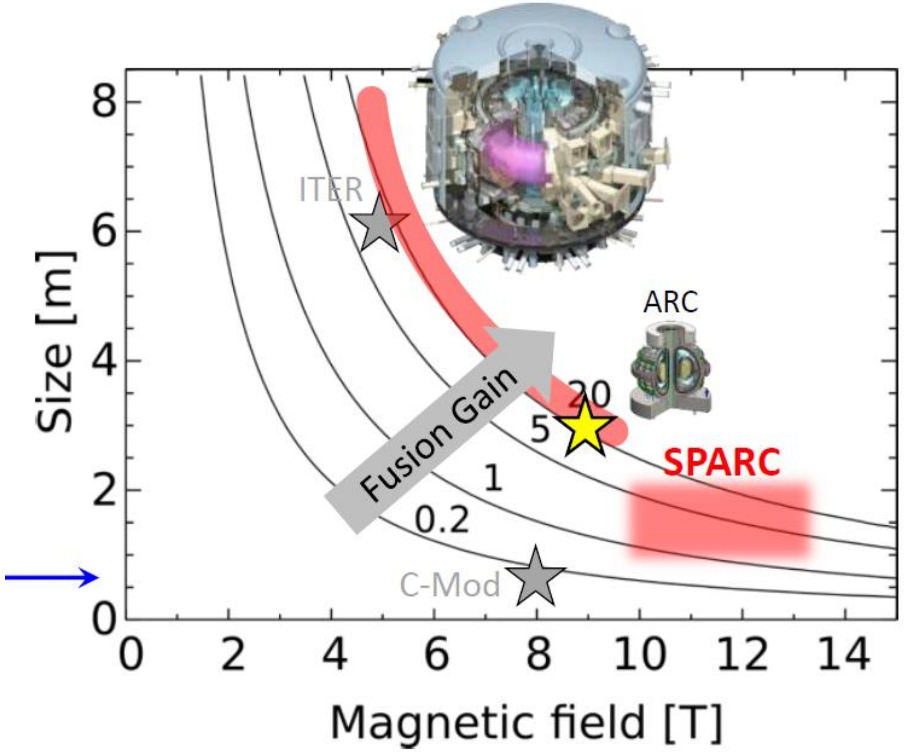
REBCO with improved pinning enables operation at high magnetic fields (> 20 T) not possible with LTS wires

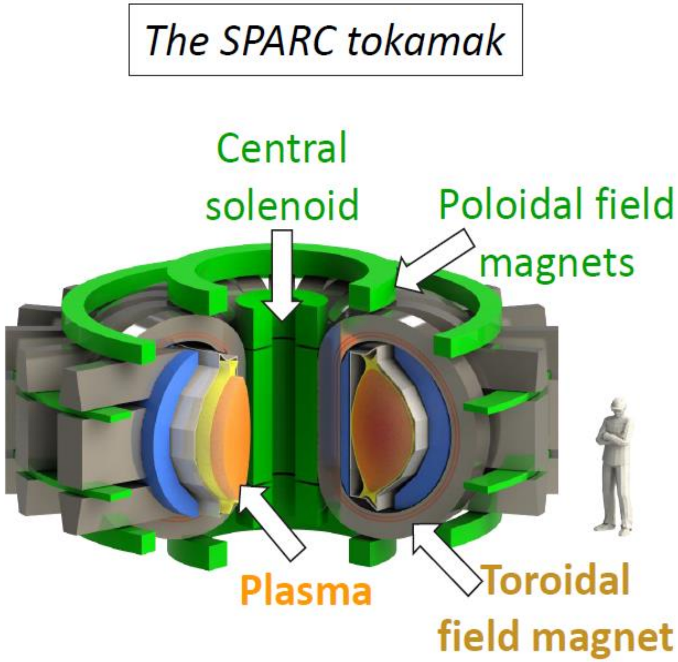


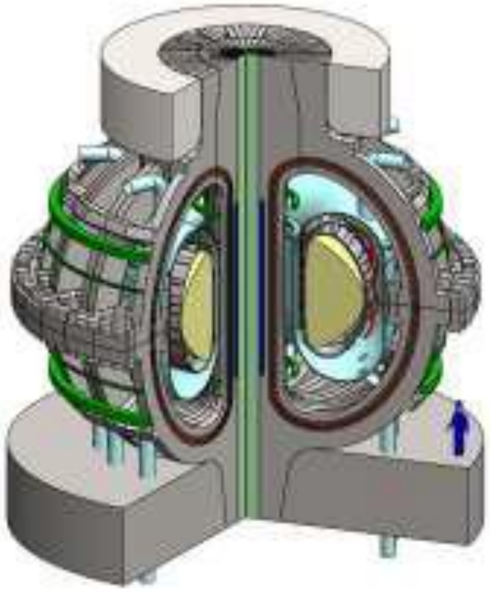
REBCO tapes can also be used at higher temperatures → simpler cryogenics

Compact Fusion Systems are rapidly driving the need for volume manufacturing of REBCO tapes

SPARC- High-field Tokamak to demonstrate net-energy fusion device by 2025





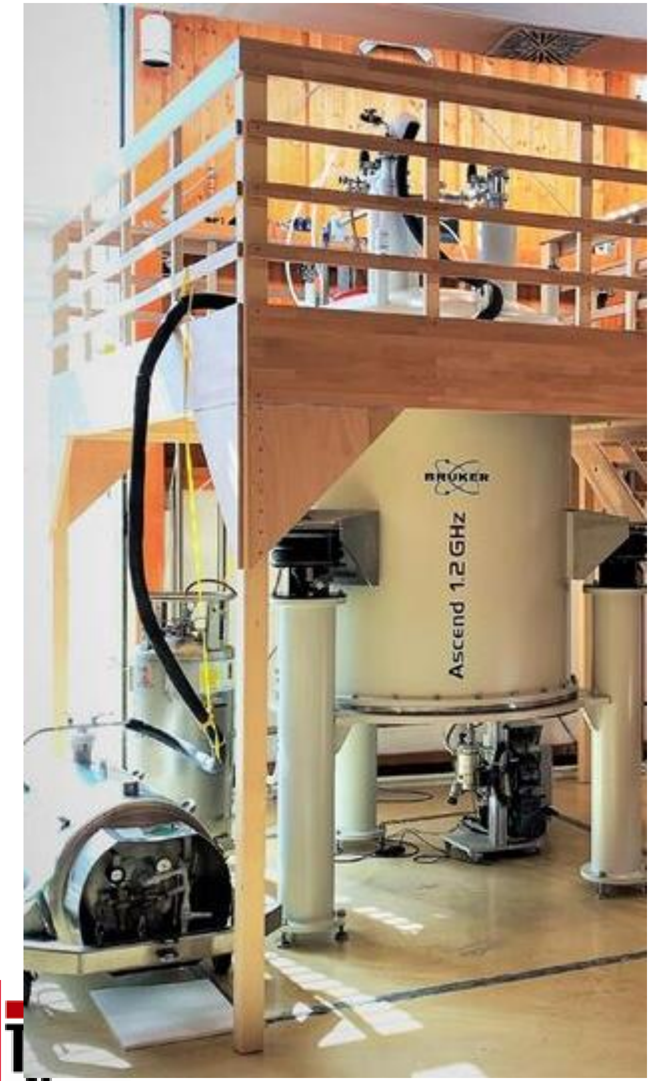


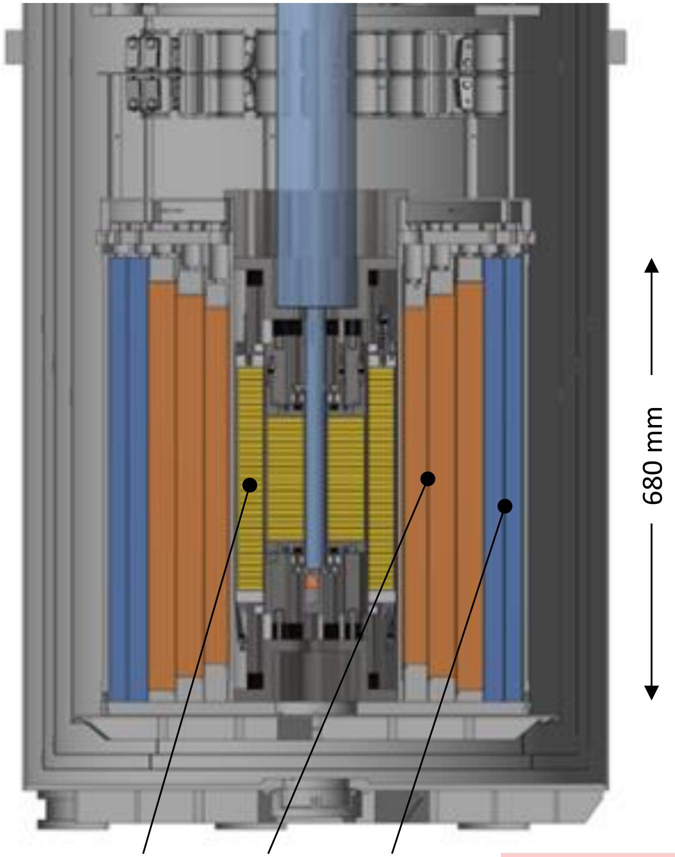
Courtesy Commonwealth Fusion Systems

HTS operating at 20+T enables 10X smaller fusion energy systems

10,000 kilometers REBCO tape order imminent for SPARC!

Higher field REBCO magnets enabling commercial 1.2 GHz NMR and 32 T Superconducting Magnet for User Facility





https://www.bruker.com/news/successful-installation-of-worlds-first-12-ghz-nmr-system.html

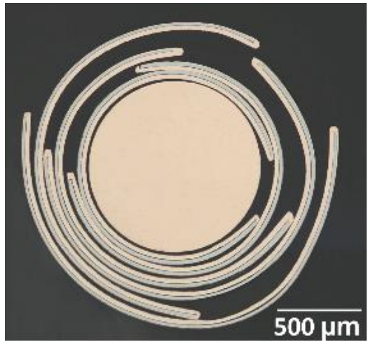
Total field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T

NATIONAL HIGH MAGNETIC FIELD LABORATORY

AMI Advanced Manufacturing Institute

Why high current REBCO tape?

1. **Applications become possible at higher temperatures – simpler cryogenics**
2. **Engineering current density will meet application requirements even in formats that use large non-superconductor cross section like round wires.**

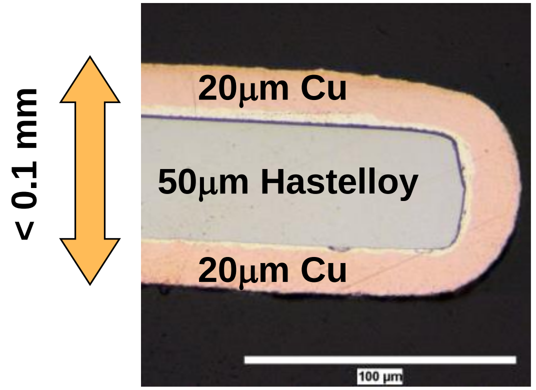


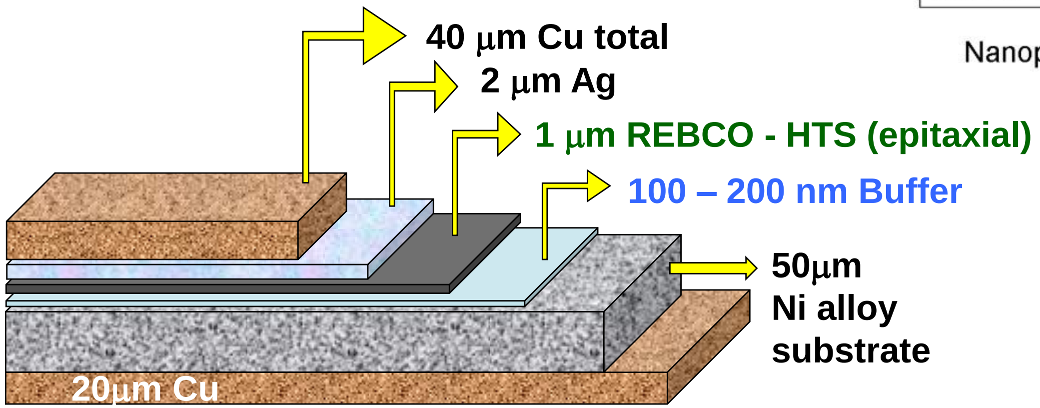
3. **Less tape will be required for the same kA-m**
   – 10,000 km of 'standard tape' for compact fusion.
   – **But with I_c 5X standard tape, need 2,000 km.**
   – Along with 2X reduction in cost → 10X reduction in total tape cost → rapid insertion of REBCO tapes into compact fusion and other applications

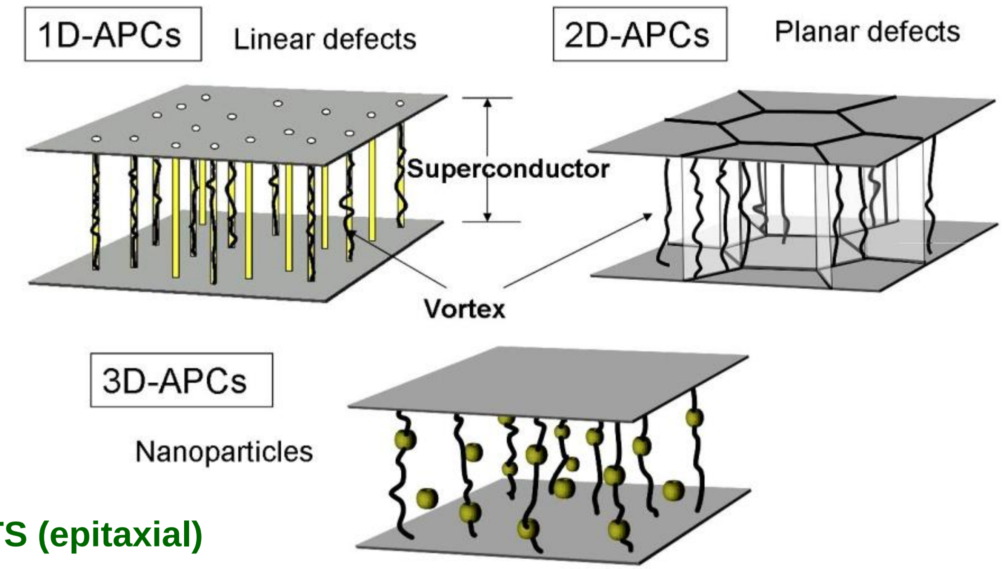
Advanced MOCVD for high-current REBCO tapes for high-field applications

Methods to increase critical current of REBCO tapes

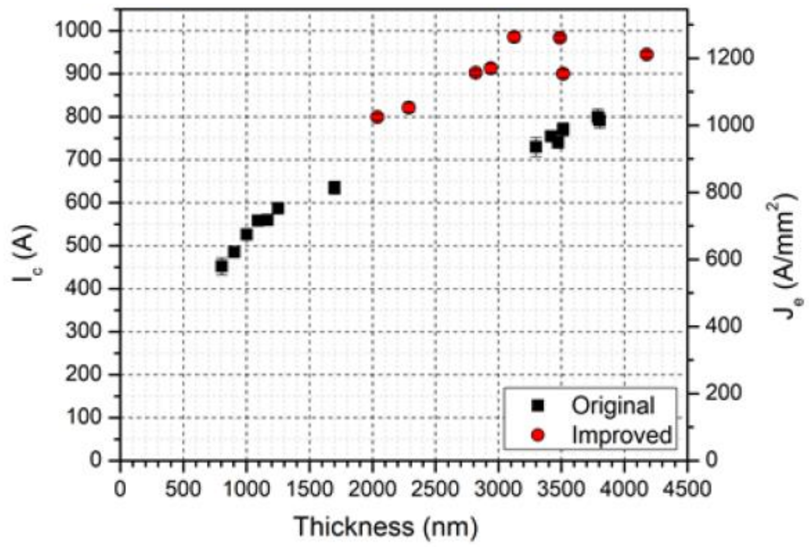
- Introduce flux pinning centers (nanoscale defects)
- Increase REBCO film thickness from 1-2 μm to 5 μm



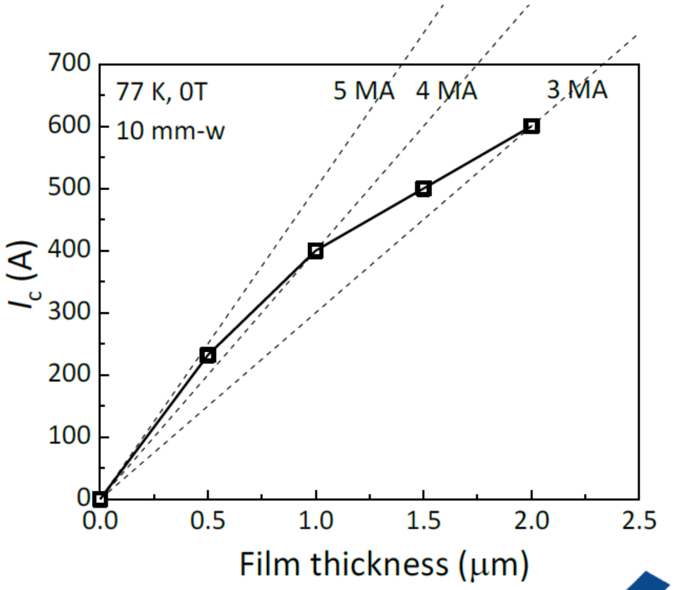




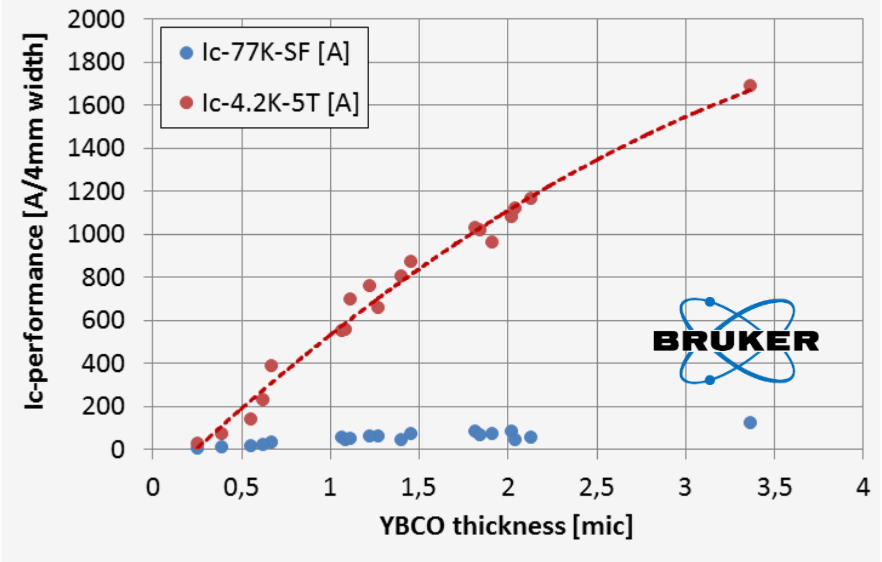
Commercial REBCO tapes: Performance limited by saturation of critical current with increasing REBCO film thickness



A. Molodyk, ASC 2020 SuperOx



Y. Yamada, ICMC, 2019 上海超导



U. Betz, EUCAS, 2019

Thickness of GdBCO [µm]	1.3	1.6	1.8	2.2	2.7
# of turns (RCE chamber)	16	18	18	18	18
Moving speed [m/min]	2.0	2.0	1.8	1.4	1.0
I_C [A/12mm-w]	600~800	700~900	800~1,000	1,000~1,200	600

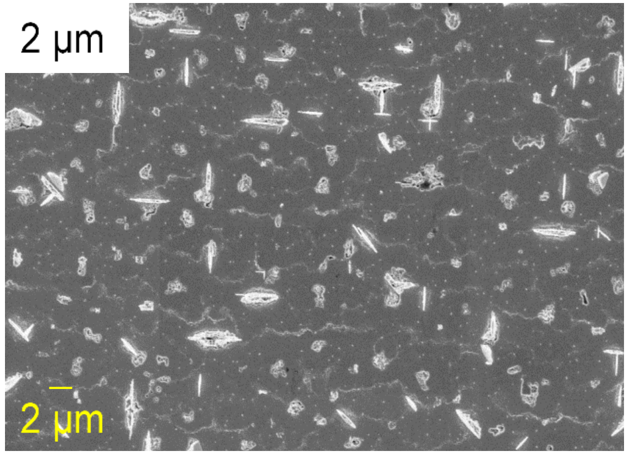
Production thickness

R&D run

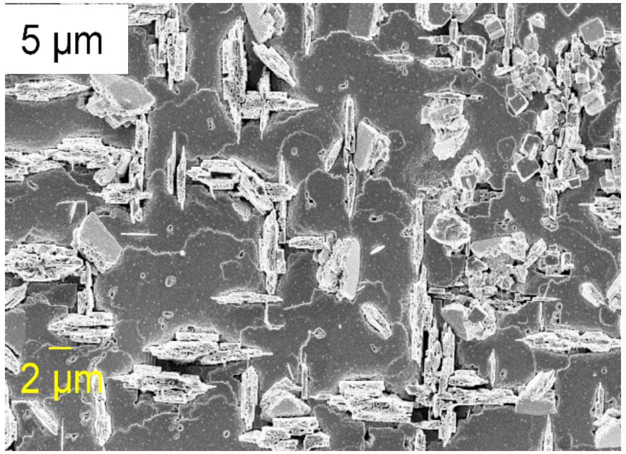
S. Moon, ICMC, 2019 SuNAM

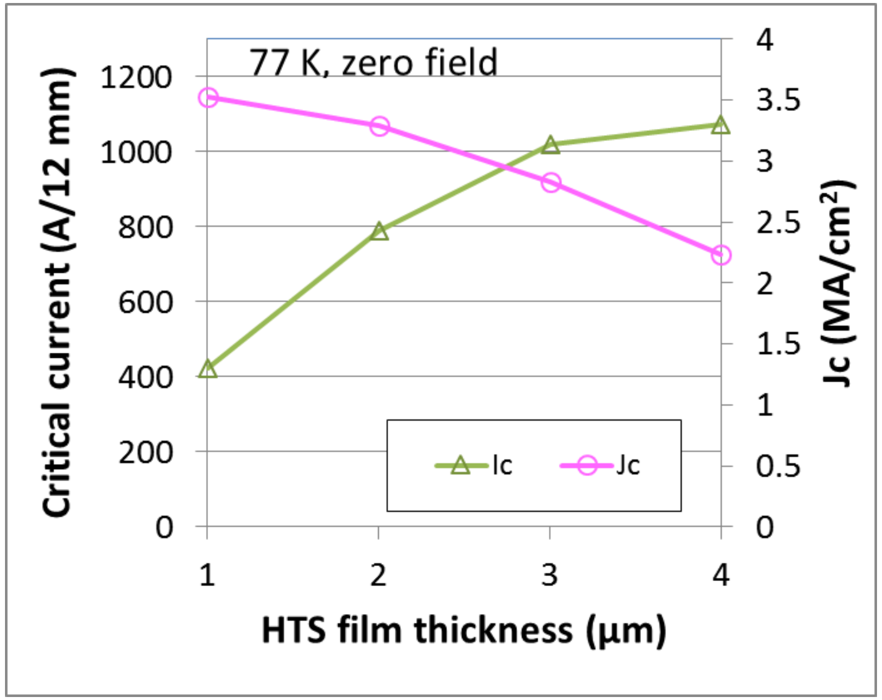
Degradation in HTS film growth with increasing thickness in conventional process

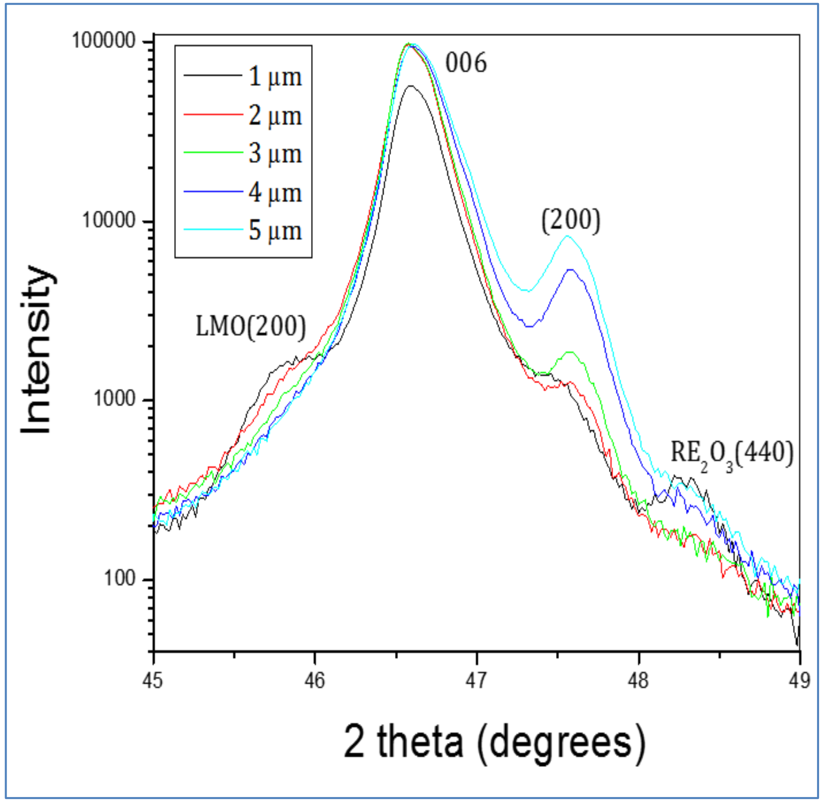
2 µm



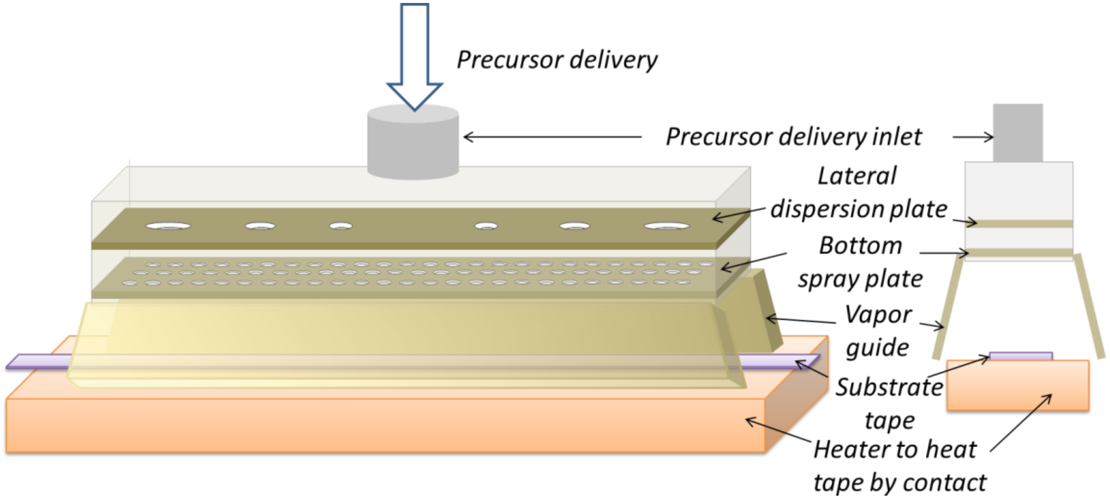
5 µm

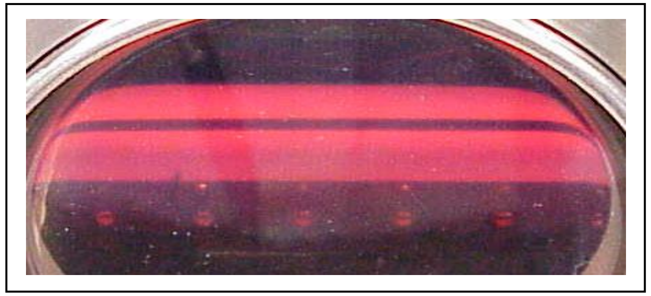




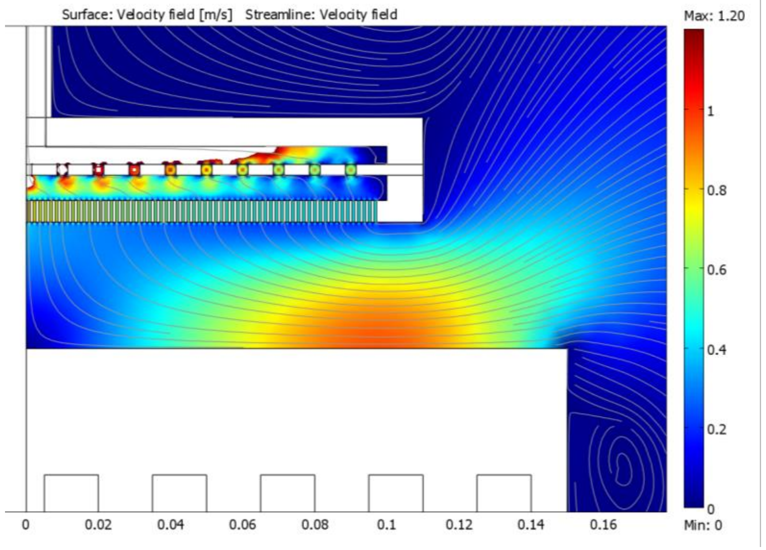


Deficiencies of conventional MOCVD reactor: Challenge in process control





Contact heating in conventional MOCVD

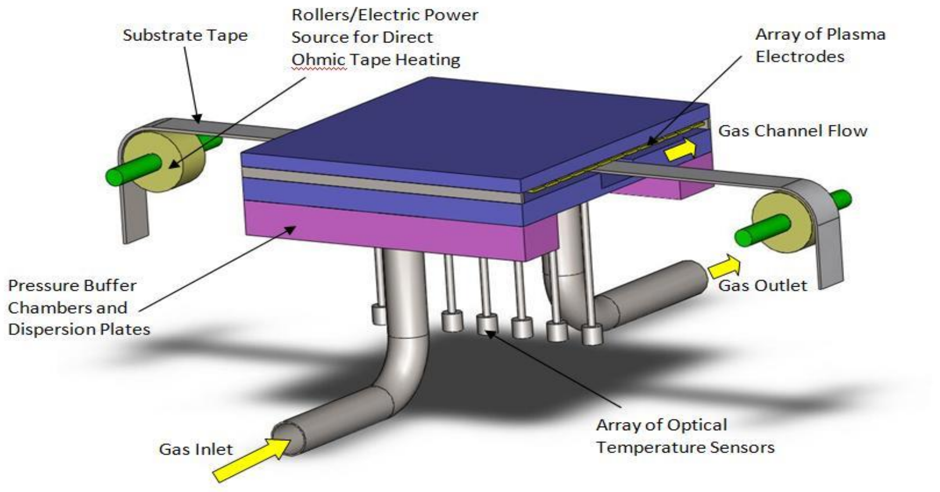


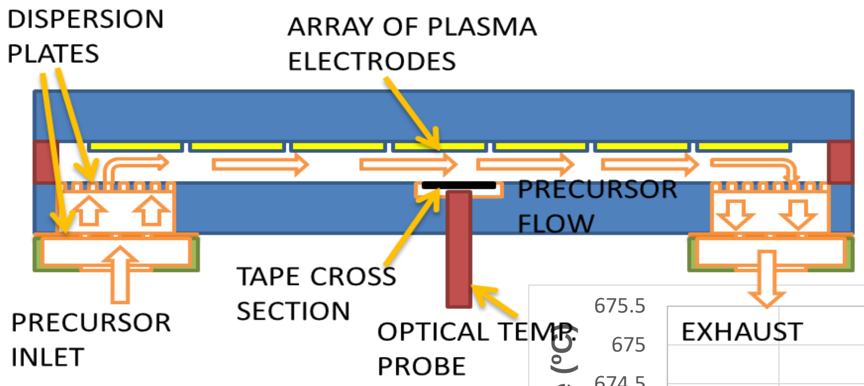
- Temperature control of tape is critical for high in-field I_c, but tape temperature is not directly monitored or controlled in all existing MOCVD systems
- Apart from uniform heating, precursor flow non uniformities cause non uniform temperatures

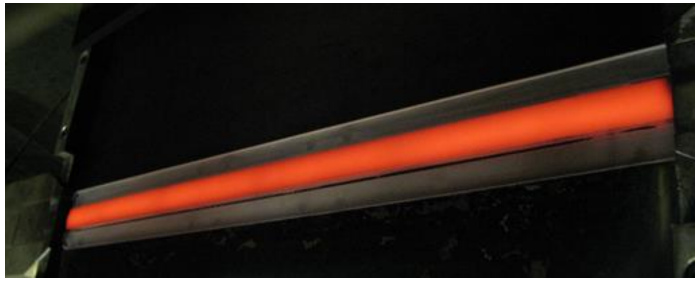
Conventional MOCVD system design is not suitable for level of process control needed for high and consistent performance that is critical for uniform in-field I_c

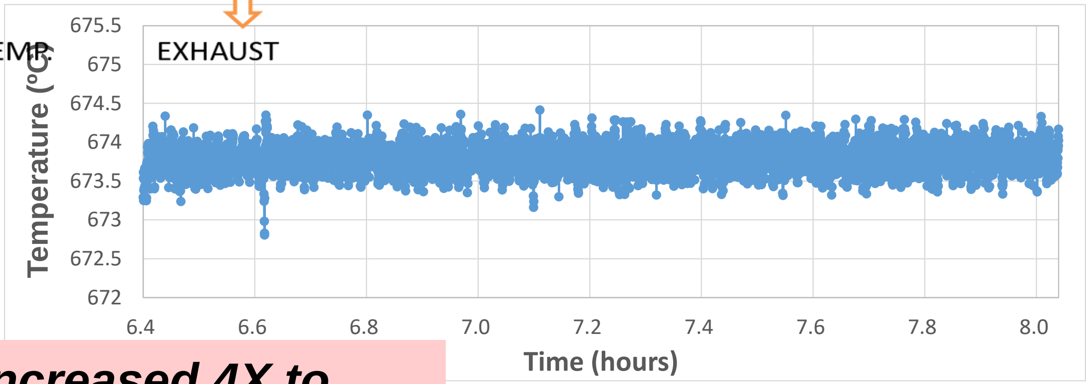
Advanced MOCVD for high performance, low-cost, high-yield production

- Advanced MOCVD reactor addresses all deficiencies of current production tools designs
  - Excellent control of tape temperature by Direct tape heating and Direct tape temperature monitoring → 5µm thick films & 10X BZO density
  - Low volume, laminar flow reactor → 5X precursor-to-film conversion efficiency





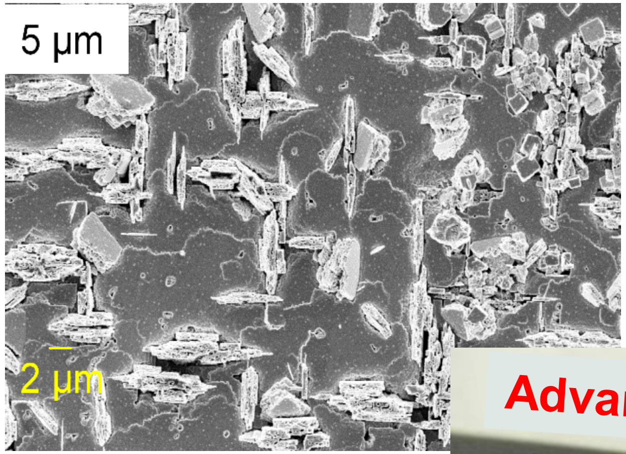




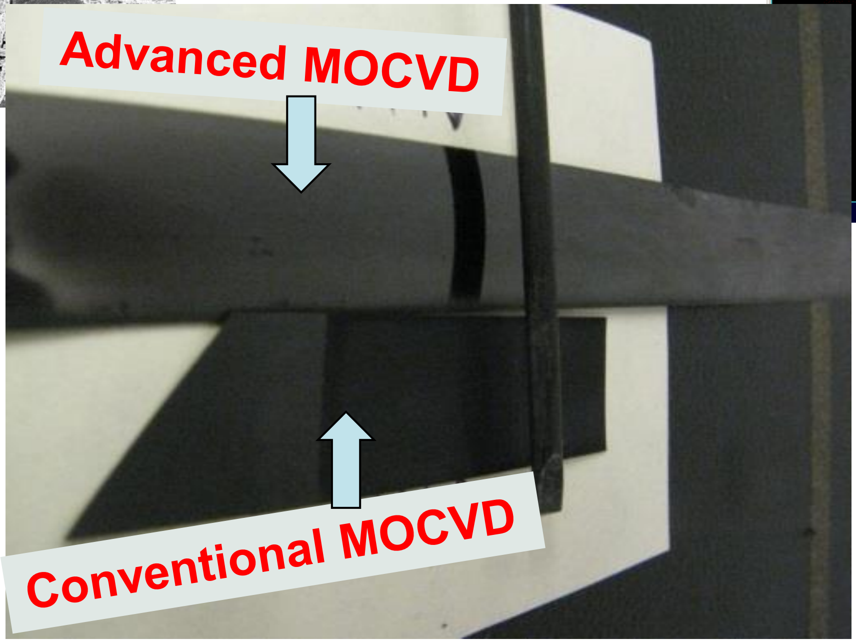
Precursor-to-film conversion efficiency already increased 4X to 46% by Advanced MOCVD → 3X reduction in total tape cost

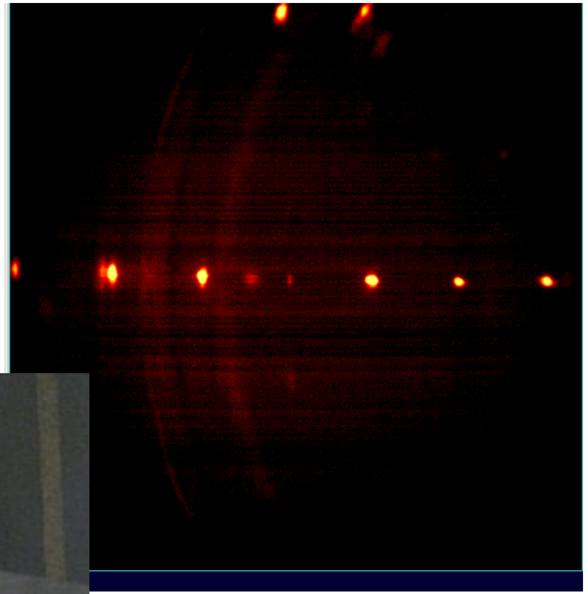
AMI Advanced Manufacturing Institute
TcSUH

4 - 5 µm thick film deposited by Advanced MOCVD in a single pass with purely c-axis oriented REBCO

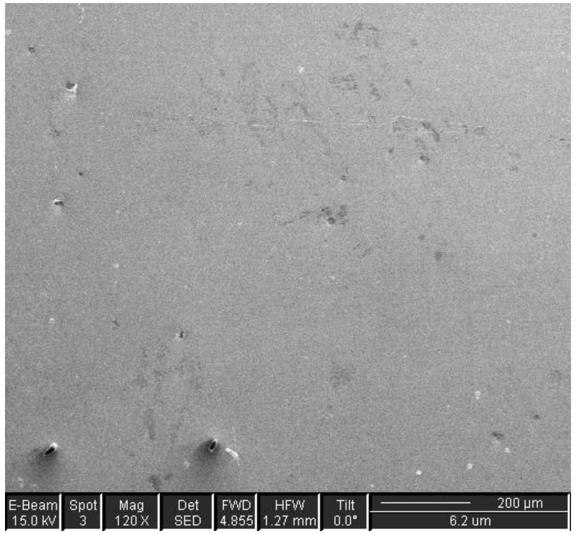


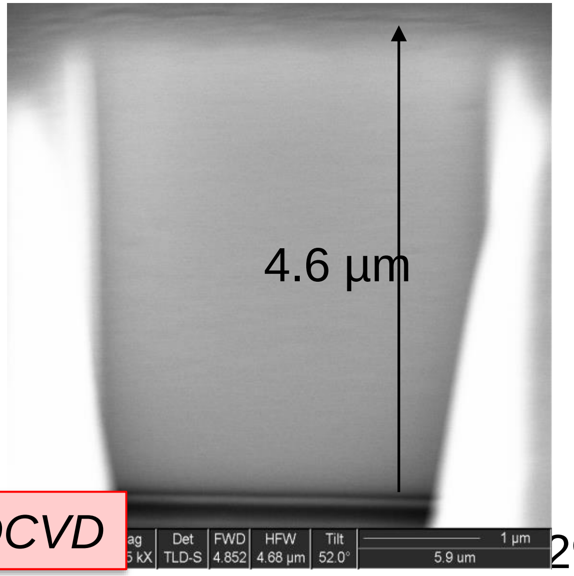
Previous 5 µm REBCO film by conventional MOCVD made in 5 passes





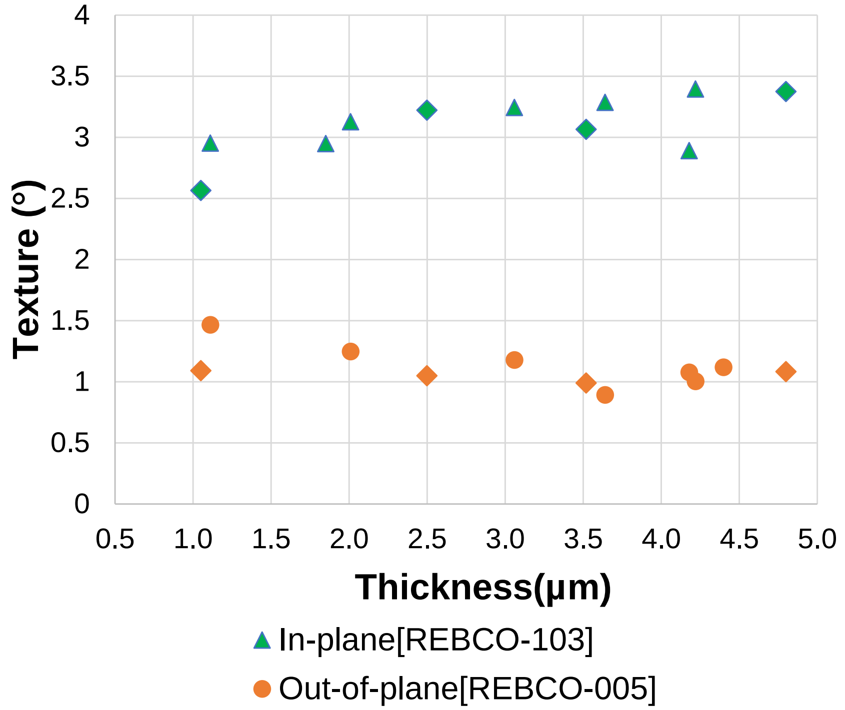
4-5 µm REBCO film by Advanced MOCVD in 1 pass

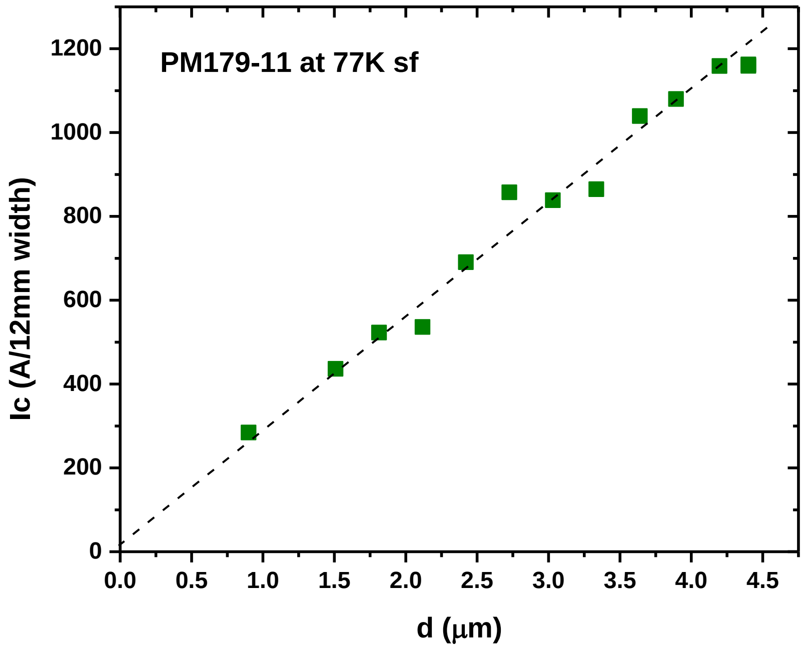


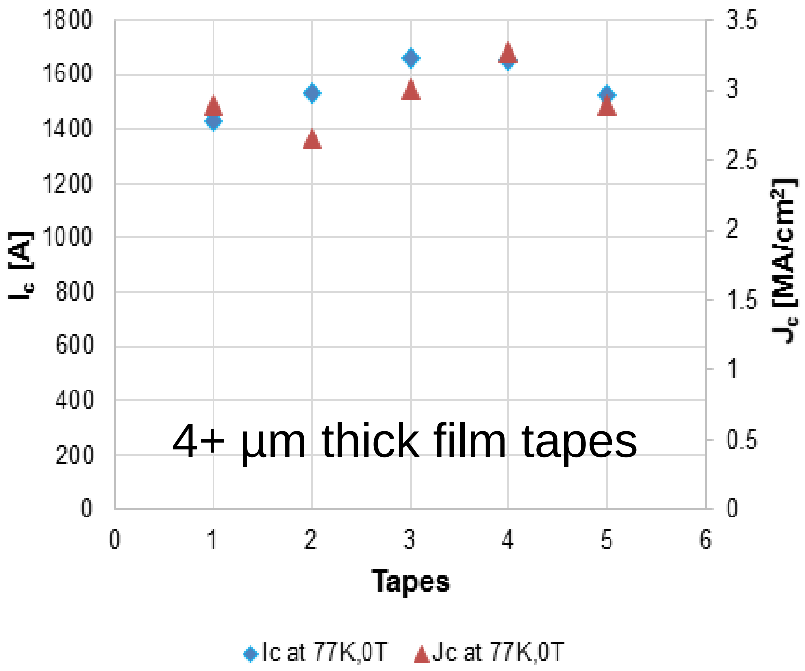


Routinely fabricating tapes with 4 – 5 µm thick films in single pass by Advanced MOCVD

High I_c thick film REBCO tapes by Advanced MOCVD







IEEE Trans. Appl. Supercond. **29,** 6600905 (2019)

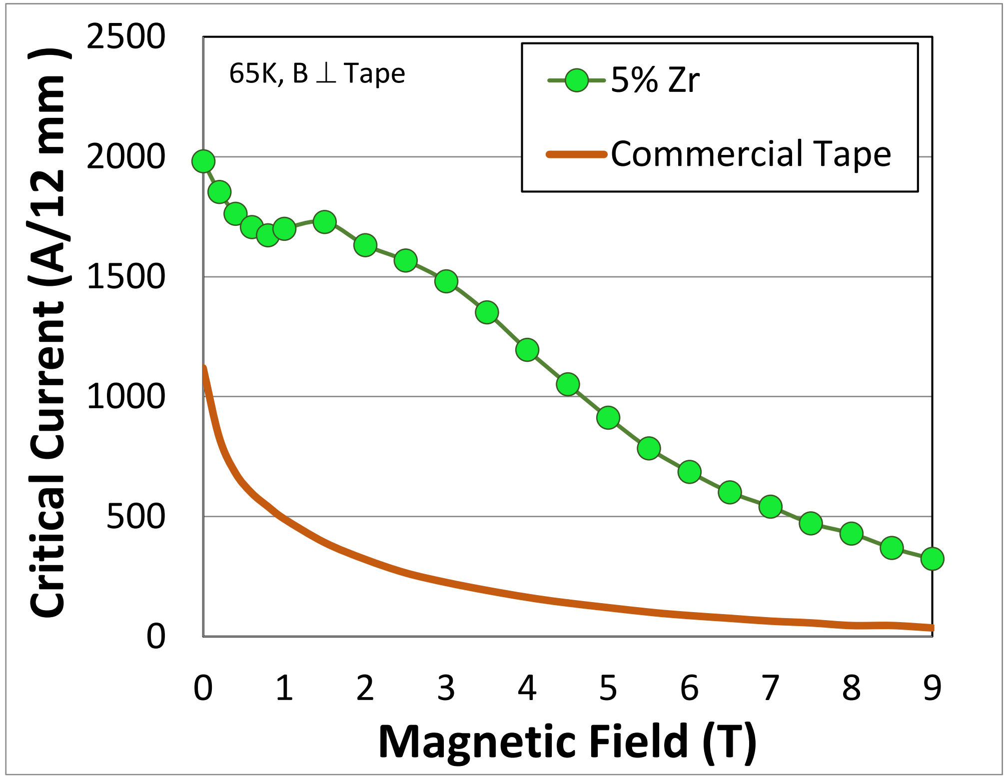
- *No change in in-plane and out-of-plane texture even up to 5 μm thick films*
- *Approx. 300 A/μm-thickness and J_c is almost constant with thickness*
- *I_c^{sf} (77K) = 1660 A/12 mm (record high current in single time deposition in a MOCVD process)*

  J_c^{sf} (77K) = 3 MA/cm^2

High critical current thick film tapes for electric machines

High Temperature, low-medium field

65K – 77K, 1 – 3 T

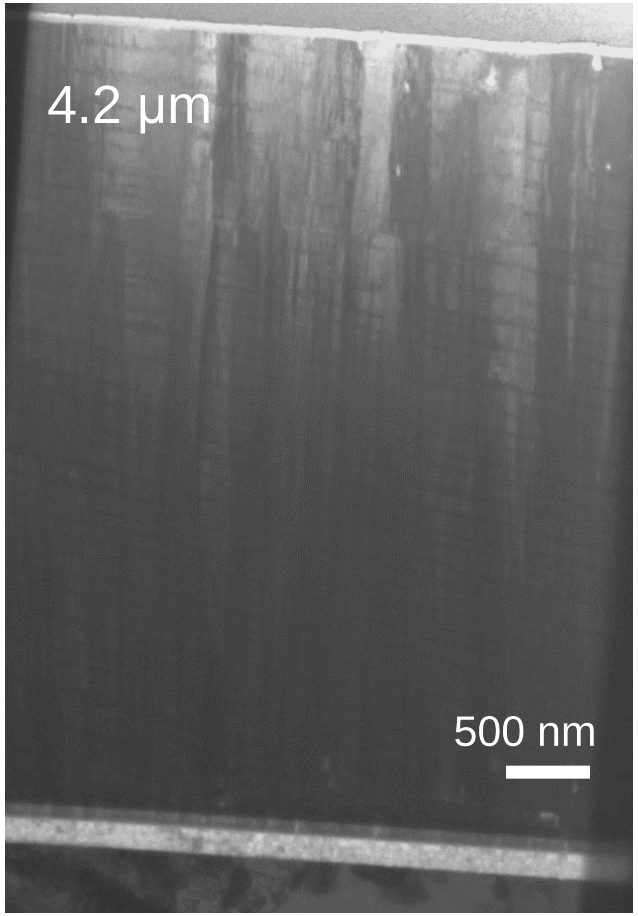


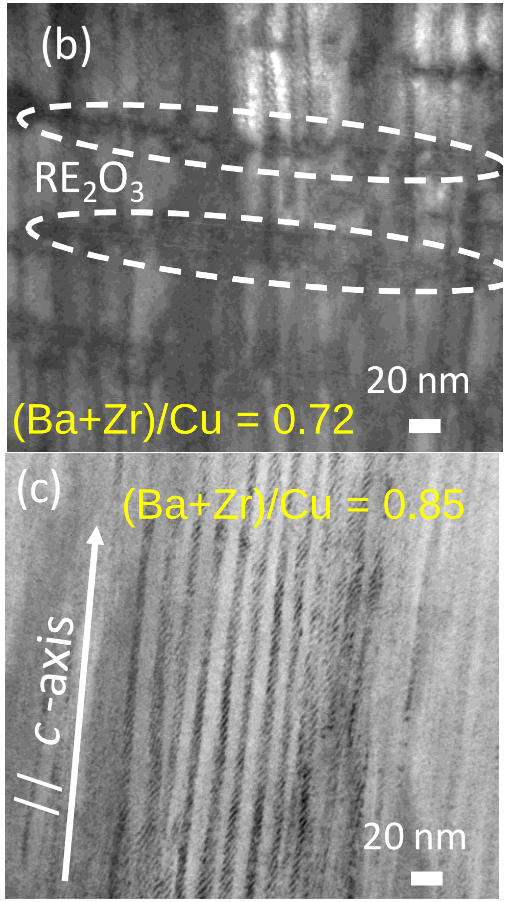
Next-generation Electric Machines

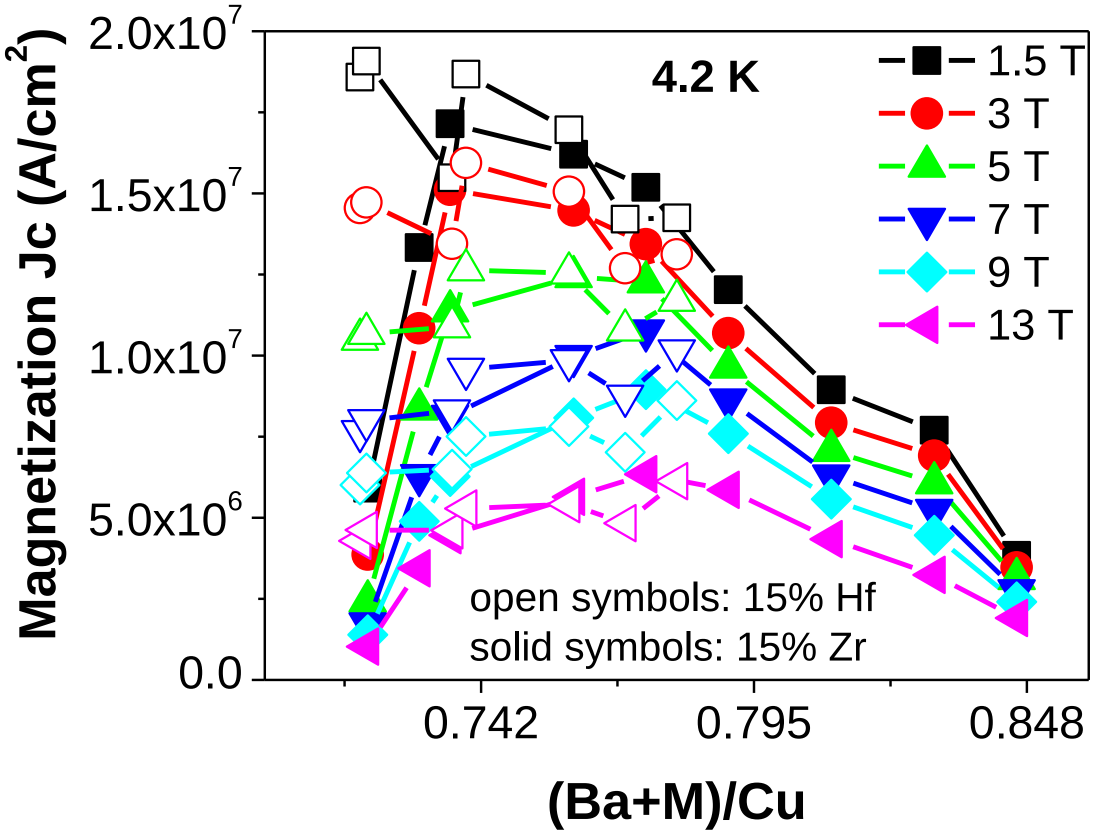
5% Zr-added thick film REBCO tapes yield the best performance at 65 K, 1.5 T
*- **4.4X critical current of commercial REBCO tape***

AMI Advanced Manufacturing Institute TcSUH

In-field J_c at 4.2 K tailored by (Ba+M)/Cu content; BZO/BHO nanocolumns and REO depend on Ba content



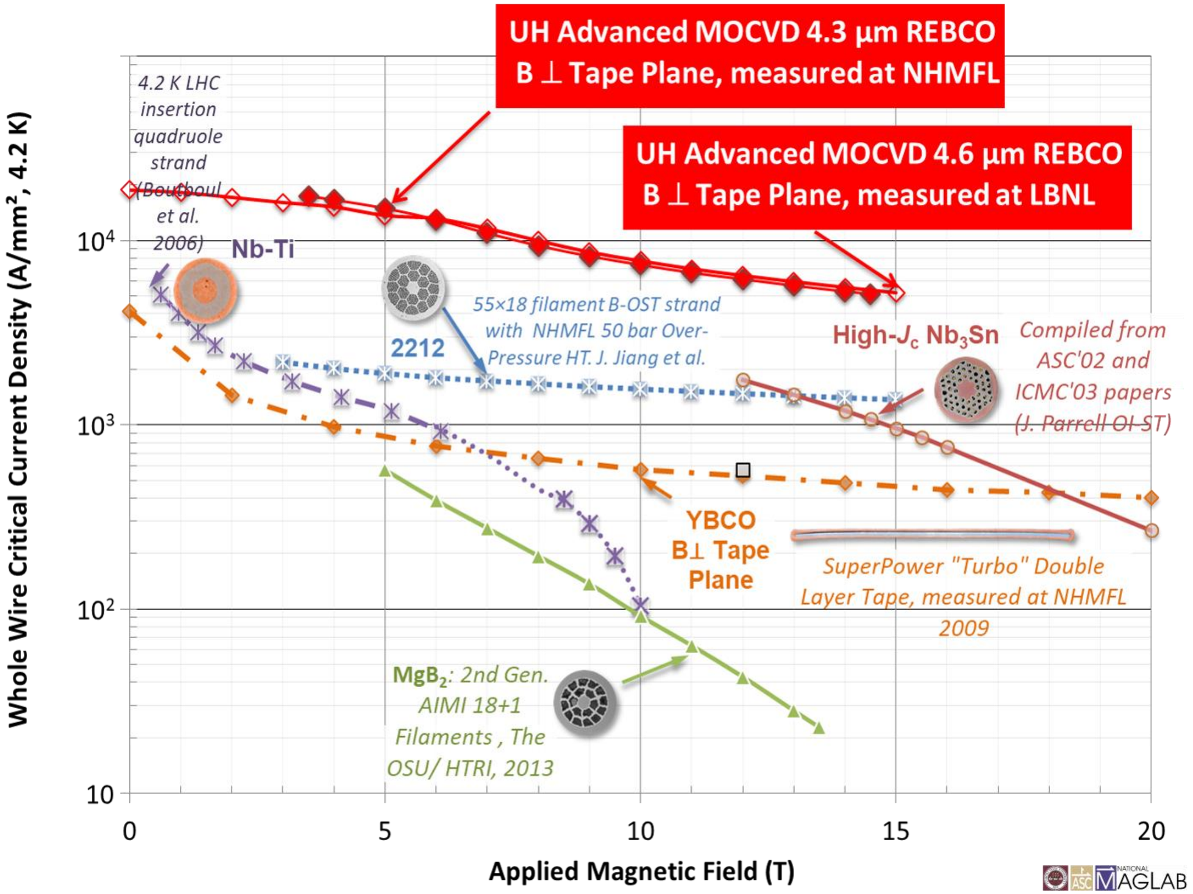


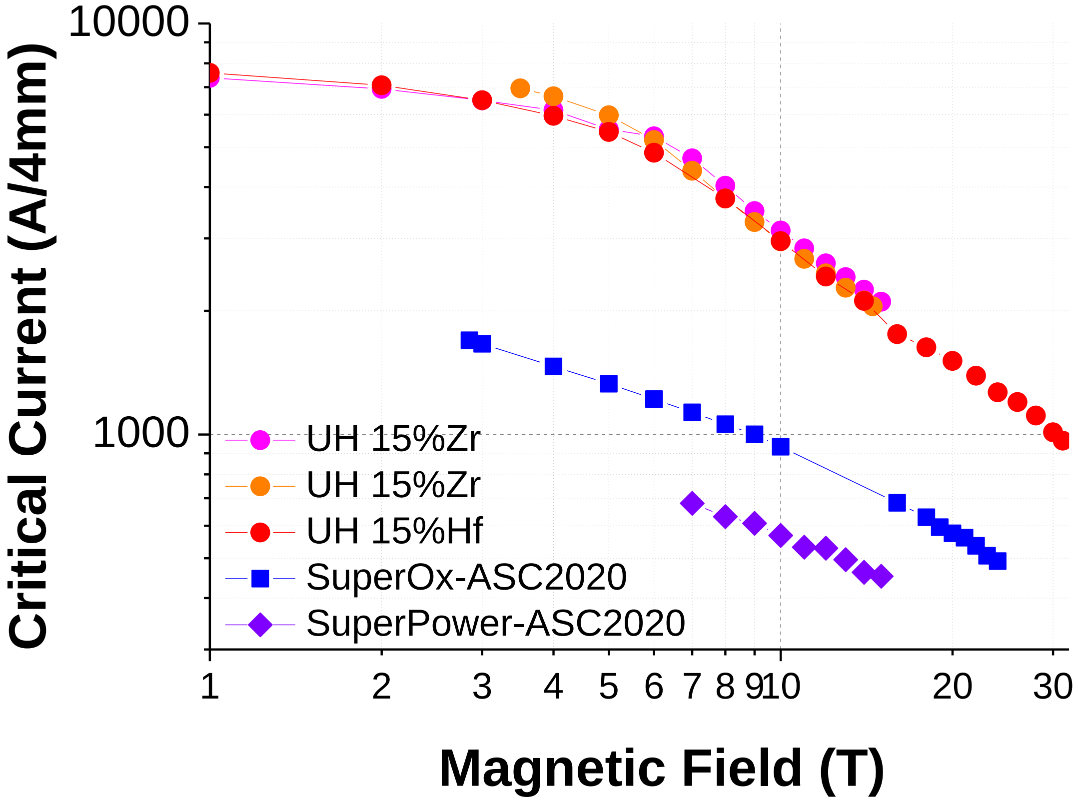


Supercond. Sci. Technol. **33** 074007 (2020)

Galstyan et al. ASC 2020

REBCO tapes made by Advanced MOCVD exhibit very high critical currents in high magnetic fields at 4.2K





J_e of UH REBCO @ 4.2 K, 15 T = 5200 A/mm^2

5.4x Nb_3Sn @ 15 T

I_c of UH REBCO @ 4.2 K, 20 T = 1510 A

2.62x best commercial (PLD) REBCO tape at 20 T

4.65x best commercial MOCVD REBCO tape at 15 T

Supercond. Sci. Technol. **31** 10LT01 (2018).

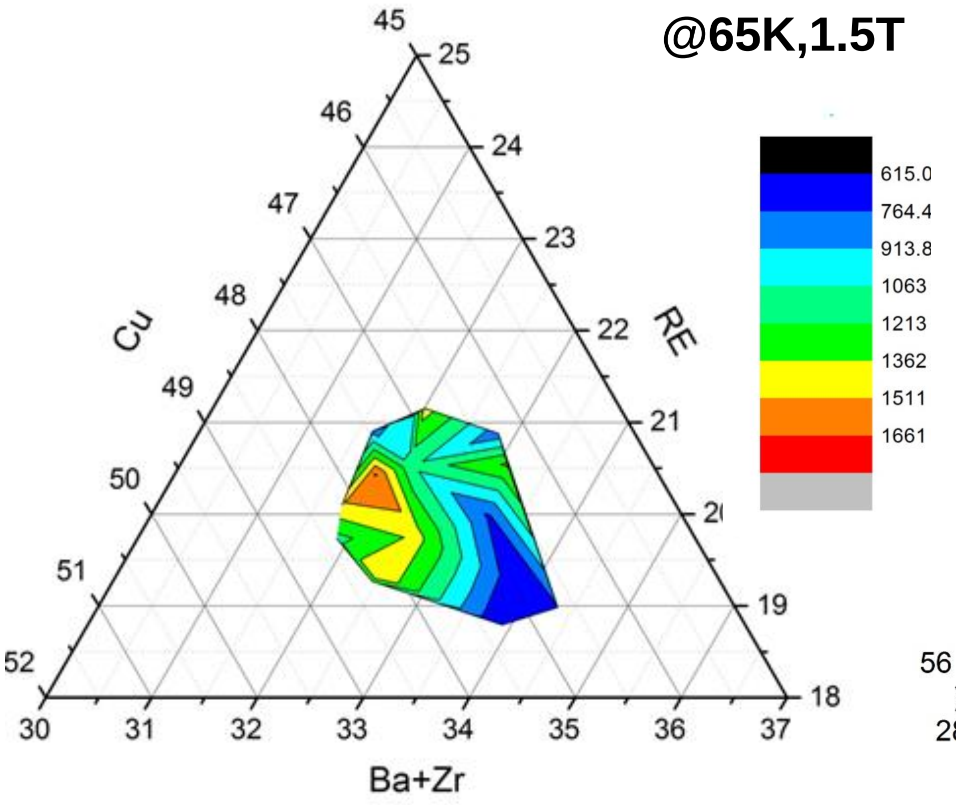
Data maintained by Peter Lee, NHMFL, http://fs.magnet.fsu.edu/~lee/plot/plot.htm

Development of In-line and Continuous Quality-Control Tools for High-yield Manufacturing

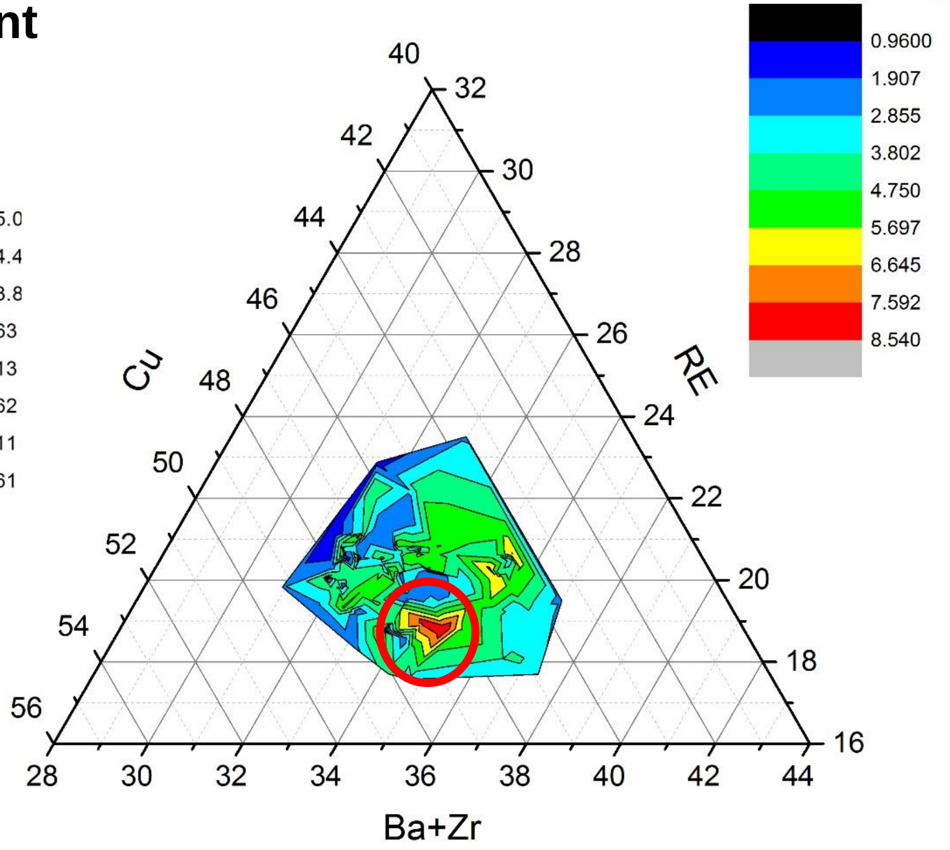
Pilot-scale Advanced MOCVD built and commissioned for REBCO tape manufacturing

Compositional control of REBCO film important for high in-field J_c

Critical current @65K,1.5T

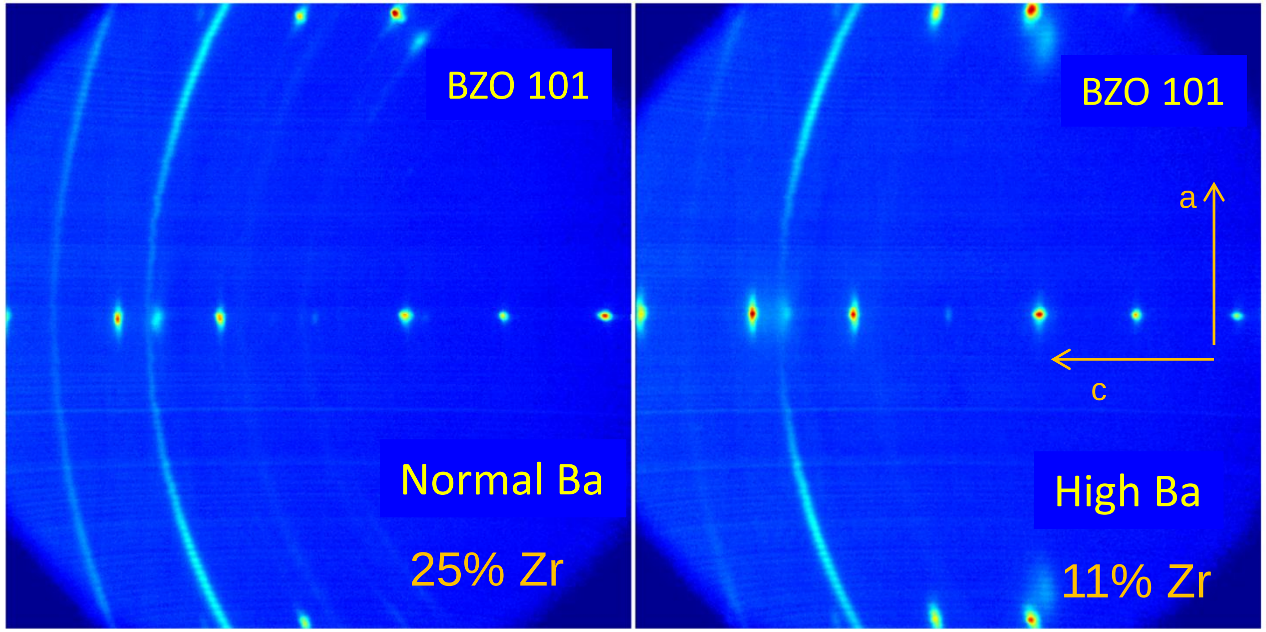


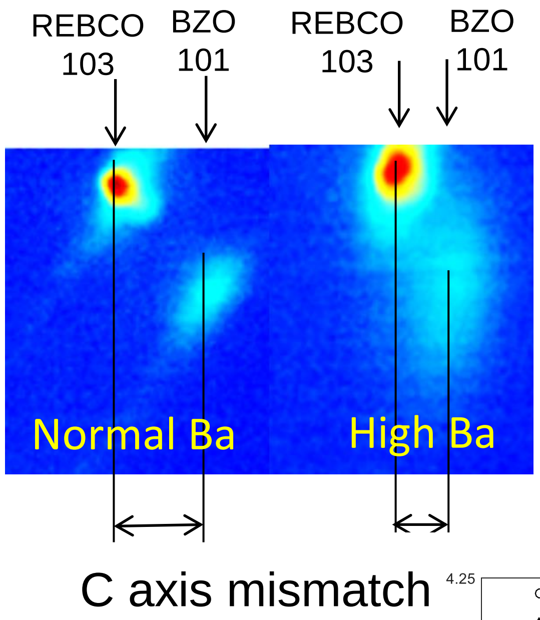
Magnetization J_c at 4.2K, 13T

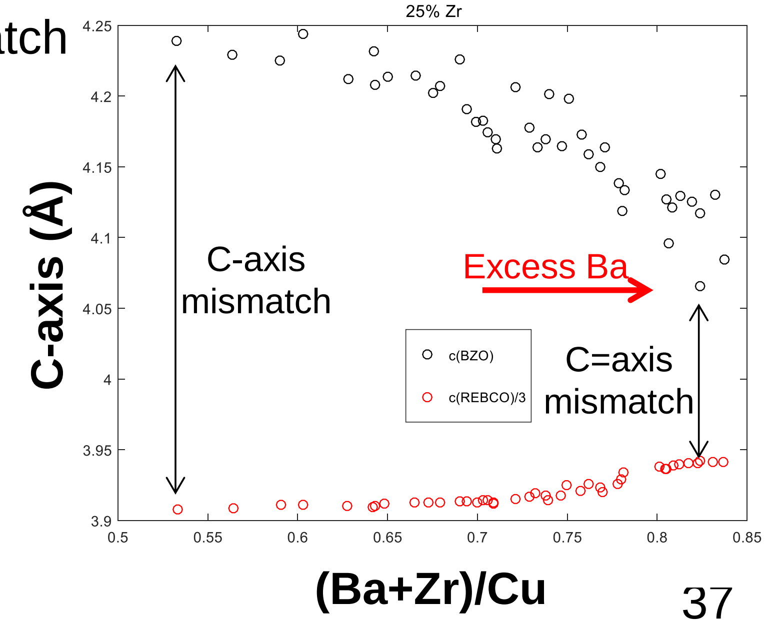


Non-destructive method needed for rapid evaluation of REBCO film composition during manufacturing of long tapes

2D-XRD: Rapid non-destructive method to evaluate REBCO film composition



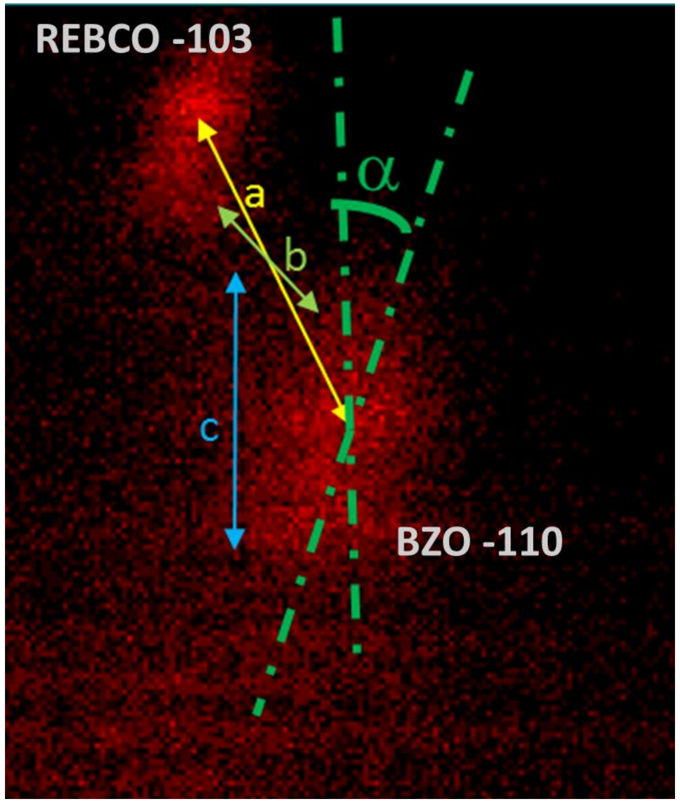


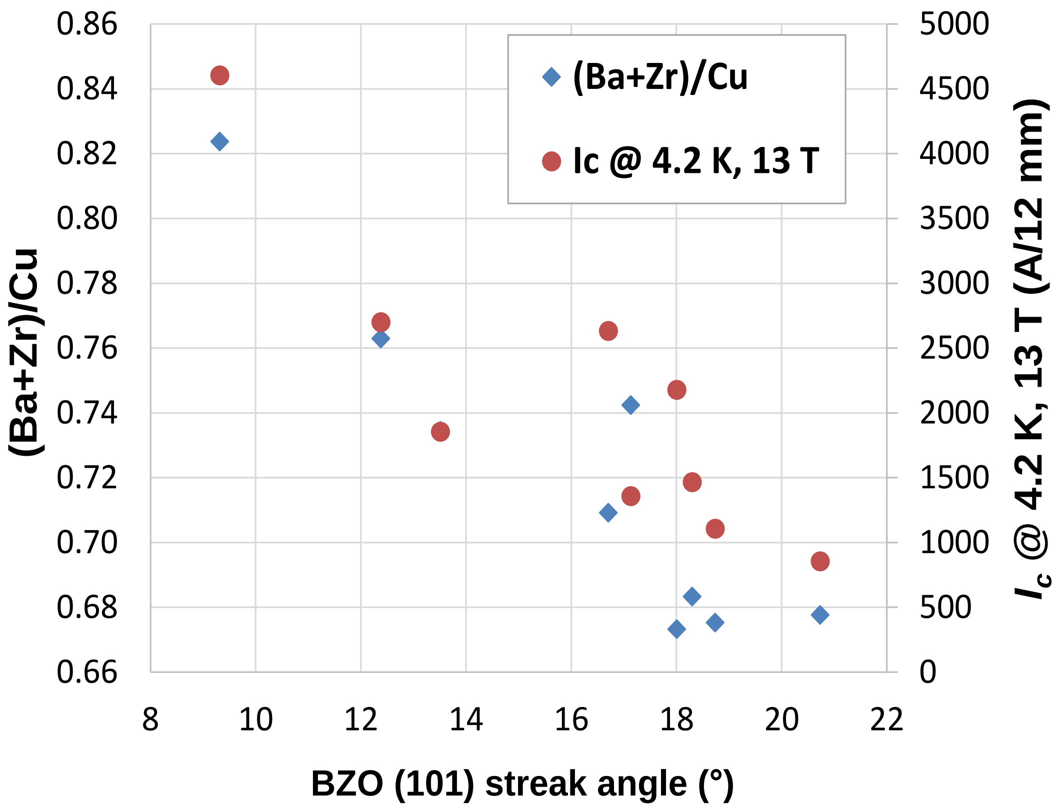


- Streaking of BZO (101) peak towards REBCO (103) peak
- C-axis lattice mismatch between REBCO and BZO decreases with increasing Ba/Cu composition

AMI Advanced Manufacturing Institute
TcSUH

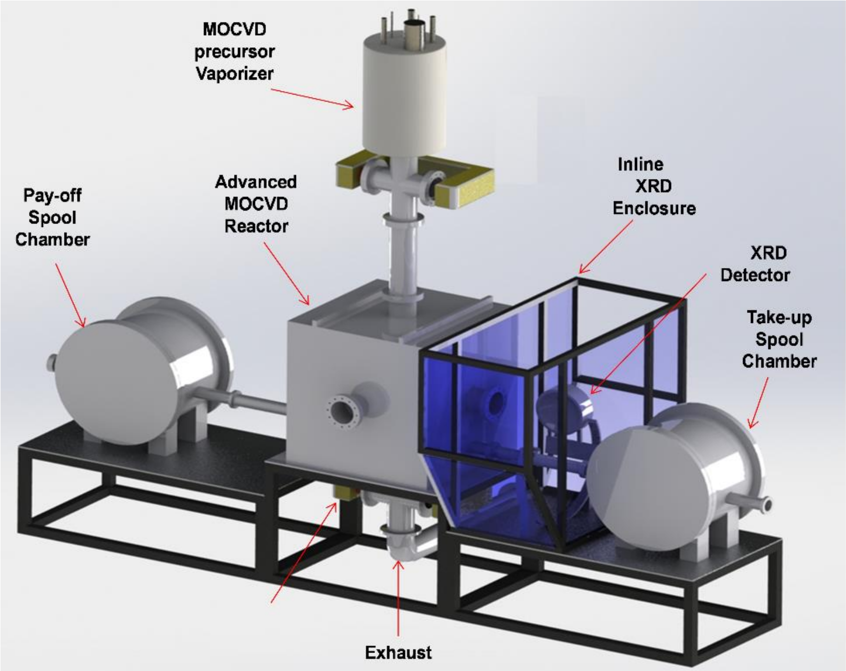
2D-XRD: Rapid non-destructive method to evaluate REBCO film composition

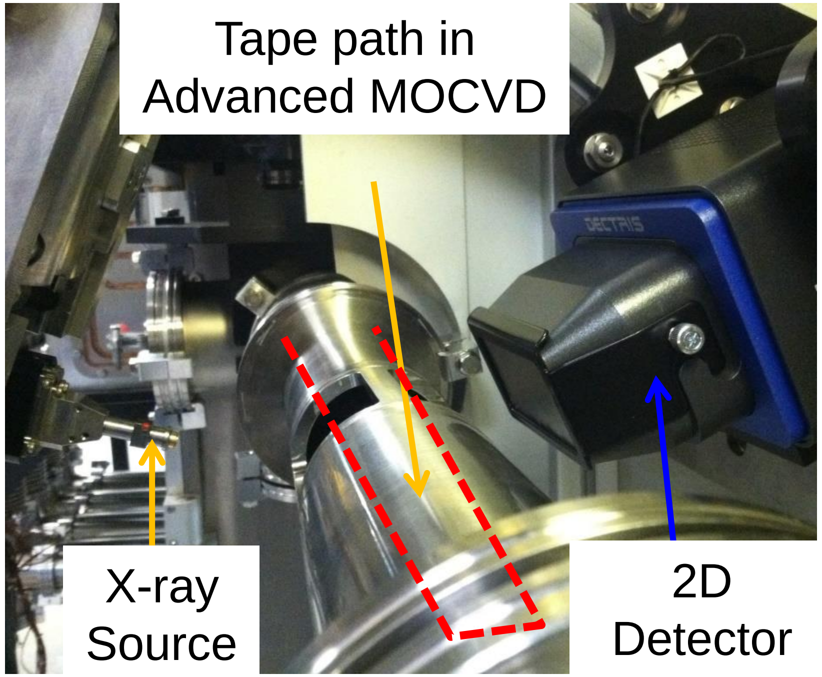




BZO (101) streak deviation angle good indicator of BZO nanocolumn size and film composition

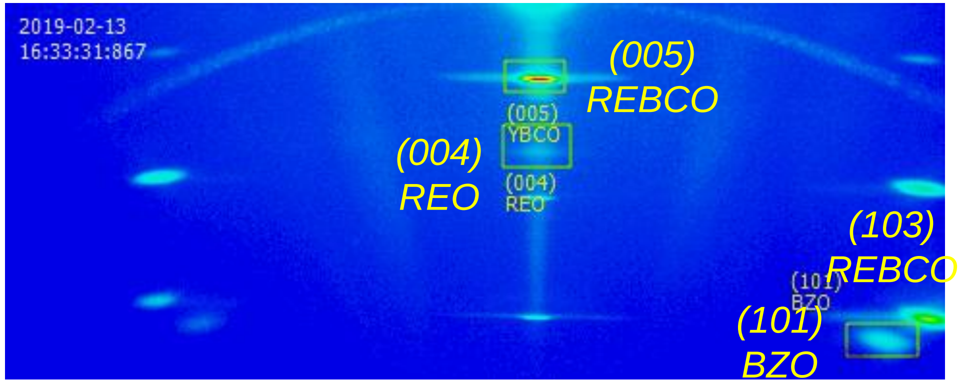
In-line 2D XRD built and installed in pilot Advanced MOCVD tool for REBCO film quality monitoring & control

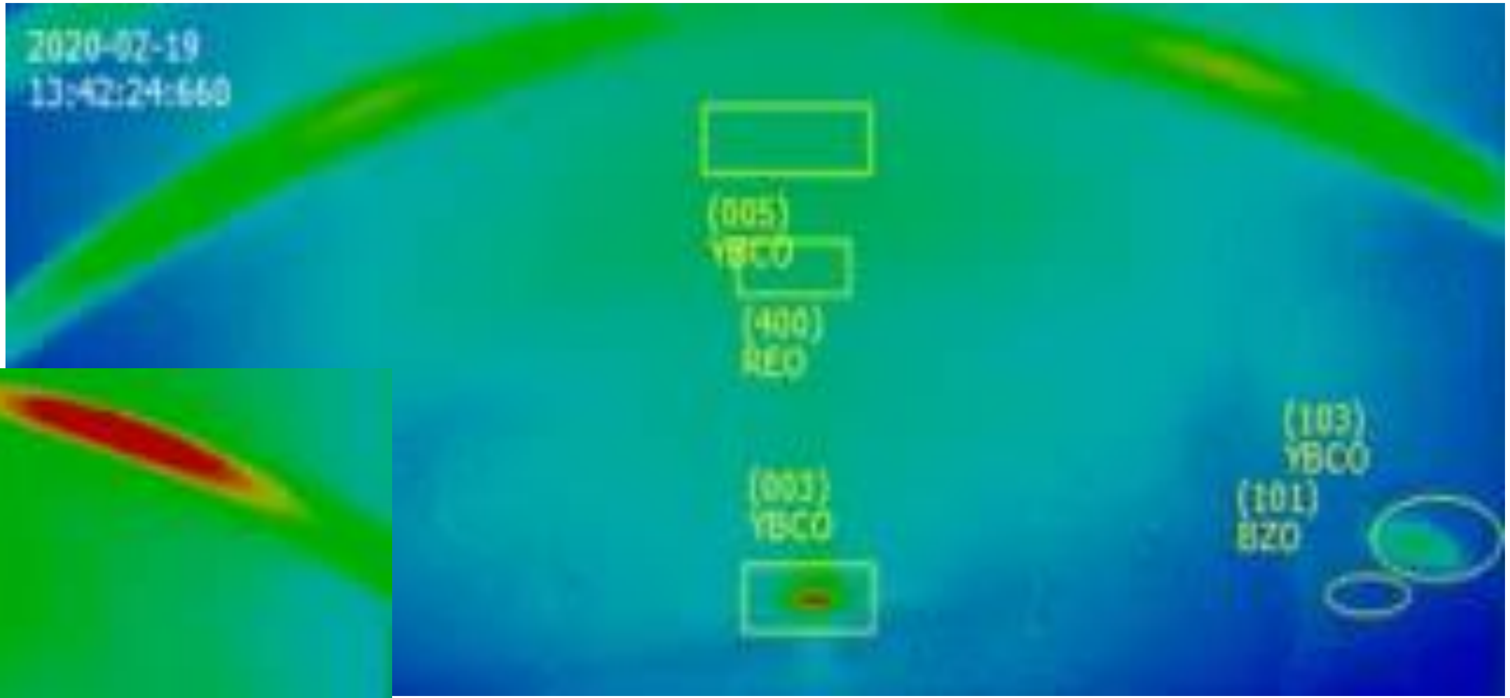


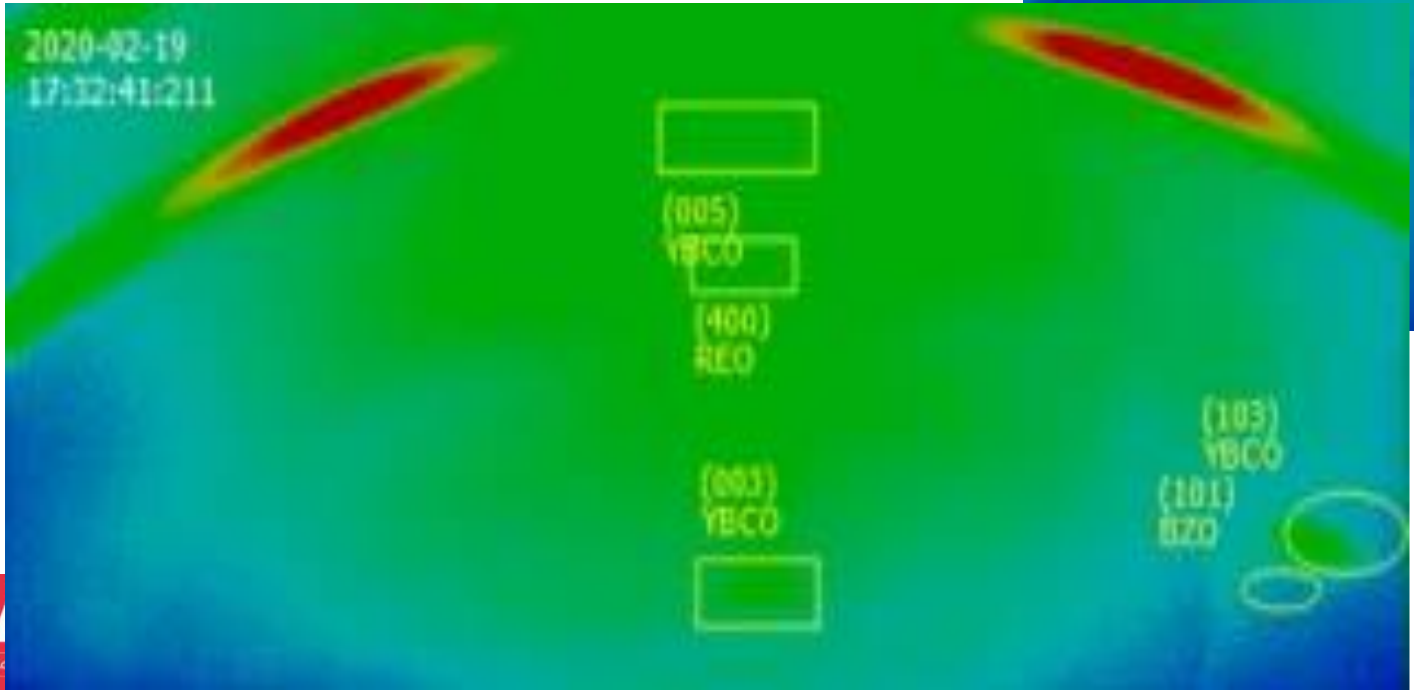


In-line 2D-XRD in MOCVD manufacturing tool for real-time measurement of BZO streak deviation angle, REBCO peak intensity, REO peak intensity → to achieve consistent in-field performance

Continuous 2D-XRD data acquisition along tape length during REBCO film deposition in Advanced MOCVD

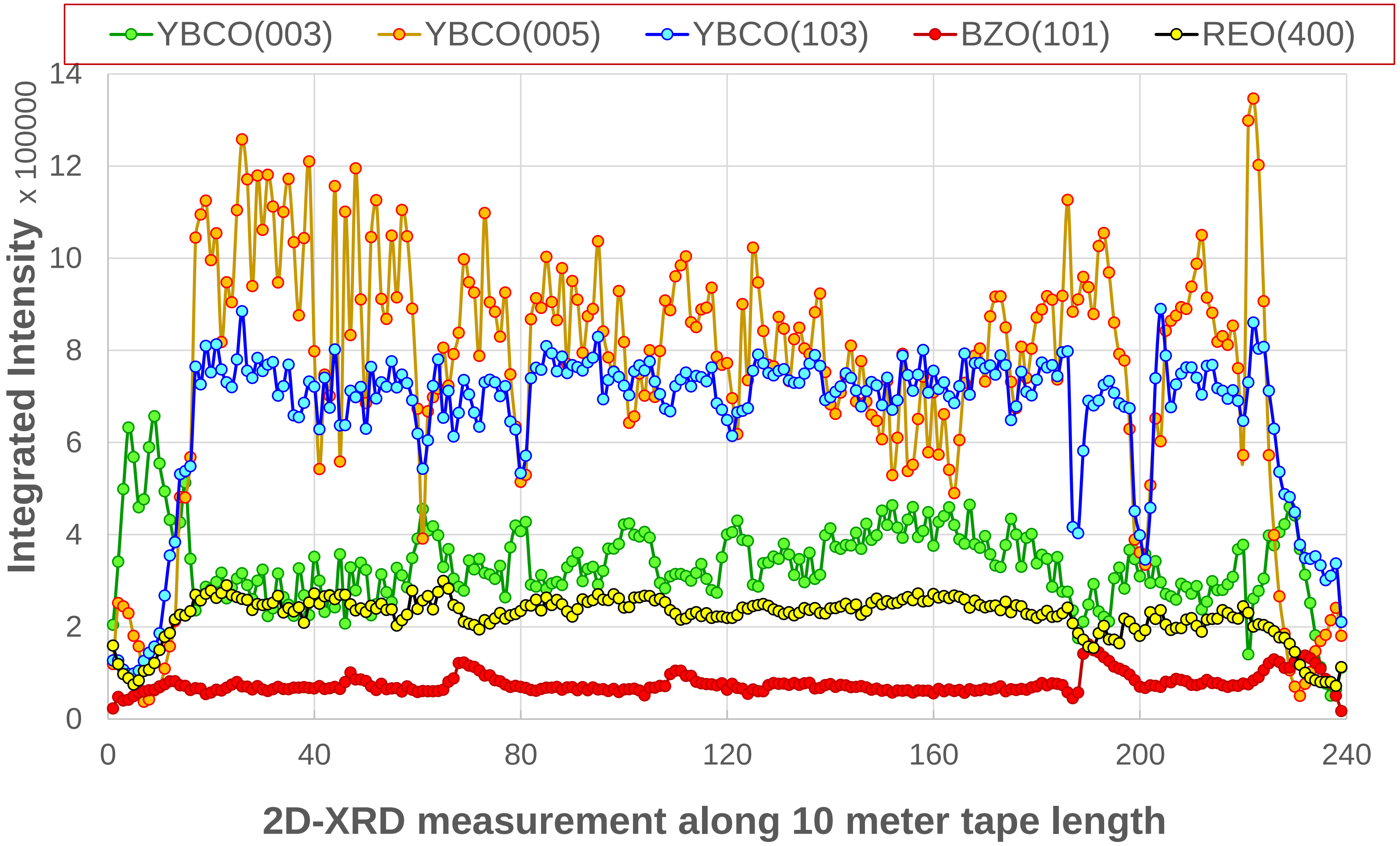




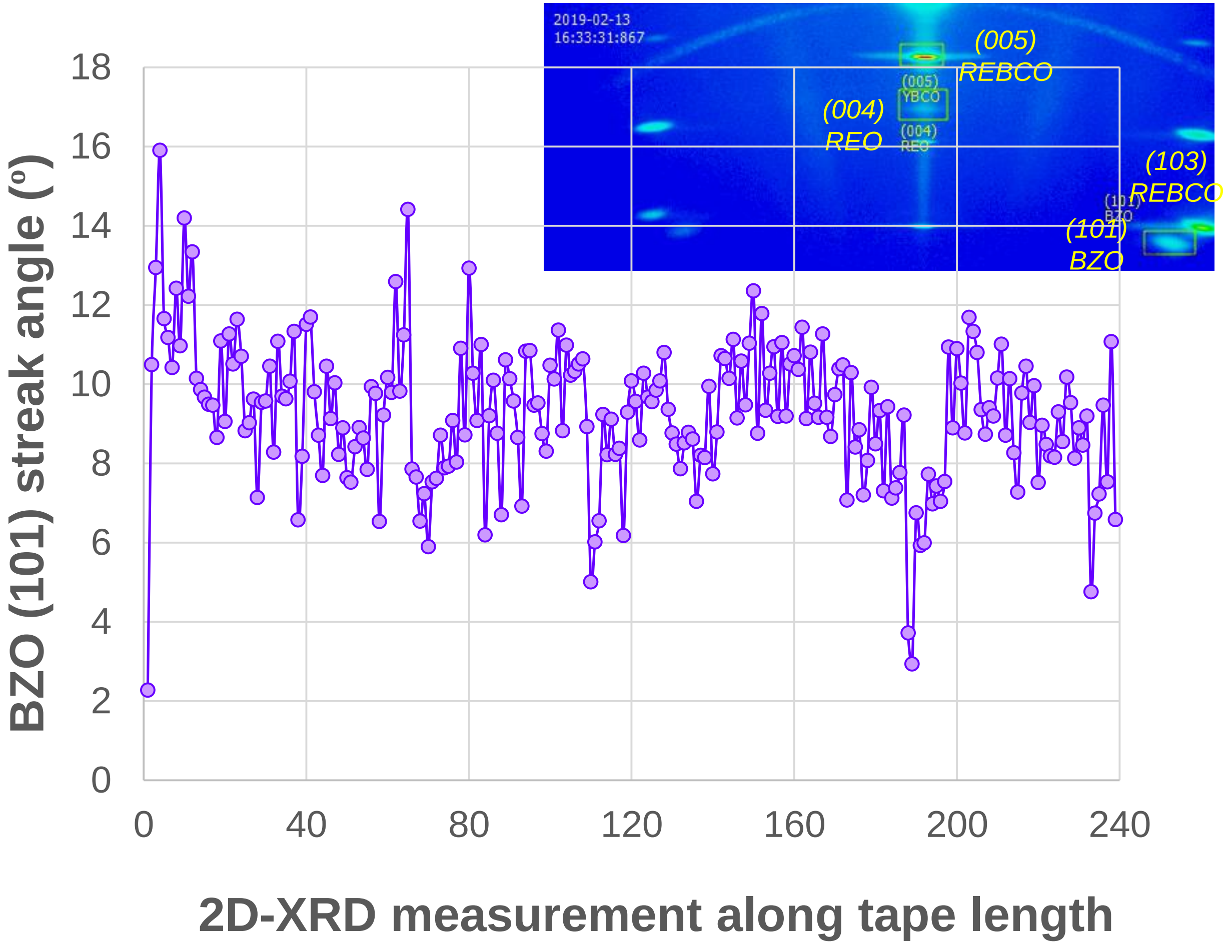


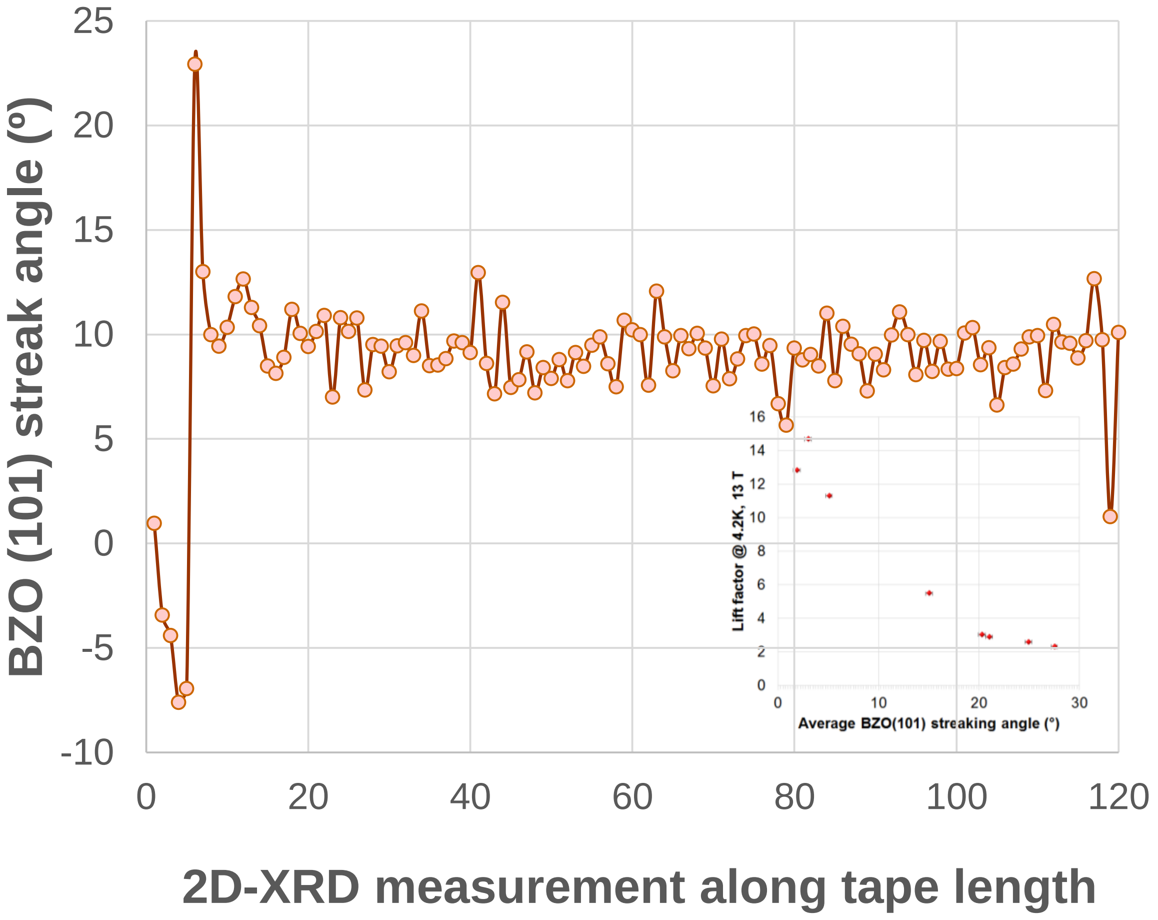
Key phases (REBCO, BZO, REO) identified in a single snapshot in in-line 2D XRD in pilot MOCVD tool

Integrated intensity of REBCO, BZO, REO peaks along tape length continuously during REBCO film deposition



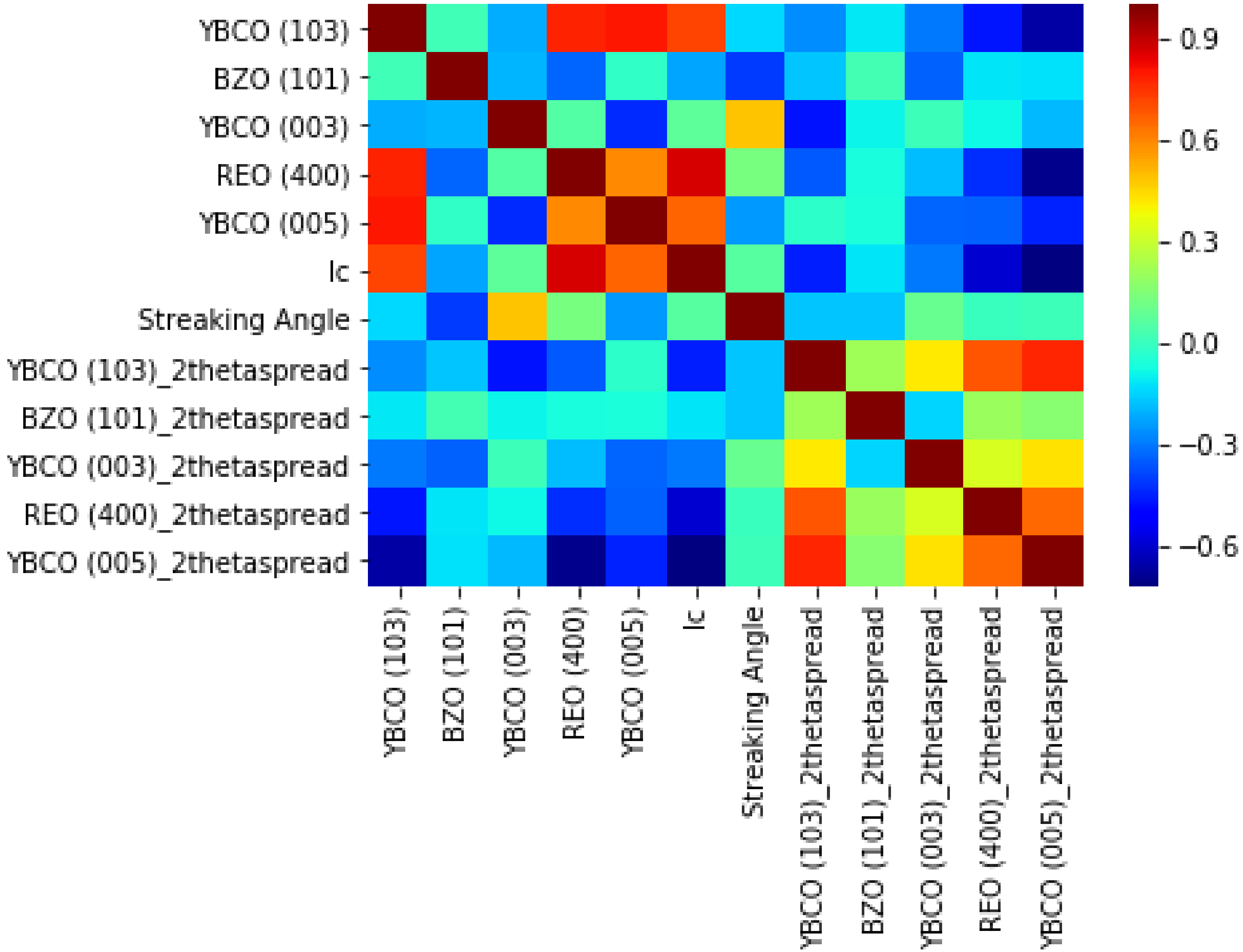
BZO (101) peak streak angle measured along tape length continuously during REBCO film deposition





Next: Use real-time 2D-XRD data to control deposition process for uniform microstructure → uniform performance

Correlation map of 10 m tape I_c at 77 K, 0 T with in-line 2D-XRD data



Opportunities in REBCO manufacturing

- High-yield manufacturing of high-performance, lower-cost REBCO tapes
    - Scale up thick film REBCO tapes to 100+ m lengths with high in-field I_c
        - Use in-line QC with feedback to process for uniform and consistent in-field I_c
    - Develop new R2R testing tools for 100% testing in-field I_c of long tapes based on correlations developed between in-field I_c at 65 K and 4.2 – 20 K.
- High throughput manufacturing
    - Scale up from 1000 km/yr to 10,000 km/yr with high throughput processes
- Incorporate features important for application in tape
    - Quench tolerance, mechanical robustness, flexibility, round geometries, low loss.

2020s – the decade HTS takes off to a real commercial, large-volume product!