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Invited presentation 1-MO-CS-01I given at EUCAS, 01 - 05 September 2019, Glasgow, UK.

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Progress in development of high-performance REBCO tapes and wires

Venkat Selvamanickam

Department of Mechanical Engineering
Advanced Manufacturing Institute
Texas Center for Superconductivity
University of Houston, Houston, TX, USA

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Outline

- Improving Performance of REBCO Tapes at 65 K, Low-fields
- Improving Performance of REBCO Tapes in High Magnetic Fields at 4.2K
- Development of In-line and Continuous Quality-Control Tools for High-yield Manufacturing
- Symmetric Tapes for round REBCO wires for high J_e with diameter < 2 mm
- Bend tolerance and high-field performance of High J_e STAR REBCO Wires
- Status and Next Steps

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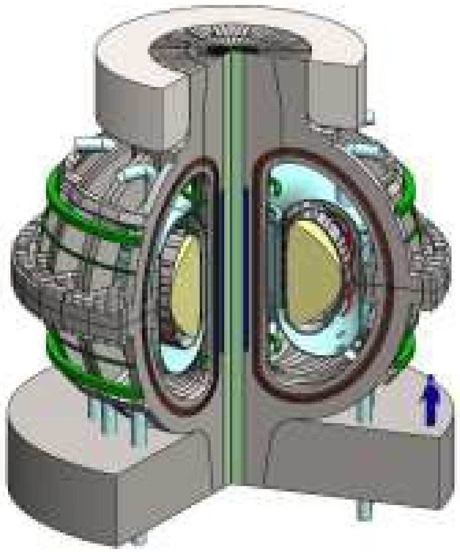
Two primary applications driving REBCO development

High Temperature, low-medium field

65K – 77K, 1 – 3 T

Next-generation Electric Machines



ARC, *Courtesy Commonwealth Fusion Systems*

Magnets for Accelerators, Fusion

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Improving Performance of REBCO Tapes at 65 K, Low-fields

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Advanced HTS Wire Development in DOE-AMO Next-generation Electric Machines (NGEM) Program

	Prod. Tape now	AMO NGEM2 Target Tape
Ic @ 65 K, 1.5 T (A/cm)	340	1440
Tape quantity for 5.5 MW motor (km)	5.9	1.3
Tape cost for 5.5 MW motor ($(,000))	236	26
% of motor cost	67%	8%

Extending nanocolumn-engineered REBCO films from 1.7 to 5µm to meet goal

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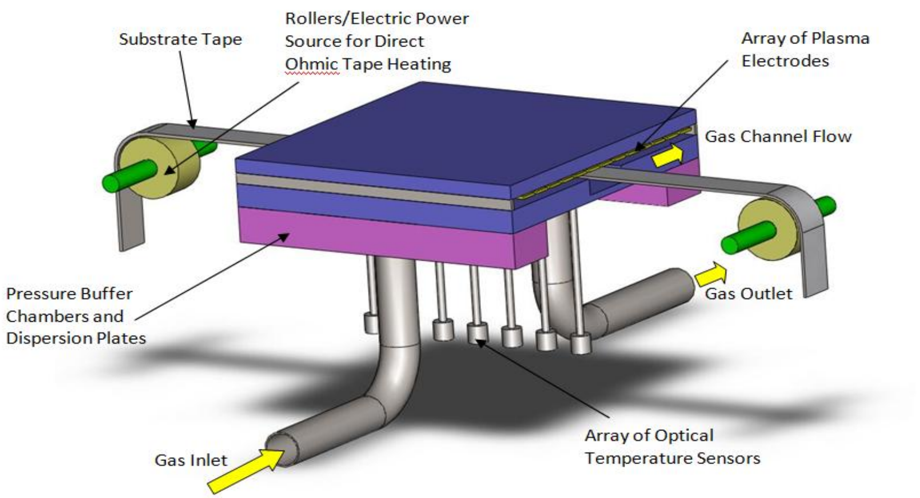
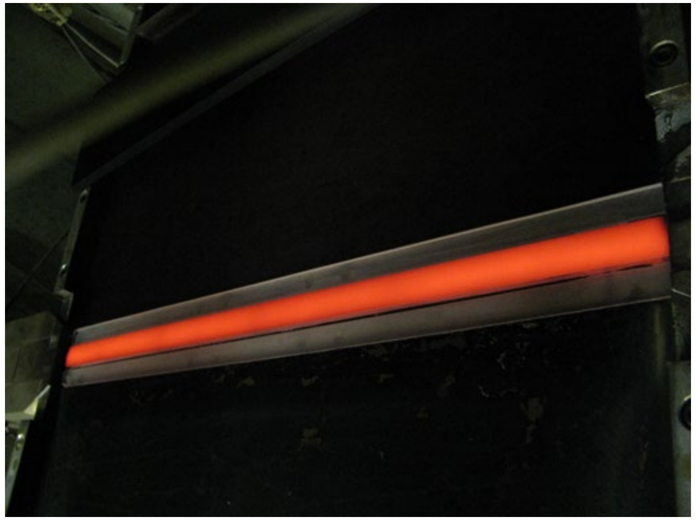
UH Advanced MOCVD system for high performance, low-cost, high-yield production

- New reactor to address all deficiencies of current production tools designs
  - 5μm thick films & 10X BZO density : Excellent control (0.1ºC) of tape temperature by Direct Tape Heating and Direct Tape Temperature monitoring
  - 5X precursor-to-film conversion efficiency: Low volume, laminar flow reactor





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

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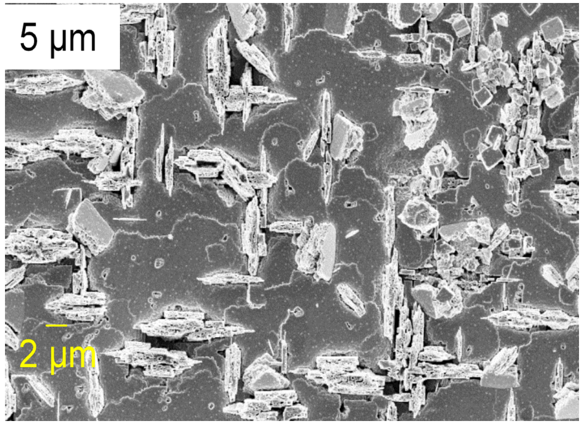
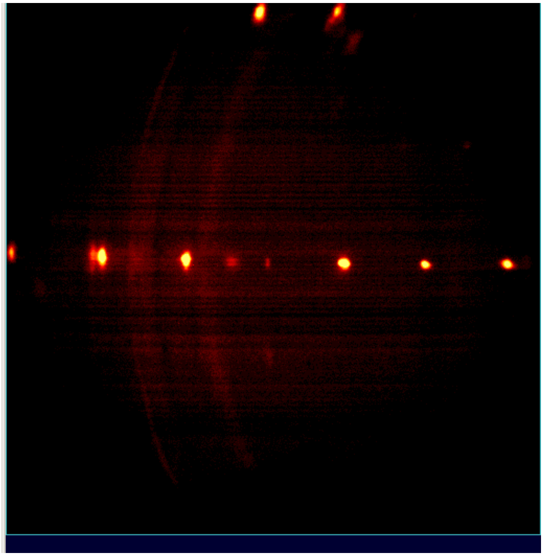
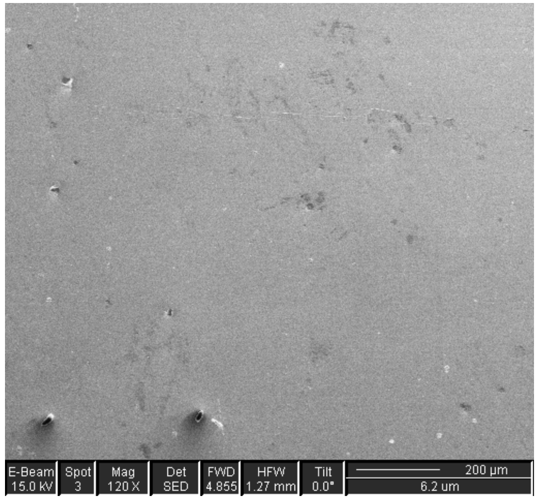
4.6 µm thick film deposited by Advanced MOCVD in a single pass with purely c-axis oriented REBCO

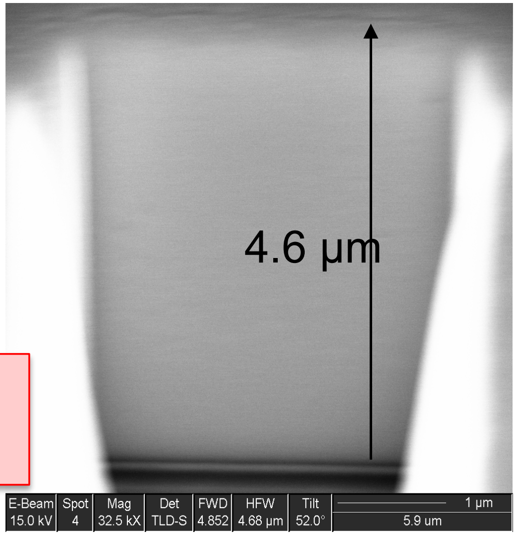


Previous 5 µm REBCO film by conventional MOCVD made in 5 passes



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

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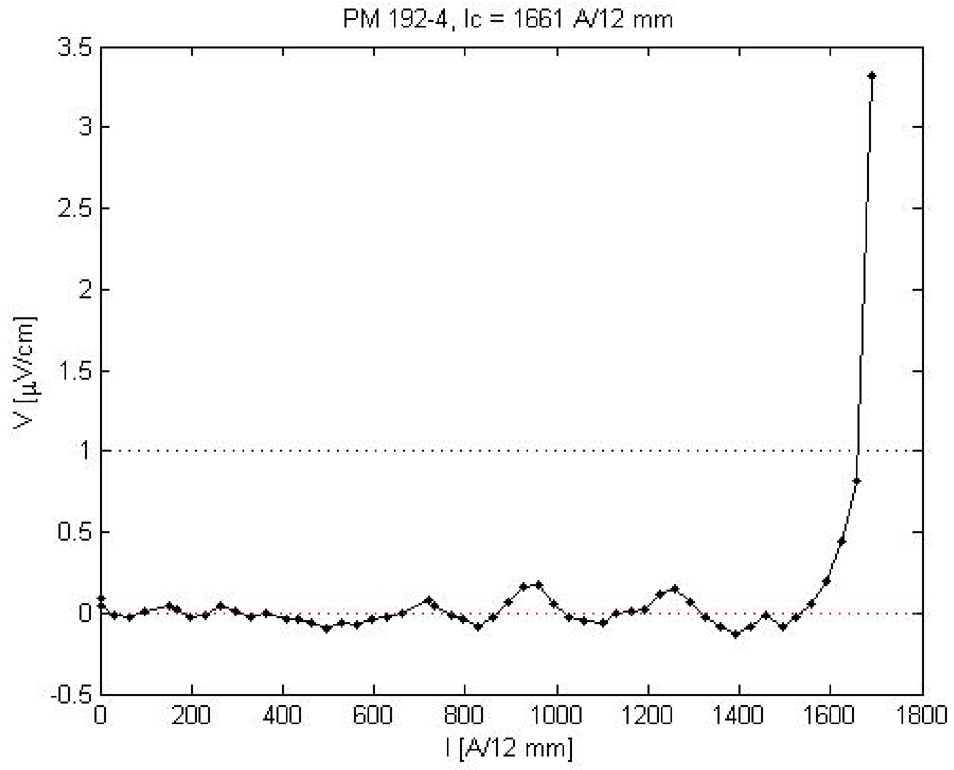
Critical currents over 1600 A/12 mm achieved in thick films made by Advanced MOCVD



(Gd,Y) $Ba_2Cu_3O_x$ (undoped)

I_c^{sf} (77K) = 1611 A/12 mm (record high current in single time deposition in a MOCVD process)

J_c^{sf} (77K) = 2.92 MA/cm²

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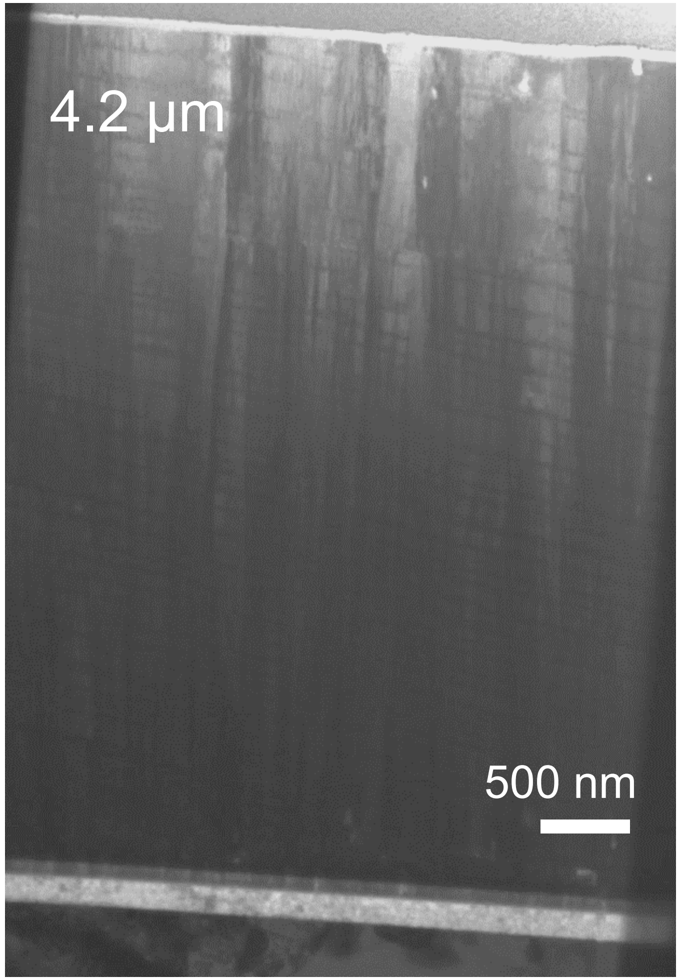
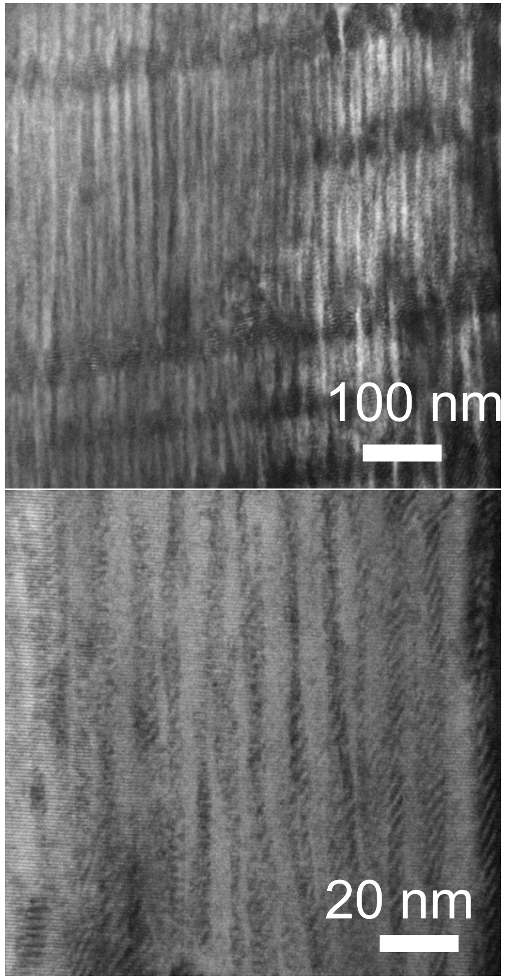
Well aligned BZO nanocolumns throughout 4.2 μm thick HTS films by Advanced MOCVD





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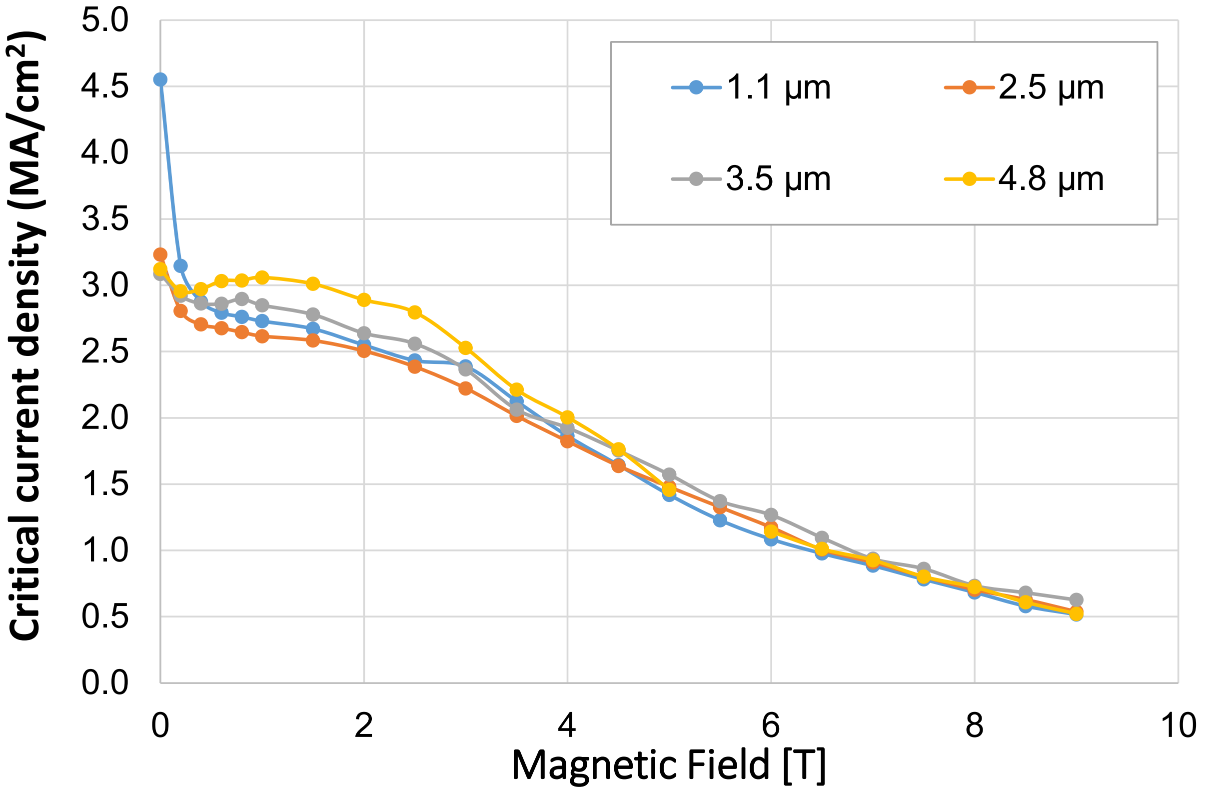
Effect of film thickness on in-field critical current density of 5% Zr-doped tapes at 65 K



- *At 65 K, 1.5 T (B // c-axis) , J_c = 2.6 – 3 MA/cm^2 with all film thickness*
- *In 4.8 μm film, J_c - 3 MA/cm^2 = 1734 A/12 mm (record high current).*
  - *F_p~ 87 GN/m^3*

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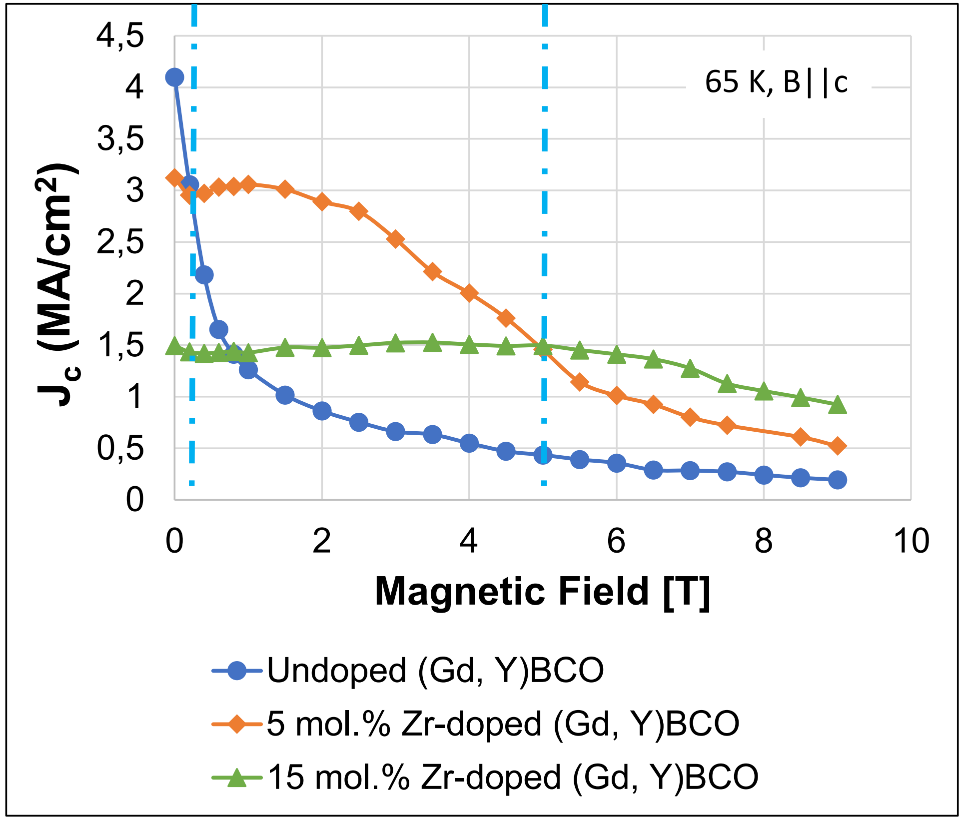
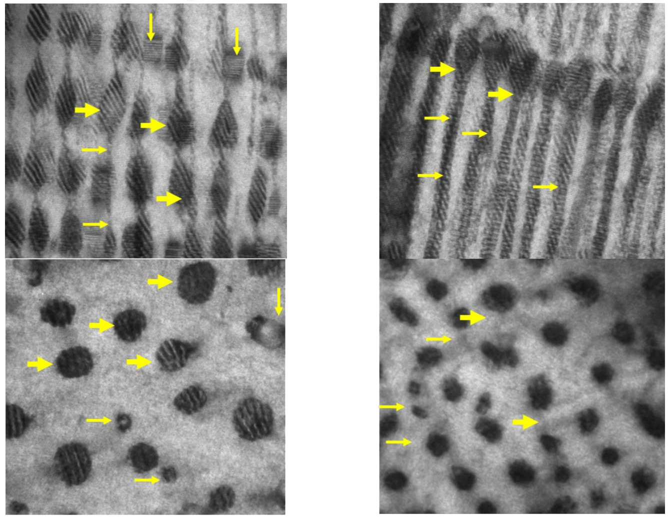
Effect of Zr concentration on in-field critical current density of 4+ μm films at 65 K



5% Zr-doped   *15% Zr-doped*



Feature	5% Zr	15 % Zr
Nanocolumn spacing (nm)	22	17
Nanocolumn density (rods/μm²)	2066	3460
Matching field (T)	4.2	7.2

5% Zr-doped films optimum below 5 T

15% Zr-doped films better above 5 T

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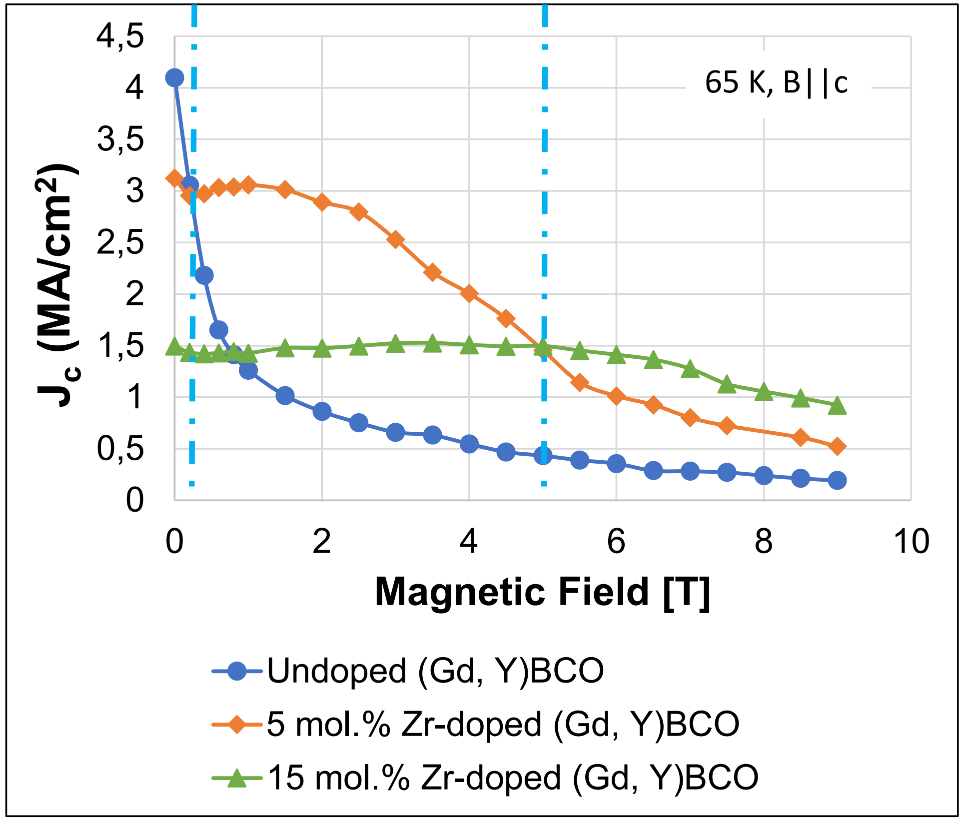
Effect of Zr concentration on in-field critical current density at 65 K



	0% Zr	5% Zr	15% Zr
Out-of-plane texture (º)	0.9	1.1	1.4
In-plane texture (º)	2.3	3.4	5.5
(GdY)BCO lattice constant (Å)	11.68	11.73	11.75
(Ba – Zr)/Cu	0.65	0.66	0.70

Lattice parameter increase, texture deterioration in 15% Zr suppress J_c at 65 K, 0 T but near-constant J_c up to 6 T.

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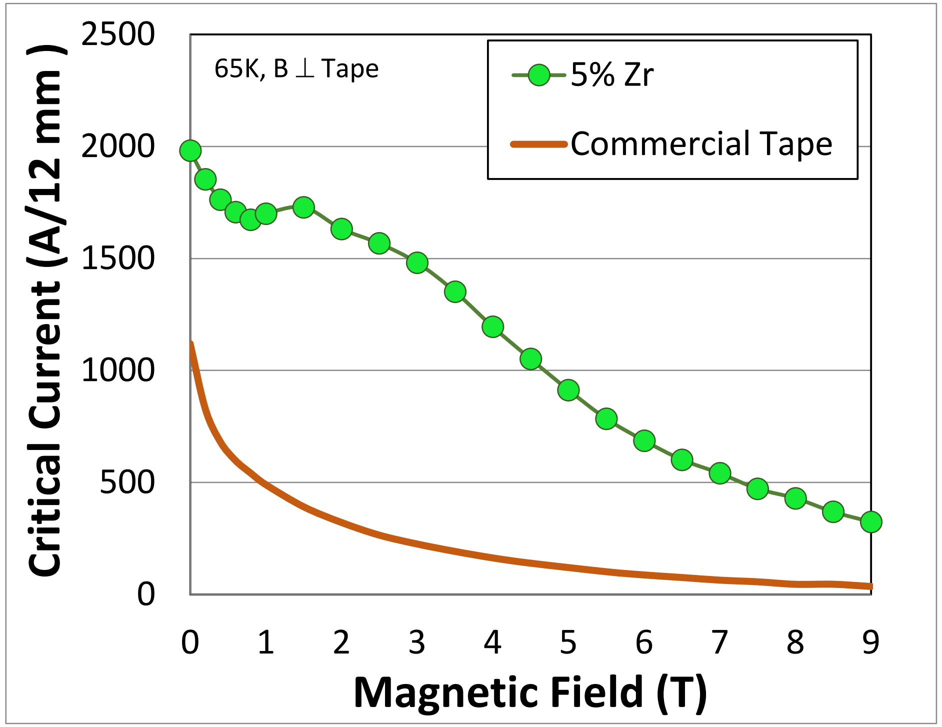
Critical current > 1440 A/cm @ 65K, 1.5T – Met DOE Advanced Manufacturing Office milestone



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***

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Improving Performance of REBCO Tapes in High Magnetic Fields at 4.2K

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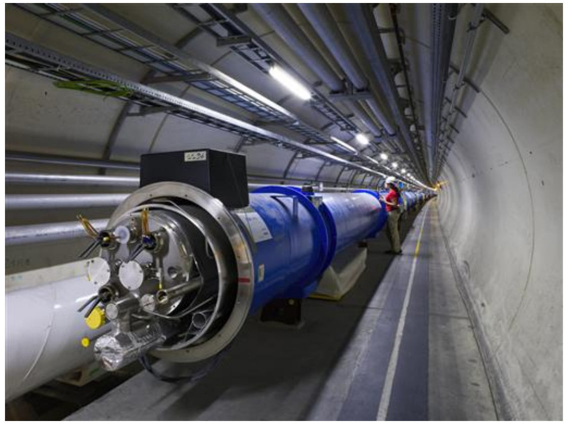
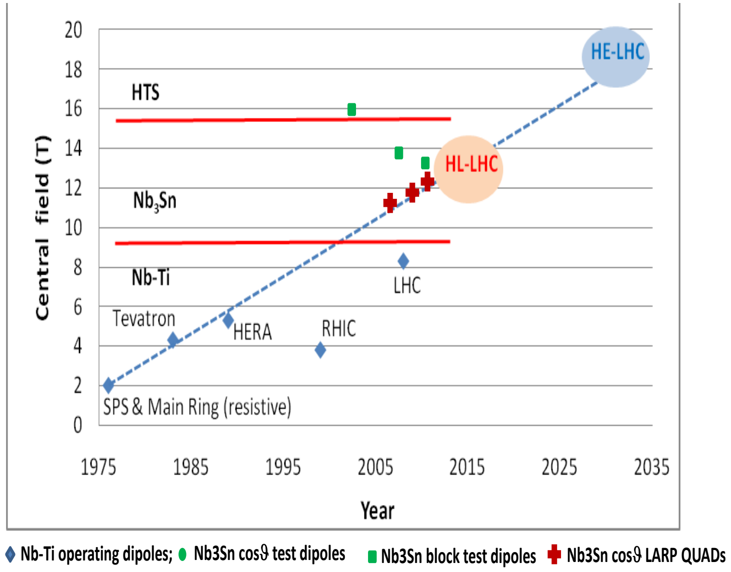
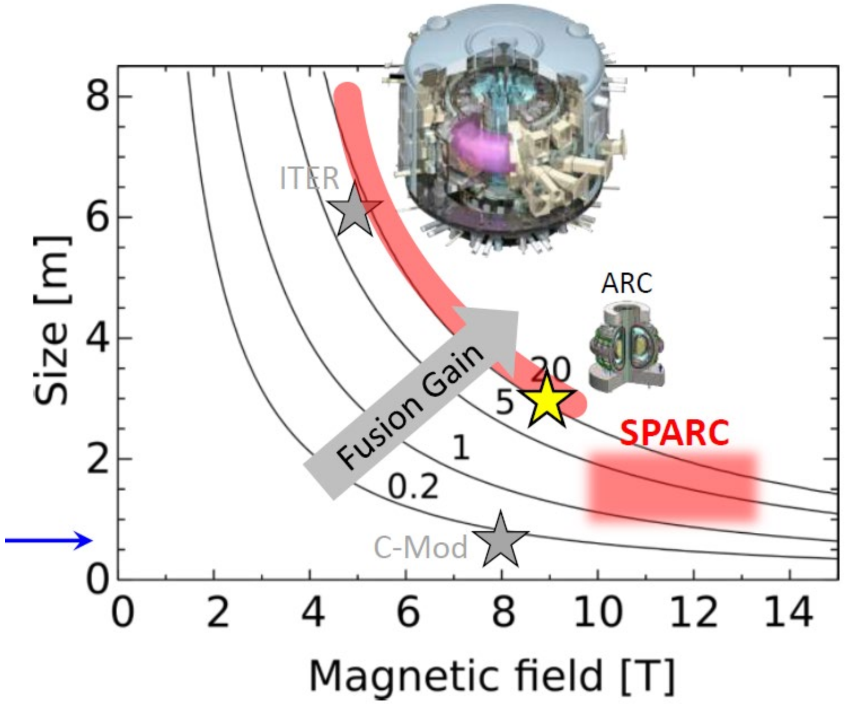
REBCO tapes for high fields at 4.2K-20 K for High Energy Accelerators and Compact Fusion Systems







Courtesy Commonwealth Fusion Systems

HTS operating at 20+T enables 10X smaller fusion energy systems and compact high energy accelerators

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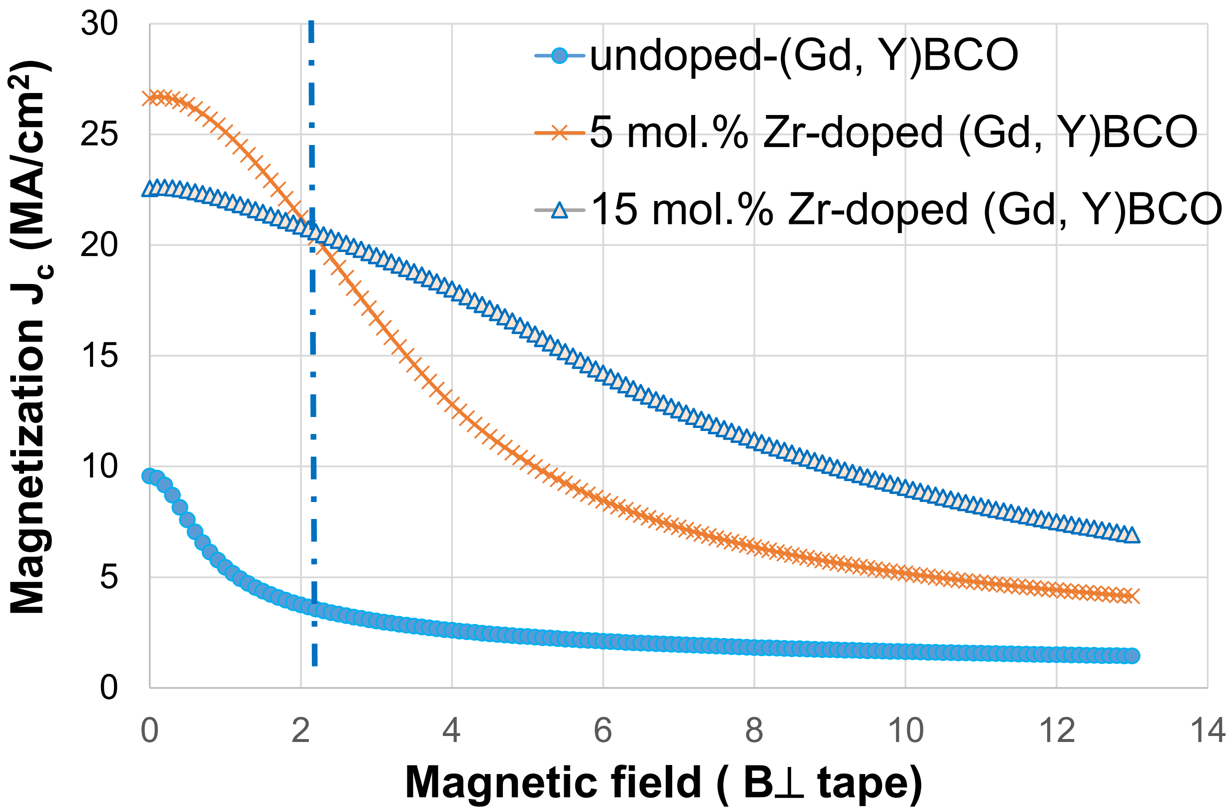
Effect of dopant concentration on in-field performance of 4+μm thick film tapes at 4.2 K



15% Zr-doped tapes superior at all fields above 2 T at 4.2 K

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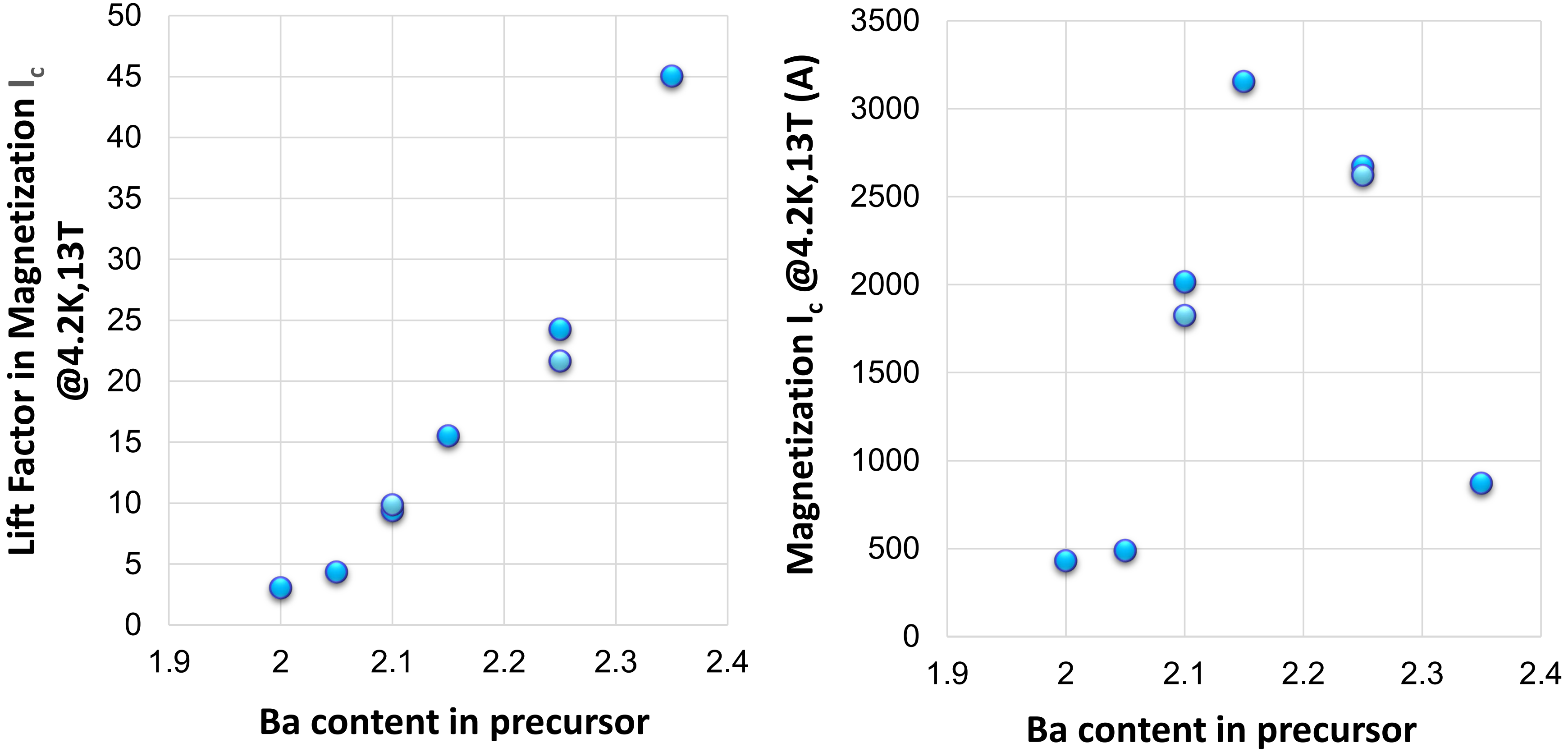
Influence of barium content at constant 15% Zr on tape performance at 4.2K,13T



Higher density of very fine BZO with increasing Ba → improved pinning
Too high Ba → degradation of REBCO texture, too high strain in REBCO

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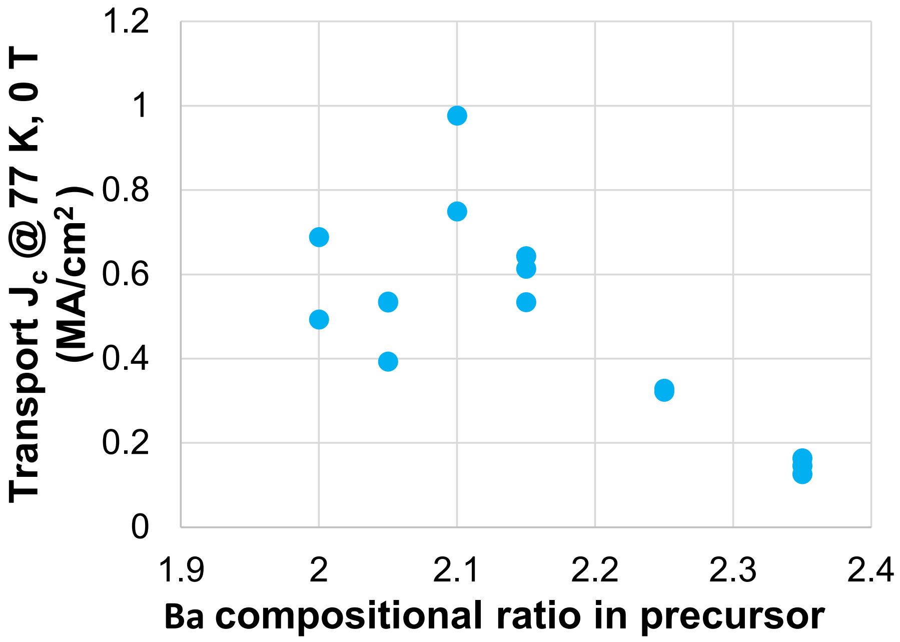
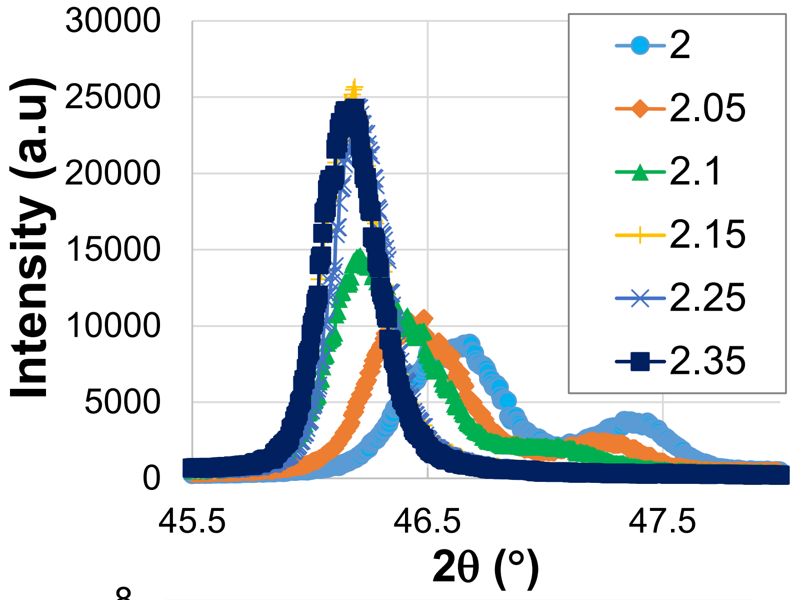
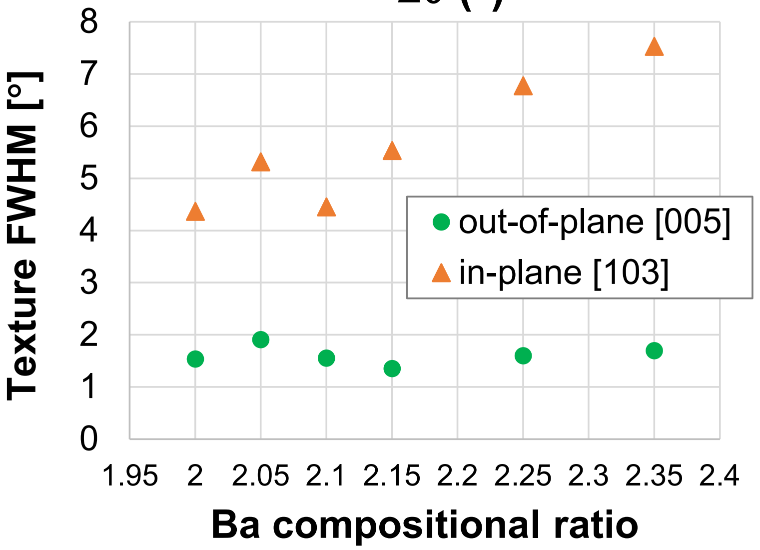
Influence of Ba content on self-field J_c of 4+ µm 15% Zr-doped (Gd,Y)BCO





For Ba content < 2.1 → a-grains

For Ba content > 2.15 → degradation of in-plane texture



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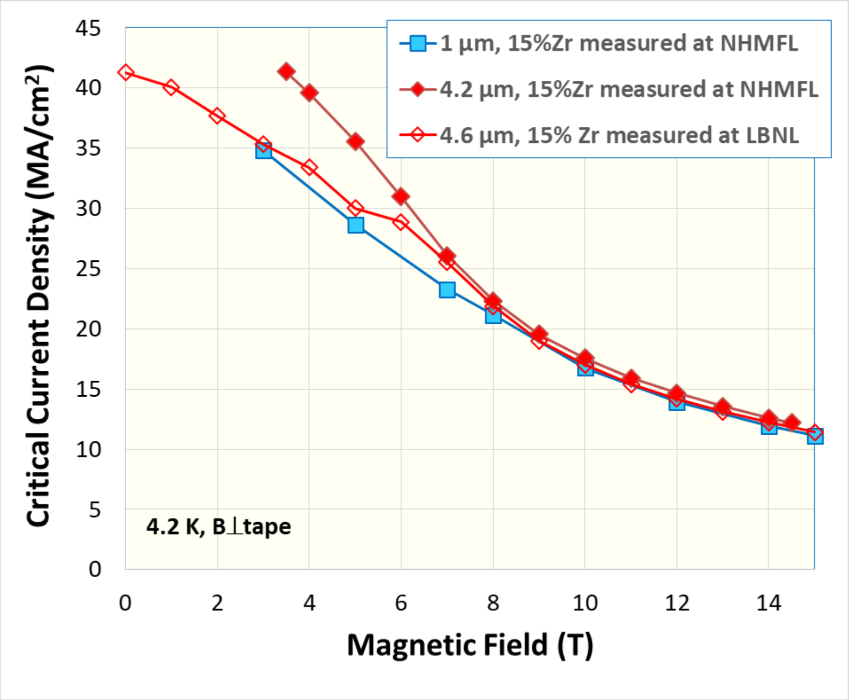
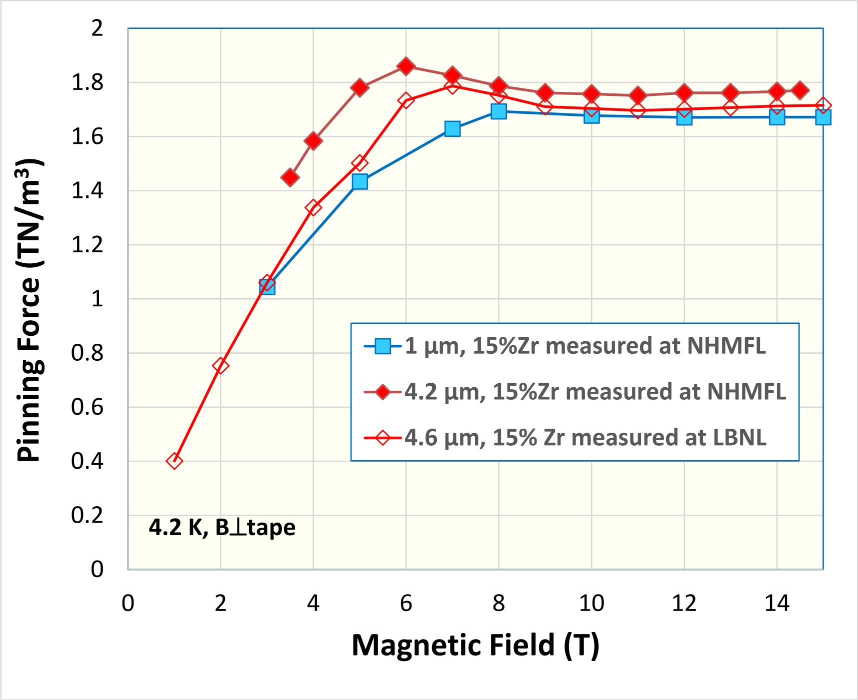
Transport J_c of 4+ μm thick film with high BZO density comparable to 1 μm thick films





Similar J_c in all tapes > 8 T at 4.2 K

Maximum pinning force of 4.2μm thick film REBCO tape = 1.86 TN/m³

Maximum pinning force of 1μm thick film REBCO tape = 1.76 TN/m³

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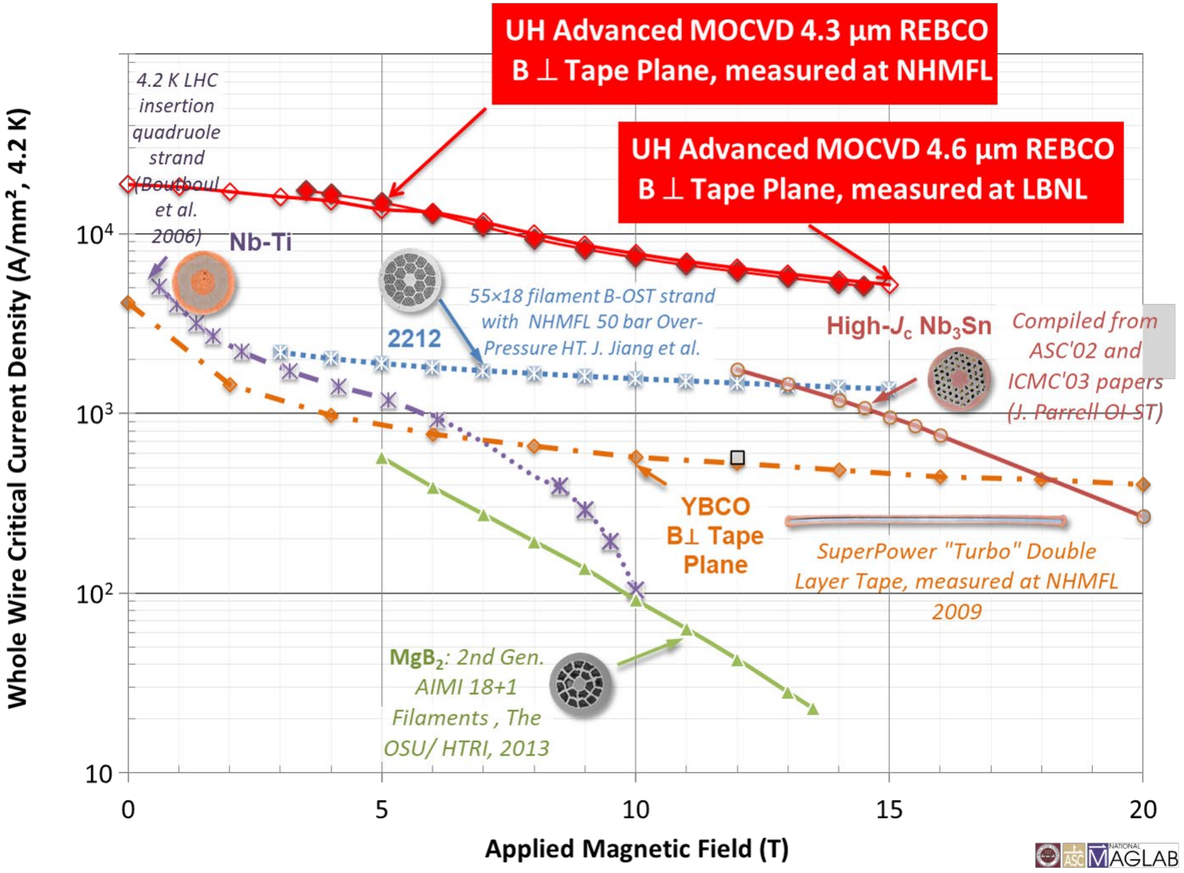
Thick film 15% Zr REBCO tapes made by Advanced MOCVD exhibit very high J_e at 4.2K



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

5.4X Nb_3Sn @ 15 T

7X present commercial REBCO @ 15 T

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

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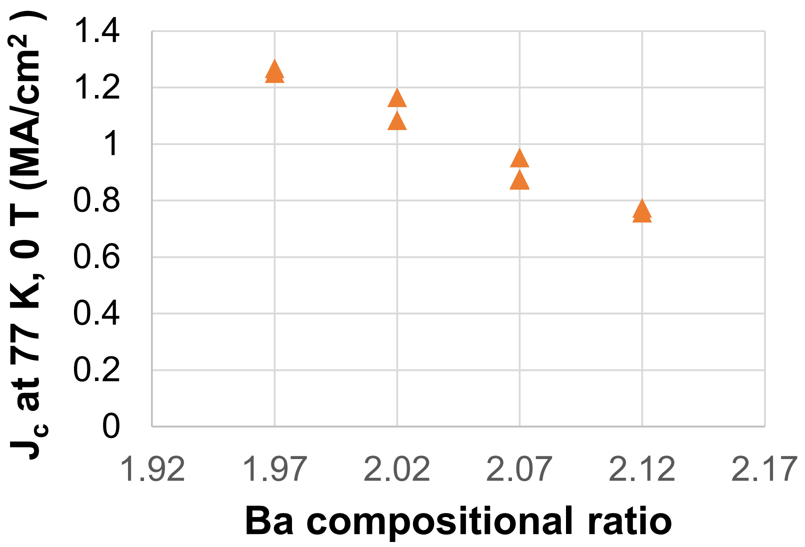
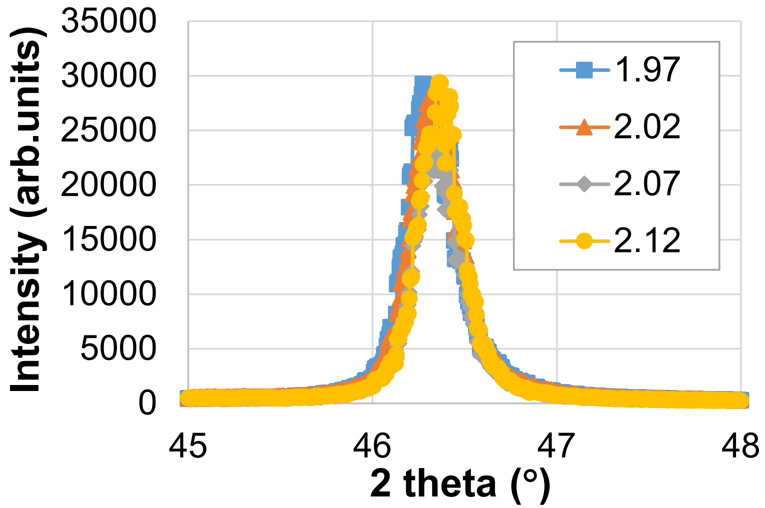
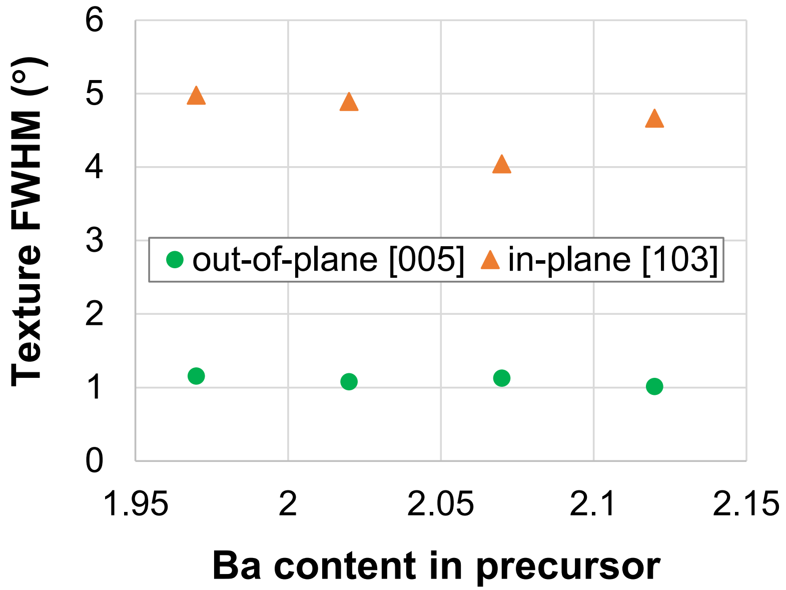
Influence of Ba content on self-field J_c of 4+ µm 15% Hf-doped (Gd,Y)BCO





Ba content in precursor	Average (Ba-Hf)/Cu
1.97	0.66
2.02	0.68
2.07	0.69
2.12	0.70



Compared to 15% Zr-doped films, with increase in Ba content, no a-grains, no increase in c-lattice constant and no change in texture in 15% Hf-doped films.

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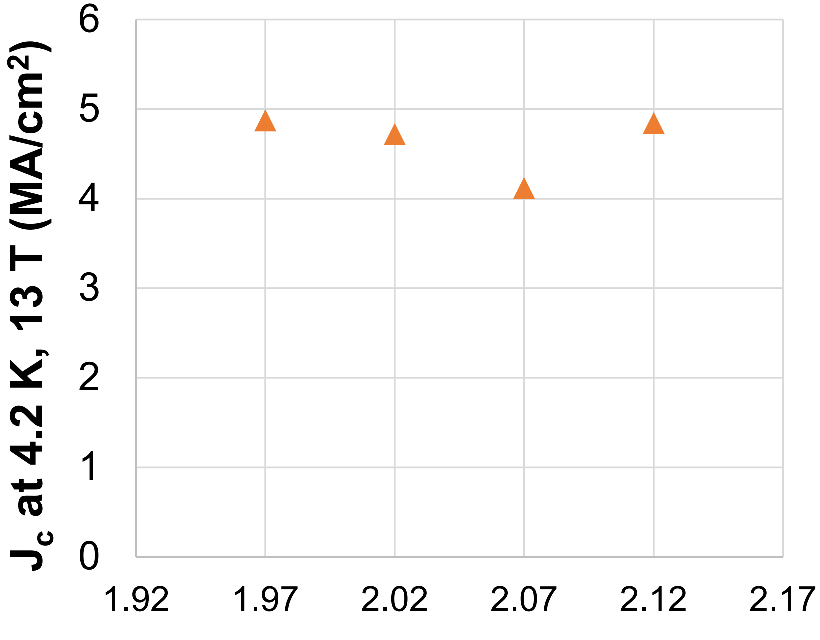
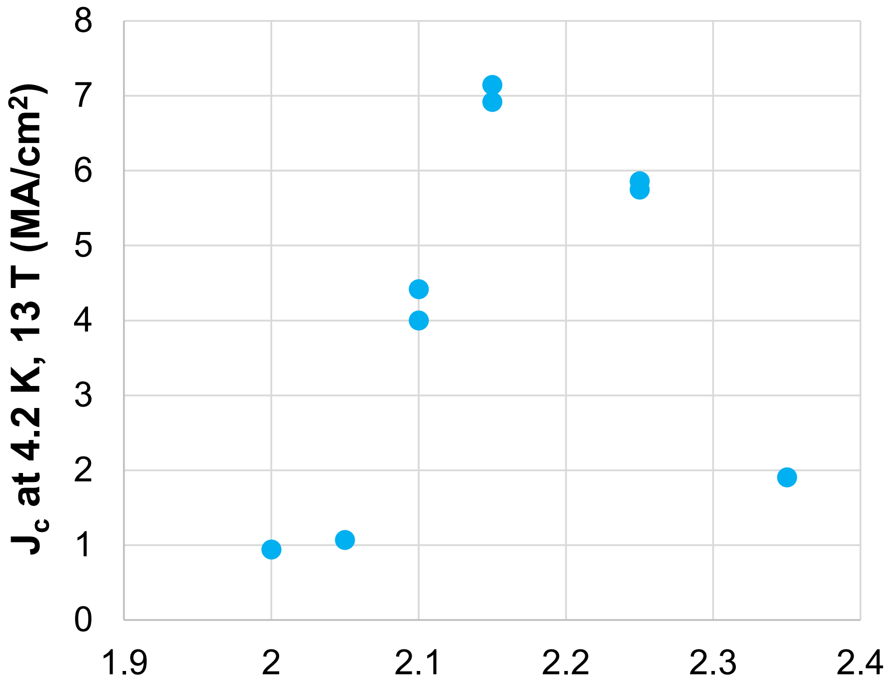
Influence of Ba content on magnetization J_c at 4.2 K, 13 T of 15% Hf-doped (Gd,Y)BCO





Wider compositional range available with 15% Hf doping for high Jc at 4.2 K

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

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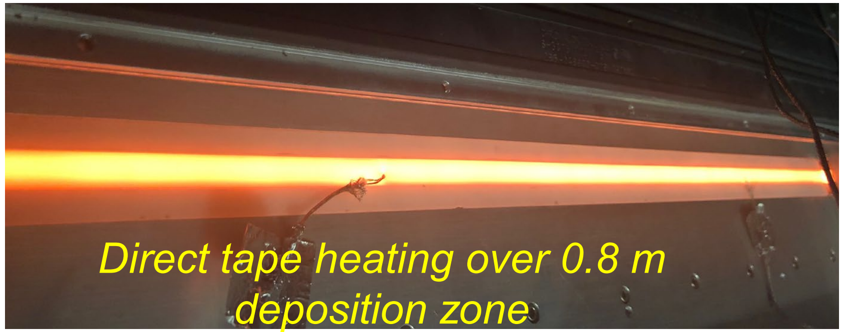
Pilot-scale Advanced MOCVD built and commissioned for wire manufacturing



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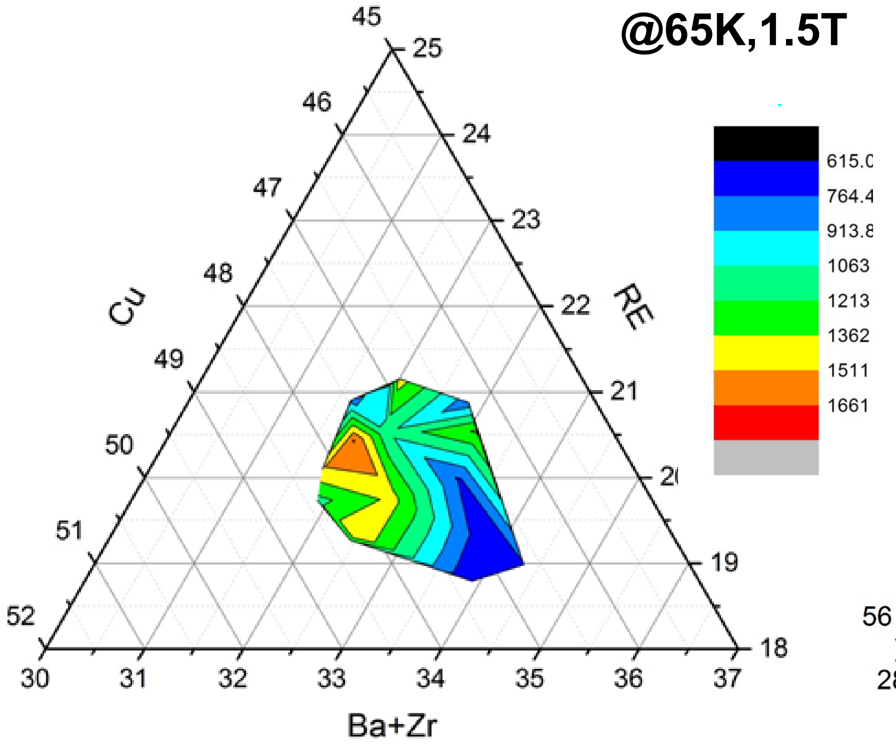
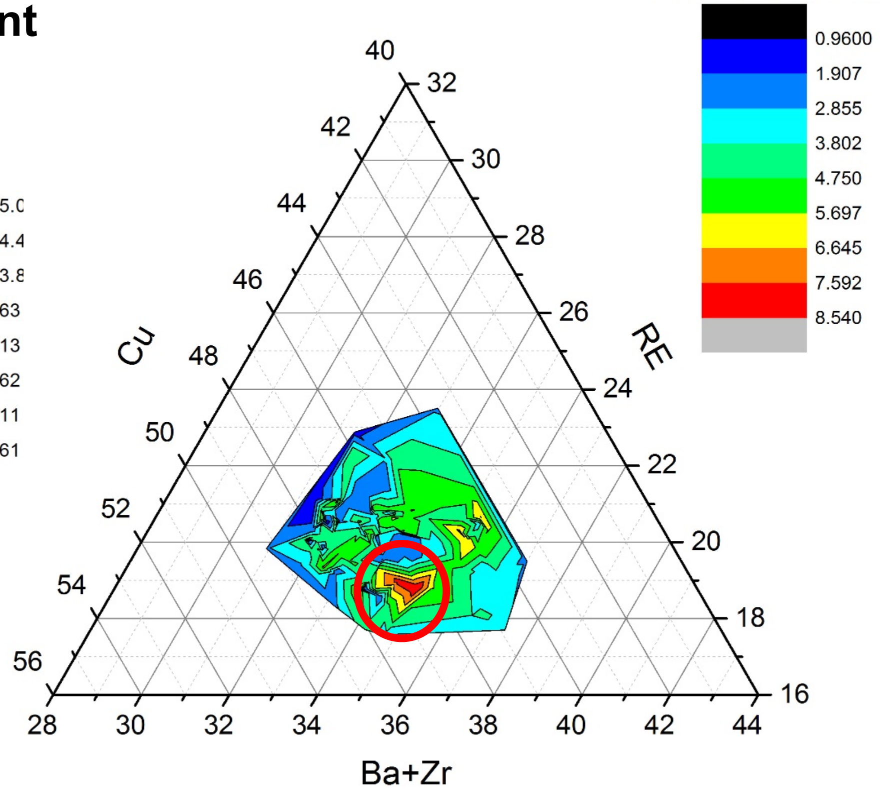
Compositional control of REBCO film important for high in-field J_c

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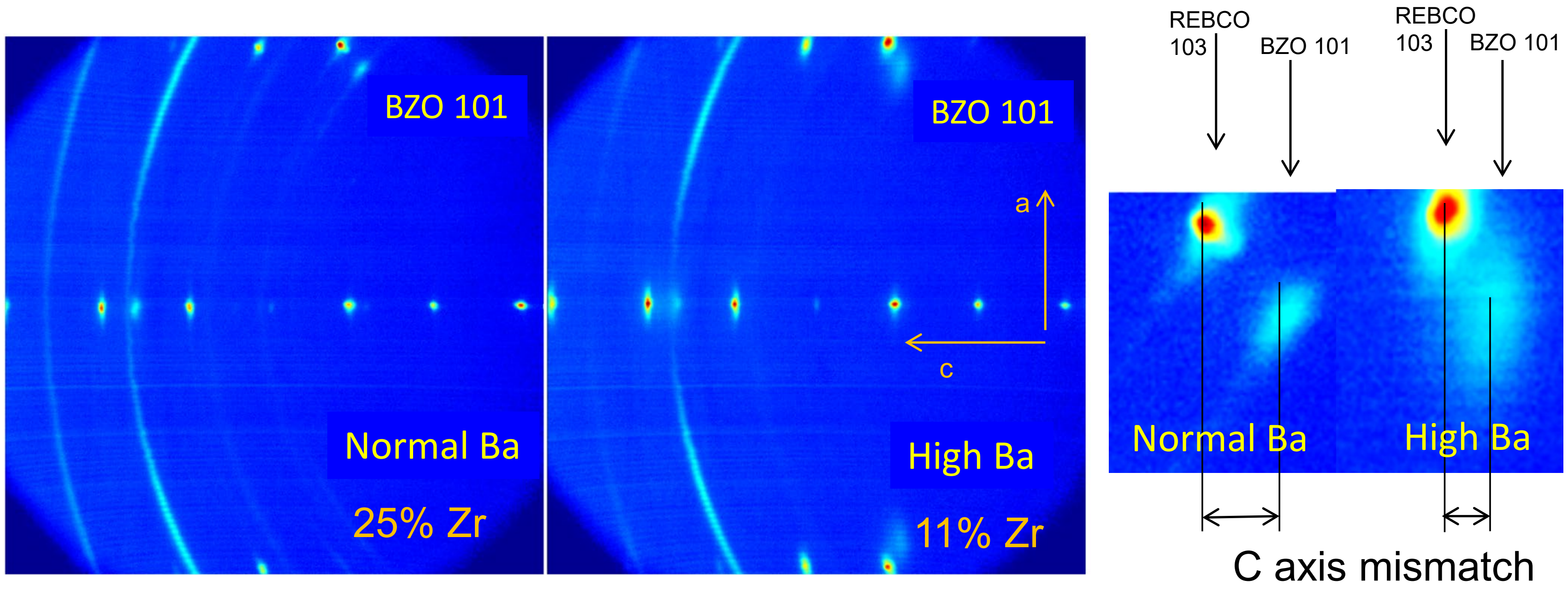
2D-XRD: Rapid non-destructive method to evaluate REBCO film composition



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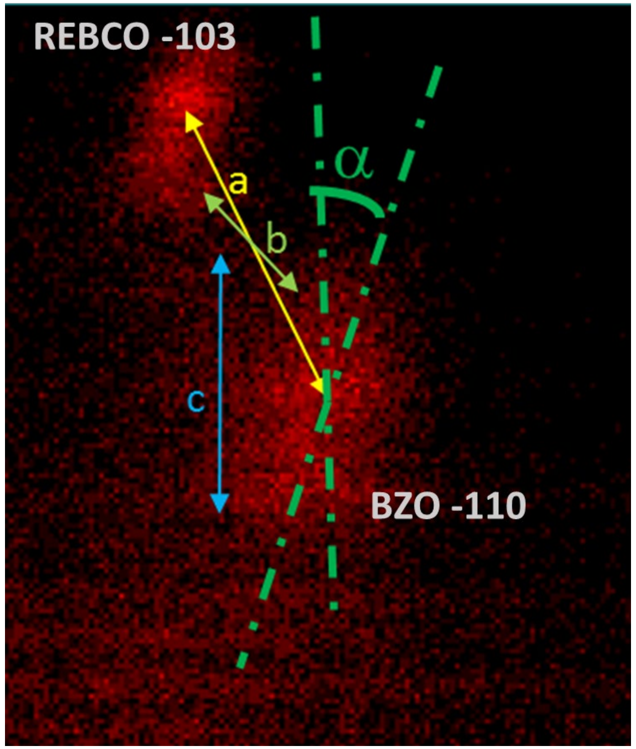
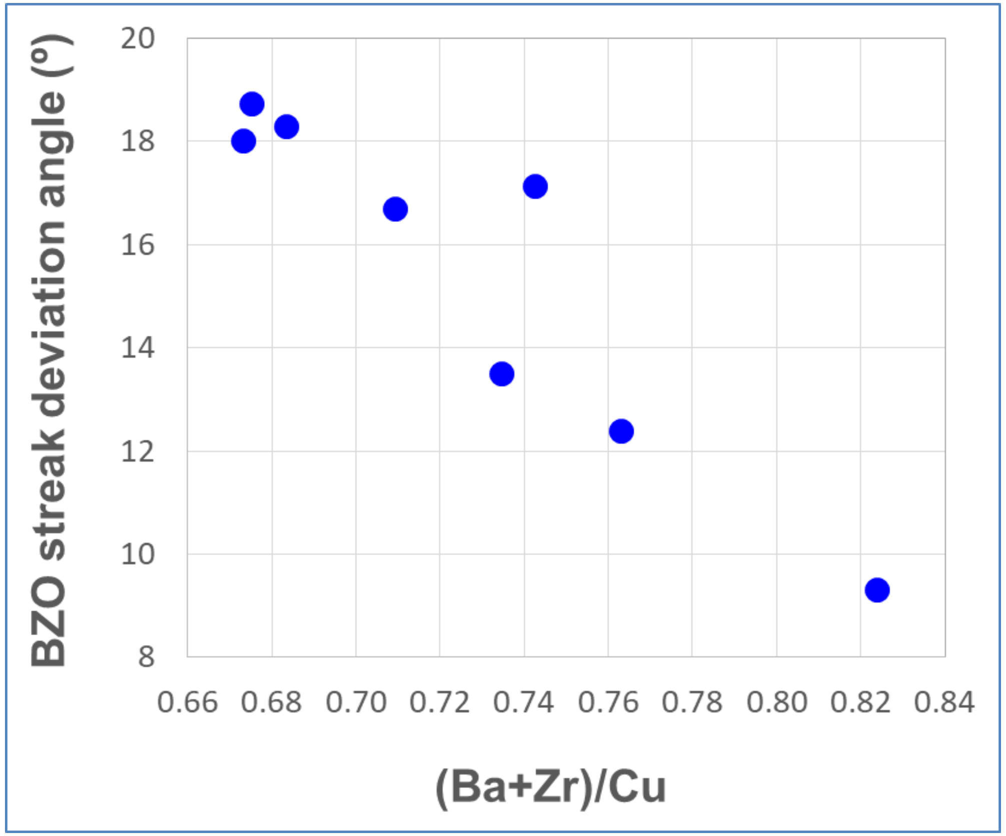
2D-XRD: Rapid non-destructive method to evaluate REBCO film composition





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

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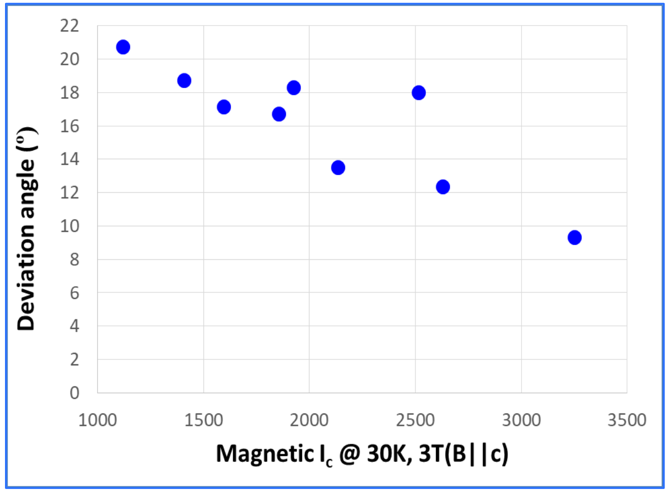
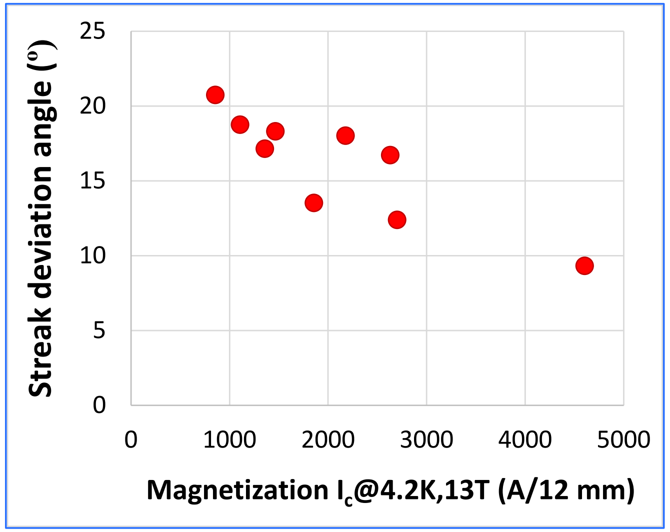
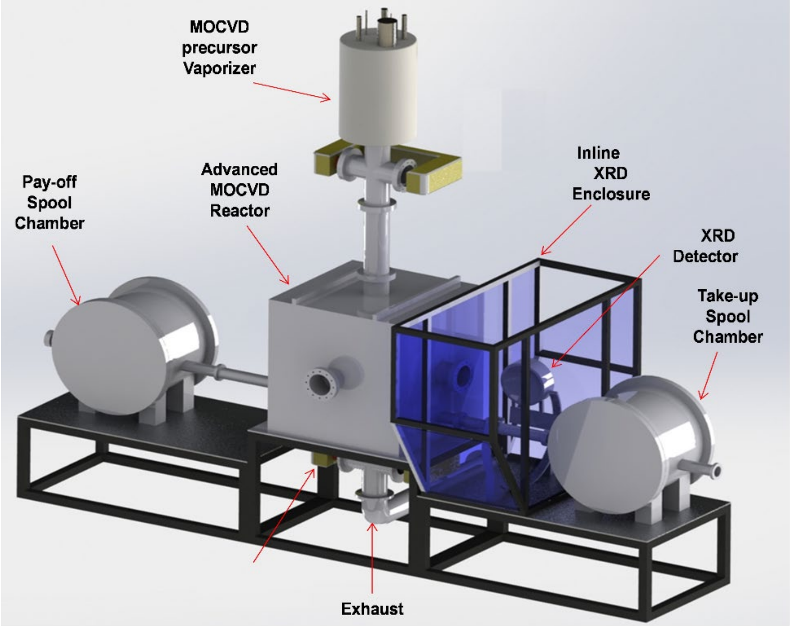
Correlation between BZO (101) streak deviation angle and I_c at 30 K, 3 T and 4.2 K, 13 T







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

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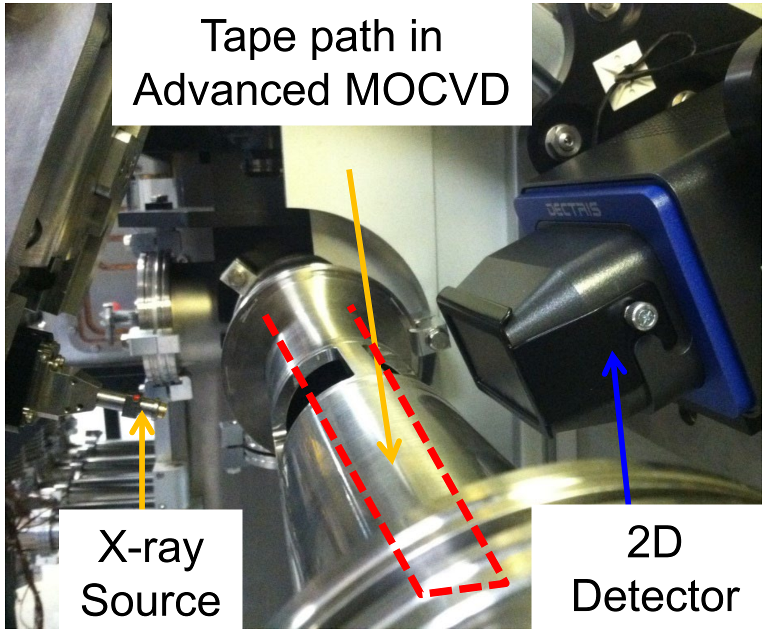
In-line 2D XRD built and installed in pilot MOCVD tool for film monitoring & control



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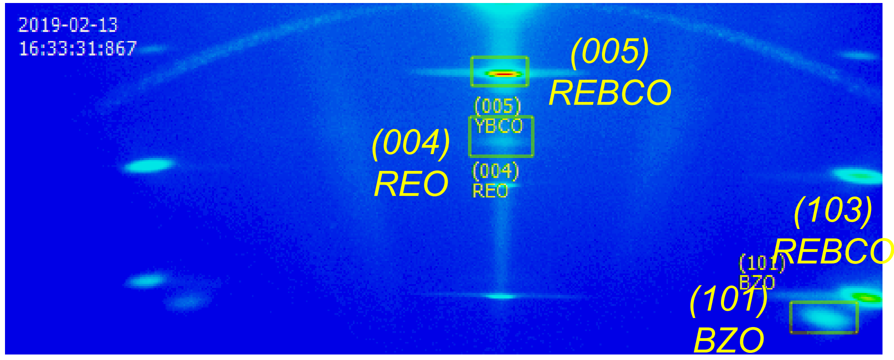
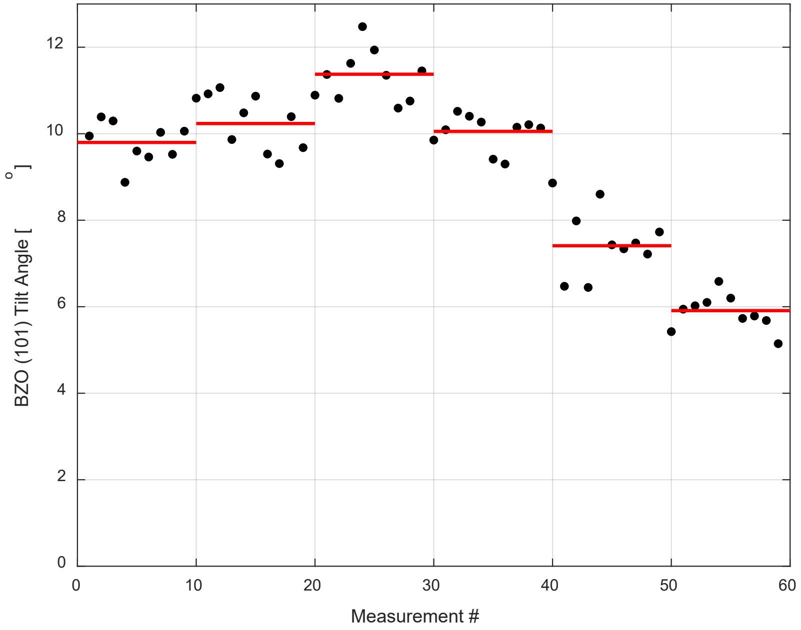
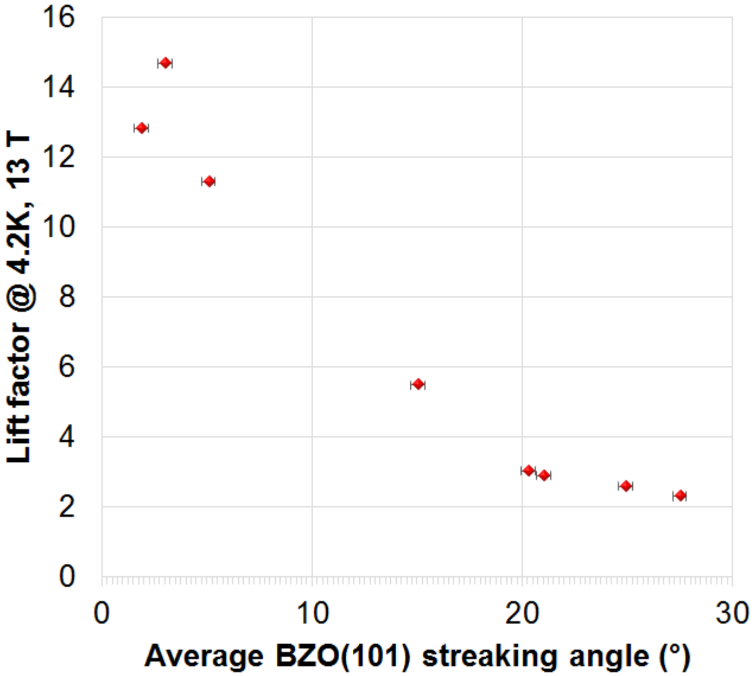
In-line XRD used to detect tape variations



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



Mapped variation in BZO (101) streak angle along tape length



BZO (101) streak angle from in-line XRD predictive of tape performance

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Round REBCO Wires with Excellent Flexibility and High Engineering Current Densities

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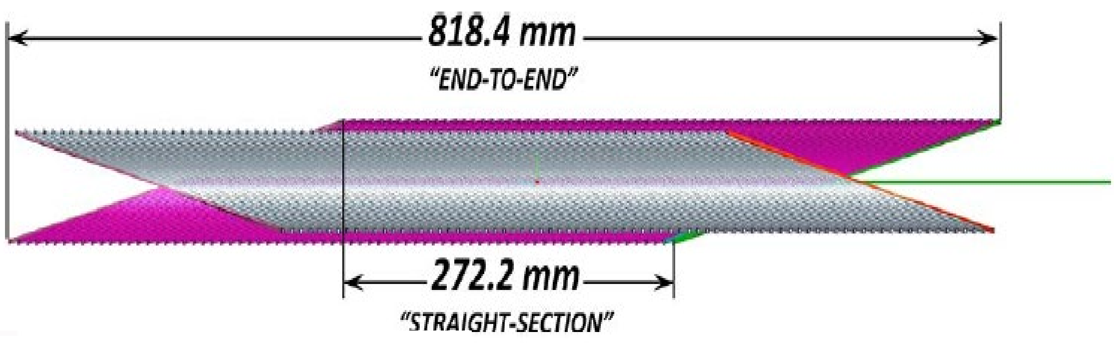
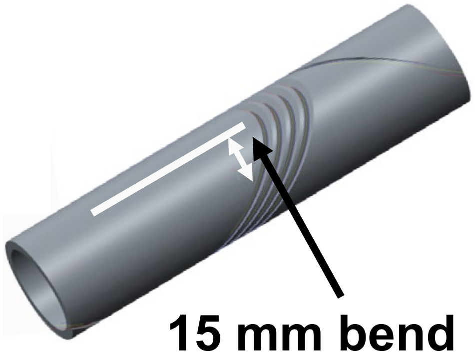
Bend strain-tolerant, round HTS wires needed for compact accelerator coils

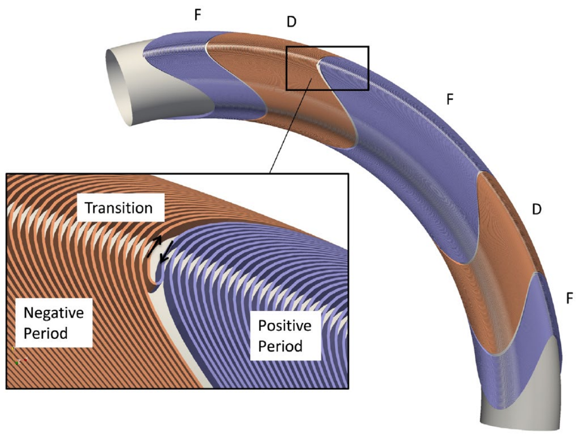
Canted Cosine Theta (CCT) coil





15 mm bend radius in the curved section

Alternating gradient CCT (AG-CCT) coil for gantry magnet



CCT coil requirements

1. Round isotropic wire architecture
2. High I_c with multi-strand geometry for low AC loss.
3. High tolerance to the bend strain.
4. ***J_e* = 540 A/mm^2 at 4.2 K, 21 T at 15 mm bend radius**.

IEEE Trans. Appl. Supercond. 24 (3), 4001904 (2014),
Physical review special topics—accelerators and beams 18, 103501 (2015)

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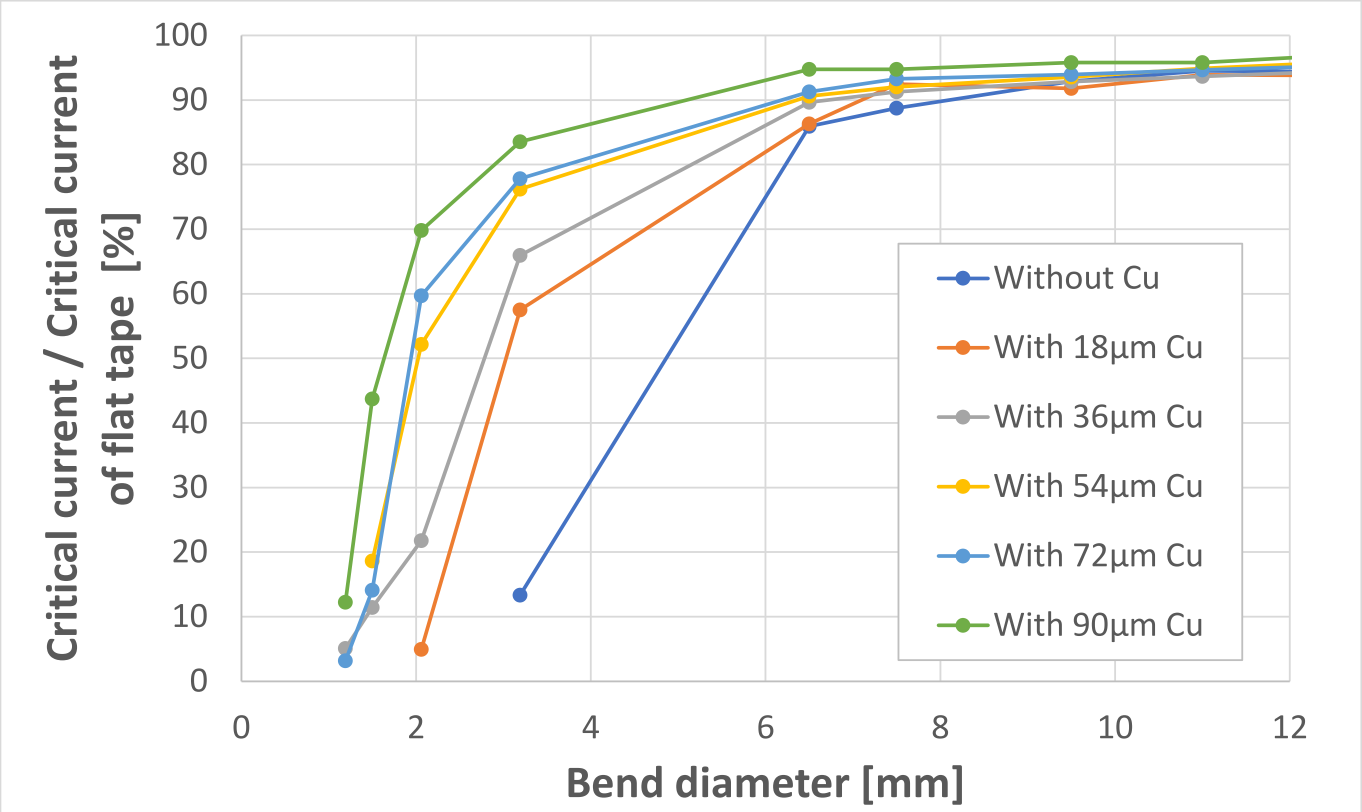
Standard REBCO tapes fail at bend diameter < 2 mm



Standard REBCO tapes cannot be used to fabricate small diameter (< 2 mm) REBCO round wires needed for 15 mm bend radius requirement in CCT coils

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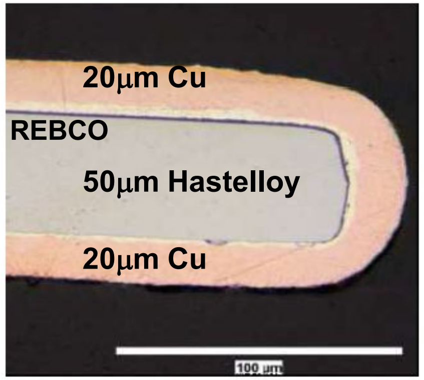
Symmetric Tape Round (STAR) REBCO Wire for high J_e with diameter < 2 mm

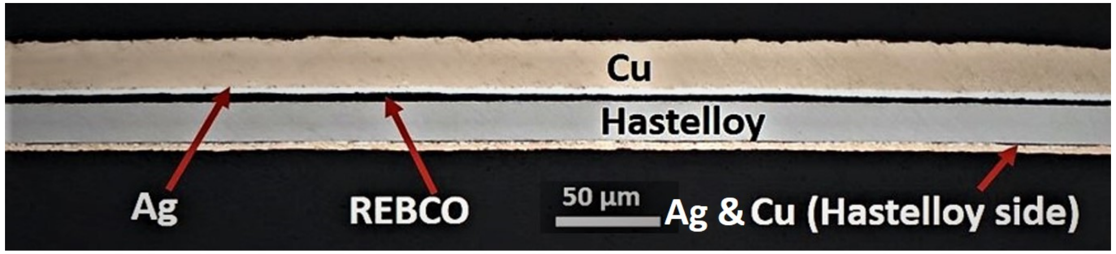


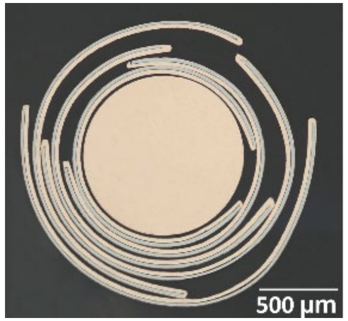
Standard REBCO Tapes:

- REBCO asymmetrically positioned far away from neutral plane

Symmetric REBCO Tape:

- Copper stabilizer primarily on REBCO side.
- REBCO positioned near geometric center.
- Minimizes the strains in the REBCO layer.





Symmetric REBCO tapes used to make round REBCO wires on 0.8 and 1 mm diameter copper former

IEEE Trans. Appl. Supercond. 27, 6603204 (2017),
IEEE Trans. Appl. Supercond. 27, 6602705 (2017), *Supercond. Sci. Technol.* 3, 04LT01 (2018)

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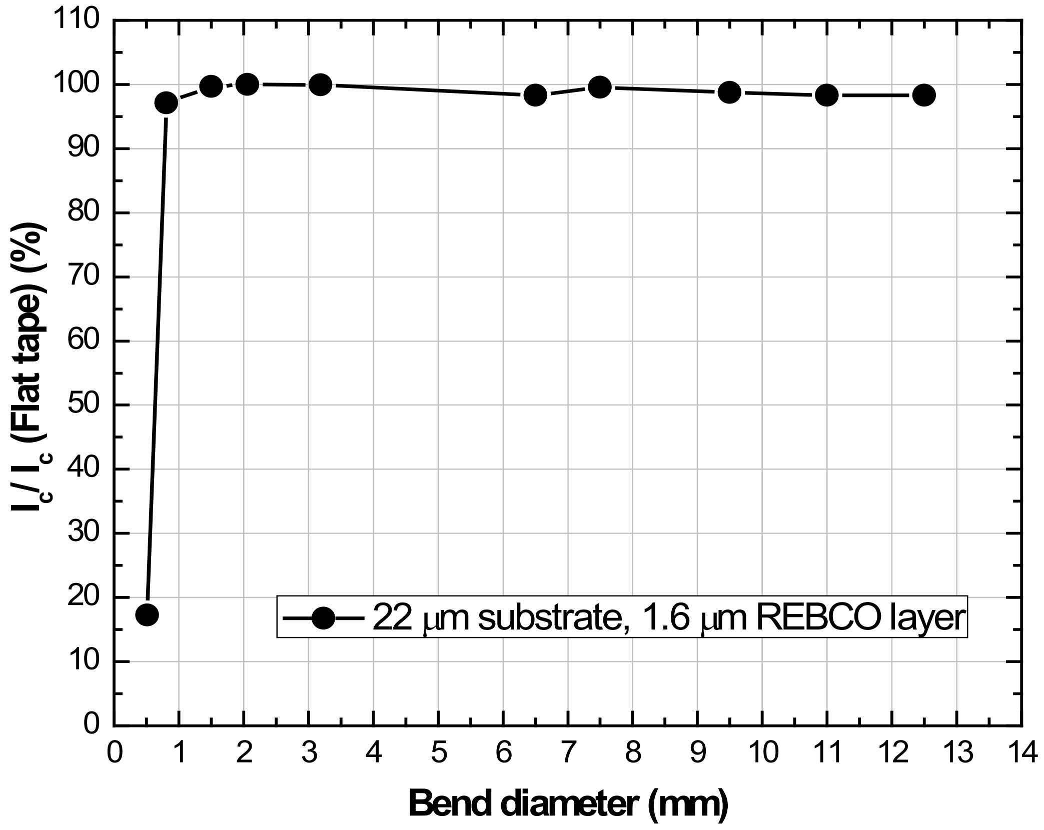
Symmetric REBCO tapes retain > 95% Ic even when bent to diameter of 0.8 mm



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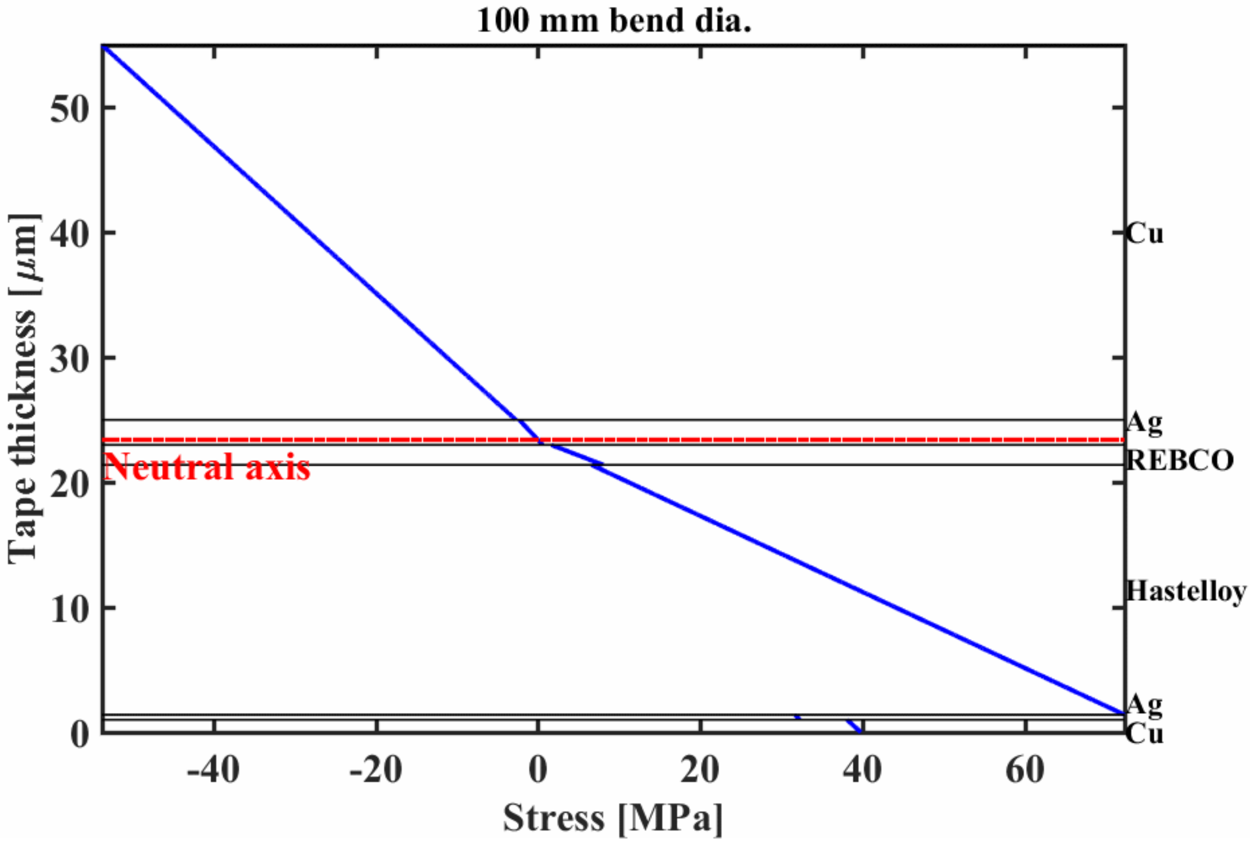
Caused by the progressive plastic deformation in the various layers.



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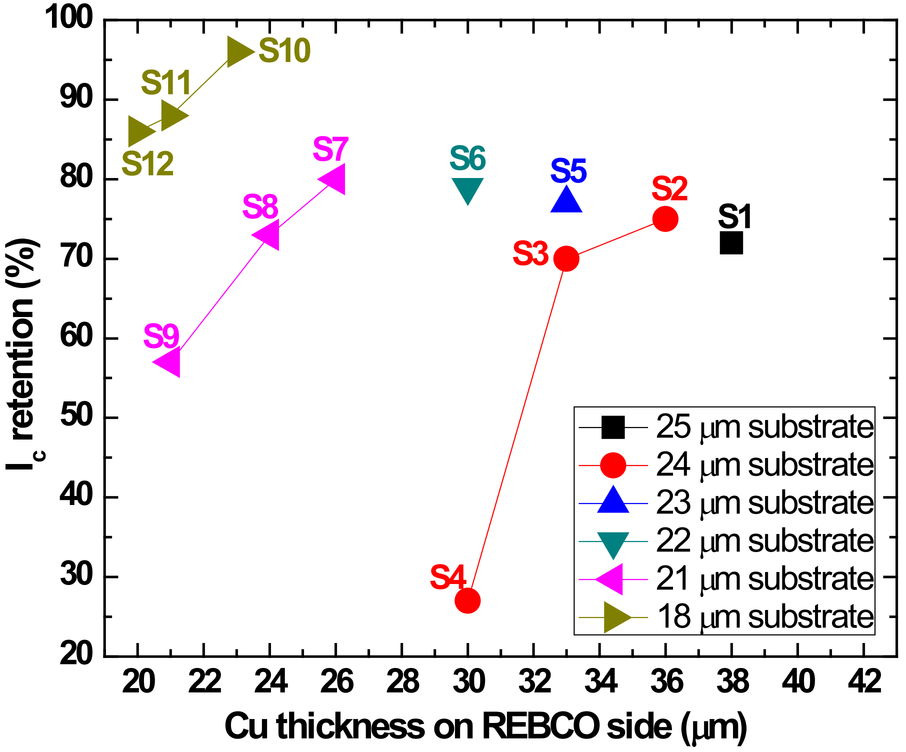
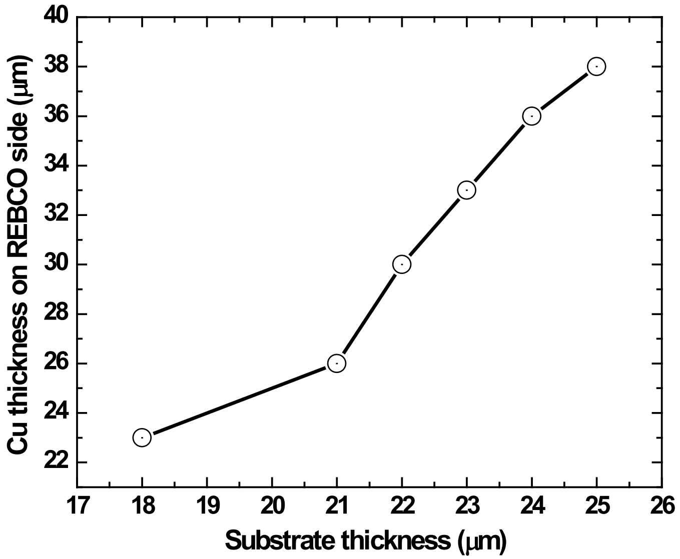
Optimized copper thickness for different substrate thickness for use in STAR wires

I_c retention for different Cu on REBCO side for 18 – 25 μm thick substrates



Copper thickness on substrate side in all tapes = 3 μm

Optimum Cu on REBCO side for different substrate thickness



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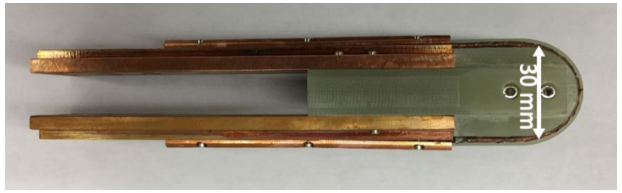
STAR wires with I_c > 600 A at 77 K at 15 mm bend radius

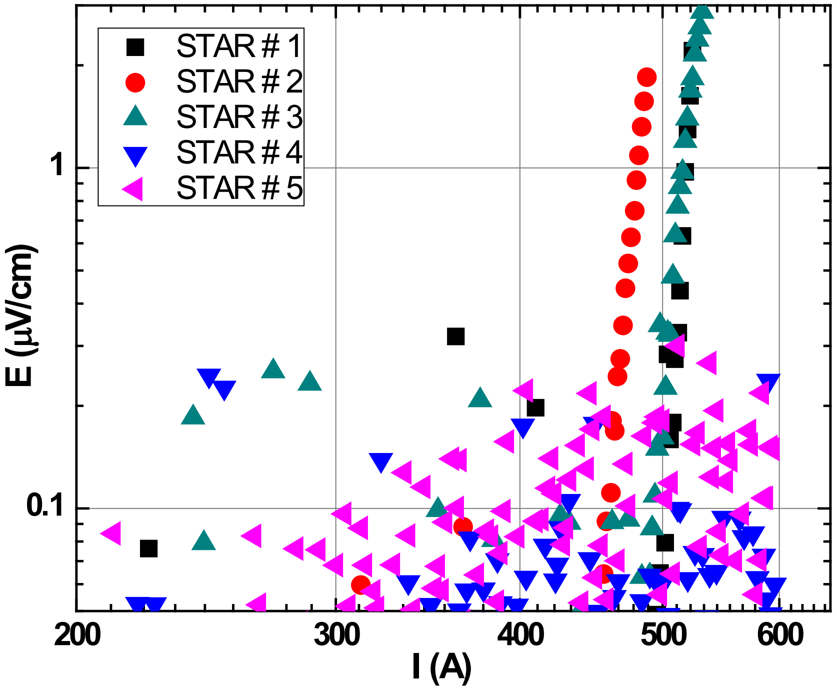
STAR wire (STAR # 2), 1.66 mm diameter

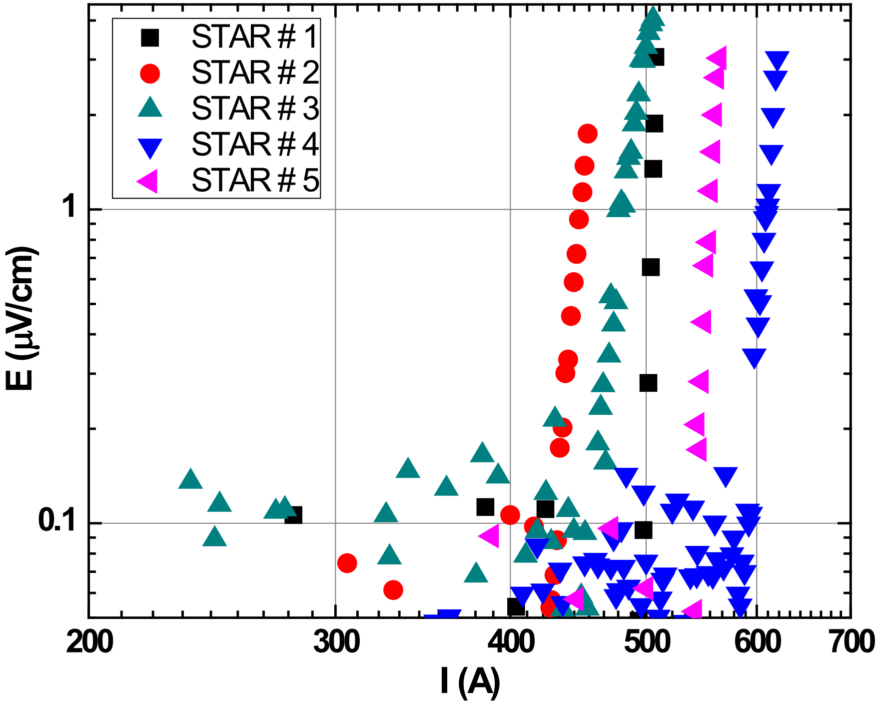
REBCO STAR wire in straight form

REBCO STAR wire at 15 mm bend radius



Bending properties of STAR wires





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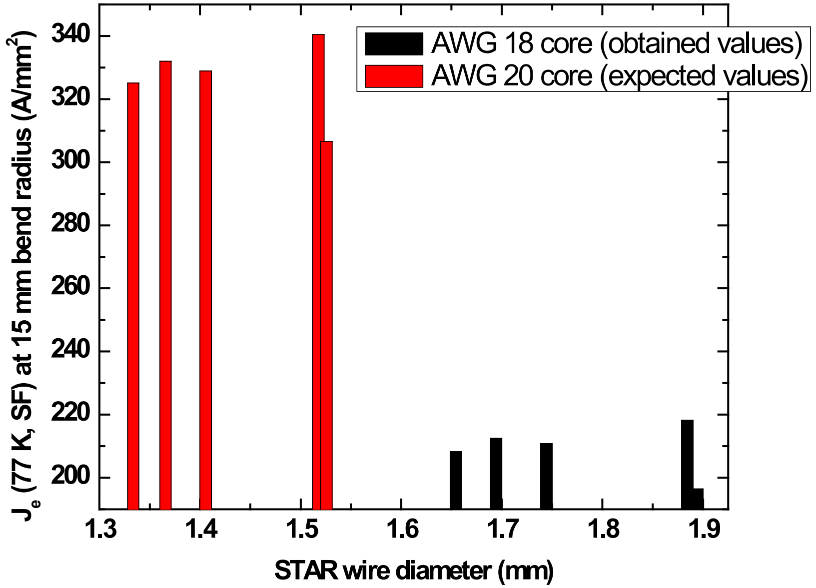
STAR wires retain 90% of their I_c even at a bend radius of 15 mm

STAR #	I_c (A) in straight form	J_e (A/mm^2) in straight form	I_c (A) at 15 mm bend radius	J_e (A/mm^2) at 15 mm bend radius	Retention of I_c (%) at 15 mm bend radius
1	518	215.8	506	210.8	97.7
2	482	223	450	208.3	93.4
3	516	227.5	482	212.5	93.4
4	>600	NA	611	218.2	NA
5	>600	NA	556	196.5	NA

Expected J_e of REBCO STAR wire at 15 mm bend radius for AWG 20 former



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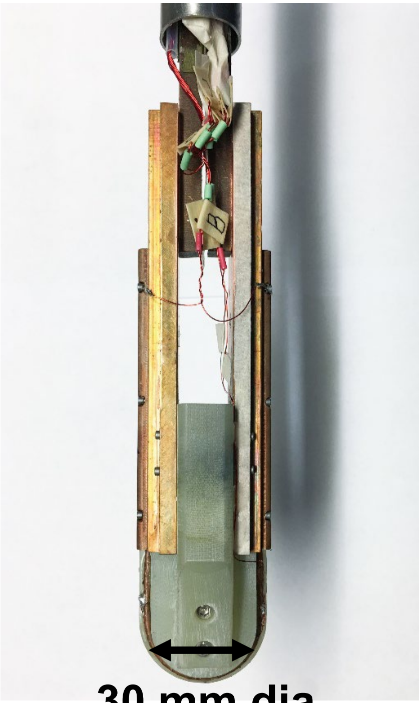
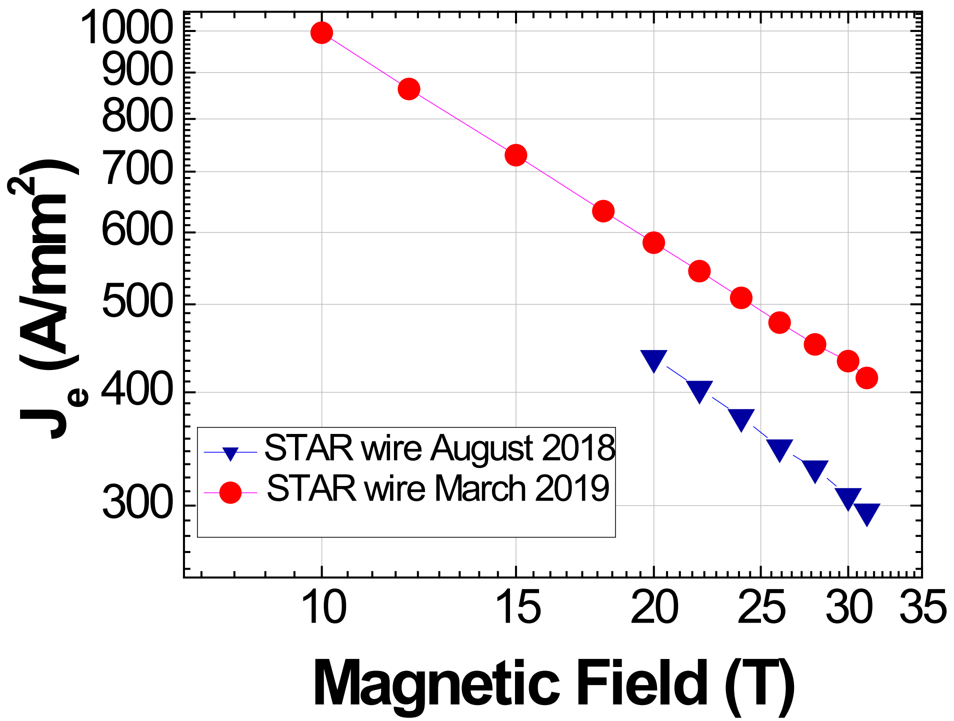
J_e ~ 600 A/mm² at 20 T in recent STAR wires

1.67 mm diameter STAR wire
bent to a radius of 15 mm



STAR wires tested at NHMFL



At a bend radius of 15 mm, using REBCO tapes with 1.7µm thick films,
2018 STAR wire: 438 A/mm² at 20 T and 299 A/mm² at 31.2T
2019 STAR wire: 729 A/mm² at 15 T and 584 A/mm² at 20 T

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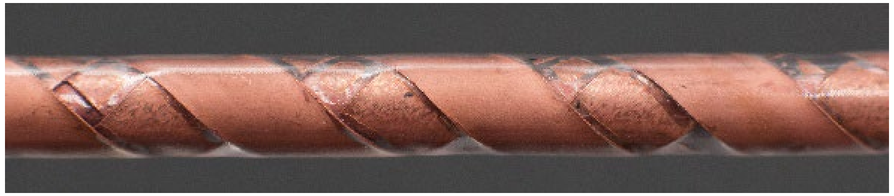
10m long, 1.9 mm dia. STAR wires produced



Average I_c = 476 A at 77 K, self-field over 10 meters

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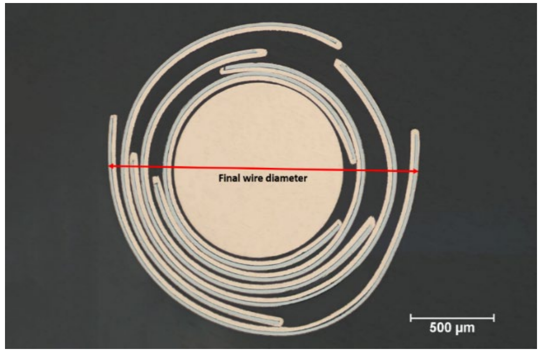
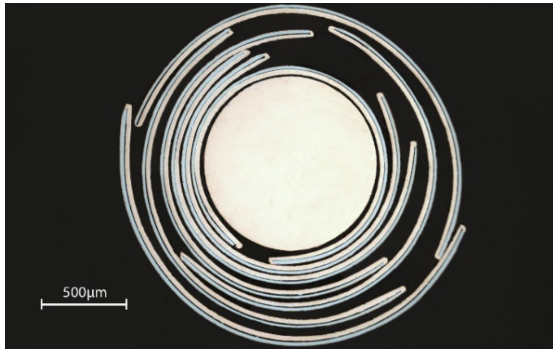
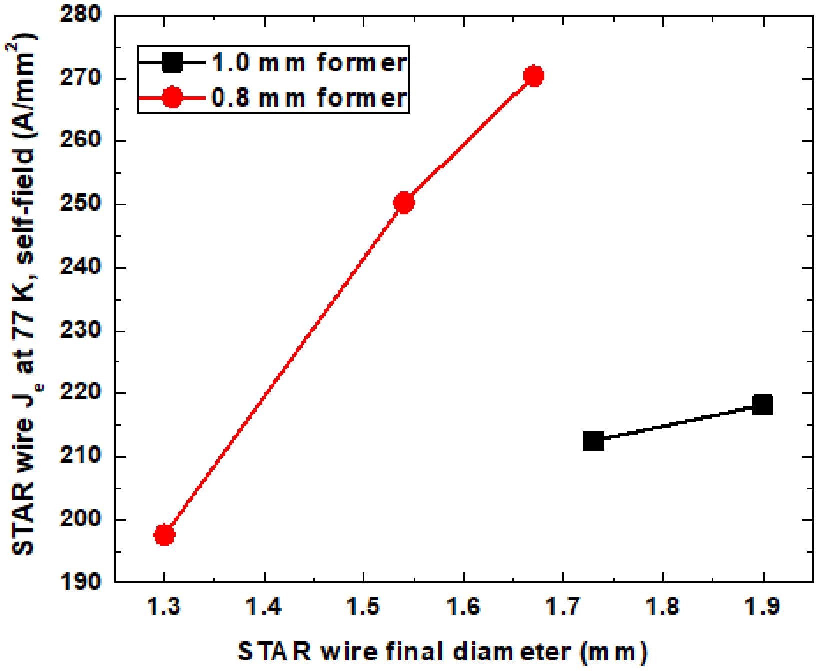
Ongoing Improvements: Higher Je with more tape layers on smaller dia (0.8 mm) former

6-layer STAR wire (1.0 mm former)



8-layer STAR wire (1.0 mm former)





20% reduction in former diameter leads to 11-12% reduction in final wire diameter and 15-19% increase in J_e at 77 K, self-field.

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Supercond. Sci. Technol. 3, 04LT01 (2018), *Supercond. Sci. Technol.* 31, 12LT01 (2018)

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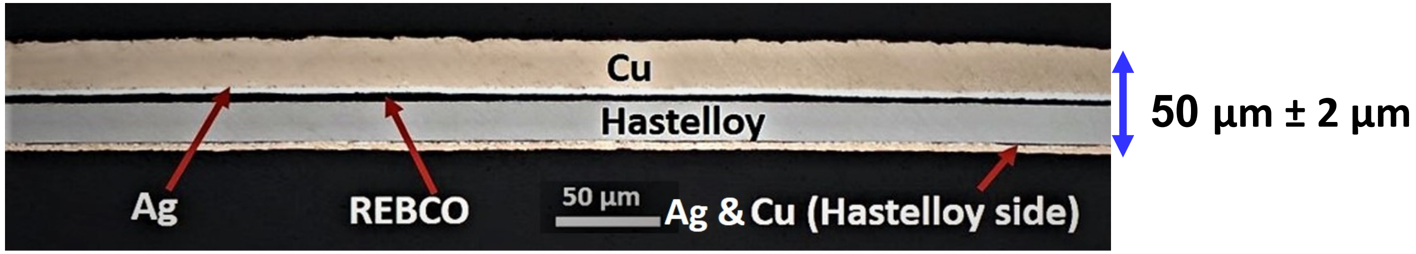
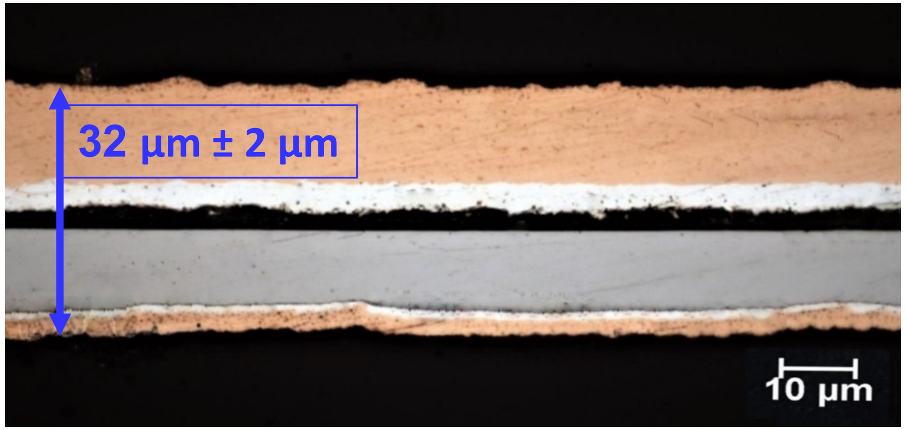
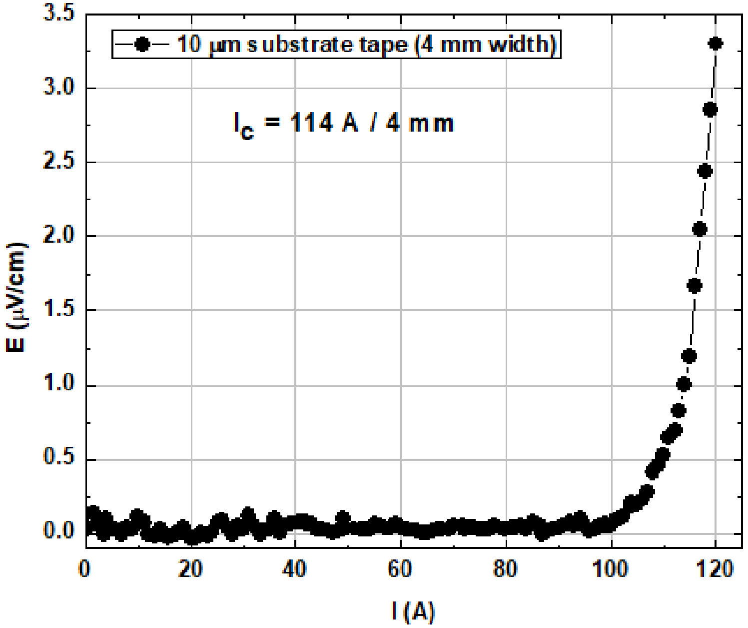
Ongoing Improvements: Symmetric Tapes with even thinner (10 μm) substrates

22 μm Hastelloy substrate



10 μm Hastelloy substrate





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Status and Next Steps

- Advanced MOCVD developed for REBCO tapes with 5 μm thick films and fine-scale BZO nanocolumns high performance over 4.2 K – 65 K
  - I_c ~ 1440 A/cm at 65 K, 1.5 T (**4.4X** I_c of commercial REBCO tape)
    (Met Department of Energy Advanced Manufacturing Office Program goal)
  - J_e ~ 5200 A/mm^2 at 4.2 K, 15 T (**5.4X** best J_e of Nb_3Sn, **7X** commercial tape)
- In-line 2D XRD installed and used in pilot Advanced MOCVD system
  - BZO (101) streak angle predicts film composition and in-field performance
- Symmetric Tape Round (STAR) REBCO wire developed
  - J_e = 584 A/mm^2 at 4.2 K, 20 T at 15 mm bend radius
  - 10 m long, 1.9 diameter STAR wire with I_c ~ 476 A @ 77 K, self-field

Next:

- Scale up thick film, fine BZO tapes to 50 m lengths with high in-field I_c
  - use 2D-XRD for in-line QC for uniform and consistent in-field I_c
- Provide high-performance, lower-cost REBCO tapes for prototype demonstrations
- Scale up STAR wires to long lengths
- Increase J_e of STAR wires > 1000 A/mm^2 at 4.2K, 20 T

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