

Manufacturing of High-Performance, Low-cost, REBCO Superconductors for Large-scale Deployment

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 Superconductors Provide Versatile Solutions Across Many Industries

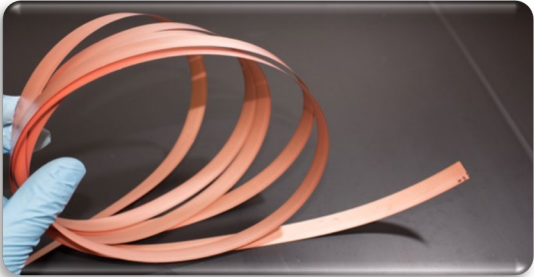
Energy

- Cables
- Transformers
- Generators
- Energy Storage
- Grid Protection



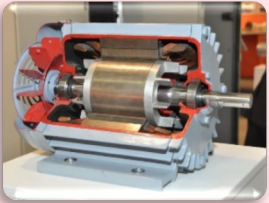
Defense

- Airborne generators
- All electric ship
- Degaussing cables
- Rail guns

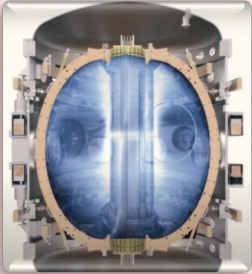


Industry

- NMR
- Fault Current Limiters
- Motors
- Induction Heaters
- Magnetic Separation



Compact Fusion




Transportation

- Maglev trains
- Electric aircraft
- All electric ship
- Rocket Propulsion

Research

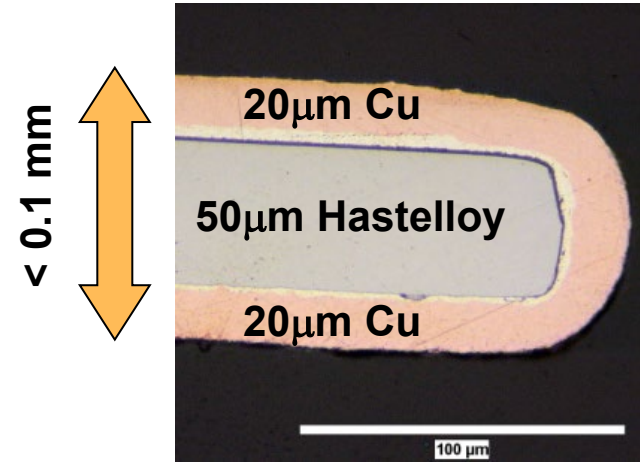
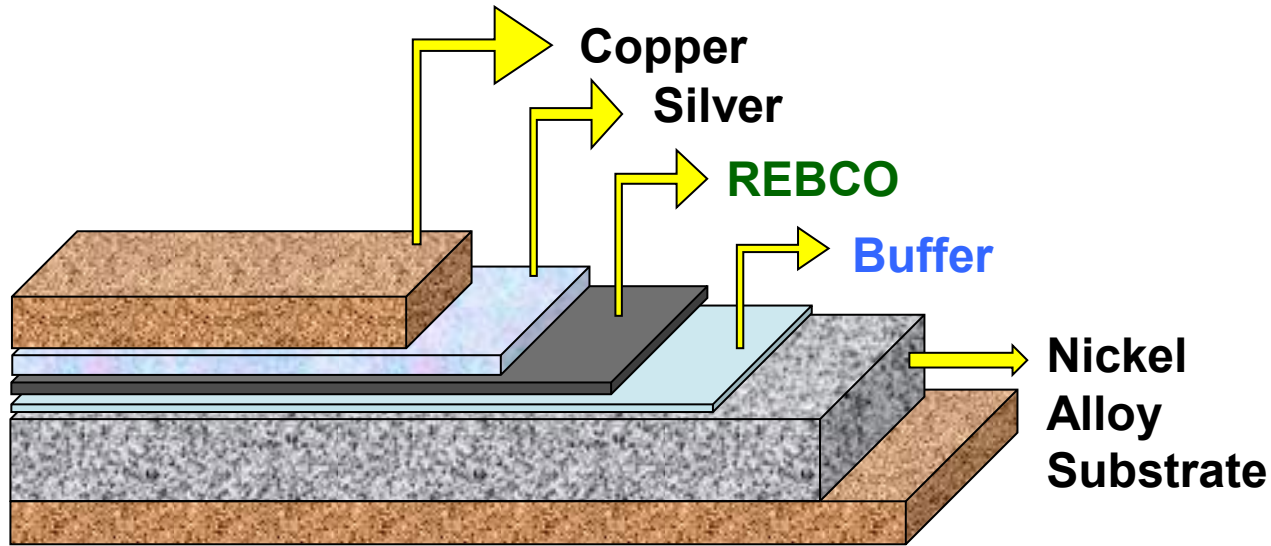
- High-field magnets
- High energy physics
- Drug discovery



- High energy efficiency
- High power density
- Less CO₂ emission
- Better power quality
- Power grid resilience
- Medical Imaging

REBCO superconductor 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



Superconductor costs and production capacity remain a barrier for widespread adoption

HTS supply severely lags fusion demand

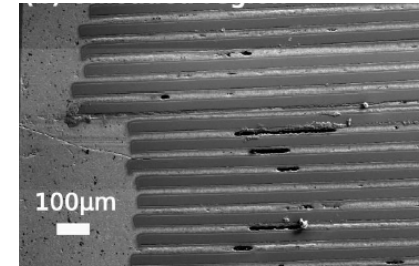
- A single fusion reactor requires **20,000 km** of HTS tape.
- Global production is only a few thousand km today.
- Over 90% of supply concentrated in China and Japan.
- At current prices, tape alone can exceed **\$400M per reactor**.

HTS supply bottlenecked by limitations of commercially-used technologies

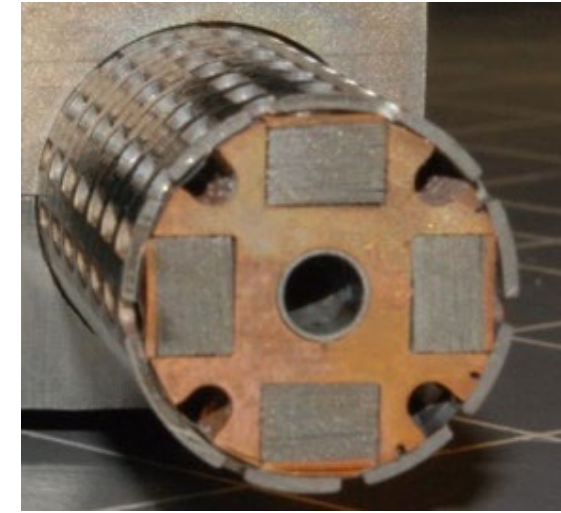
- Pulsed Laser Deposition (PLD) is constrained by **extremely small deposition areas** and **expensive excimer lasers**.
- Conventional MOCVD suffers from **poor material efficiency** and limited process control, **hindering scalability**.

High critical current REBCO is the best way to achieve the additional 3x cost reduction

- Most ultra-high field applications use stacks of many REBCO tapes:
 - ~ 200 - 400 tapes/cable for compact fusion.
- **With higher performance, less tape needed**
 - 3 – 4 GA-m for commercial fusion device.
 - 20,000 km of 'standard tape' needed.
 - **But with I_c 3x standard tape, need 6,600 km.**
 - **Less tape → less burden on tape production**
- **Applications become possible at higher temperatures – simpler cryogenics; fields > 20 T.**



Hartwig, ASC 2020

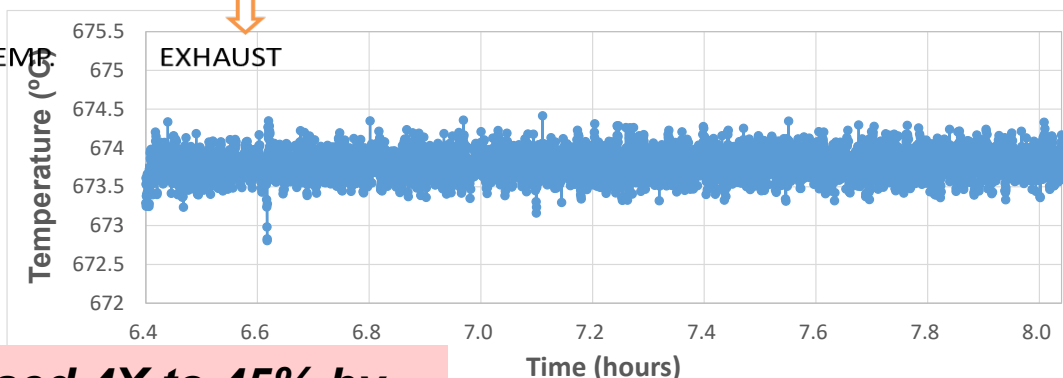
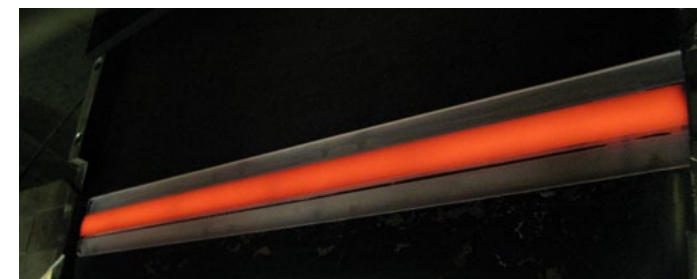
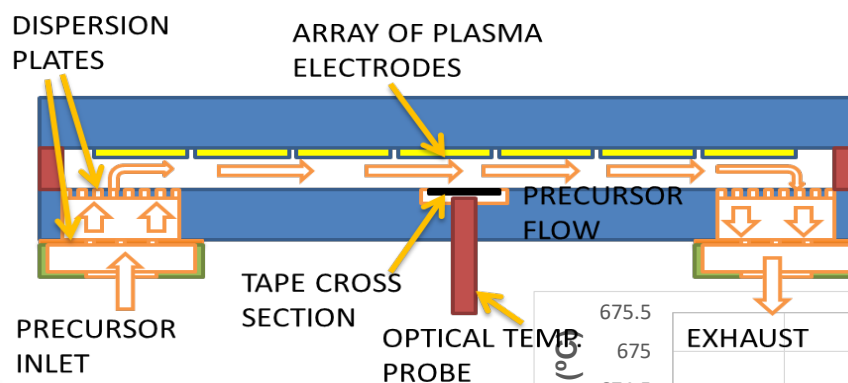
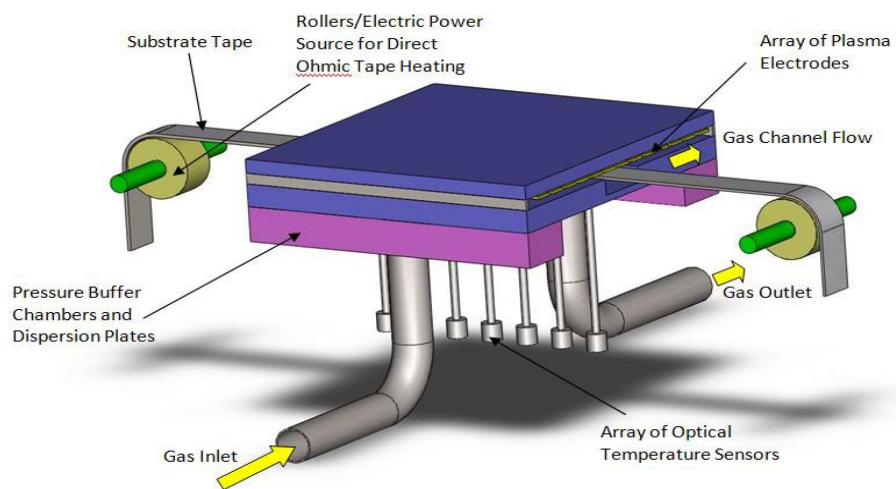


McIntyre et al. *IEEE TAS* 31, 4801705 (2021)

REBCO cables use substantial copper content; current sharing can be engineered to safely use high current REBCO tapes

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

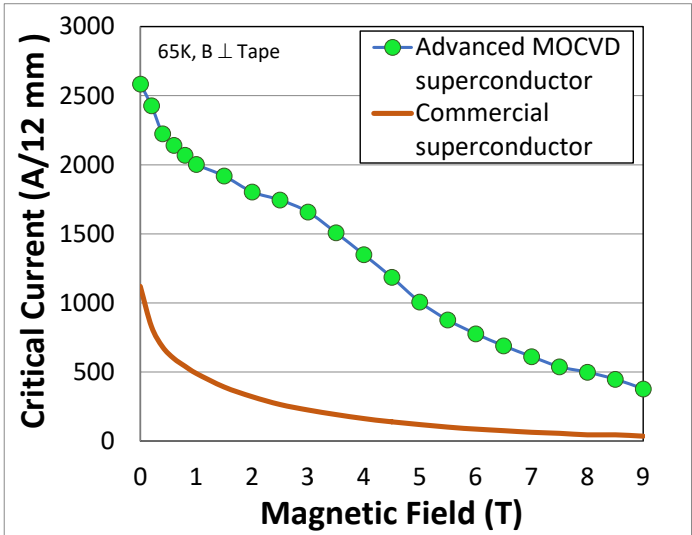
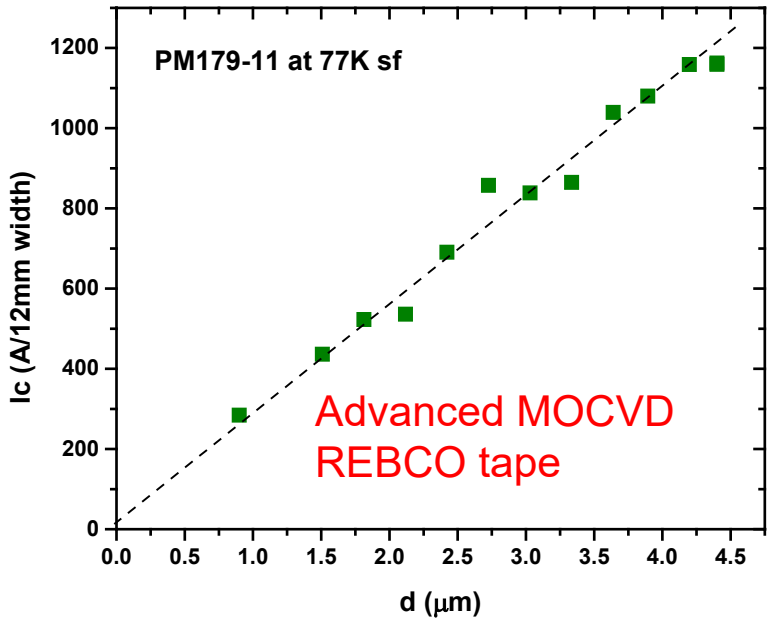
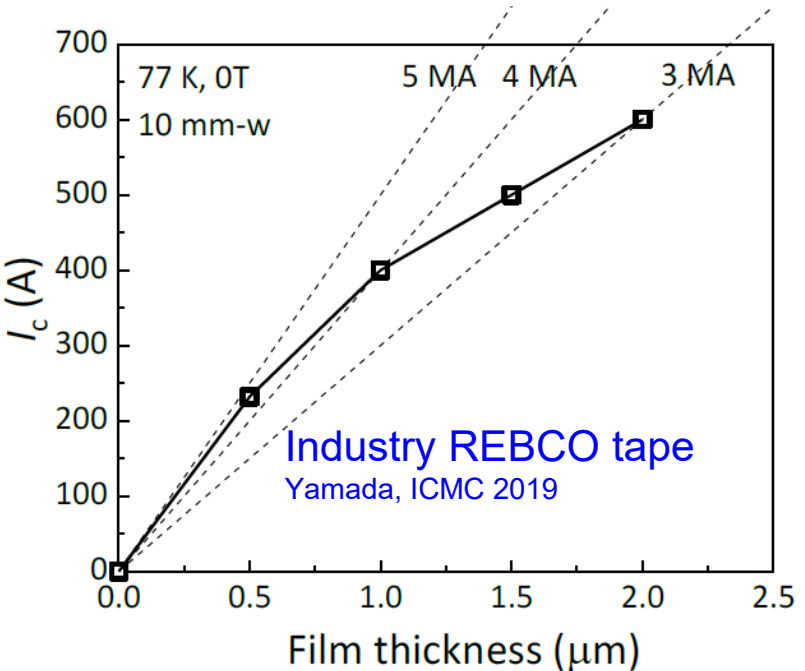
- Advanced MOCVD reactor addresses all deficiencies of current production tools designs
 - Excellent control of tape temperature by Direct tape heating and Direct tape temperature monitoring → 5μm thick films & 10X BZO density
 - Low volume, laminar flow reactor → 5X precursor-to-film conversion efficiency



Precursor-to-film conversion efficiency already increased 4X to 45% by Advanced MOCVD → 3X reduction in total tape cost

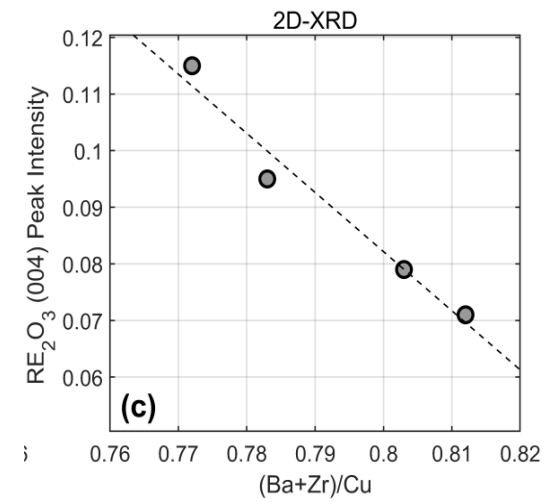
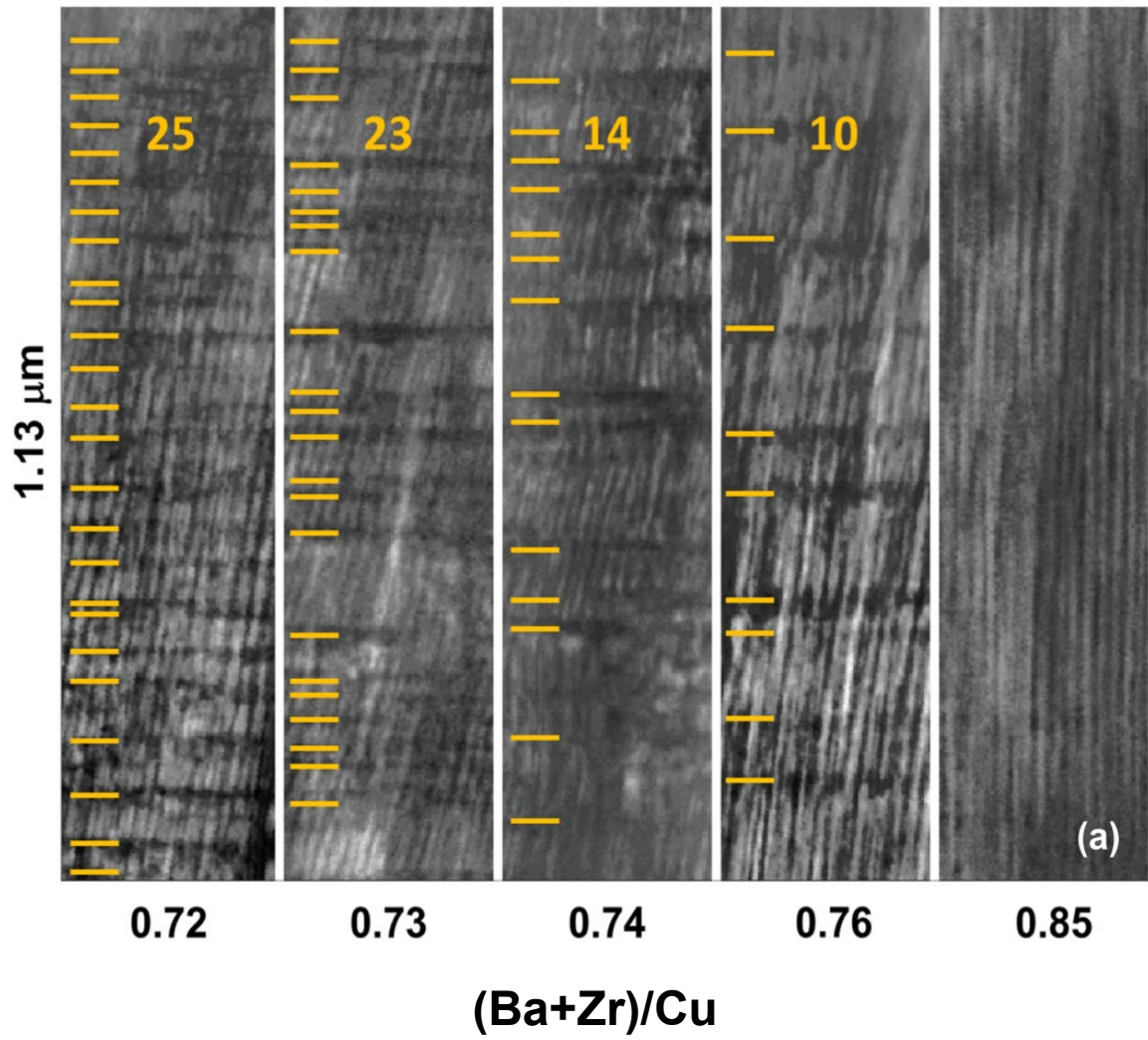
High I_c thick film REBCO tapes by Advanced MOCVD

- Advanced Metal Organic Chemical Vapor Deposition (MOCVD) reactor addresses deficiencies of current REBCO production tools designs
 - 4+ μm thick films & excellent control of nanoscale defects for pinning \rightarrow high critical current.
 - Low volume, laminar flow reactor \rightarrow 5x precursor-to-film conversion efficiency \rightarrow cost reduction.



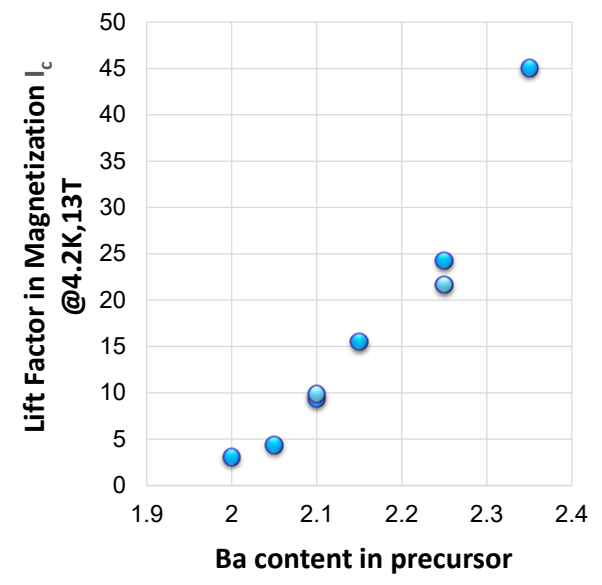
High current REBCO tapes \rightarrow Opportunity to greatly reduce **both** $\$/\text{kA}\cdot\text{m}$ and conductor volume needed per device.

In-field J_c of 4+ μm films at 4.2 K tailored by (Ba+M)/Cu content; BZO/BHO nanocolumns and REO depend on Ba content

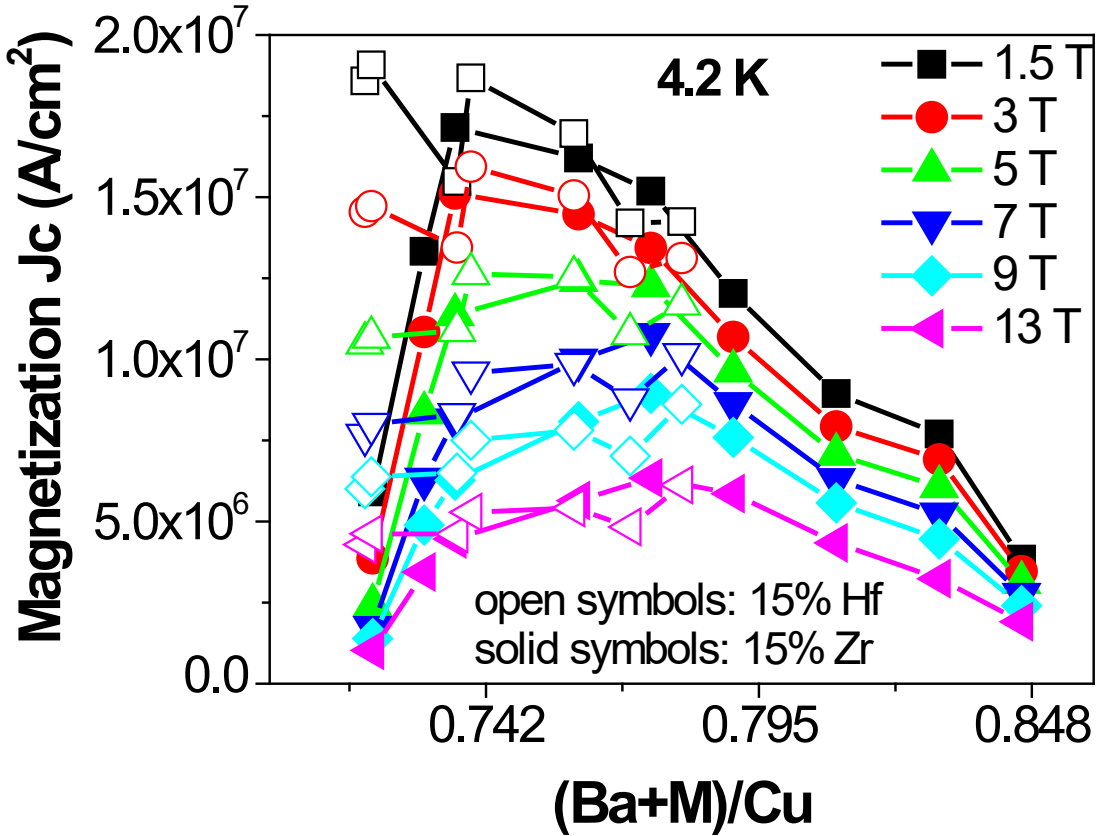
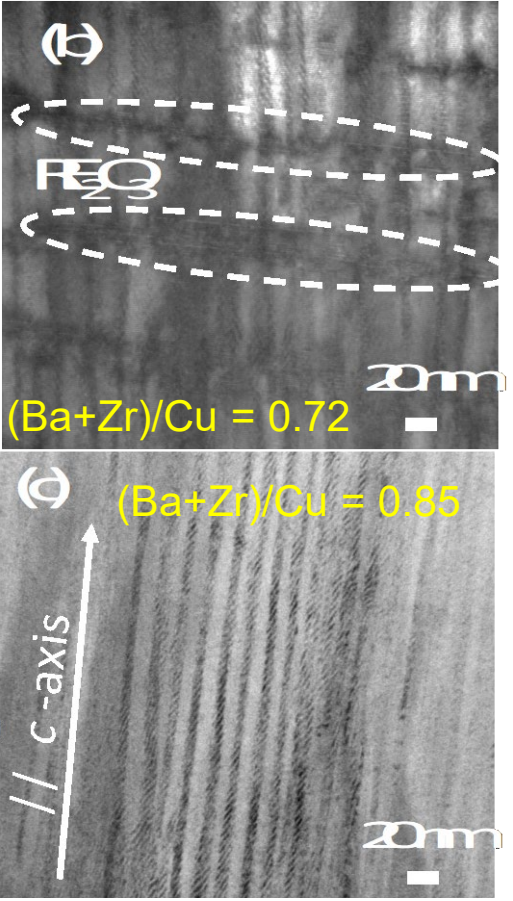
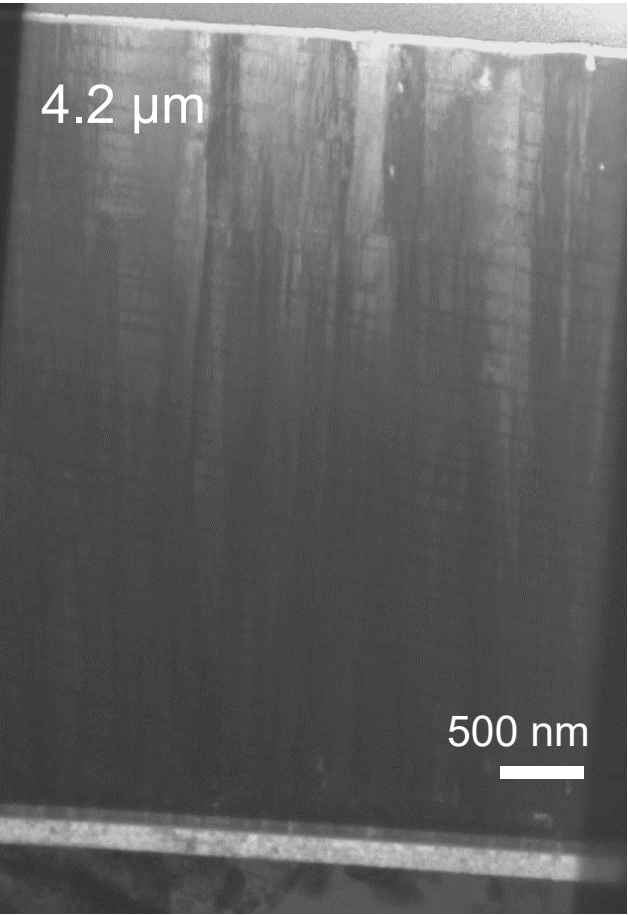


RE₂O₃ intensity in 2D X-ray Diffraction decreases with increasing Ba content

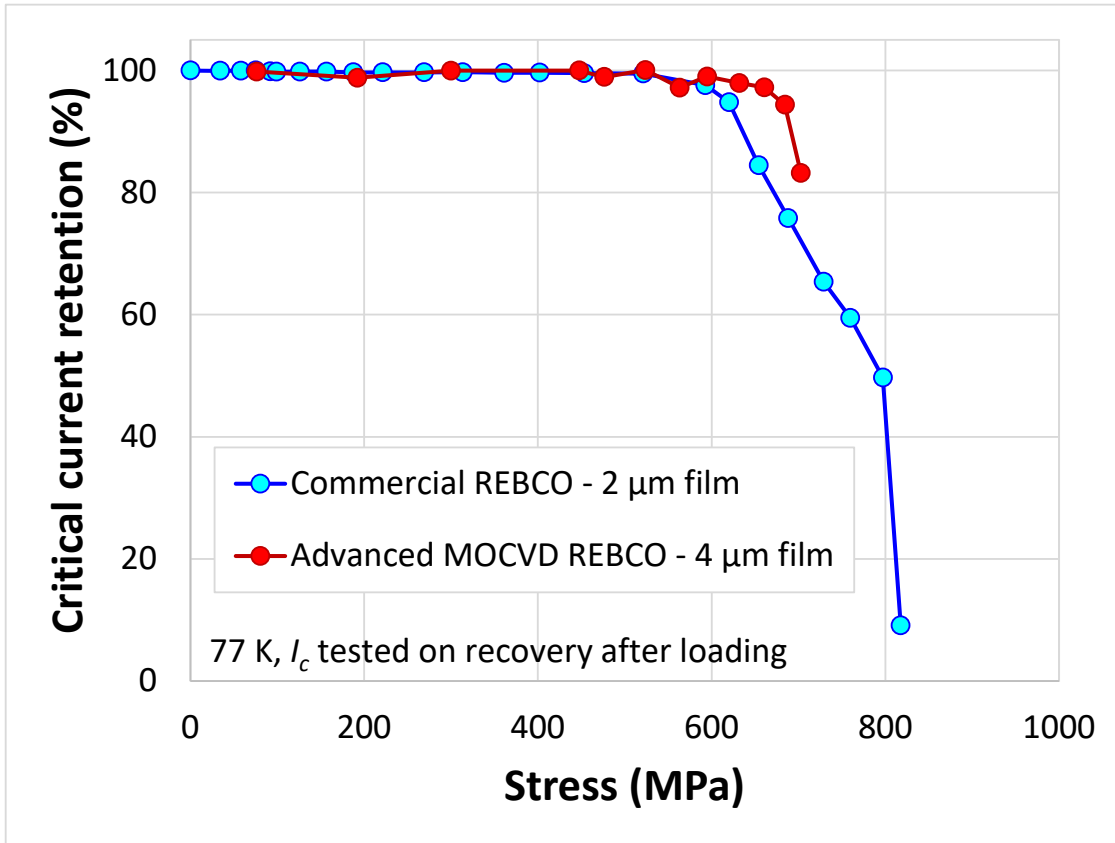
With increasing Ba content, interruptions to BMO nanorods decrease and lift factor in I_c at 4.2 K, 13 T increases.



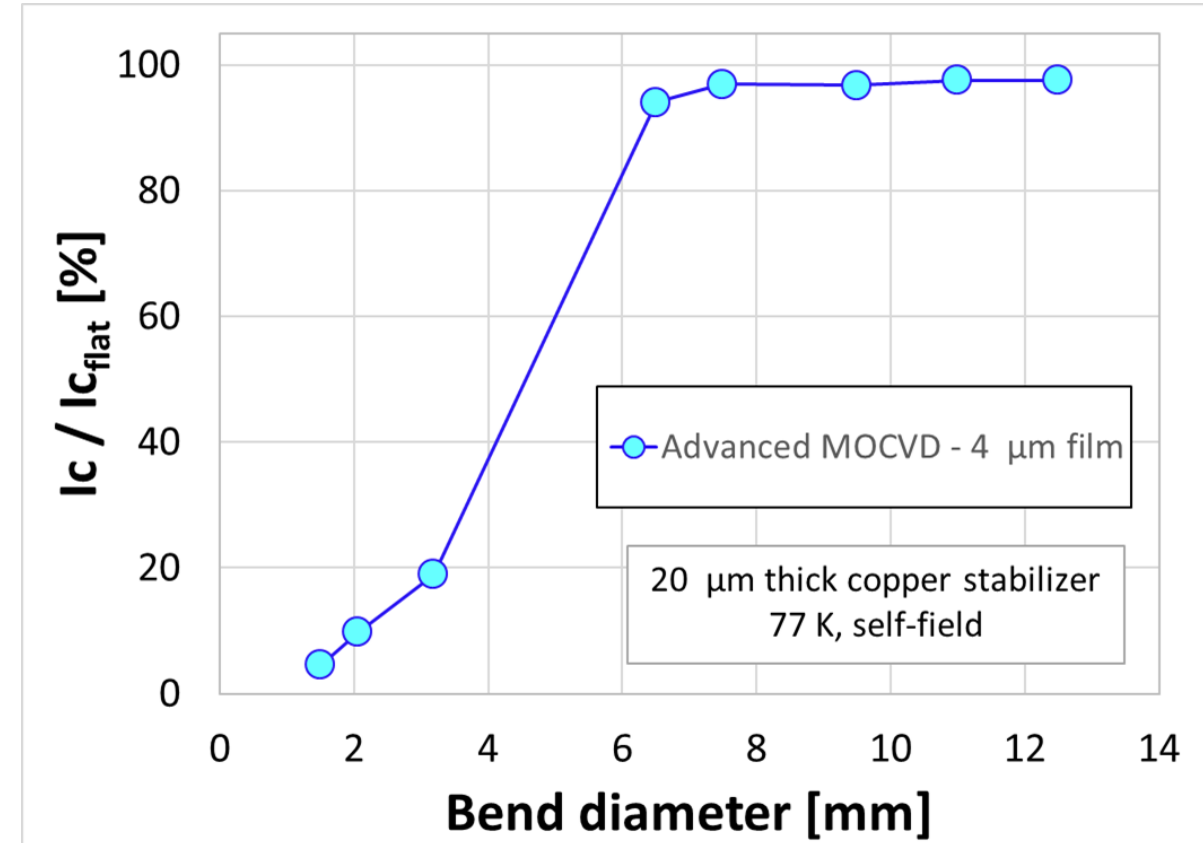
In-field J_c of 4+ μm films at 4.2 K tailored by (Ba+M)/Cu content; BZO/BHO nanocolumns and REO depend on Ba content



4- μm -thick film Advanced MOCVD tapes exhibit good mechanical properties

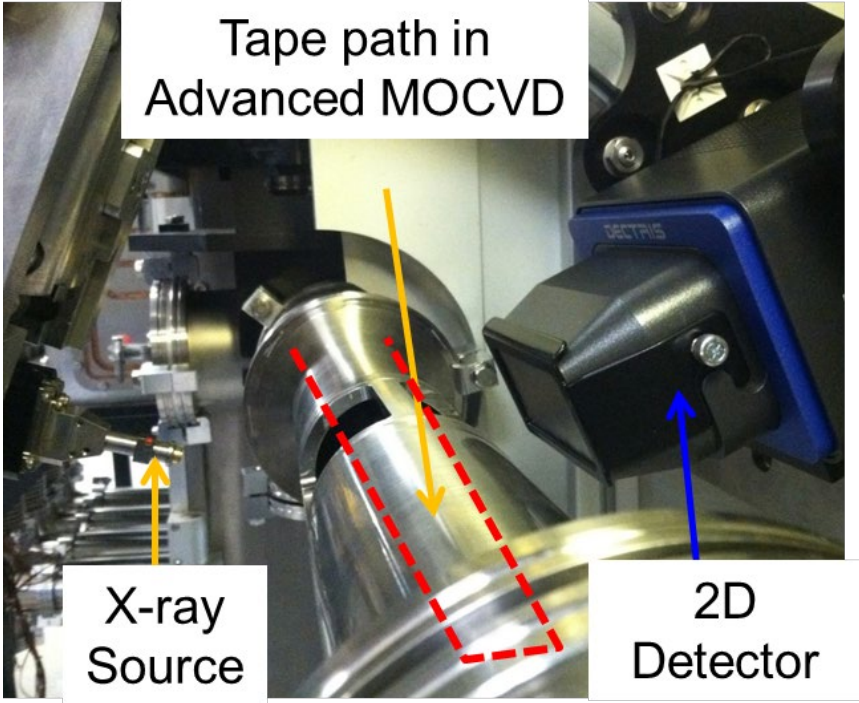
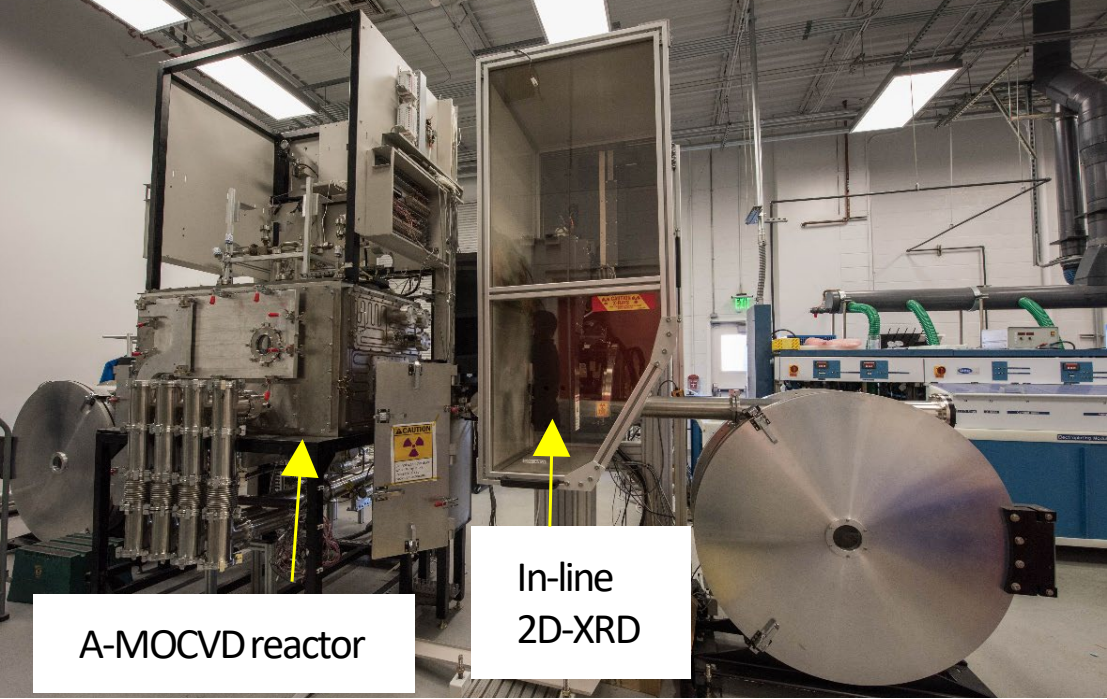


- Overall thickness $\sim 100 \mu\text{m}$ (20 μm copper on each side)
- Irreversible I_c at $\sim 650 \text{ MPa}$.



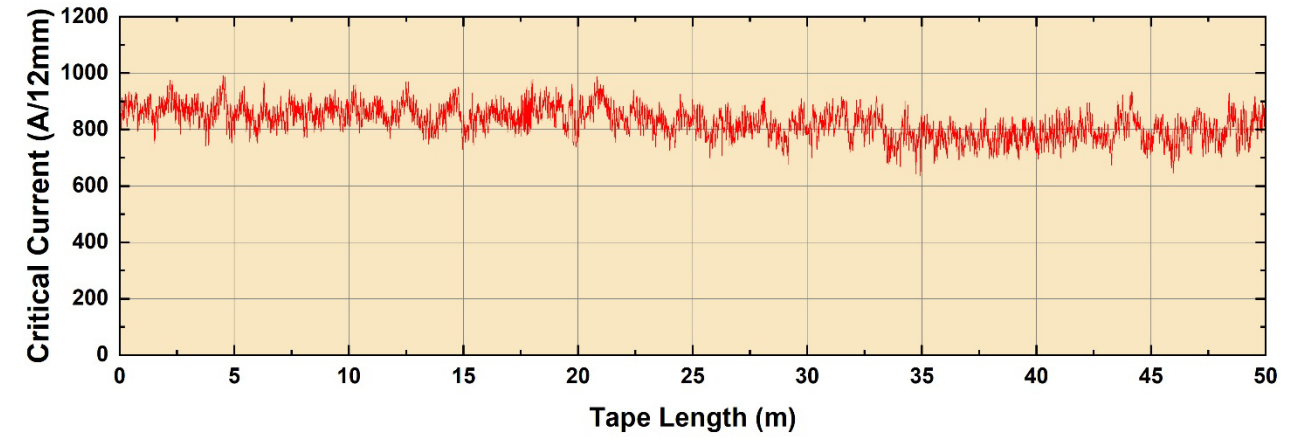
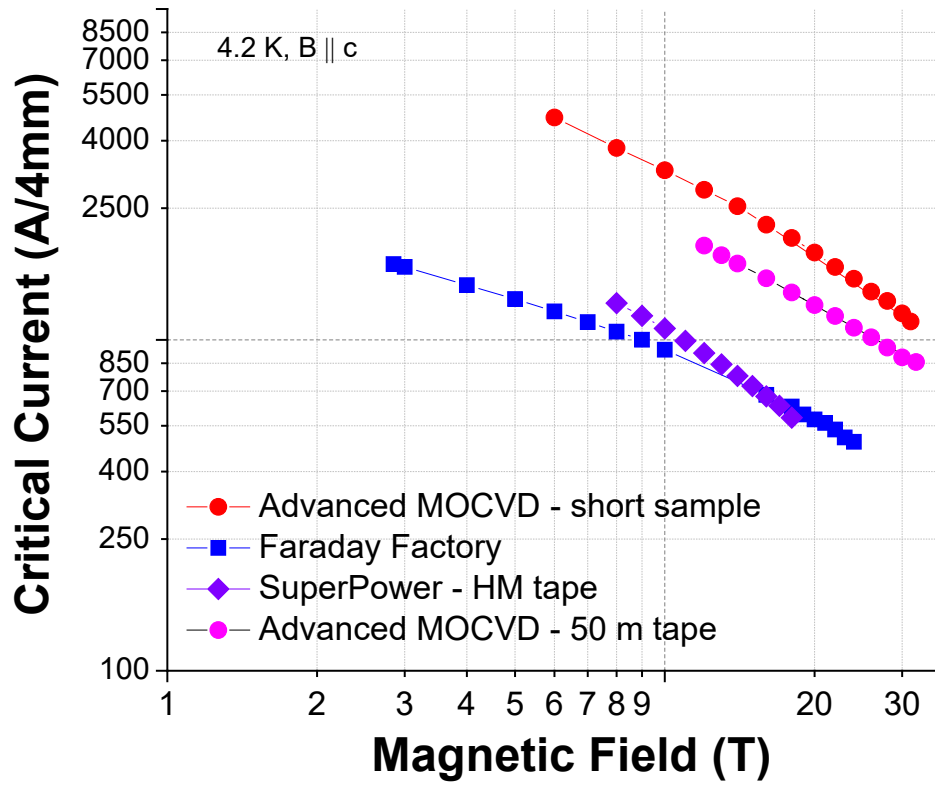
- 4- μm -thick film tapes can be bent to 6 mm diameter.

Pilot-scale Advanced MOCVD establish to scale up high-performance, low-cost REBCO tapes to long lengths



In-line 2D-XRD in Advanced MOCVD manufacturing tool for real-time measurement of REBCO film quality → to achieve consistent in-field performance

High current REBCO tapes made by Advanced MOCVD scaled up to 50 meters



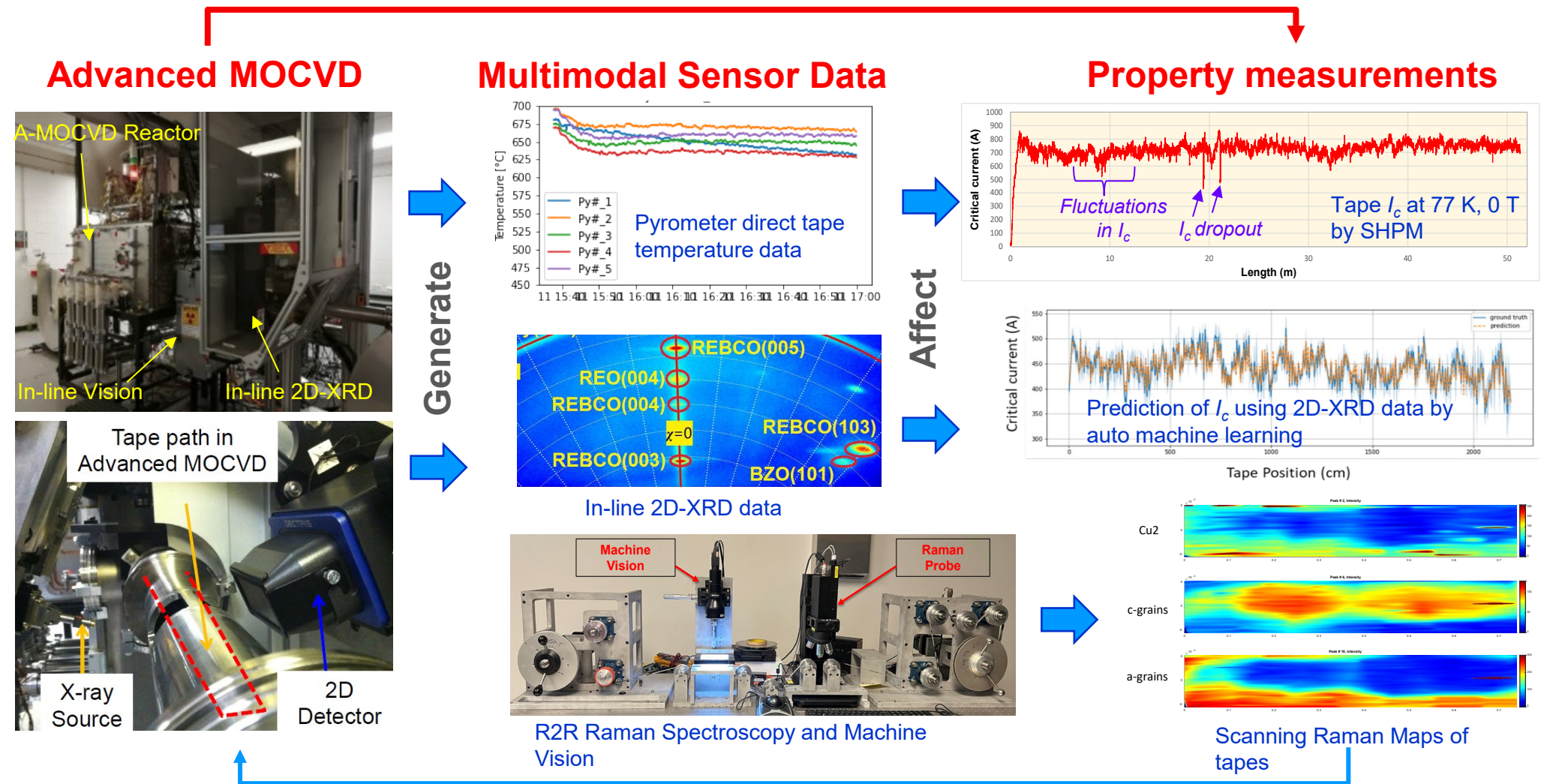
- Advanced MOCVD scaled up to 50 meter lengths
- I_c of 50 m Advanced MOCVD tape **74% of I_c of champion short Advanced MOCVD tape** at 4.2 K, 30 T.
- I_c of 50 m REBCO tape = **1274 A/4mm 4.2 K, 20 T**
 → corresponds to **> 600 A/4mm at 20 K, 20 T.**



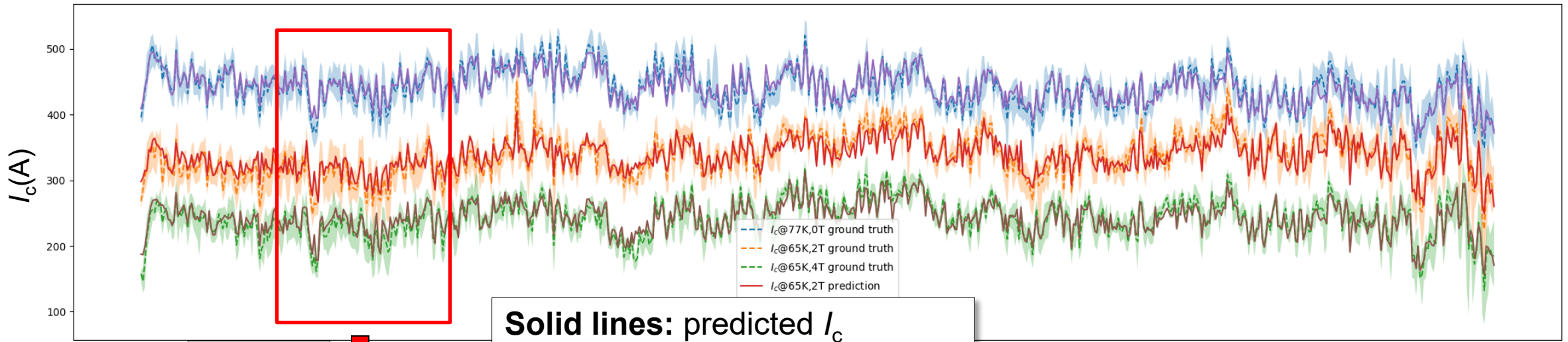
50-m-long Advanced MOCVD tape

Machine-Learning-Assisted, Multi-Modal In-situ-Sensors-Driven, Real-time Feedback Control for high-yield manufacturing

Process-structure-property (PSP) modeling

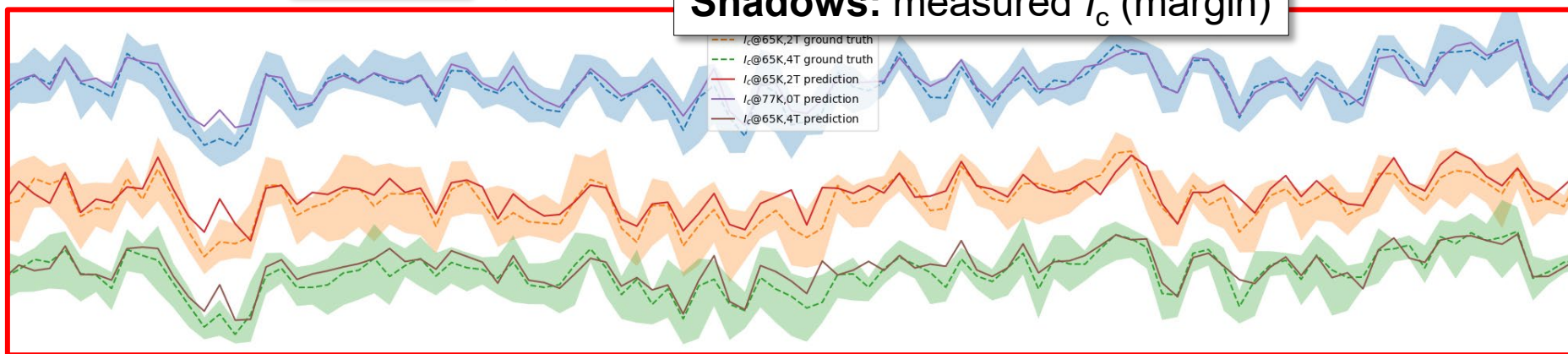


Prediction of critical current performance of superconductor tape from inline 2D XRD data using Auto Machine Learning



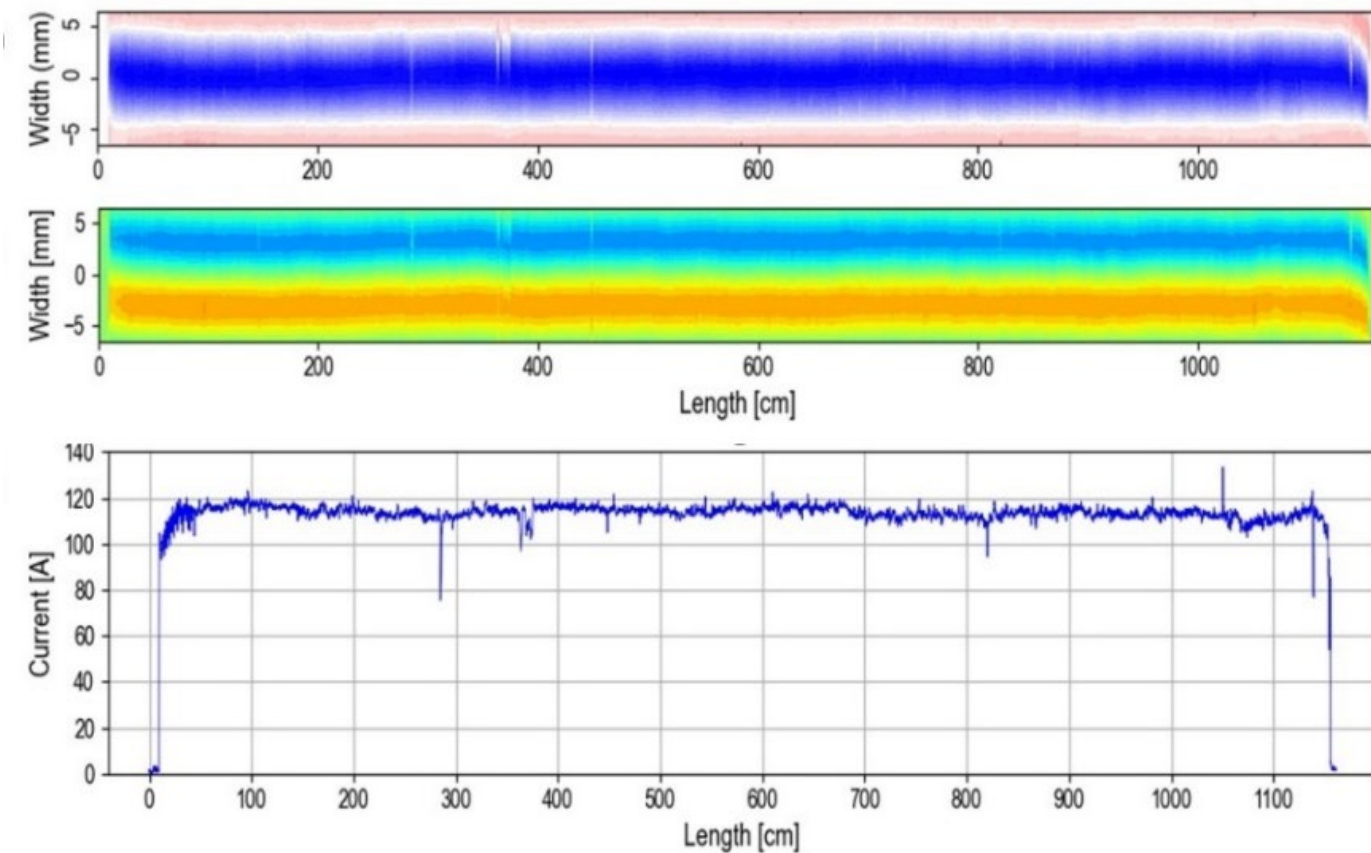
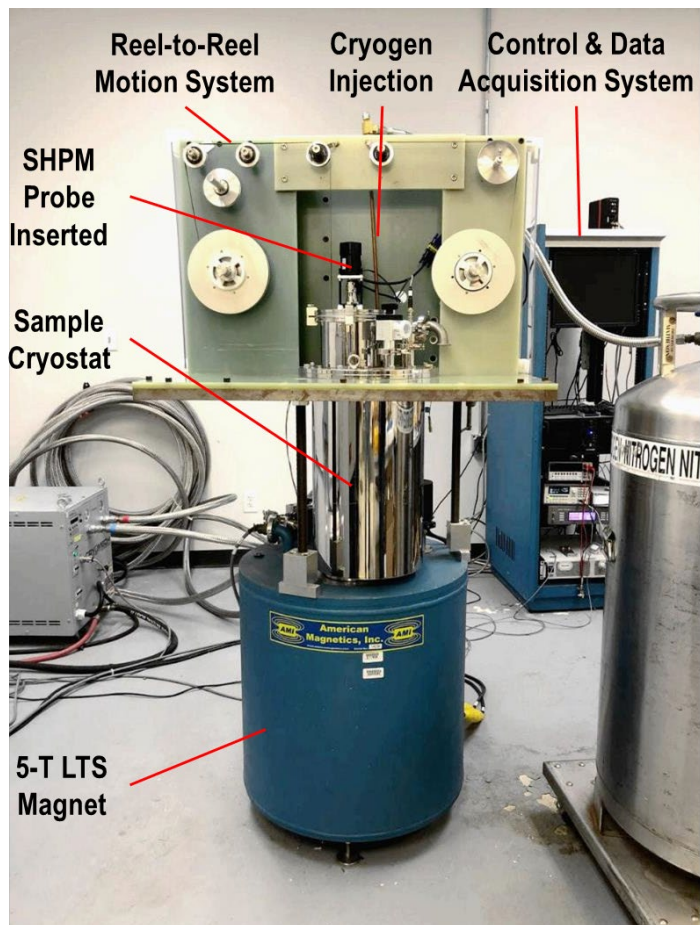
Zoom in

Solid lines: predicted I_c
Dash lines: measured I_c (mean)
Shadows: measured I_c (margin)



	Avg error	Within margin
77K 0T	10.3A	94%
65K 2T	16.6A	85%
65K 4T	11.5A	89%

Reel-to-reel in-field I_c measurements at 65 K by non-contact Scanning Hall Probe Microscopy (SHPM)



Next: Upgrade tool for 20 K, 12 T reel-to-reel measurement

Very high production capacity/tool achievable by large-area MOCVD



Deposition zone length (m)	Deposition zone width (m)	Deposition rate (nm/s)	Tape speed for 12 mm wide tape (m/h)
1	0.2	6	80
1	0.65	6	270
1	0.2	20	270

Longer charge lengths enable much high production capacity

Tape Length (m)	Tape Speed (m/h)	Annual production per tool ¹ (km)
500	80	285
1000	80	400
500	270	410
1000	270	700
5000	270	1,520

¹ Shown for 12-mm-wide tape. The production capacity will be 3x for 4-mm-wide tapes (used in most applications)

Important to maintain process stability for uniform Ic over long tapes.

Our pathway to low-cost and high production capacity: 3x I_c tapes with 5x throughput by Advanced MOCVD

REBCO deposition technology	Annual production per tool ¹ (km)	Tape Cost ² (\$/m)	I_c @ 20 K, 20 T (A/4mm)	Tape Cost@ 20 K, 20 T (\$/kA-m)
Today's commercial production	150 - 800	20	200	100
Our goal	3000	6	600	10

5x increase in production capacity/tool with 3x critical current will be a breakthrough for large-scale deployment of REBCO tapes in all applications.

¹ For 4-mm-wide tapes

² For uniform long tape with no I_c dropouts.

Advanced conductor development and manufacturing

- High critical current tapes by large-area Advanced MOCVD
- High throughput manufacturing by large-area Advanced MOCVD
- High yield manufacturing by real-time quality control
- Mechanically-robust tapes with enhanced delamination strength
- High yield strength composite tapes
- Neutron radiation tolerant REBCO tapes
- Highly flexible symmetric tapes (0.8 mm bend diameter)
- Reel-to-reel, in-field critical current measurement of long tapes