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Invited presentation MS-2 was given at the virtual CCA 2021, October 11-15, 2021.

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Overcoming Challenges in Utilizing High-Performance REBCO Tapes in Ultra-high Magnetic Field Applications

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CCA, October 11 - 15, 2021

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*VS has financial interest in AMPeers

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Outline

- Advanced MOCVD for high-current REBCO tapes for high-field applications.
- How to achieve high in-field performance over long lengths?
- Technical Roadmap for large-scale commercialization of REBCO.

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

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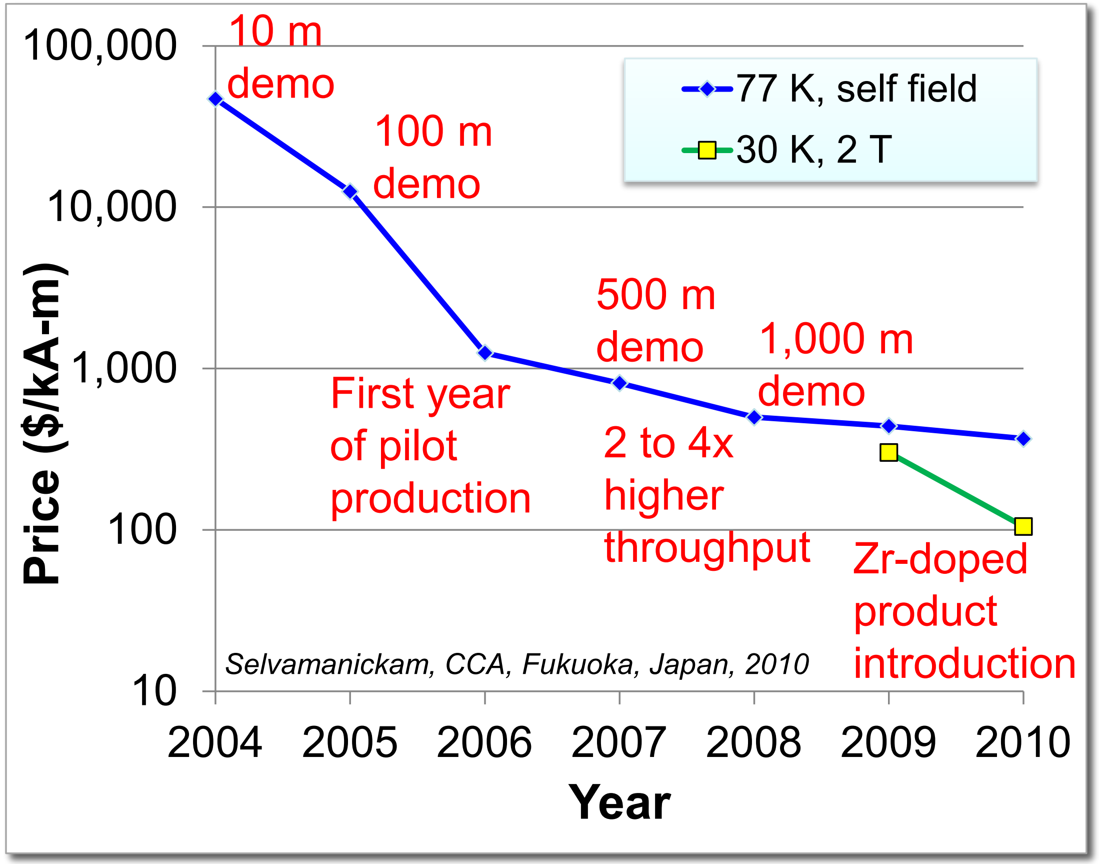
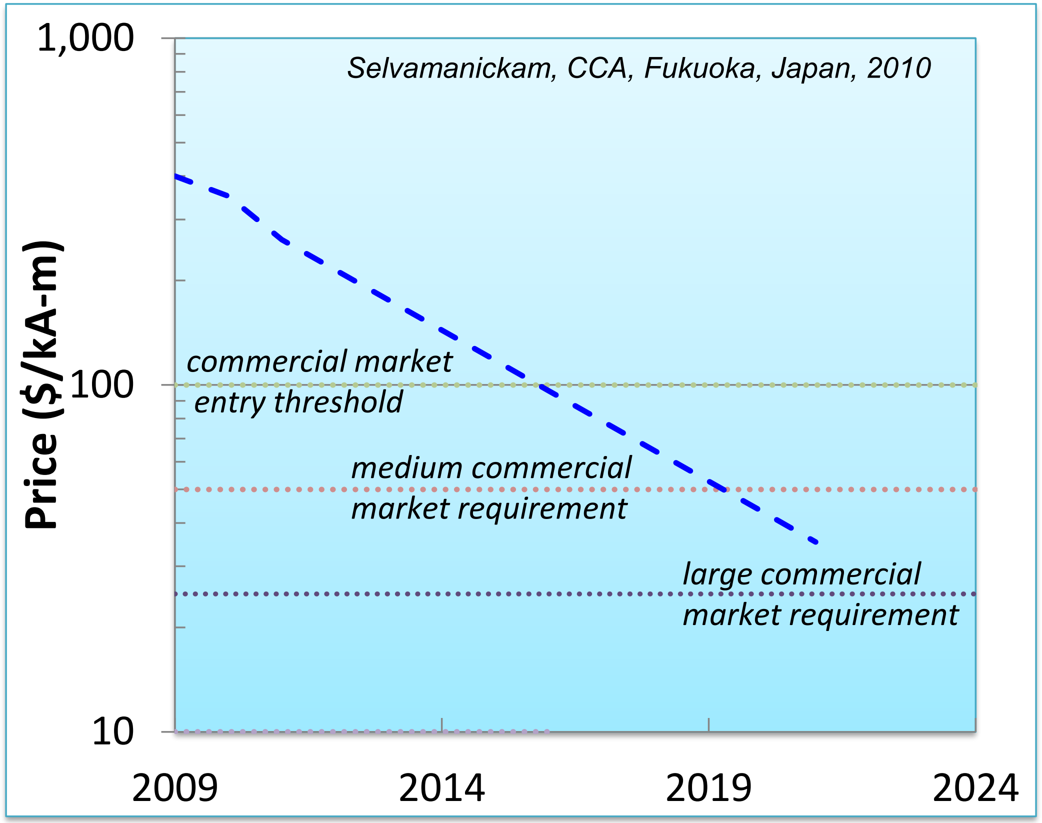
REBCO tape price has decreased only ~ 2.5x in the last 11 years; 4x higher than that predicted in 2010 CCA





2010 CCA → REBCO price: $360/kA-m; 2021 price projected in 2010: $35/kA-m
Actual 2021 REBCO prize: $150 – 200/kA-m

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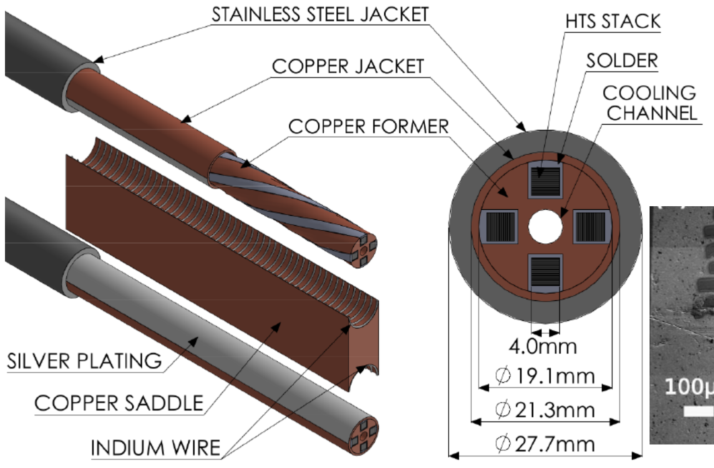
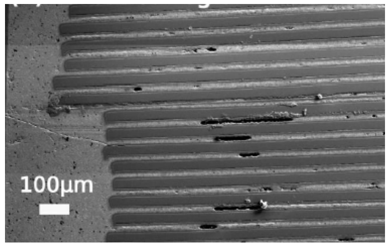
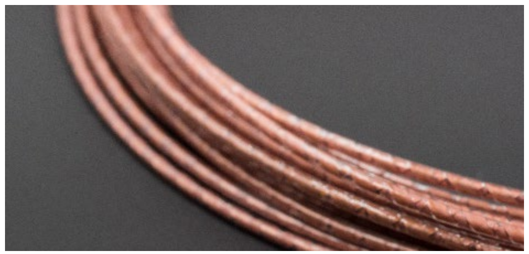
High I_c REBCO is the best way to achieve drastic cost reduction

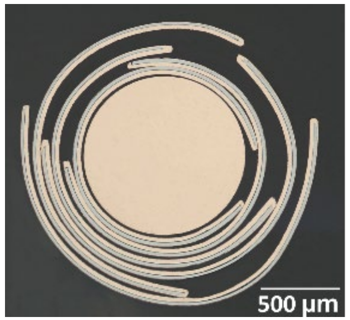
- Most ultra-high field applications use stacks of many REBCO tapes: ~ 100 tapes/cable for compact fusion
- **With higher performance, less tape needed**
  - 3 – 4 GA-m for commercial fusion device.
  - 20,000 km of 'standard tape' needed.
  - **But with I_c 5x standard tape, need 4,000 km.**
  - **Less tape → less burden on tape production**
- With high I_c tape, J_e will meet application requirements in formats that use large non-superconductor cross section like round wires.
- Fewer high I_c tape strands → more compact, more flexible round wires



VIPER cable of CFS
Hartwig, ASC 2020







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

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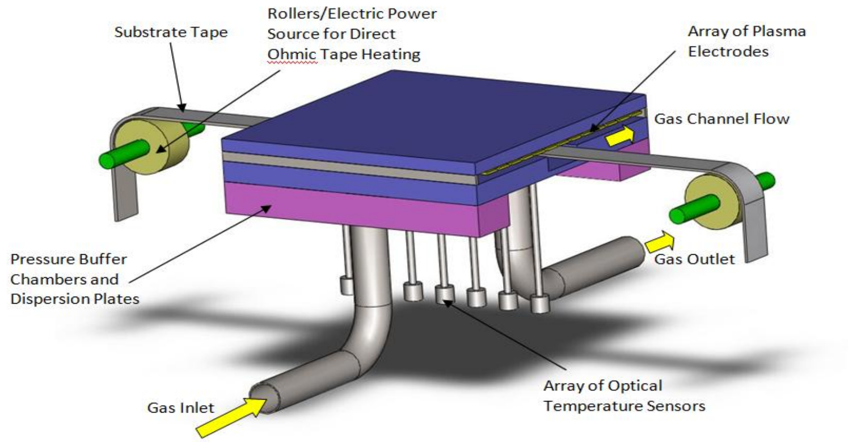
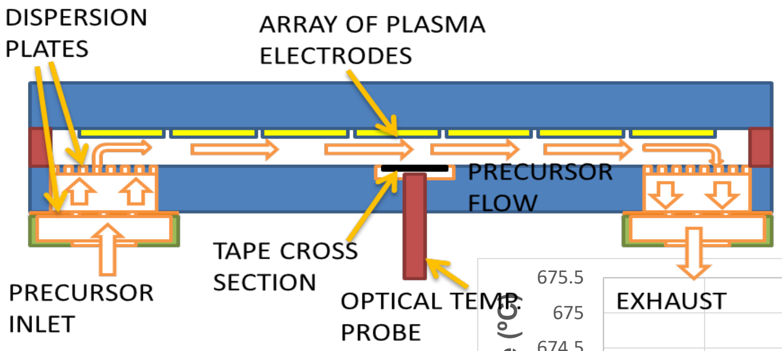
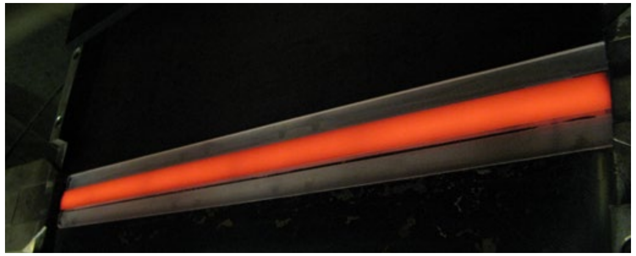
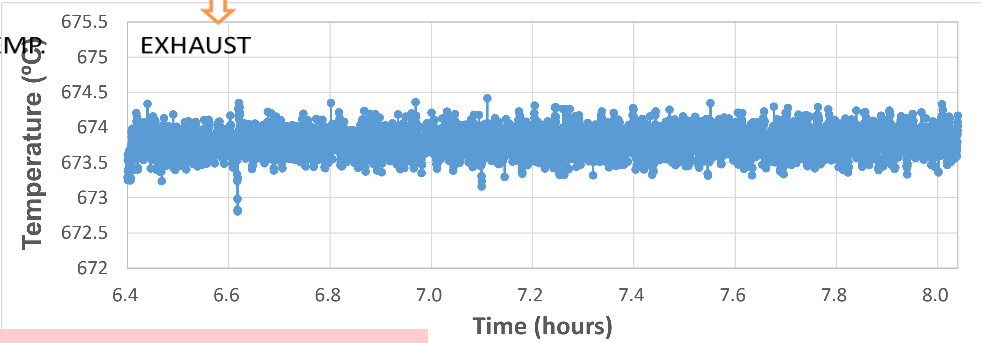
Advanced MOCVD for high I_c, low-cost, high-yield manufacturing of REBCO tapes

- Advanced MOCVD reactor addresses all deficiencies of current MOCVD 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

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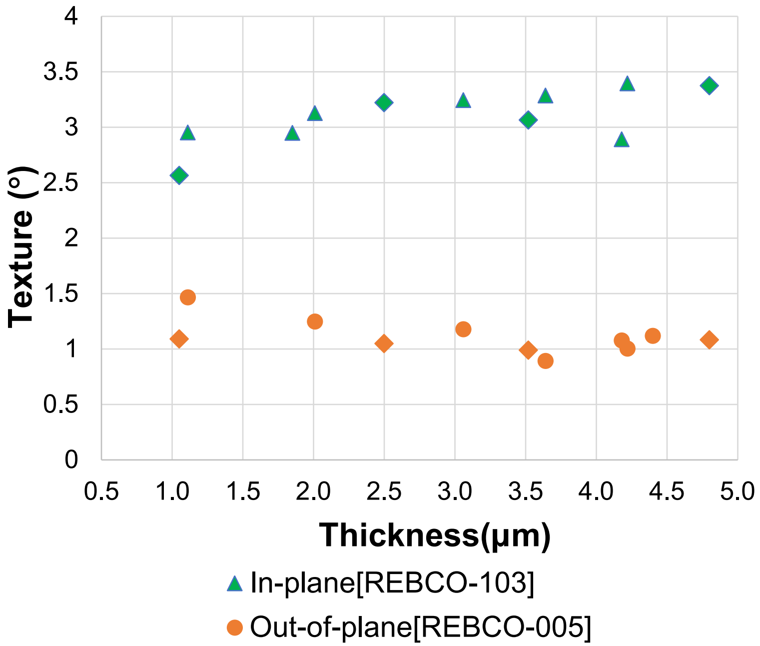
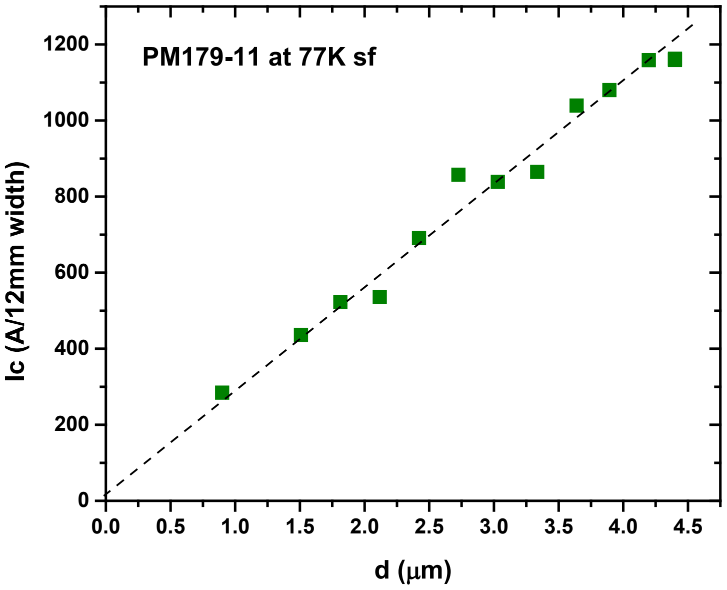
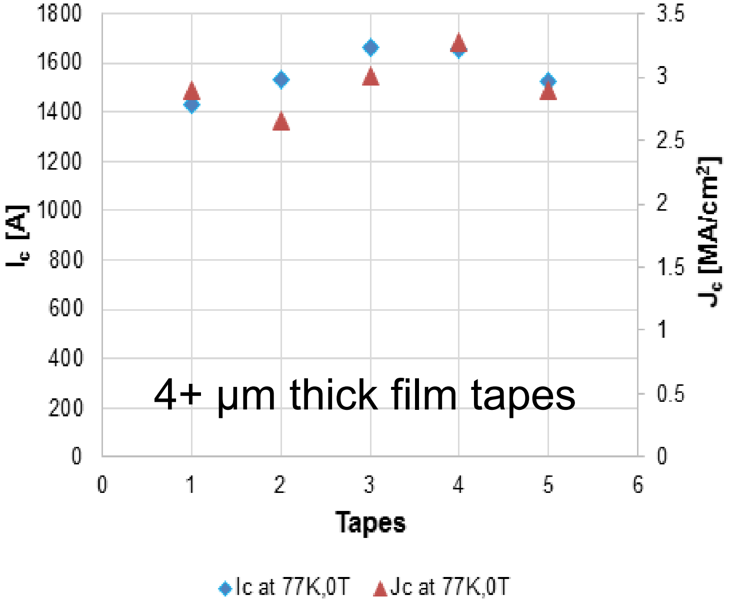
High I_c thick film REBCO tapes by Advanced MOCVD







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/cm²

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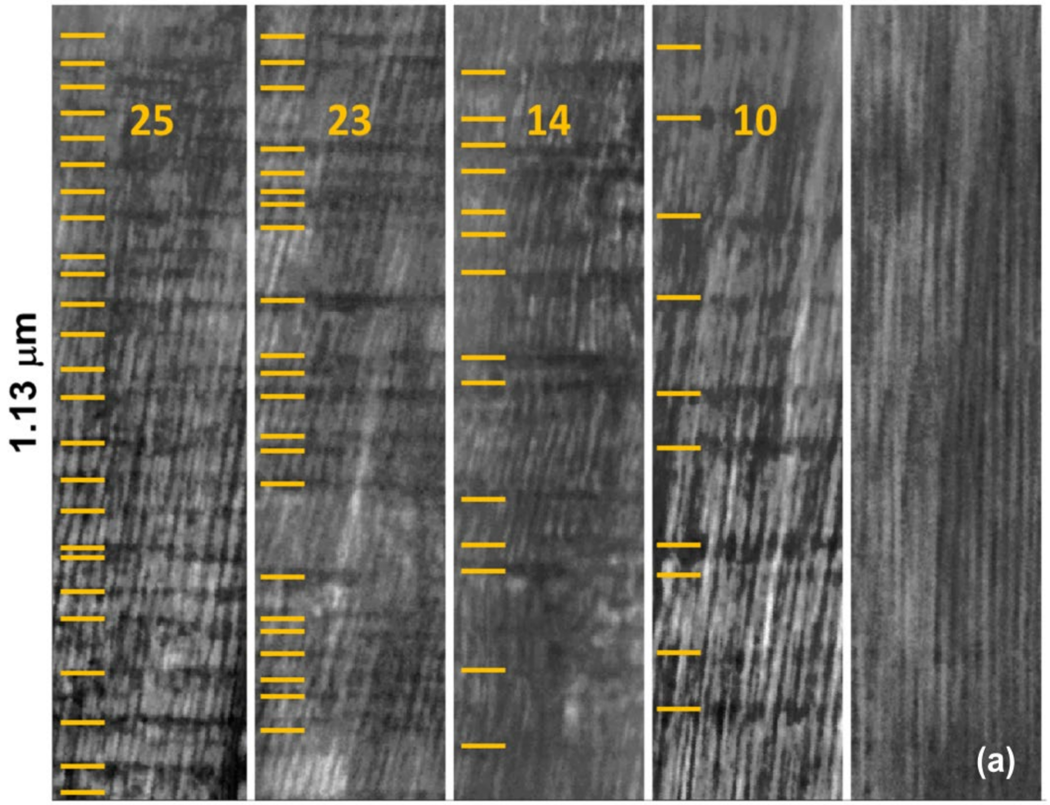
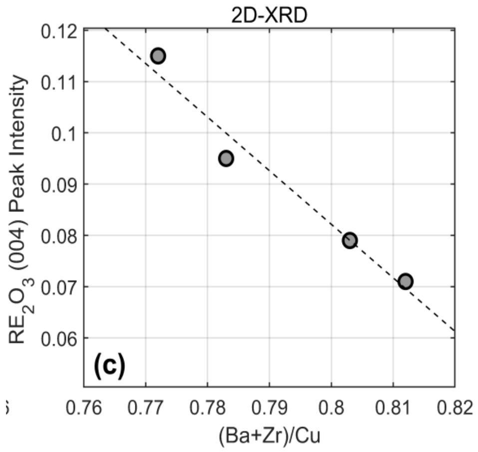
In-field J_c at 4.2 K tailored by (Ba+M)/Cu content; BZO/BHO nanocolumns and REO depend on Ba content



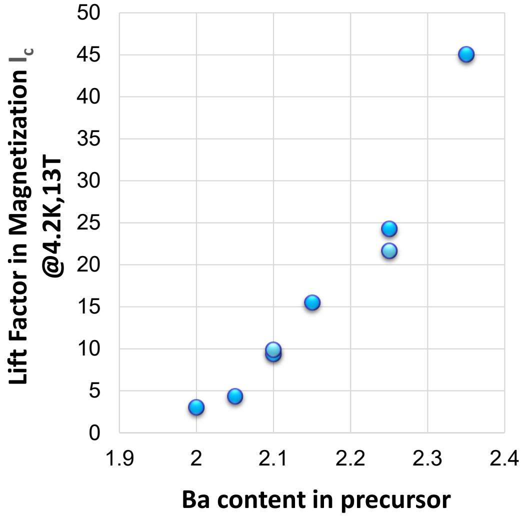
(Ba+Zr)/Cu



RE_2O_3 intensity in 2D X-ray Diffraction decreases with increasing Ba content

Supercond. Sci. Technol. **34** 115002 (2021)

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



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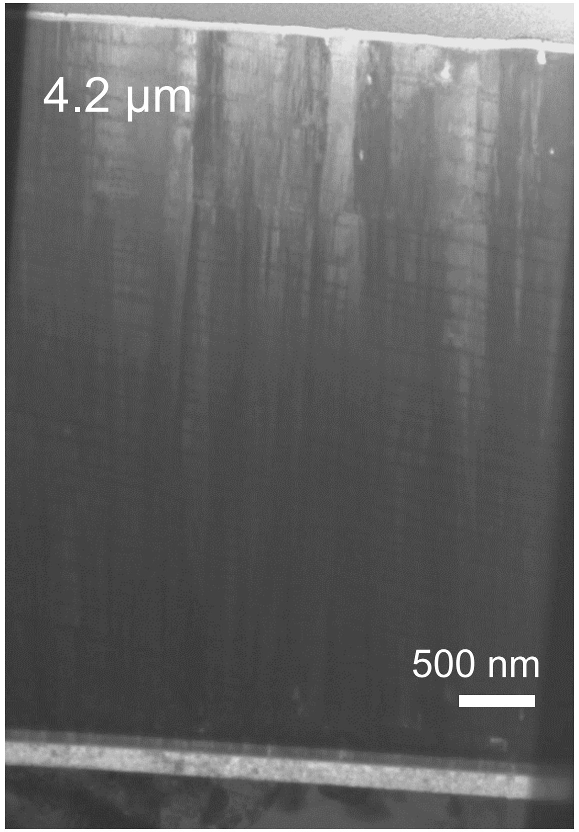

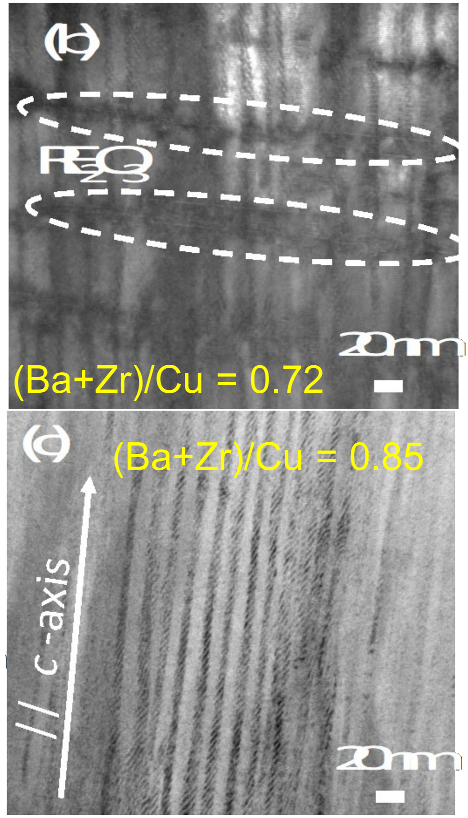

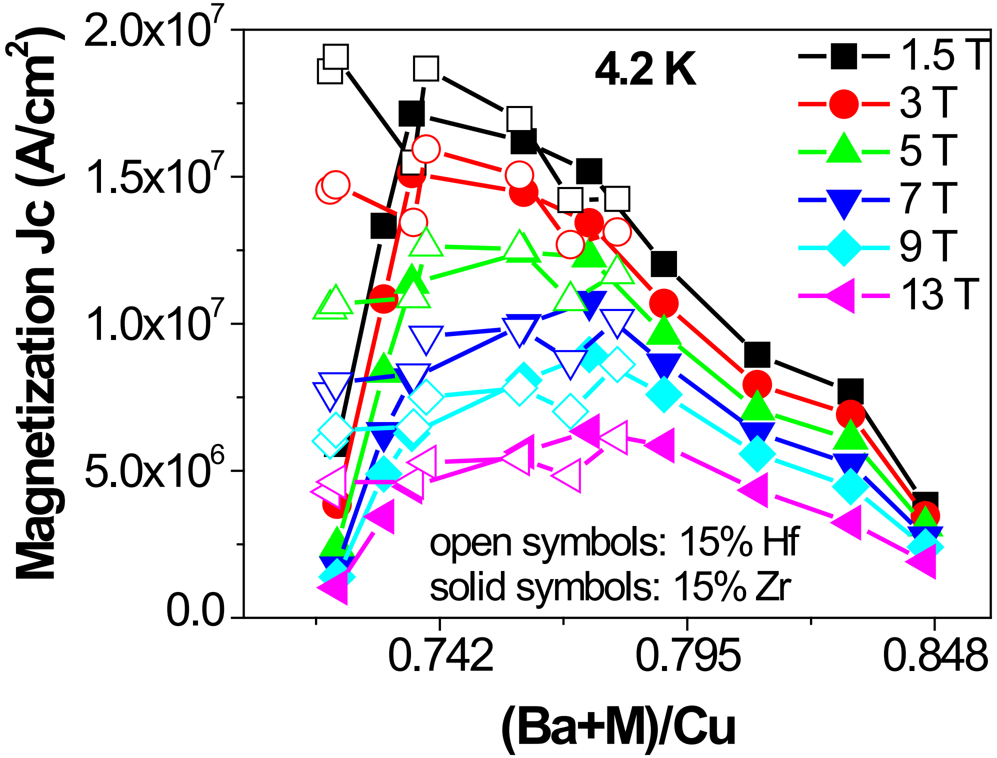

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Supercond. Sci. Technol. **33** 074007 (2020)

Galstyan et al. ASC 2020

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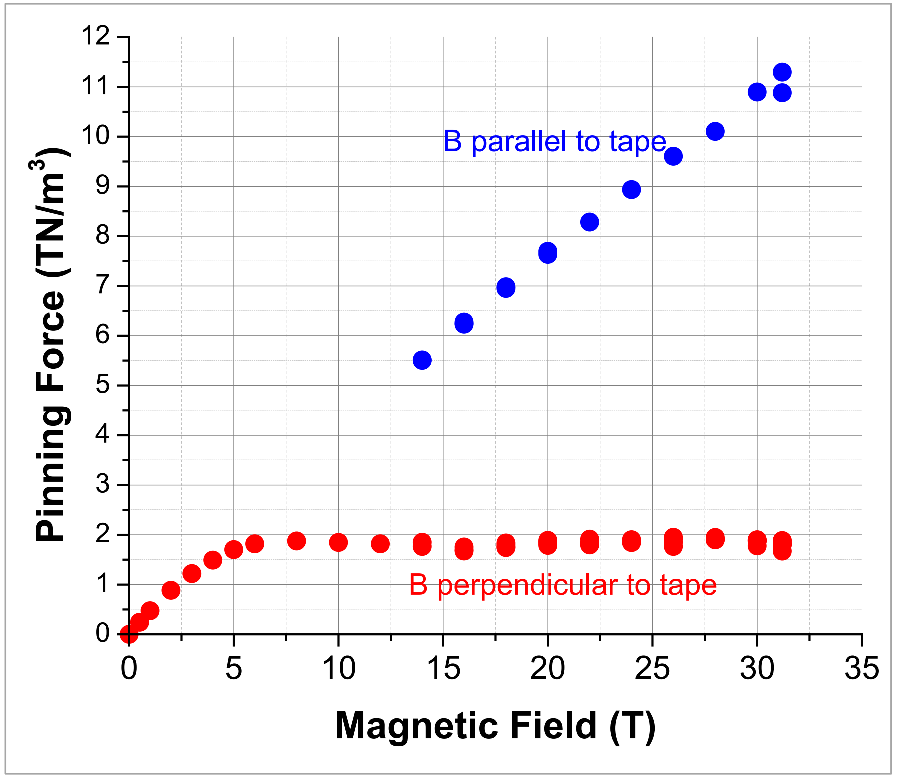
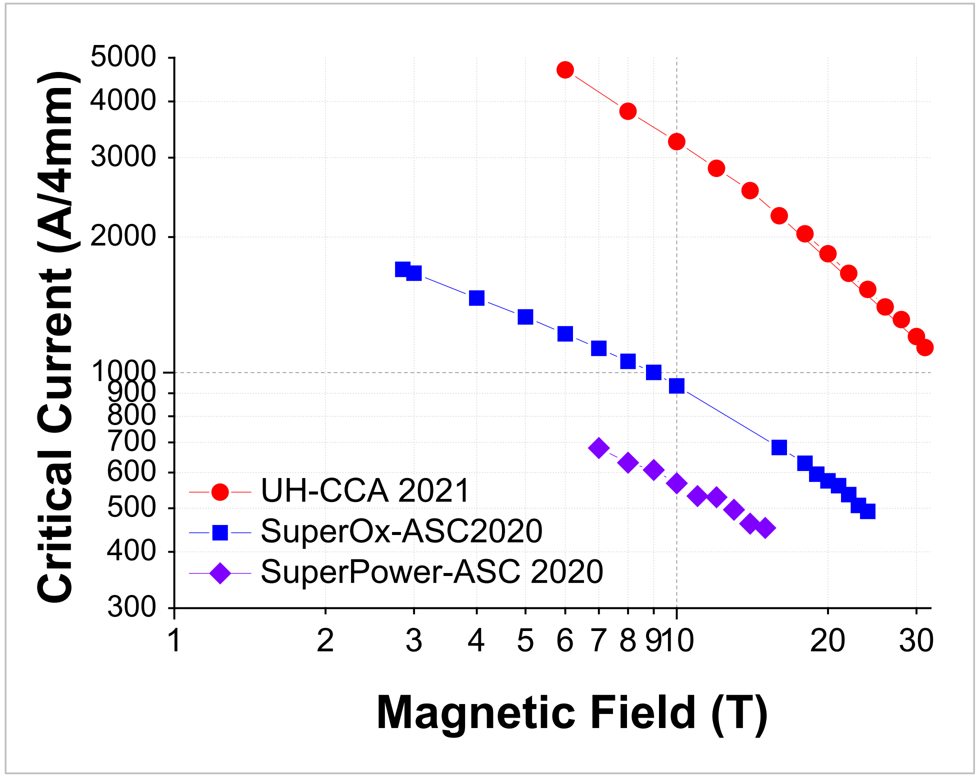
4+ µm thick film REBCO tapes made by Advanced MOCVD exhibit very high critical currents in high fields at 4.2K





Maximum pinning force of 4 µm film tape = 1.9 TN/m³ (B ⊥ tape)

I_c of UH REBCO @ 4.2 K, 20 T = **1,836 A**

3.19x best commercial (PLD) REBCO tape at 20 T

5.27x best commercial MOCVD REBCO tape at 15 T

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Supercond. Sci. Technol. **33,** 07LT03 (2020)

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How to achieve high in-field performance over long lengths?

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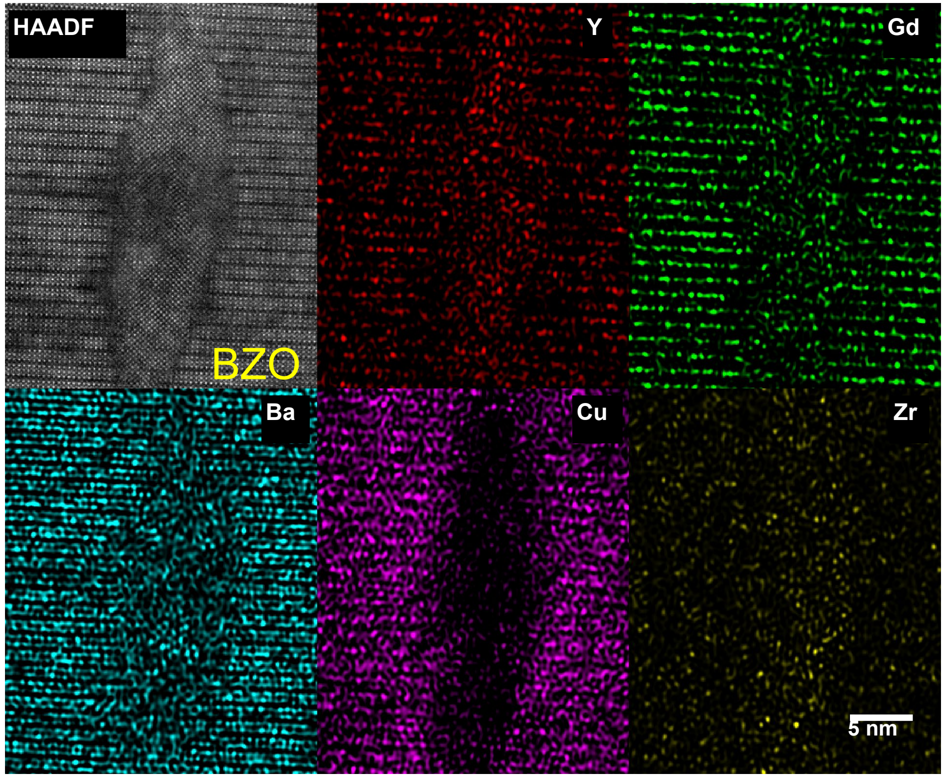
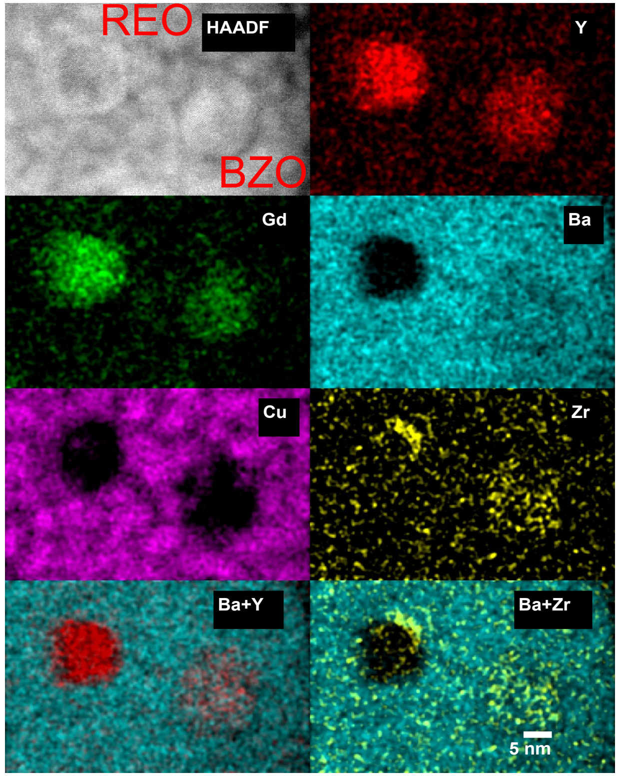
Gd and Y dissolve in BZO: BZO is actually a solid solution $Ba^{2+}(Zr^{4+}_{1-z}RE^{3+}_{z})O_{3-\delta}$ perovskite





Supercond. Sci. Technol. **34** 115002 (2021)

Even with a constant 15% Zr, by varying the Ba content, BZO can be tuned from 5 to 23%, and the linear density of RE_2O_3 precipitates from 18 to 1 μm^{-1}.

Ba compositional control is critical to achieve uniform high in-field I_c in long tapes

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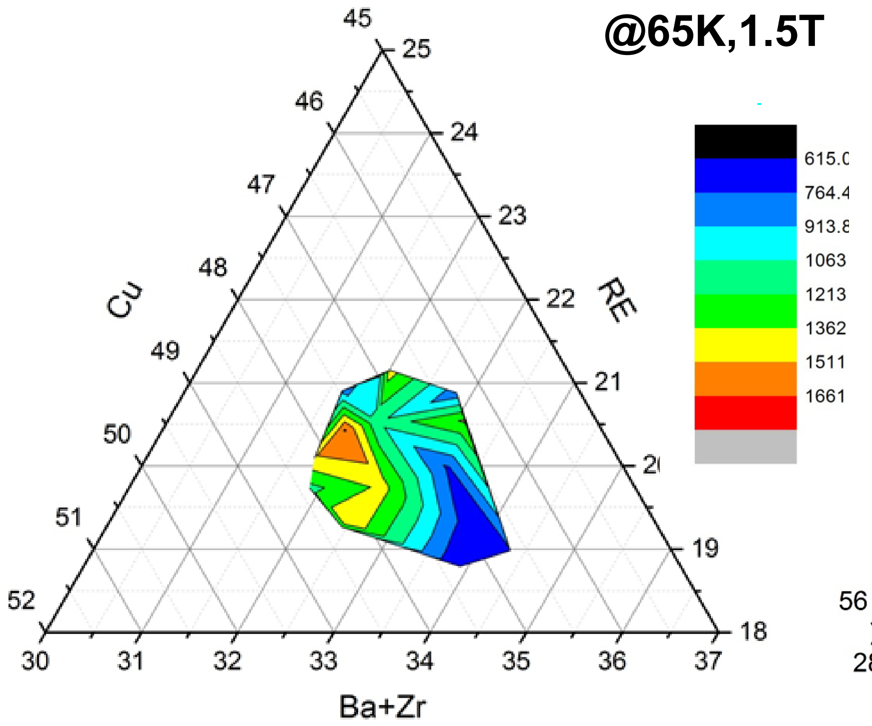
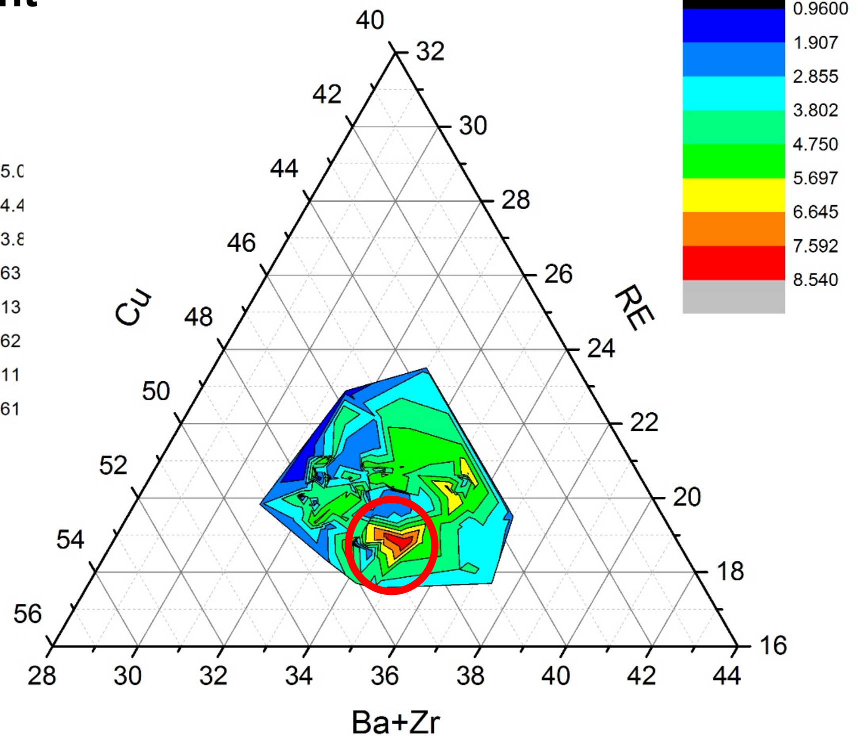
Compositional control of REBCO film important for high in-field J_c

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

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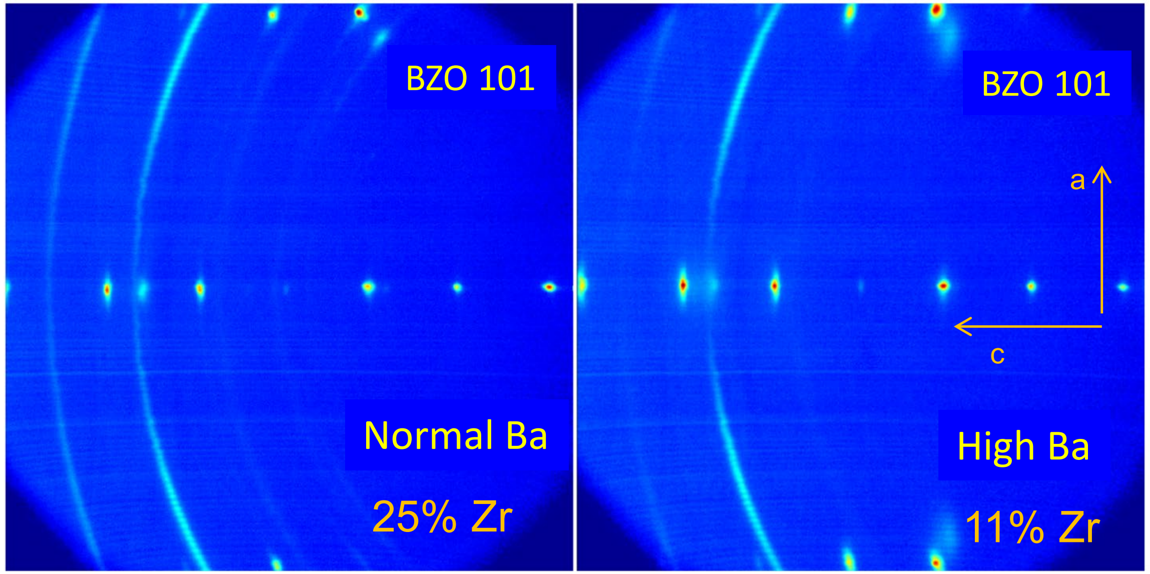
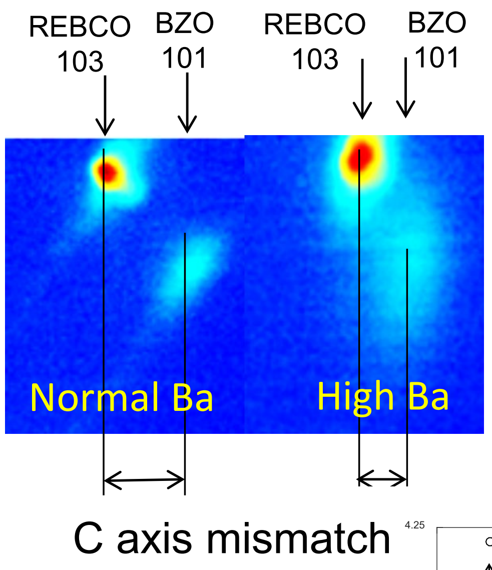
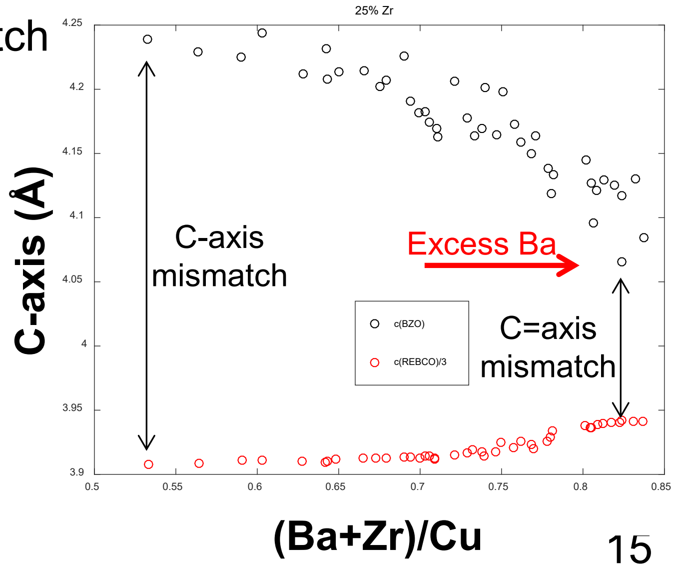
2D-XRD: Rapid non-destructive method to evaluate REBCO film composition







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

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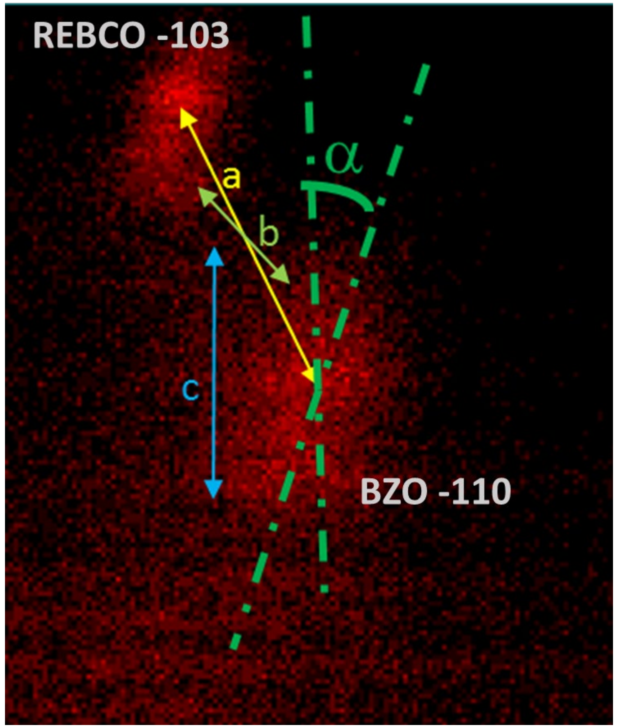
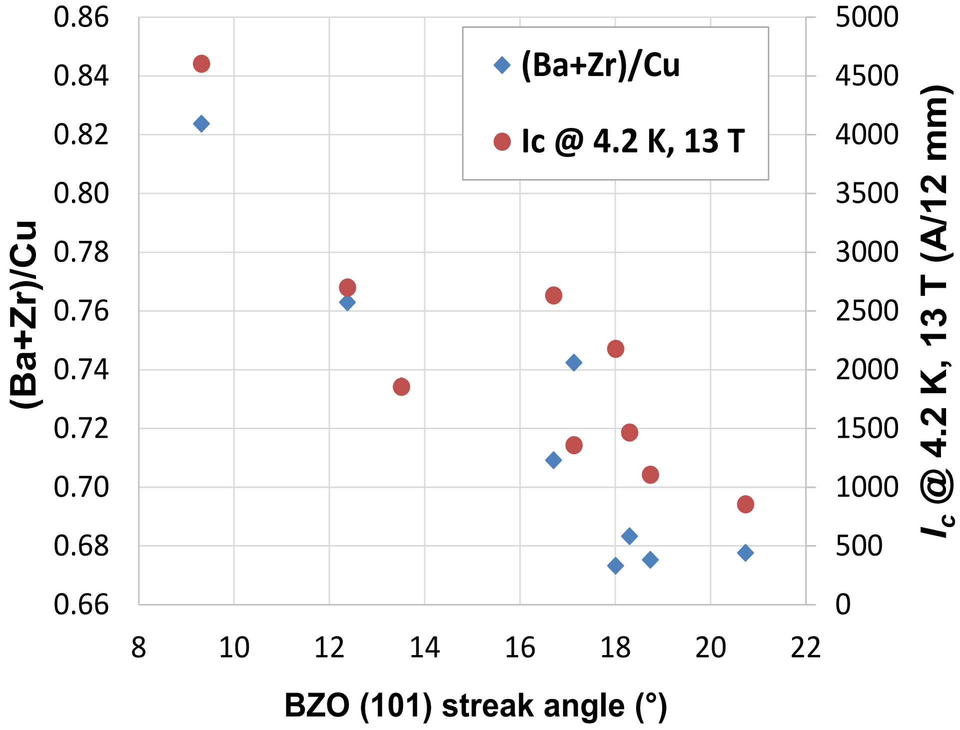
2D-XRD: Rapid non-destructive method to evaluate REBCO film composition





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

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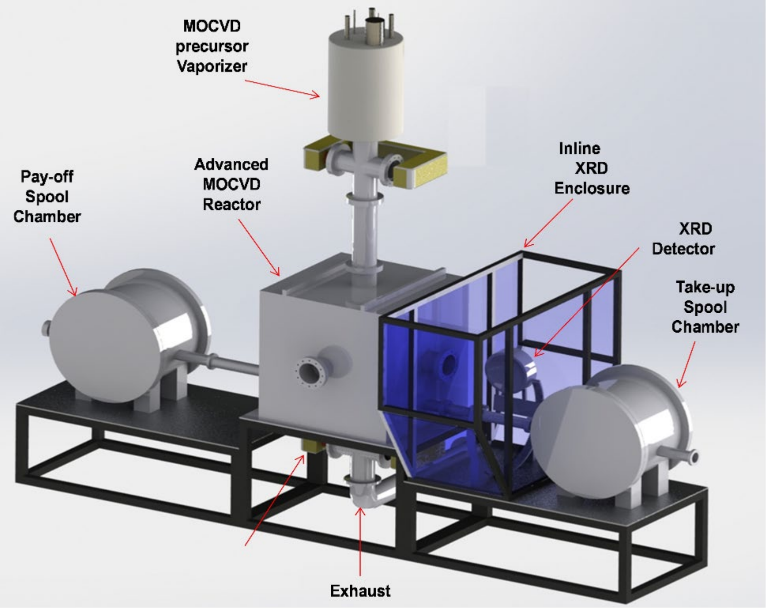
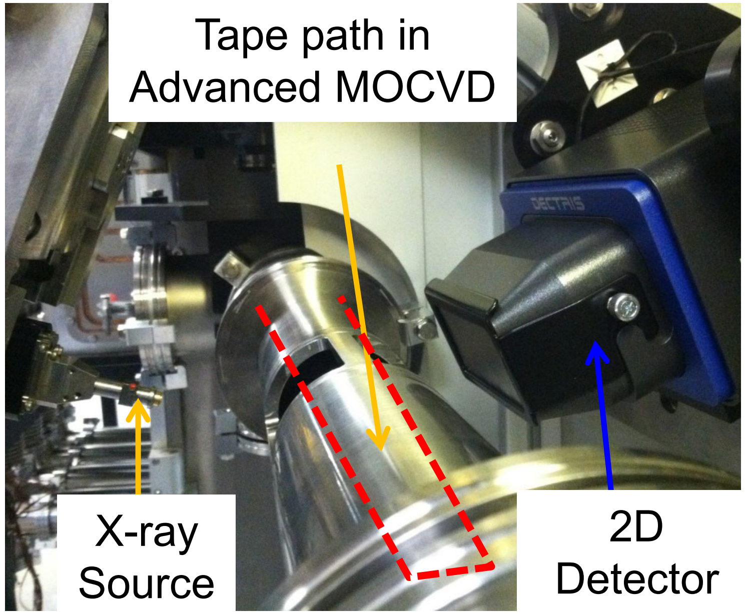
In-line 2D XRD built and installed in pilot Advanced MOCVD tool for REBCO film quality monitoring & control





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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

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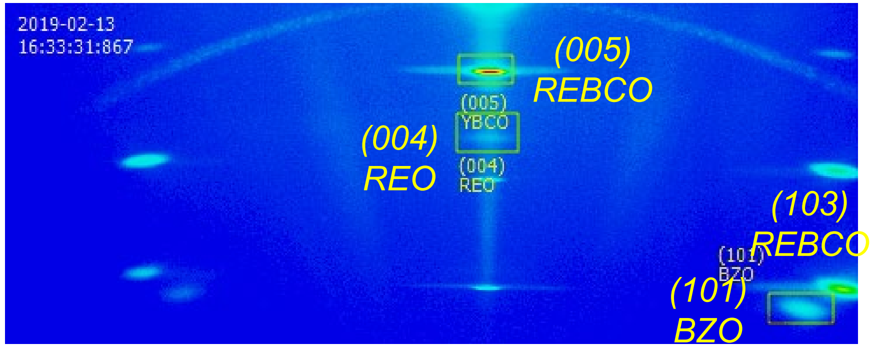
Continuous 2D-XRD data acquisition along tape length during REBCO film deposition in Advanced MOCVD



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

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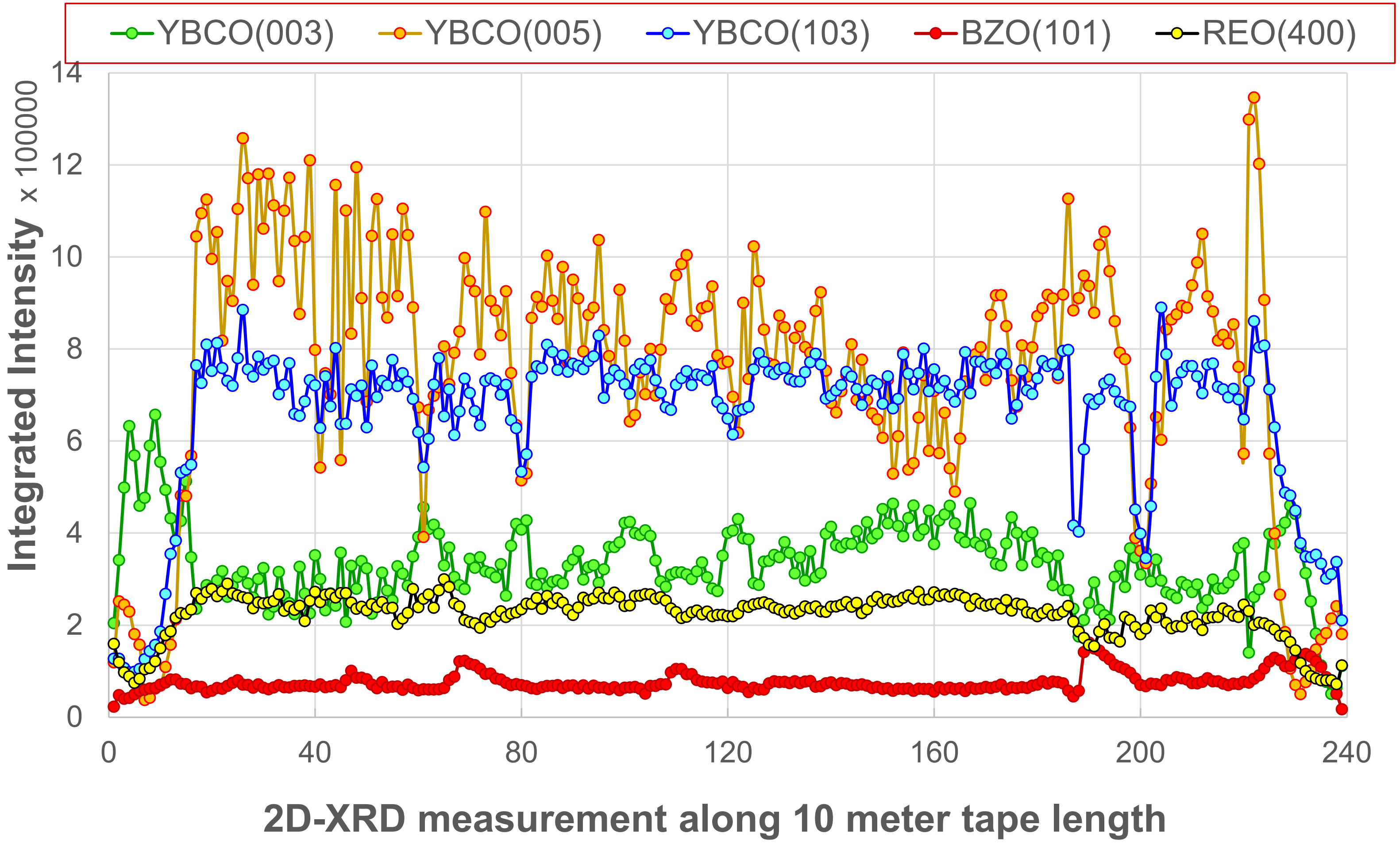
Integrated intensity of REBCO, BZO, REO peaks along tape length continuously during REBCO film deposition



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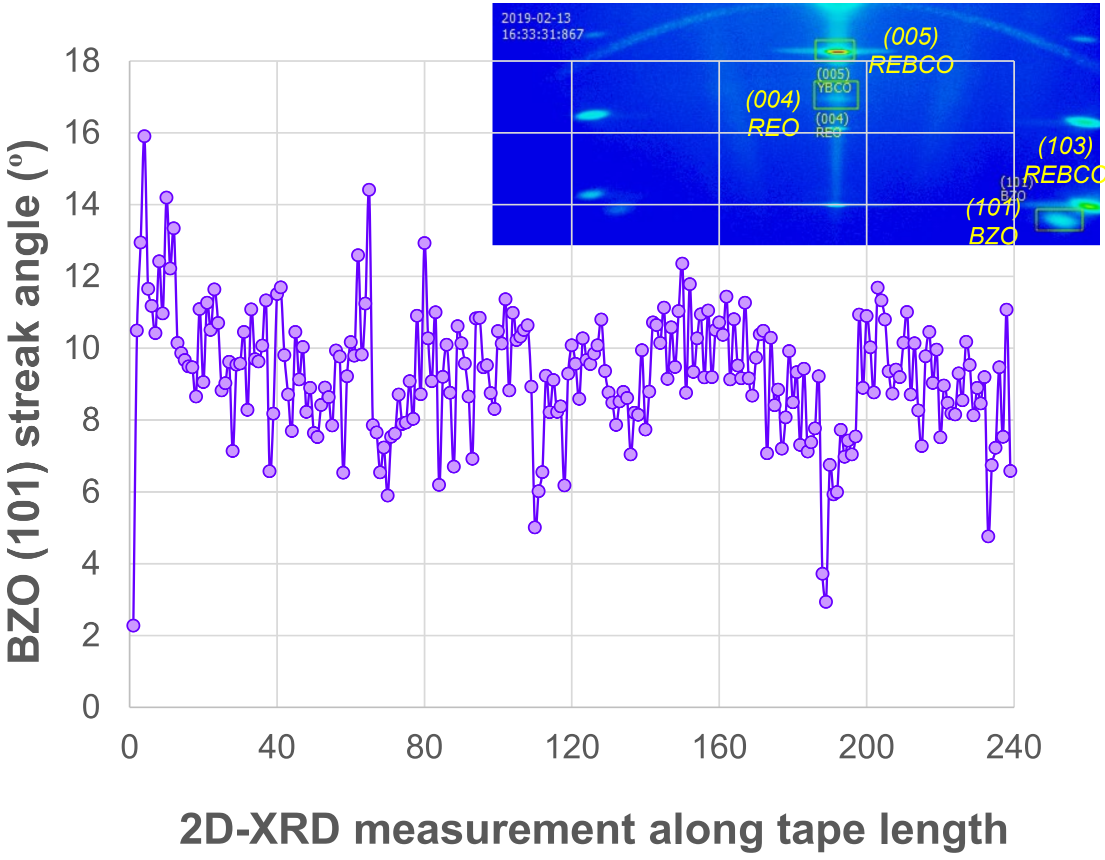
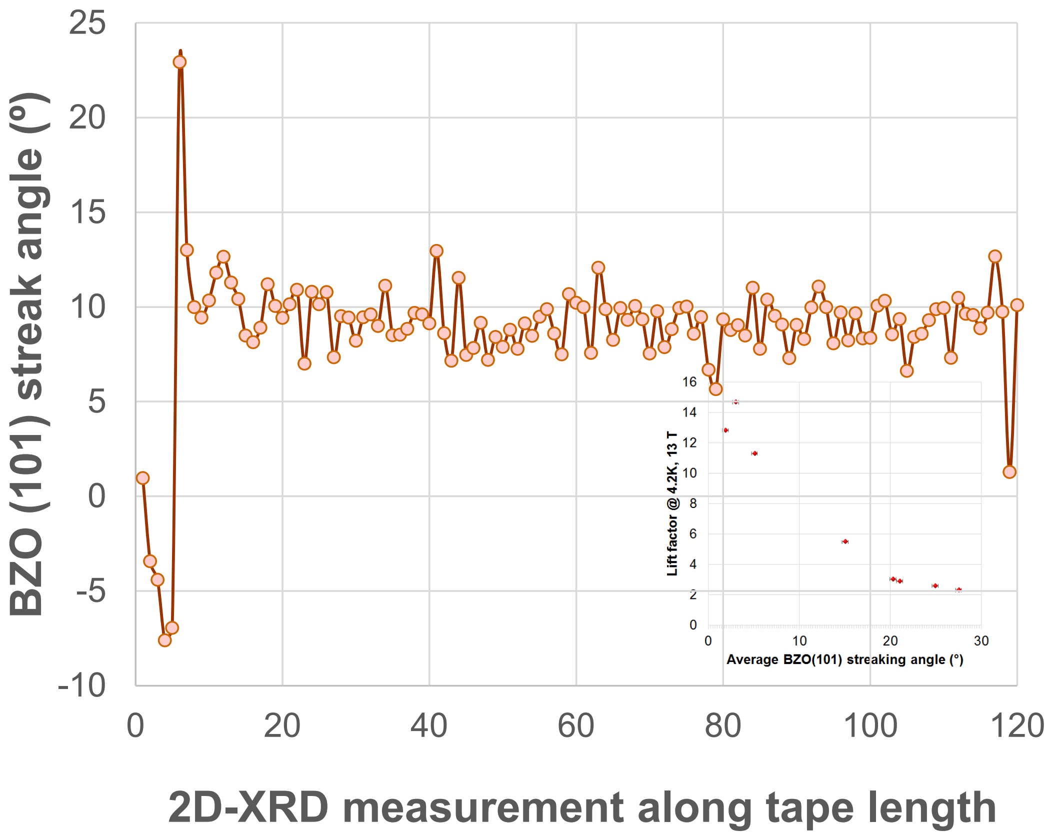
BZO (101) peak streak angle measured along tape length continuously during REBCO film deposition





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

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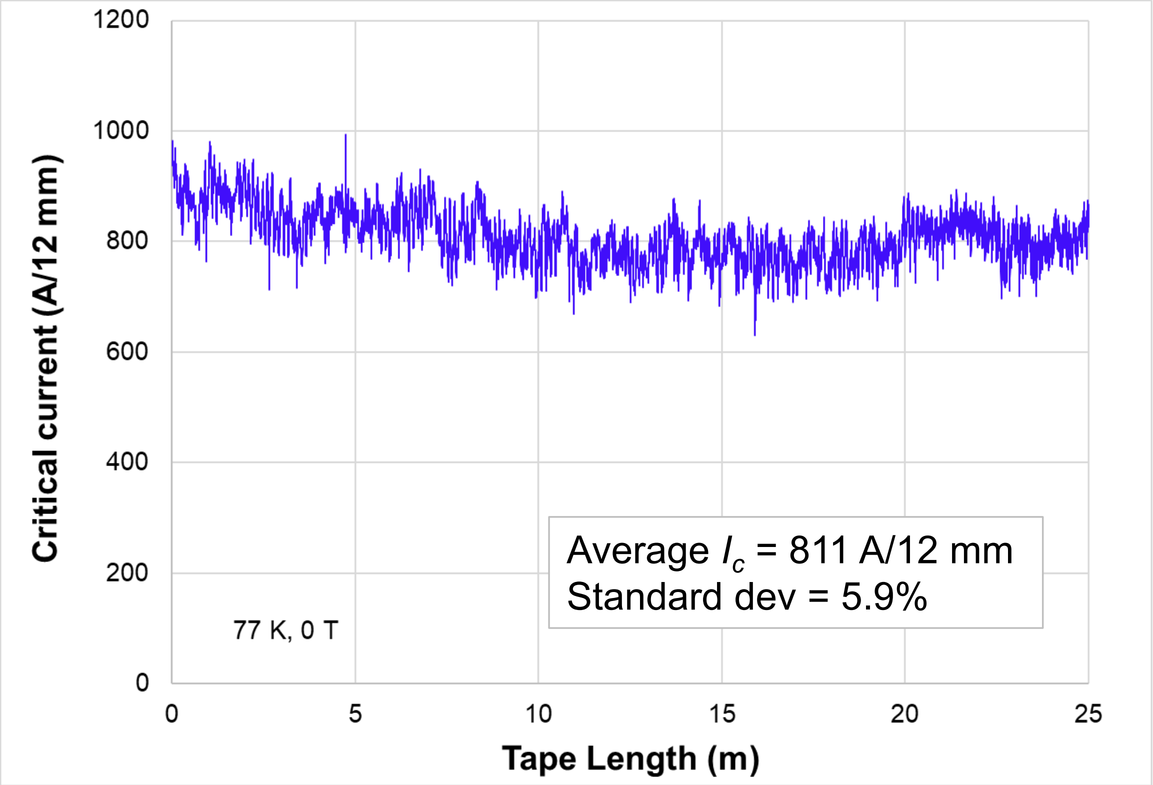
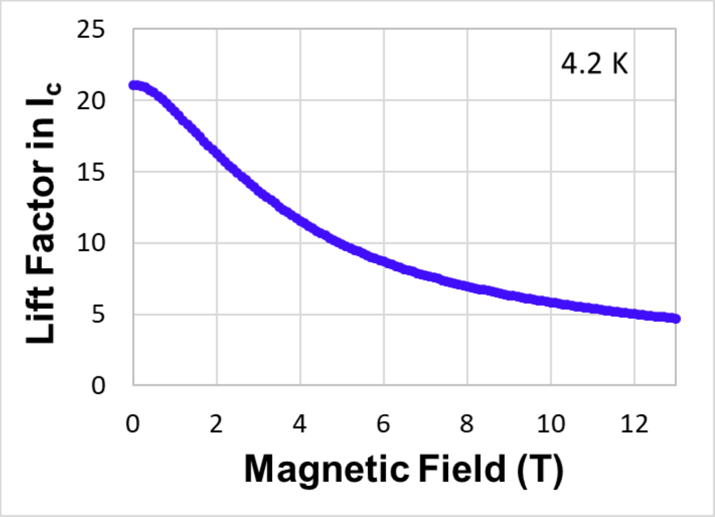
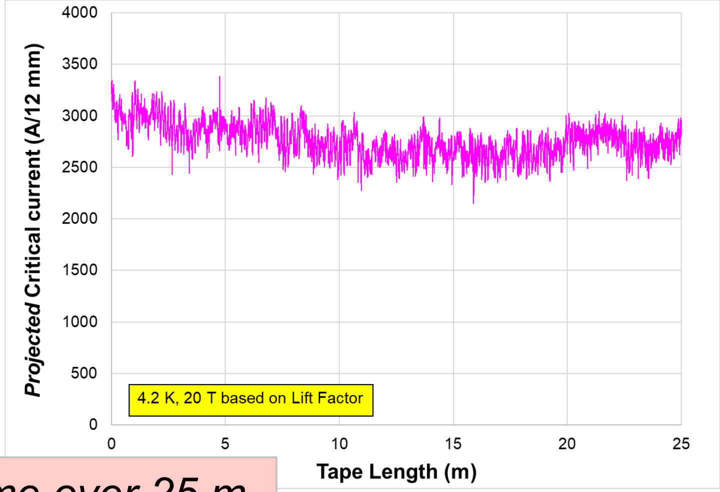
Performance of 25 m long Advanced MOCVD tapes







- Measured Lift Factor in I_c @ 4.2 K, 13 T = 4.71
- alpha value @ 4.2 K = 0.772
- Projected Lift Factor in I_c @ 4.2 K, 20 T = 3.41

Lift factor measured at one end of tape may not be same over 25 m

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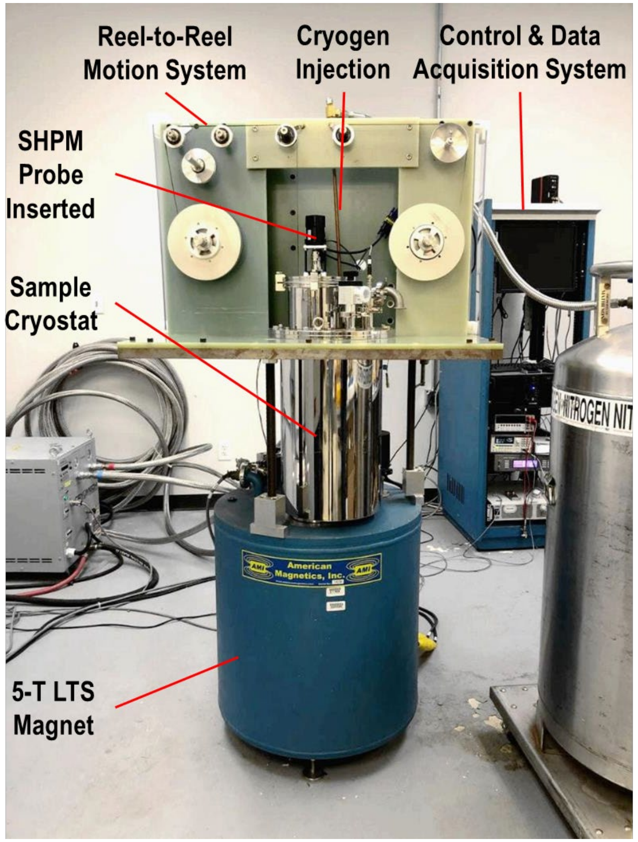
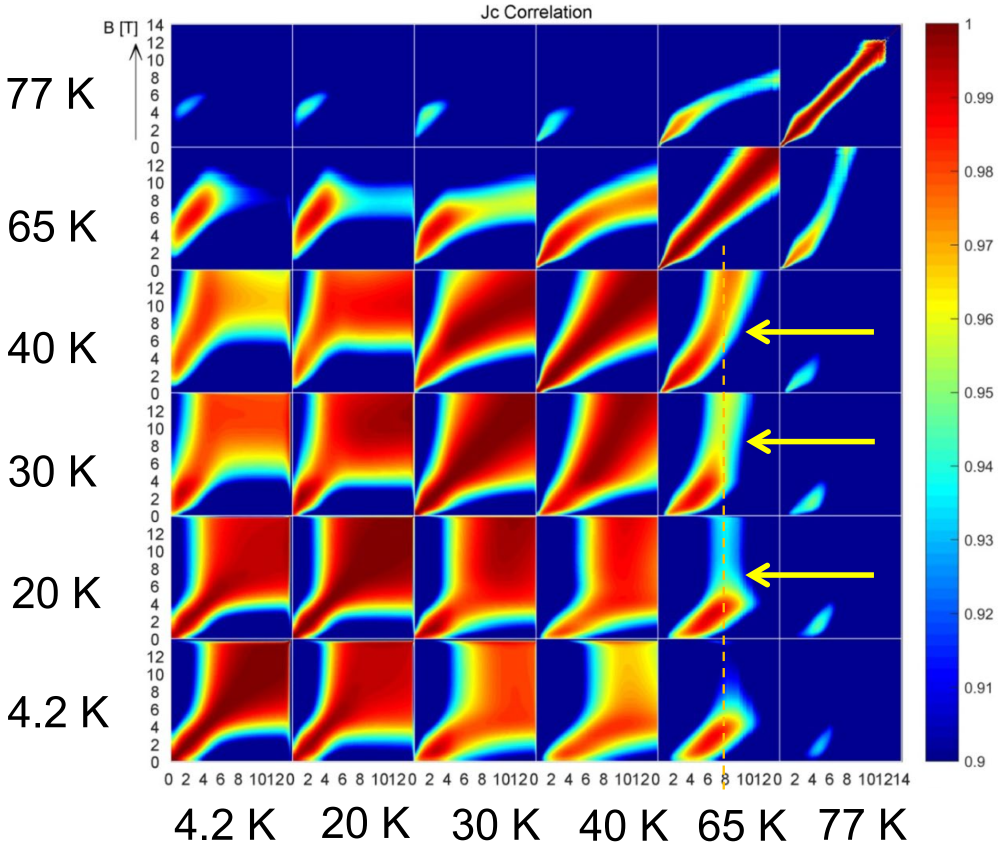
Reel-to-reel in-field I_c measurements of long tapes at 65 K by non-contact Scanning Hall Probe Microscopy (SHPM)





IEEE Trans. Appl. Supercond. **29,** 6602005 (2019)

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In-field I_c at 65K measured by reel-to-reel SHPM can be used to determine I_c over entire tape length in high magnetic fields at 4.2 – 20 K using the discovered strong correlations.

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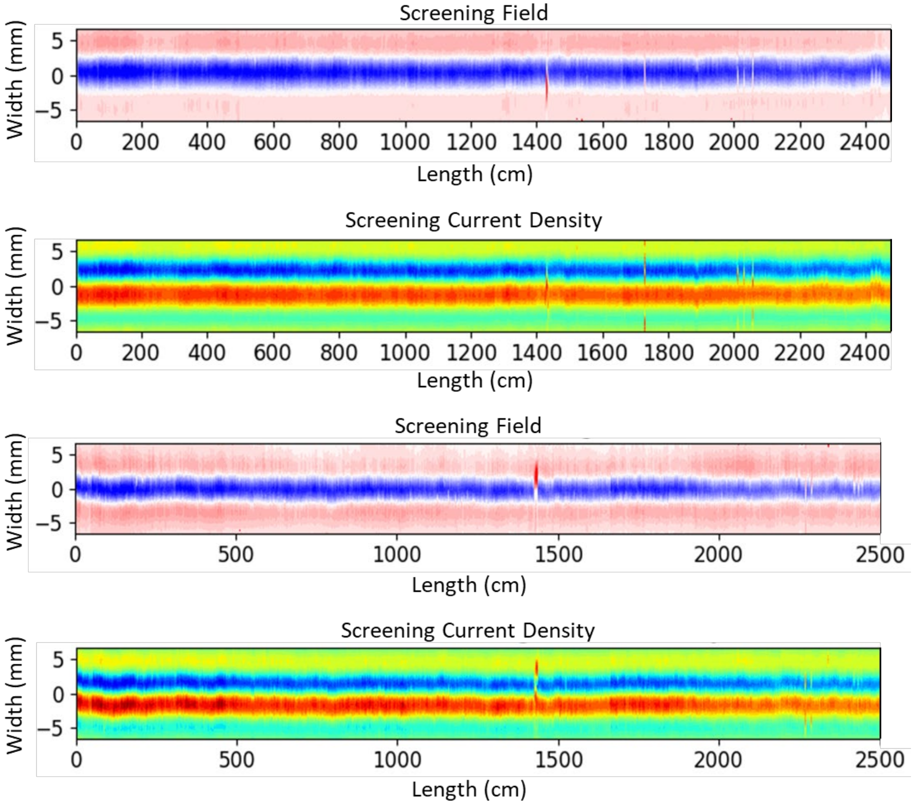
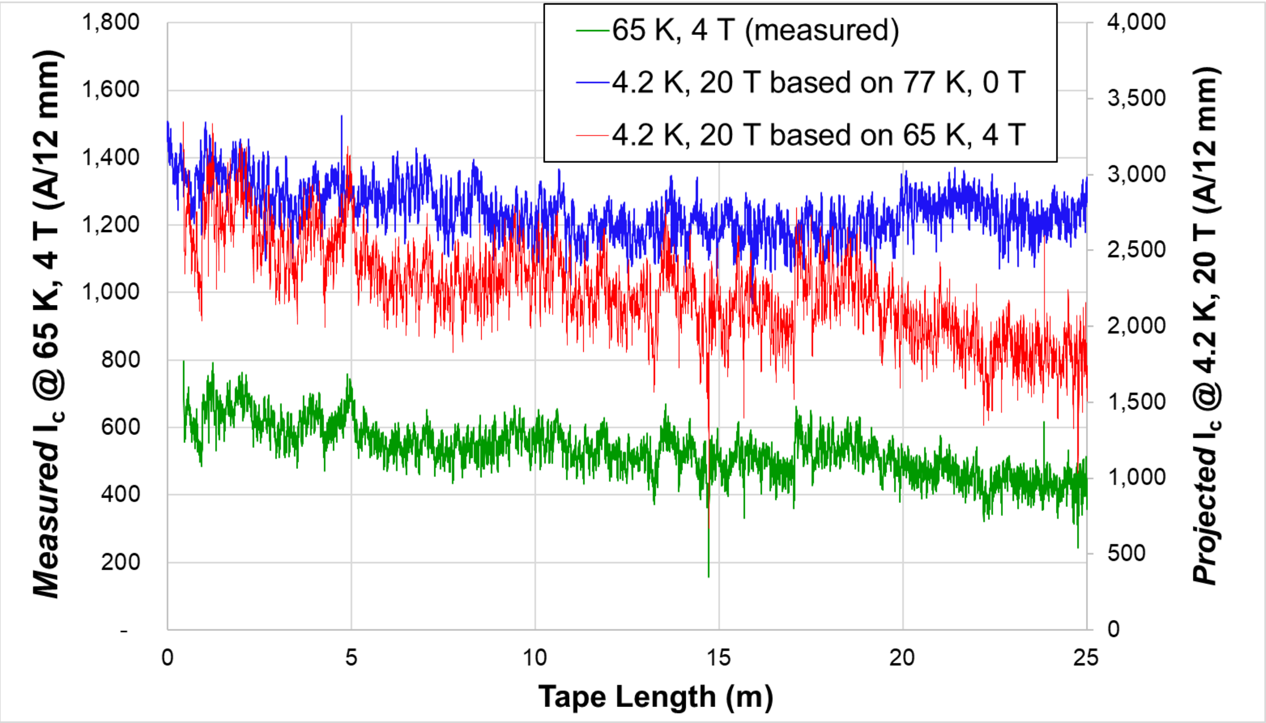
Reel-to-reel I_c measurements at 65 K, 2 T and 4 T over 25 m long tape 1 mm intervals by reel-to-reel SHPM

2 T

4 T





Expect more I_c non-uniformity in high fields at 4.2 K and 20 K than that measured at 77 K, 0 T

I_c @ 4.2 K, 20 T	Uniformity over 25 m
Based on I_c @ 77 K, 0 T	5.9%
Based on I_c @ 65 K, 4 T	14.2%

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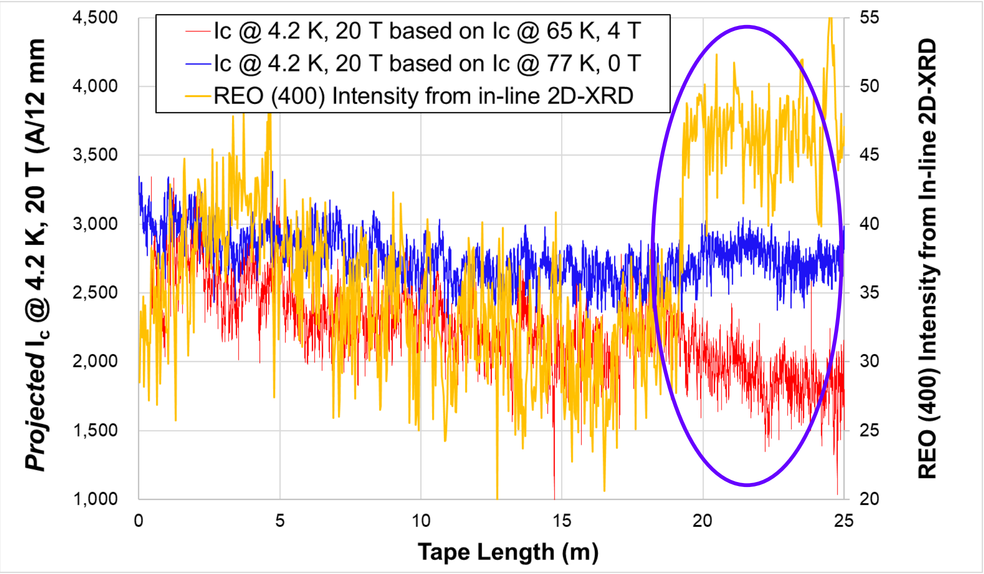
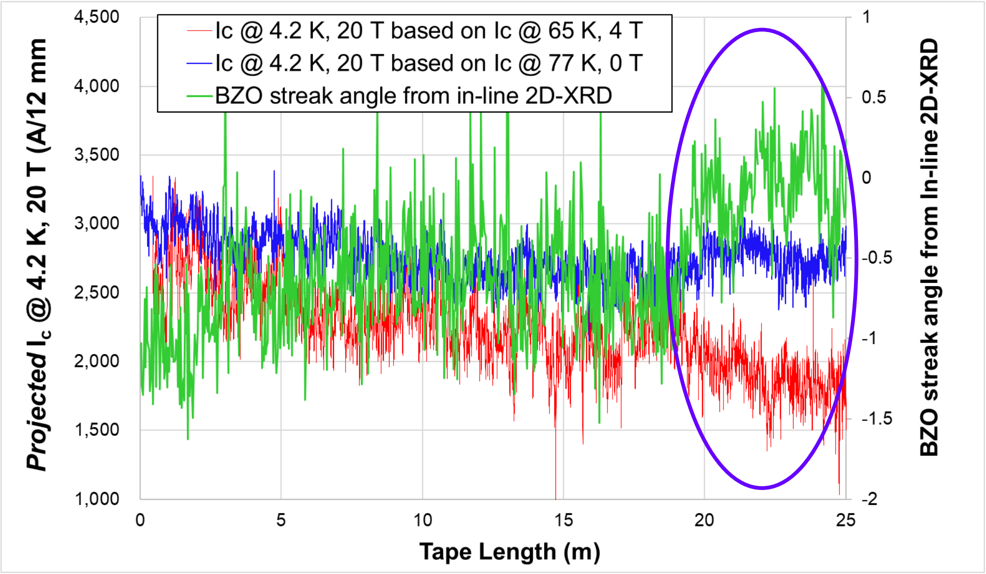
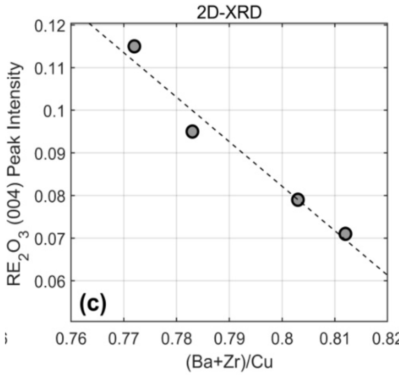
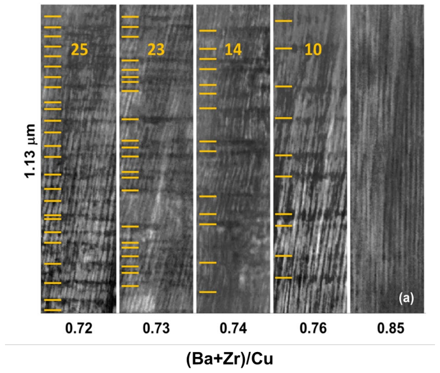
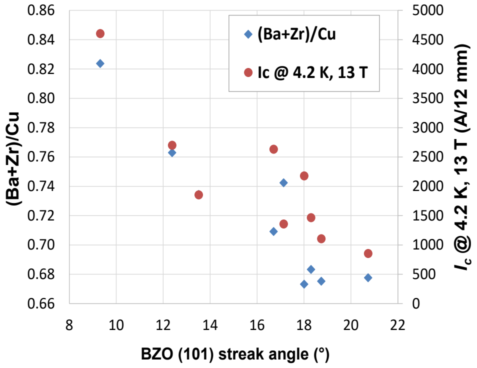
Decrease in in-field I_c in R2R SHPM predictable by decreasing REO peak intensity and increasing BZO streak angle in in-line 2D-XRD











Less Ba in film → more RE_2O_3 interfering with BZO growth → reduced in-field I_c

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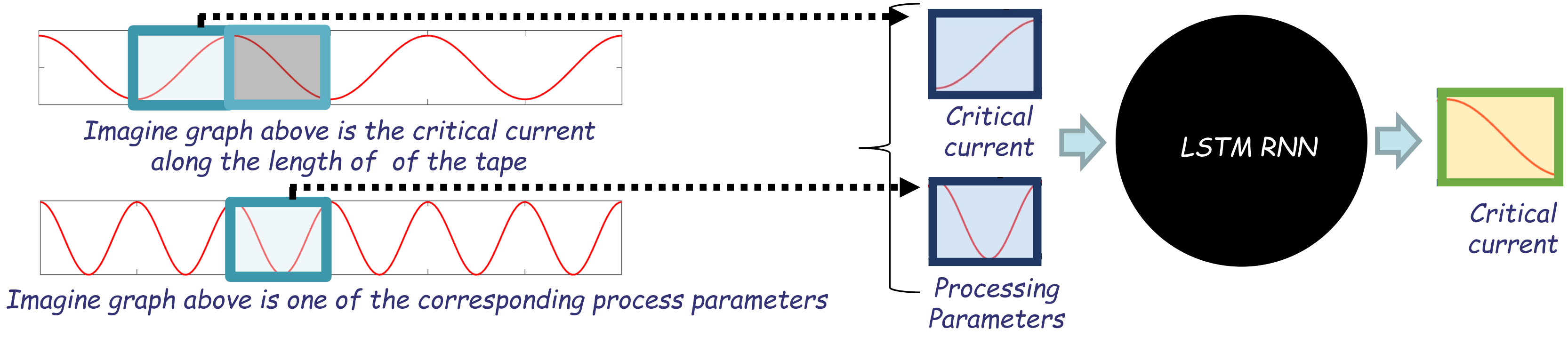
Creating a feedback for process control: Machine learning based predictive model using LSTM recurrent neural network (RNN)

- Goal: Using information on critical current in *earlier* part of the tape and manufacturing process parameters of *later* parts of the tape, predict the critical current of the *later* part of the tape.



- A window size of 500 time steps (roughly 40 cm of tape) used to create the dataset.
- Training done on dataset from 39 long HTS tapes. 32 process parameters used to create and train LSTM RNN network.

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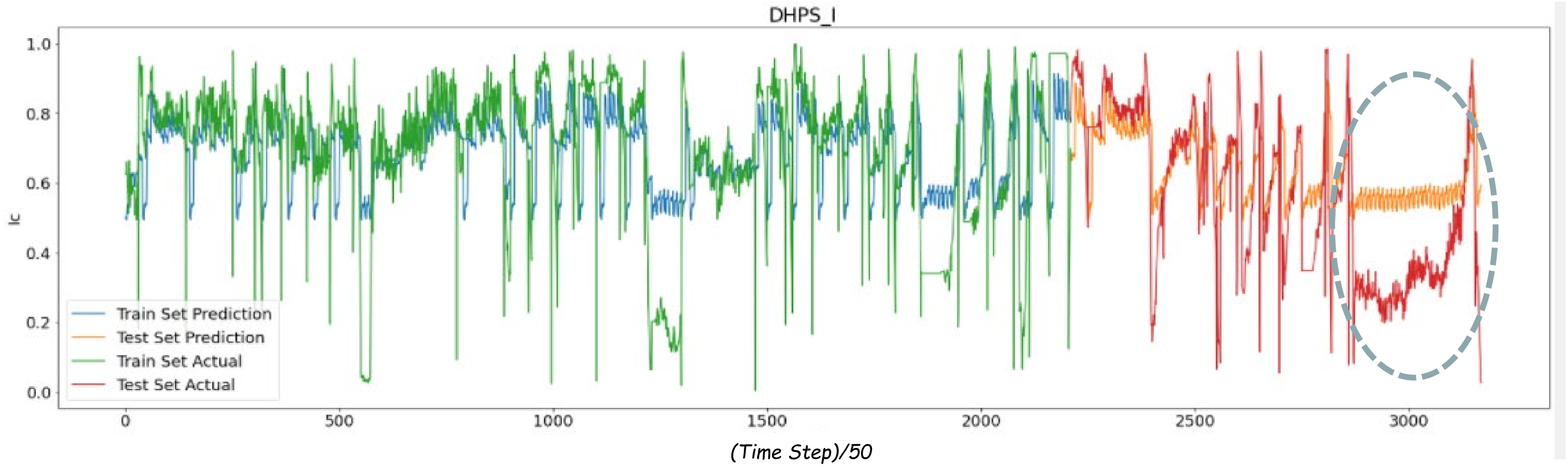
Training with only one process parameter does not enable the network predict critical current

Training using critical current and only one process parameter as inputs of the RNN



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IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation MS-2 was given at the virtual CCA 2021, October 11-15, 2021.

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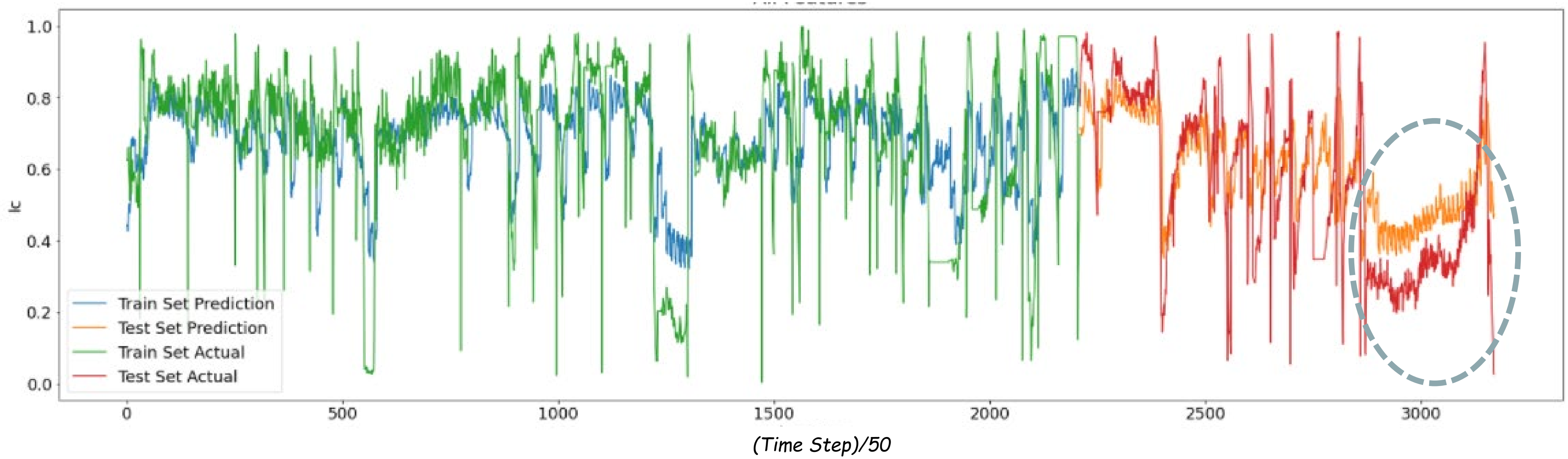
Training with all process parameters enables the network predict critical current

Training using critical current and all process parameters as inputs of the RNN



<u>Next</u>: Use in-line 2D-XRD data and machine learning for real-time prediction of tape quality in REBCO tape manufacturing

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Technical Roadmap for large-scale commercialization of REBCO

4 – 5 μm thick films + Tailored BMO structure by optimized Ba content

=

1.8 kA @ 4.2 K, 20 T
(3.2x best commercial tape)

Lift factor at 4.2 K 20 T = 4.6
2.2x commercial tape

↓

High-yield manufacturing
(>90%)

Scale up to long lengths

Uniform composition, defect structure

- In-line 2D-XRD, In-line Raman, R2R In-field SHPM
- Machine learning neural network

New built-in features

- Defect tolerance
- Higher yield strength (2.5 GPa)
- Superior flexibility
- Quench detection
- Lower losses

↓

High-throughput manufacturing
(5,000 km/year/tool)

Large area deposition

– 2 m^2 deposition zone
(advantage of MOCVD)

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