UNIVERSITY of HOUSTON

AMI Advanced Manufacturing Institute

Conductor and Cable Challenges and Opportunities (Performance and R&D)

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*VS has financial interest in AMPeers

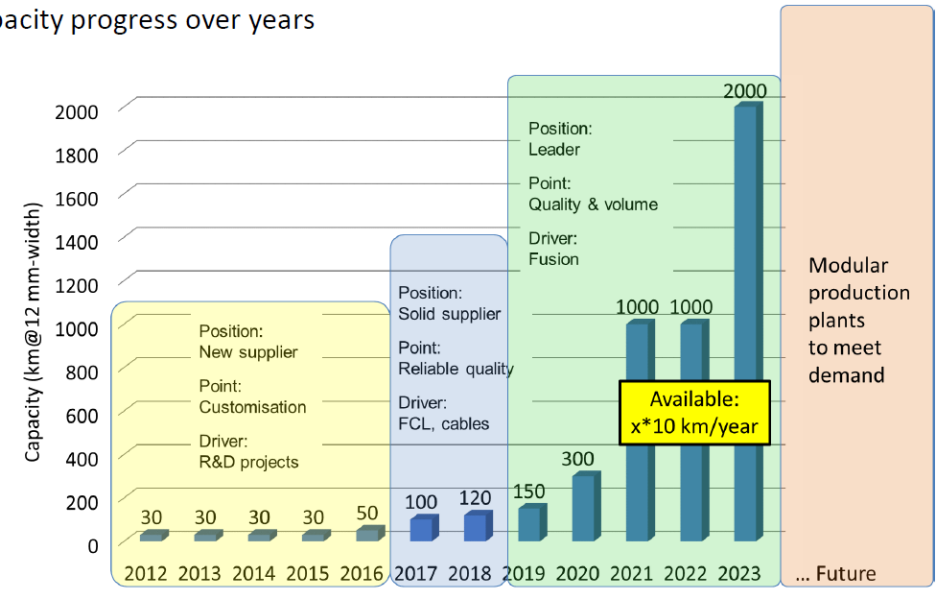
REBCO Grand Challenges

- Production volume
  - Few thousand kilometers now/need 20,000 km for just one compact fusion system.
- Cost
  - >10x more than that needed for widespread commercial implementation.
- Piece-length and uniformity along length of tape
  - Few hundred meters now; critical current dropouts in long lengths.
- Mechanical strength
  - Limited delamination strength.
  - Tensile strength limits ultra-high field magnets.
- Geometry
  - Flat tape; certain applications benefit from a round, transposed, multifilament geometry.
- Neutron-radiation tolerance
  - Degradation of critical current limits lifetime of HTS magnets in compact fusion reactors.

REBCO Grand Challenges

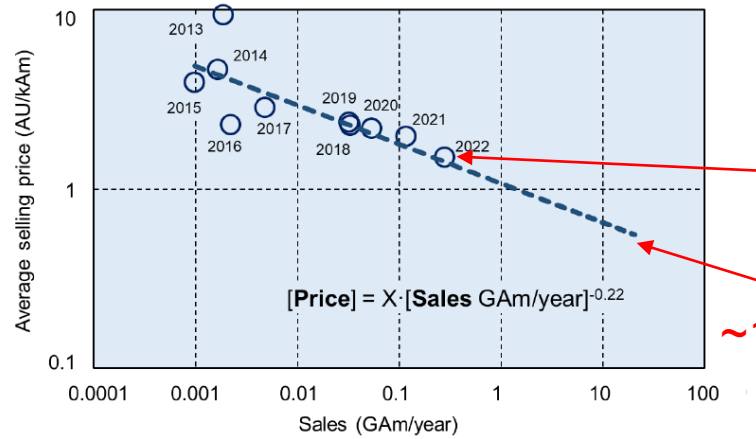
- Production volume
  - Few thousand kilometers now/need 20,000 km for just one compact fusion system.
- Cost
  - >10x more than that needed for widespread commercial implementation.
  - **Just volume manufacturing is insufficient for significant cost reduction → Need technology advancement.**

Capacity progress over years



- Demand drives capacity scale-up
- Economies of scale bring the price down

Actual price learning curve



~1000 km

~100,000 km

- Fusion creates demand, promotes capacity; large volume drives the cost down
- HTS price halves with every 10-fold volume increase

Only 3.6x cost reduction from 1,000 km now to 100,000 km in the future!

REBCO Grand Challenges

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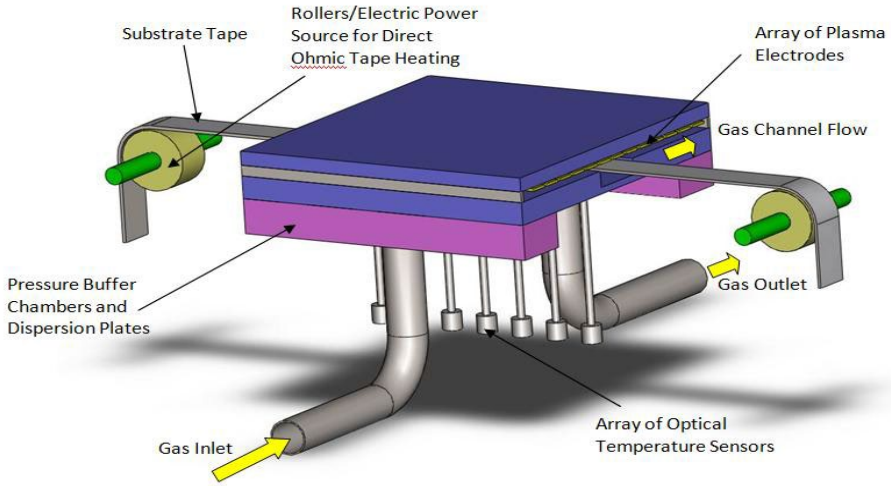
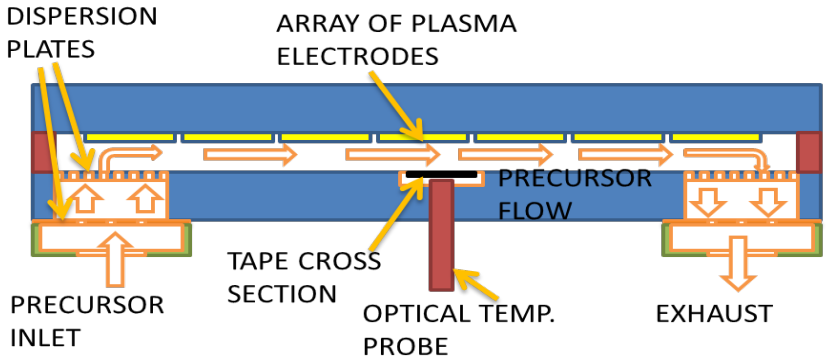
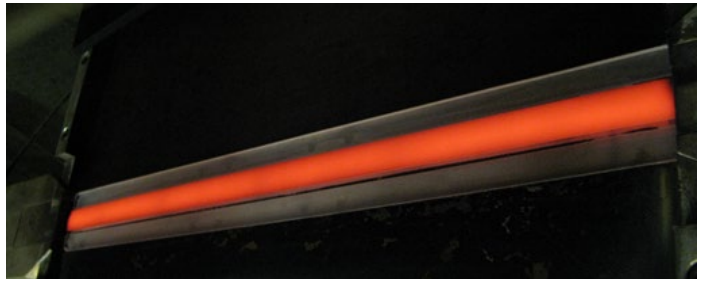
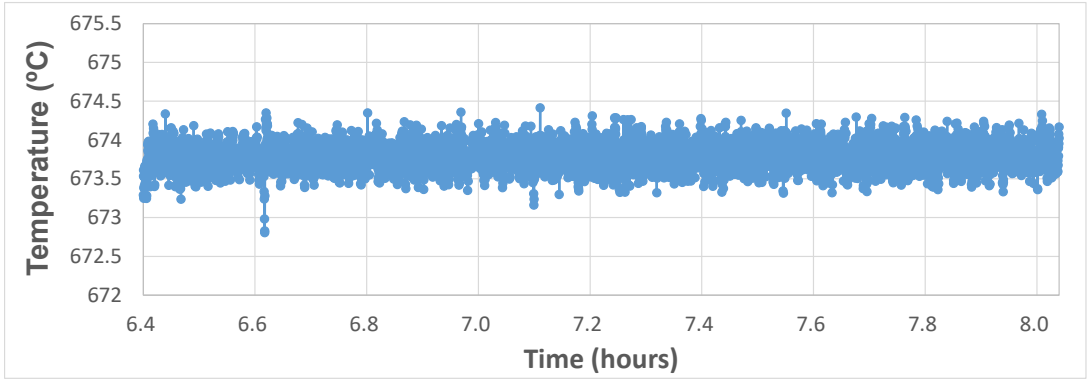
Advanced Metal Organic Chemical Vapor Deposition (MOCVD) for high performance, low-cost superconductor

- Advanced MOCVD reactor addresses all deficiencies of current production tools designs
  - Excellent control of tape temperature by Direct Ohmic tape heating and Direct tape temperature monitoring → 5 μm thick films & excellent control of nanoscale defects for pinning → high critical current.
  - Low volume, laminar flow reactor → 5x precursor-to-film conversion efficiency → cost reduction.

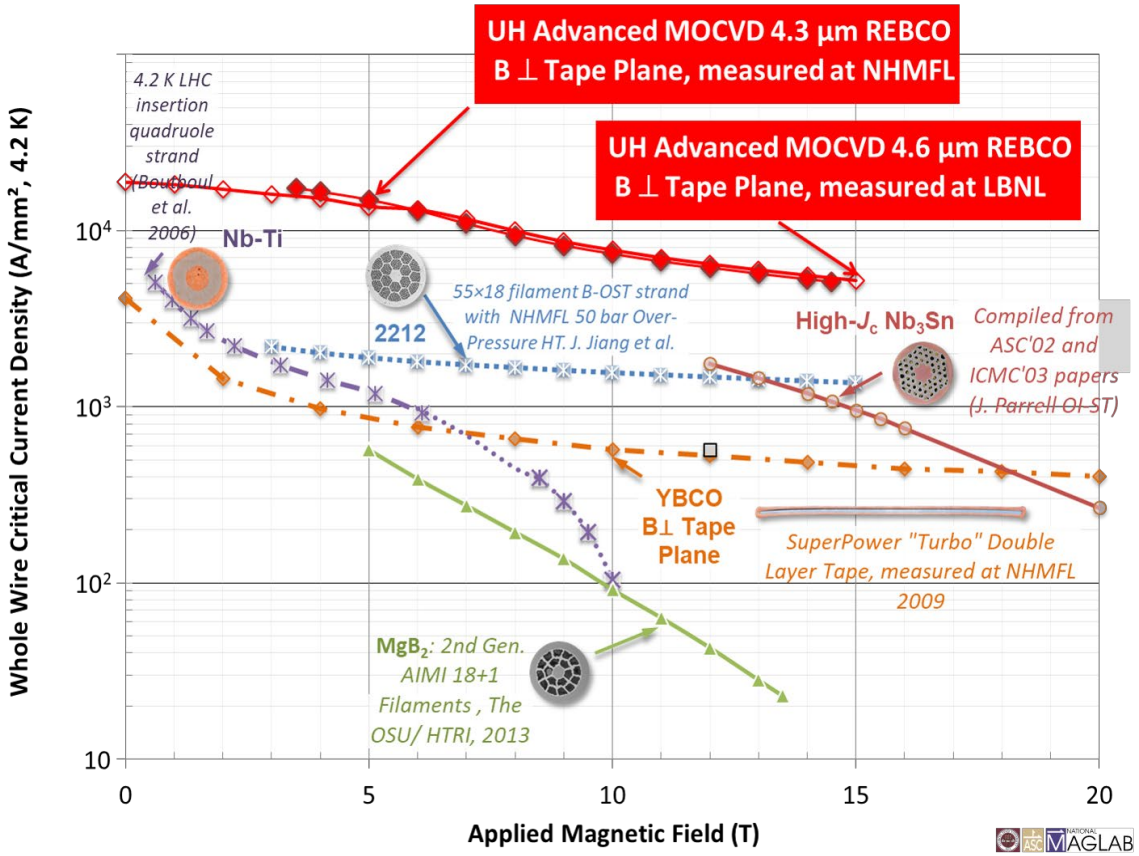


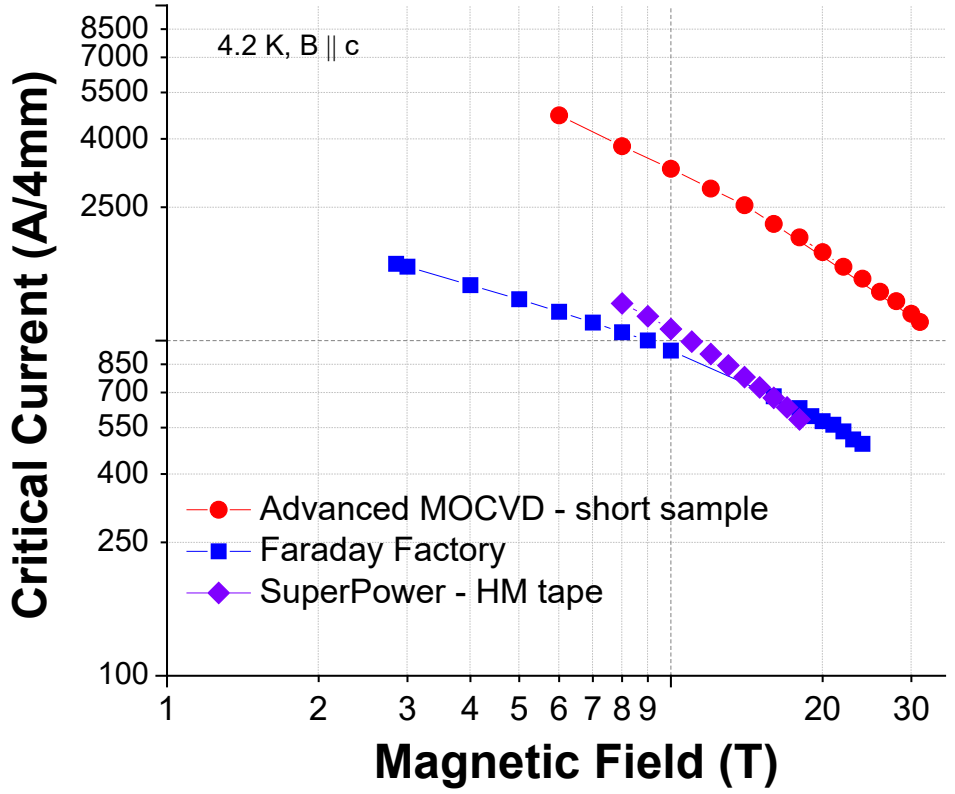






REBCO tapes made by Advanced MOCVD exhibit very high critical currents in high magnetic fields at 4.2K





J_e of UH REBCO @ 4.2 K, 15 T = 5200 A/mm²
5.4x Nb_3Sn @ 15 T

Supercond. Sci. Technol. **31** 10LT01 (2018).
Data maintained by Peter Lee, NHMFL, http://fs.magnet.fsu.edu/~lee/plot/plot.htm

I_c of UH REBCO @ 4.2 K, 20 T = **1,836 A/4mm**
3.23x best commercial (PLD) REBCO tape at 18 T
3.5x best commercial MOCVD REBCO tape at 18 T

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

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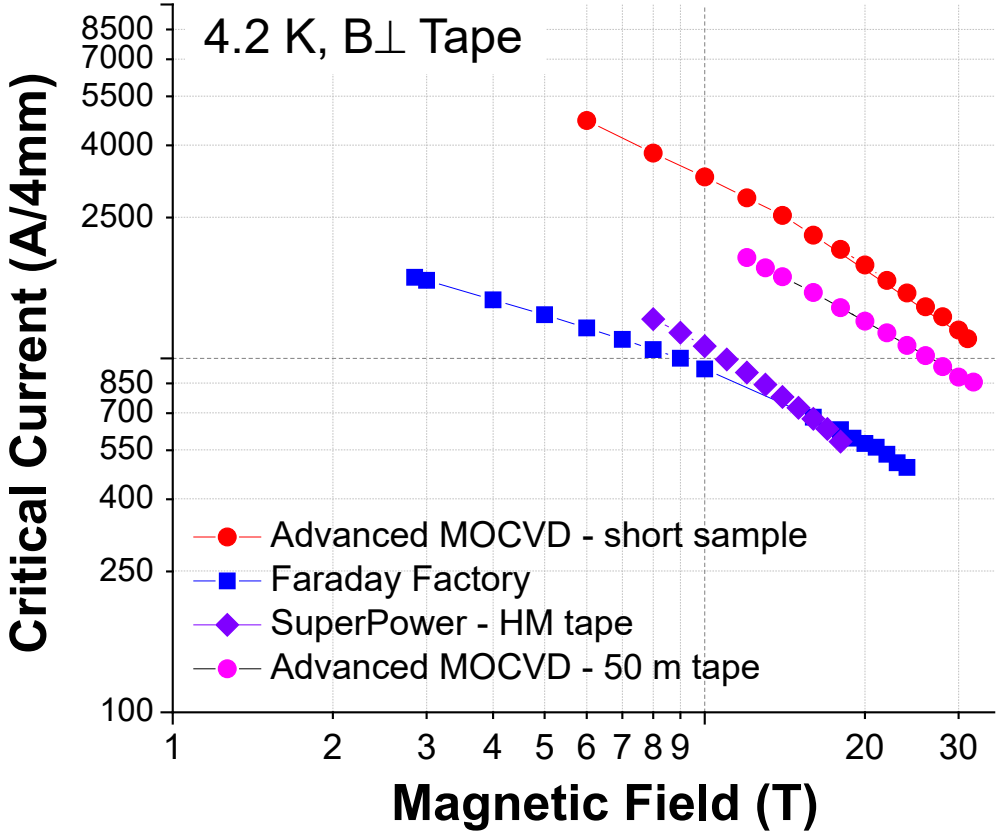
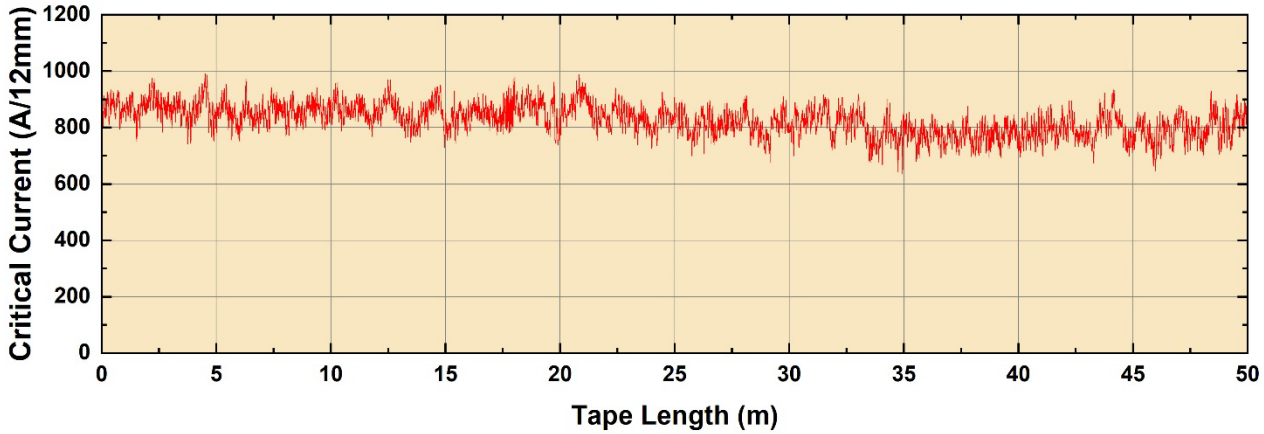
Advanced MOCVD REBCO tapes scaled up to 50 meters with very high critical currents in high fields at 4.2K



I_c of A-MOCVD short tape @ 4.2 K, 20 T = **1,836 A/4mm**

I_c of A-MOCVD 50-m tape @ 4.2 K, 20 T = **1,274 A/4mm**

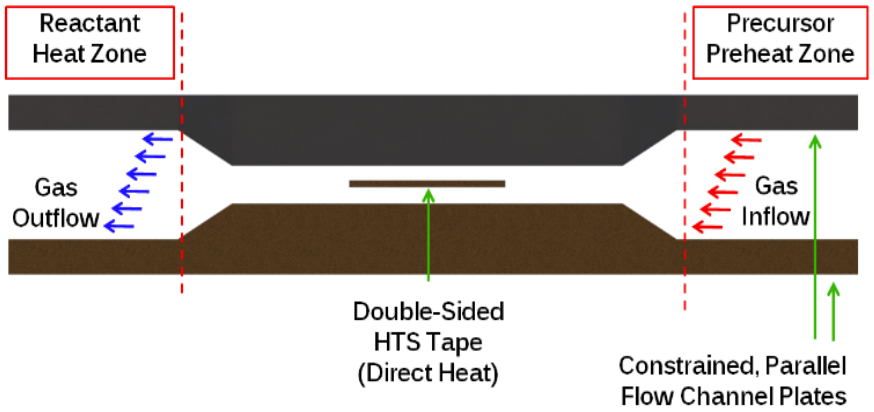


- Advanced MOCVD scaled up to 50 meter lengths
- Lift factor in I_c of 50 m Advanced MOCVD tape at 4.2 K, 20 T = 3.3 → **50% higher than lift factor of commercial tape.**
- I_c of 50 m Advanced MOCVD tape **74% of I_c of champion short Advanced MOCVD tape** at 4.2 K, 30 T.
- I_c of 50 m Advanced MOCVD tape **3.5x I_c of typical commercial REBCO tape** at 4.2 K, 20 T.

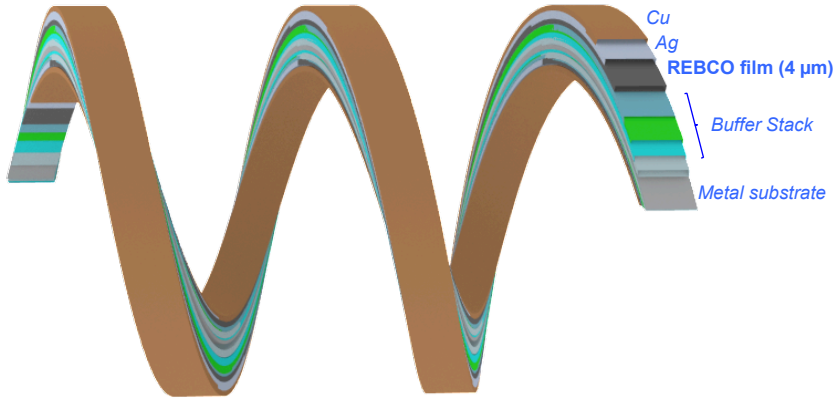
IEEE Trans. Appl. Supercond. vol. **33,** 6600105 (2023).

Double-sided REBCO tapes

Double-sided REBCO tapes by Advanced MOCVD



*Advanced MOCVD for double-sided REBCO film in a **single step.***

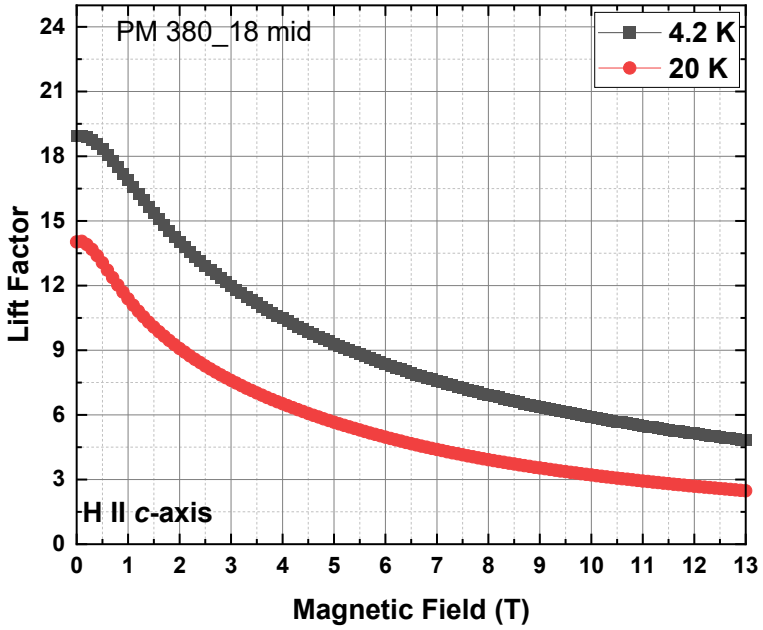


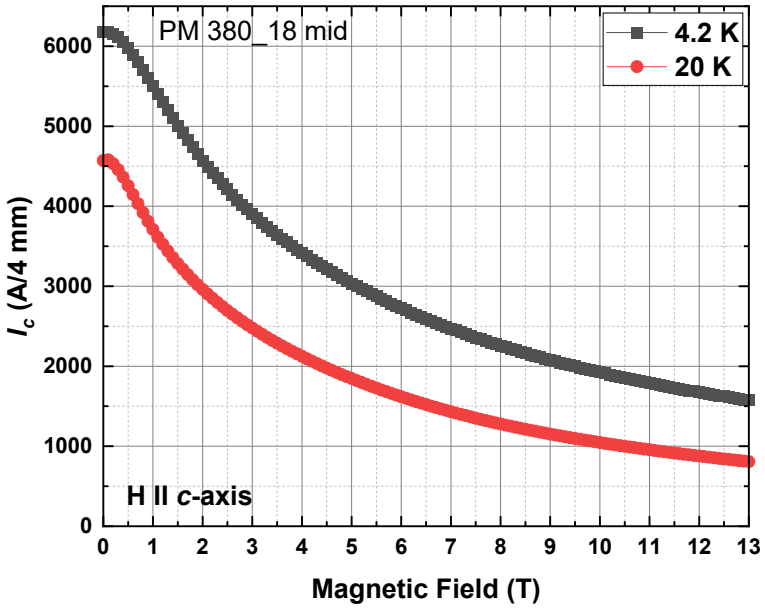
Double-sided 5 μm thick films with 10x I_c and 7x precursor-to-film conversion efficiency

REBCO tapes @ 20x lower cost: $10/kA-m at 20 K, 20 T

Double-sided, 15% Zr-added tapes with I_c > 500 A/4mm at 20 K, 20 T → 3.5x I_c of typical commercial tape

Film thickness each side (μm)	Zr (%)	Ic (A/4mm) @ 77 K, 0 T	Lift Factor @ 4.2K 13T	I_c (A/4mm) @ 4.2K 13T	Alpha @ 4.2K	I_c (A/4mm) @ 4.2K 20T	Lift Factor @ 20K 13T	I_c (A/4mm) @ 20K 13T	Alpha @ 20K	I_c (A/4mm) @ 20K 20T
3.4	15	321	4.8	1547	0.7	1129	2.5	793	0.95	533



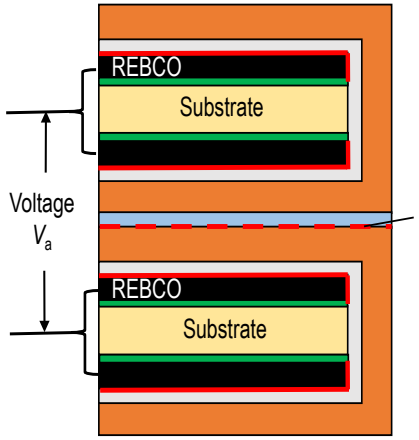


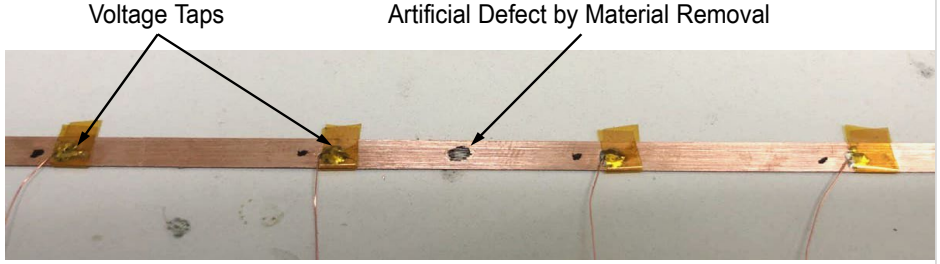
3.4 μm thick, 15% Zr-added film on each side

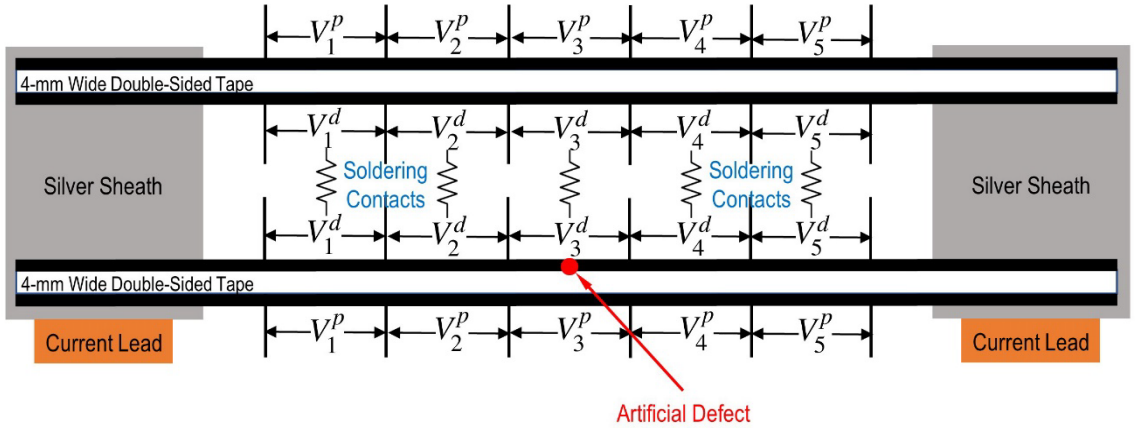
Supercond. Sci. Technol. **36,** 095016 (2023)

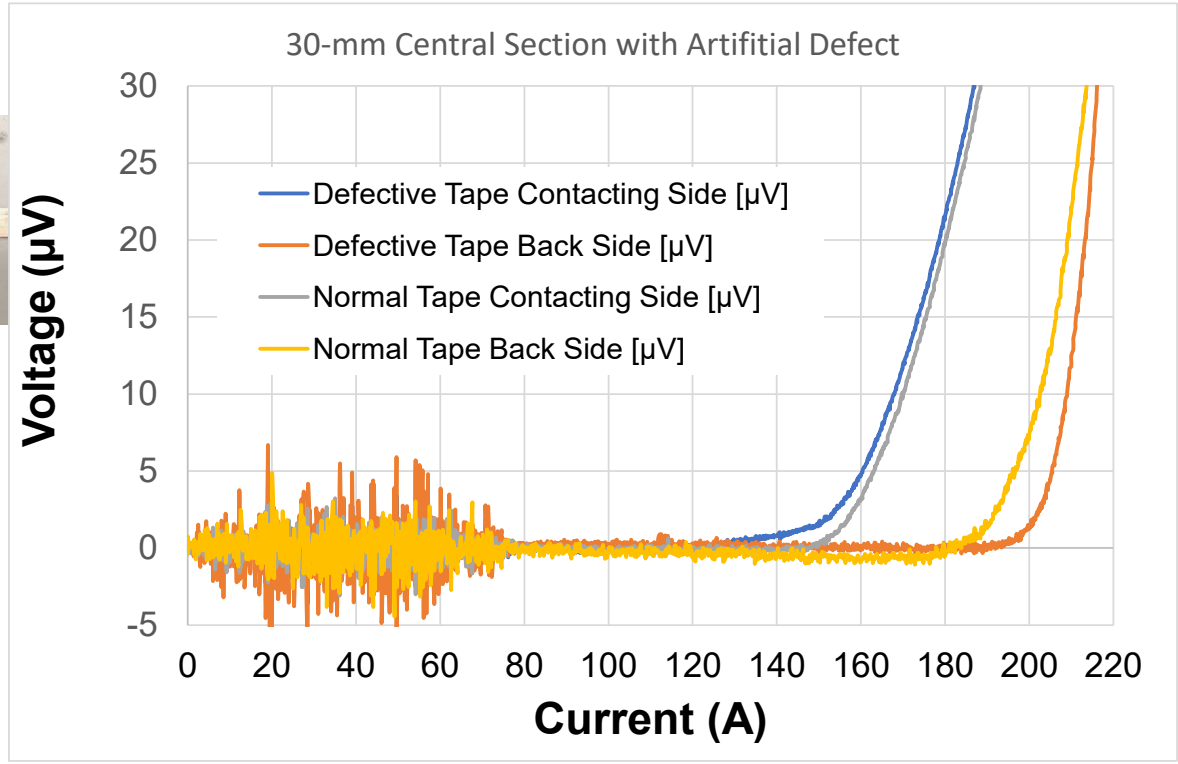
I_c of double-sided tape 533 A/4mm at 20 K 20 T → 2x I_c at 77 K, 0 T and 65% higher lift factor at 20 K, 20 T compared to typical commercial tape

Additional benefit of double-sided REBCO tapes: Current sharing to promote defect-tolerance







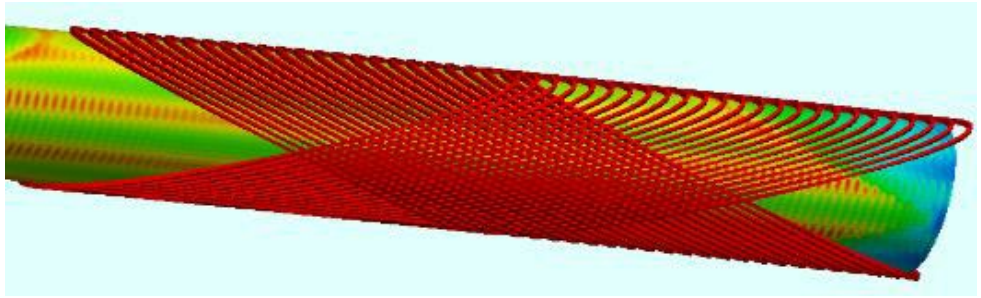


Double-sided REBCO tapes offer face-to-face contact that can promote current sharing

Round REBCO Wires using high-performance REBCO tapes

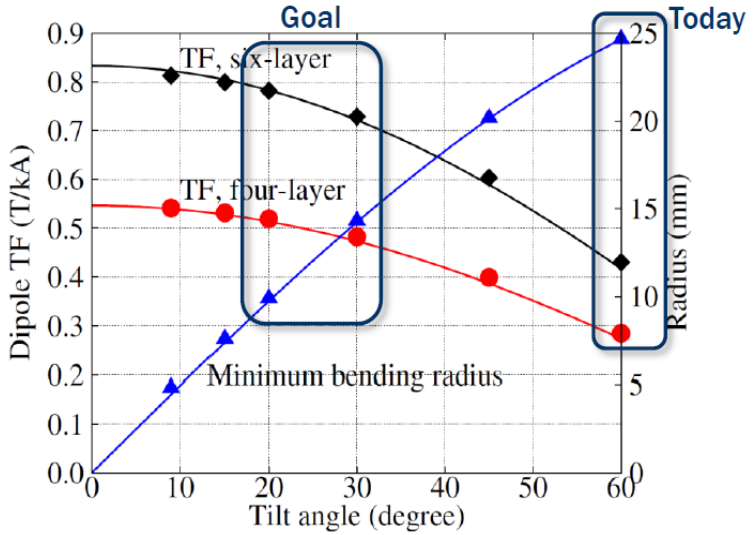
Round HTS wires with 15 mm bend radius can enable high magnetic fields in compact accelerator coils

Canted Cosine Theta (CCT) coil



X. Wang, LBNL

15 mm bend radius in the curved section



Round wire bend radius (mm)	Winding tilt angle (°)	Dipole transfer function (T/kA)	
		4-layer CCT	6-layer CCT
25	60	0.28	0.42
15	30	0.48	0.72

X. Wang et al. *Supercond. Sci. Technol.* **31**, 045007 (2018).

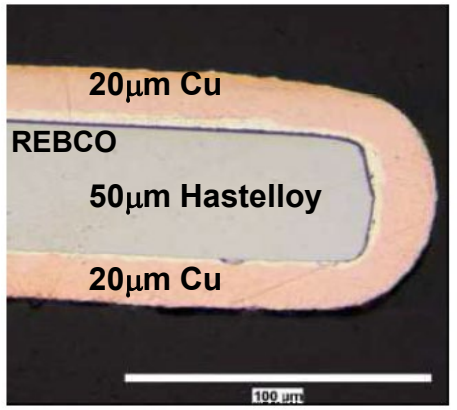
Symmetric Tape Round (STAR®) REBCO wire to achieve 15 mm bend radius

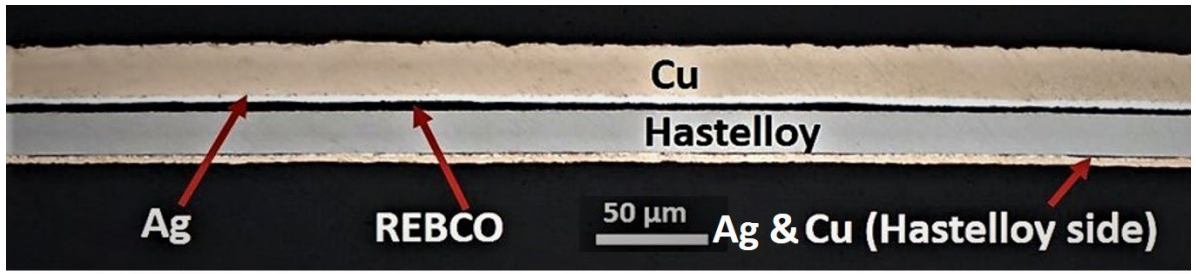
Standard REBCO Tapes:

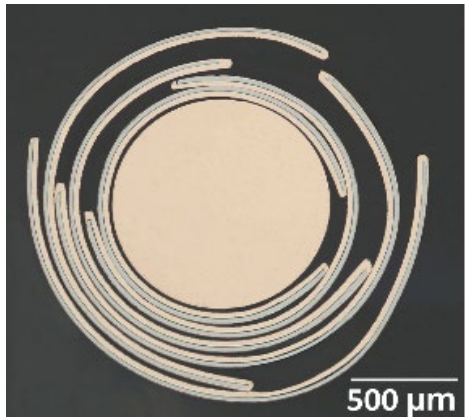
- REBCO asymmetrically positioned far away from neutral plane

Symmetric REBCO Tape:

- Copper stabilizer primarily on REBCO side.
- REBCO positioned near neutral plane
- Minimizes the strains in the REBCO layer.





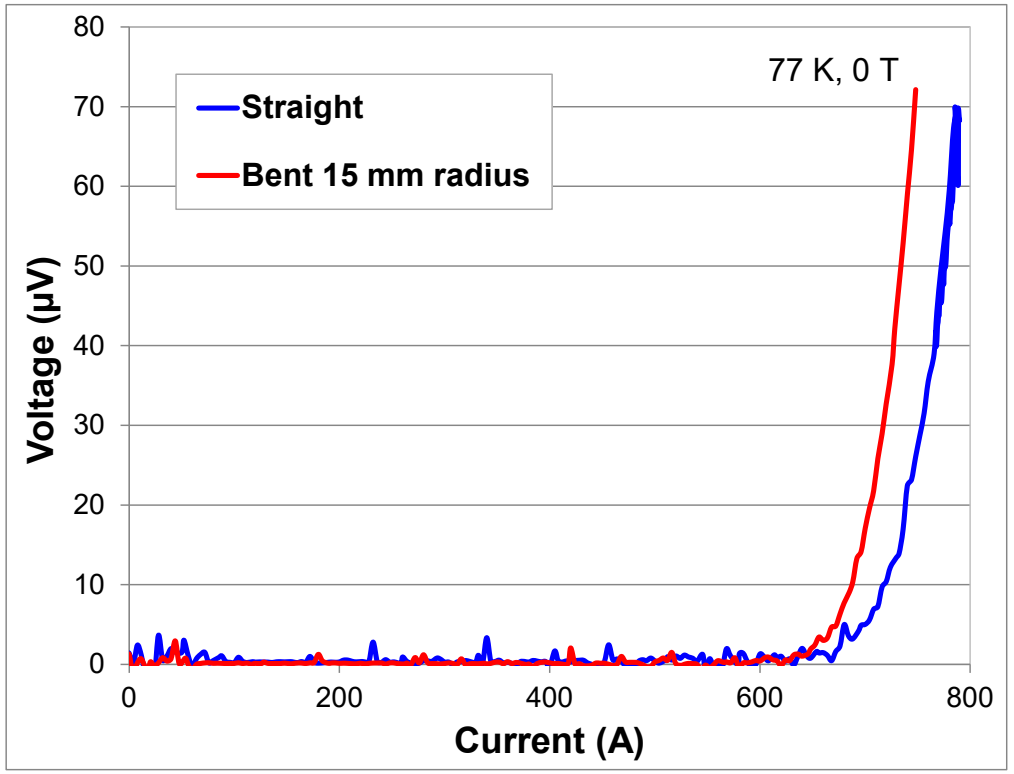


Symmetric REBCO tapes used to make round REBCO wires on 0.6 – 0.8 mm diameter copper former

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

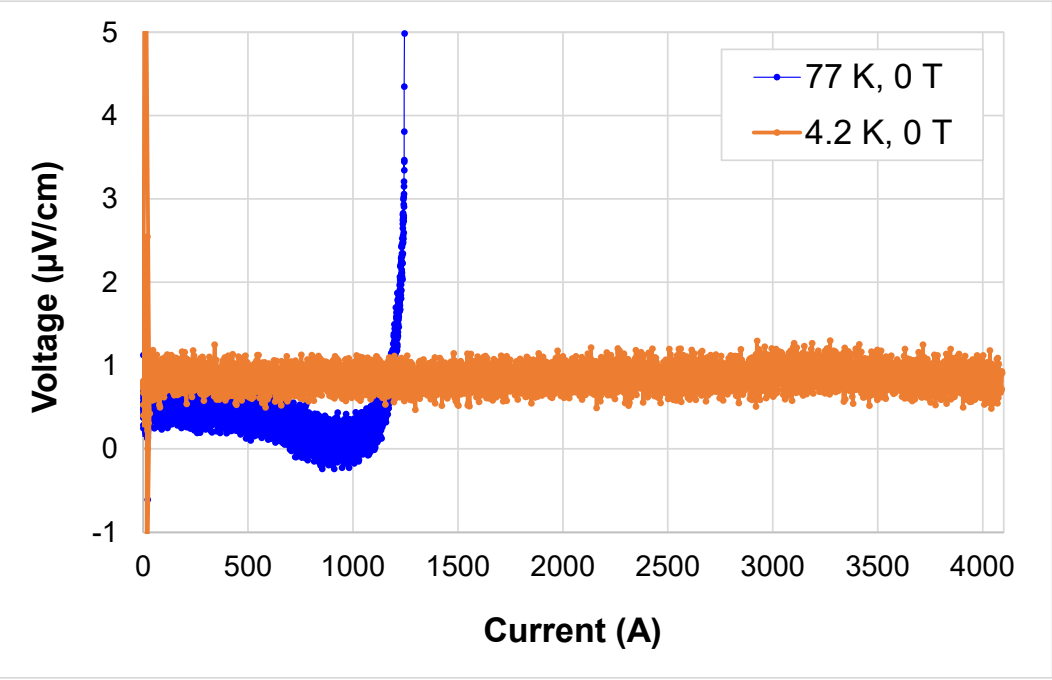
STAR® wires retain over 90% of critical current even at 15 mm bend radius

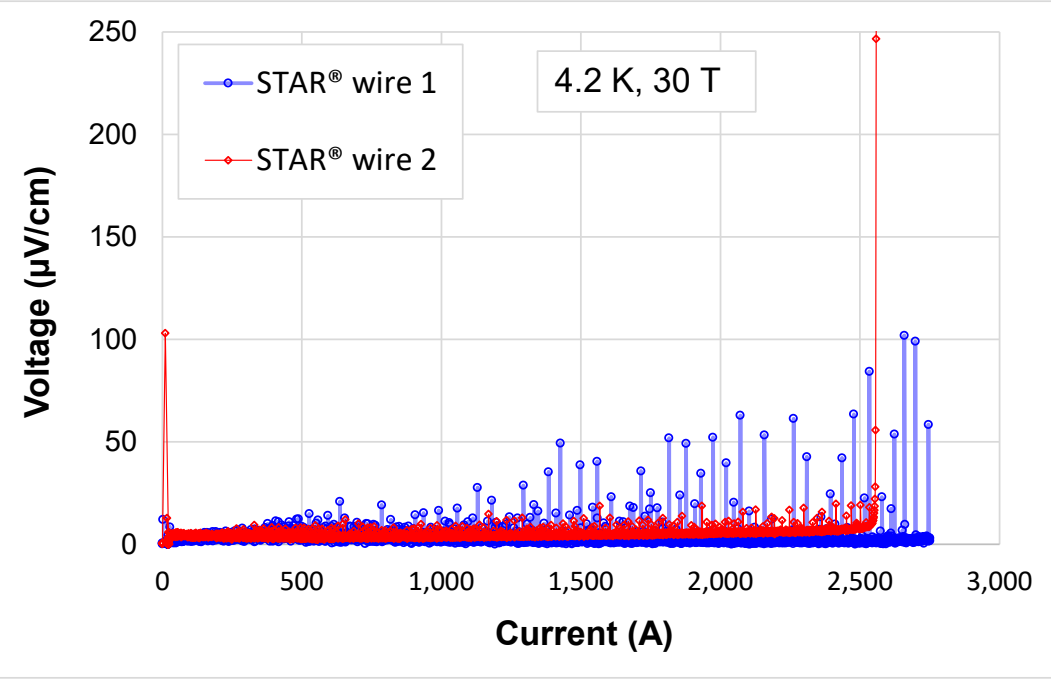
- 2.29 mm diameter STAR® wire on 0.81 mm former (11 symmetric tape strands)
- I_c in straight form = 728 A at 77 K, self-field
- I_c when bent to 15 mm radius = 690 A (**95% retention**)



2.52 mm diameter STAR® wires made with high I_c Advanced MOCVD REBCO tape strands tested > 2.5 kA at 4.2 K, 30 T

- 2.52 mm diameter STAR® wire on 0.81 mm former (12 symmetric tape strands with 4 μm thick films).
- I_c when bent to 15 mm radius = **1090 A** at 77 K, self-field.
- STAR® wire quenched at 2550 A @ 4.2 K, 30 T; J_e > 500 A/mm^2 at 4.2 K, 30 T.

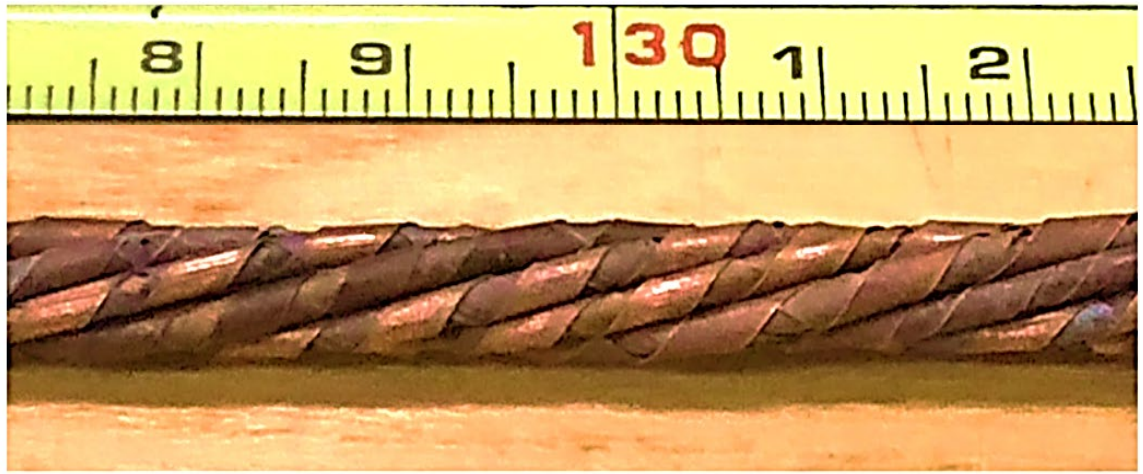




Supercond. Sci. Technol. **36**, 055007 (2023)

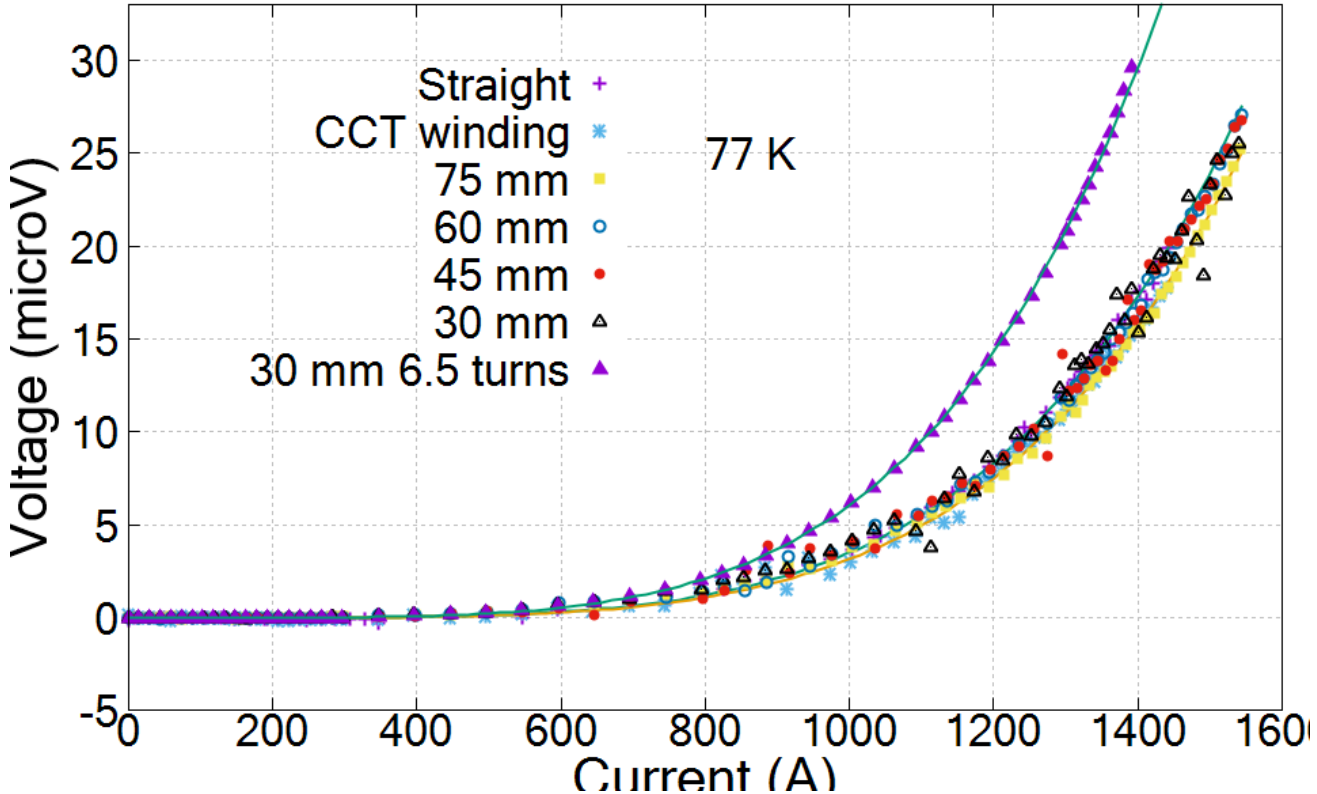
Measurement at CNRS, Grenoble

2-m-long, 5.8 mm diameter 6-around-1 cable demonstrated by LBNL with 6 STAR® wires (1.8 ± 0.1 mm diameter)



I_c of compact multi-strand STAR® cable = 1,444 A at 77 K, self-field
→ 80% of sum of I_c of individual STAR® wires

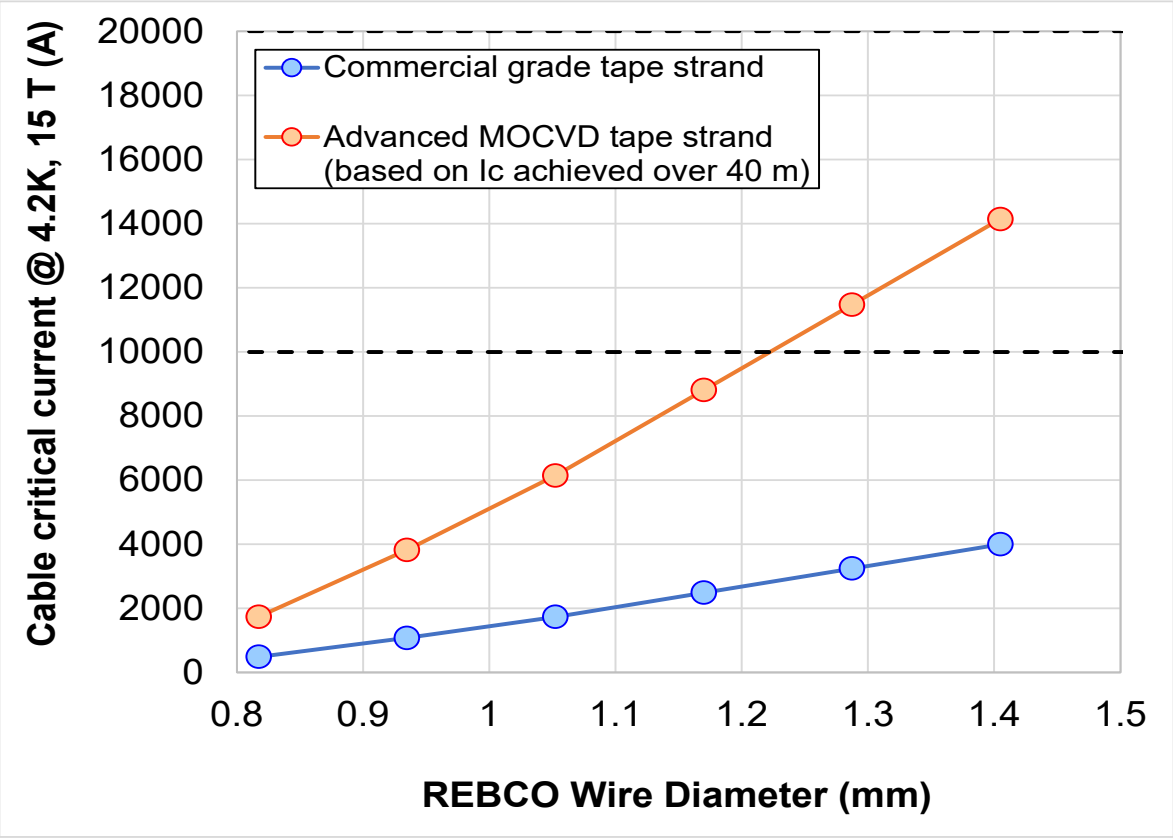
6-around-1 compact multi-strand STAR® cable retains high critical current even at 30 mm bend radius



5.8 mm diameter cable made with **6 STAR® wires** on central copper core with I_c = 1.44 kA at 77 K, self field

BERKELEY LAB
U.S. MAGNET DEVELOPMENT PROGRAM

4 mm diameter STAR® cable targeted with six 1.3 mm diameter STAR® wires with Advanced MOCVD tape strands



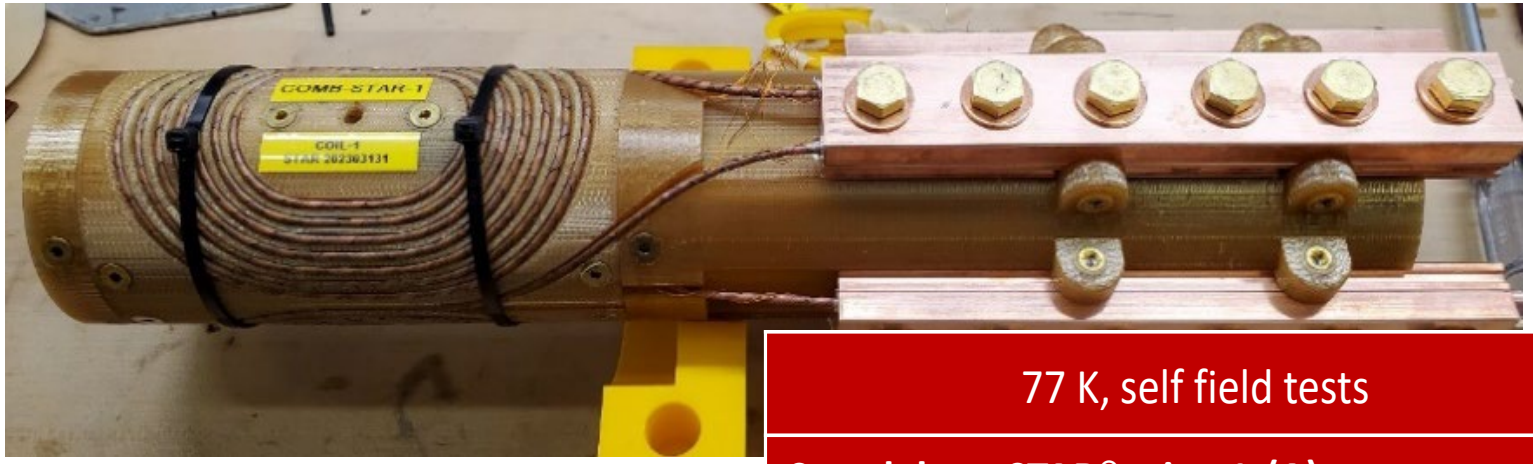
Expected I_c of 6-around-1 cable using six STAR wires.

Each wire made with symmetric REBCO tapes on 0.7 mm former.

***10 kA at 4.2 K, 15 T** achievable with 4 mm diameter STAR® cables at targeted 25 mm cable bend radius.*

Robustness of high current tape strands in STAR® wire tested in COMB magnet

- Conductor on Molded Barrel (COMB) magnet using 10 meters of STAR® wire made with 11 strands of high current, 4-μm-thick film REBCO tapes.
- Bend diameter of 33 mm in inner turn.



77 K, self field tests	STAR® wire # 131	STAR® wire # 151
Standalone STAR® wire I_c (A)	594.6	606.3
Expected COMB magnet I_c (A)	446	450
STAR® wire in COMB magnet I_c (A)	442.9	421.6
I_c retention of STAR® wire in COMB magnet	**99%**	**94%**

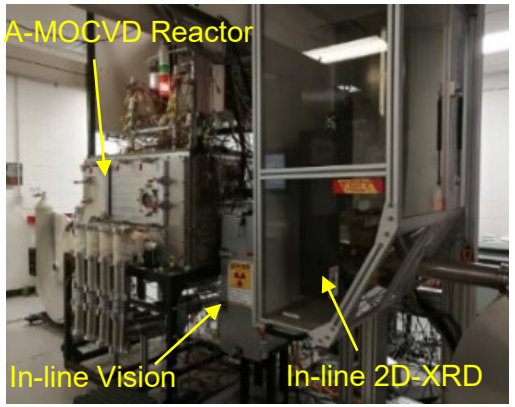
REBCO R&D Opportunities

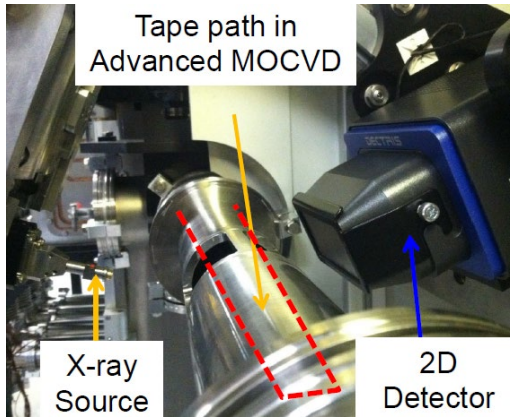
- Methods to enable high-yield manufacturing of high-performance, lower-cost REBCO tapes
    - Develop processes and statistical/machine learning tools for uniform and consistent high in-field critical current.
    - Develop new metrology tools for high-speed testing of tape performance over 100% of length.
- Method to enable high throughput manufacturing
    - Develop processes for high growth rates of thin film architecture while maintaining superior performance.
- Incorporate features important for application in tape
    - Quench tolerance, mechanical robustness, flexibility, round geometries, low loss.

Machine learning assisted feedback control of Advanced MOCVD process for high-yield manufacturing

Process-structure-property (PSP) modeling

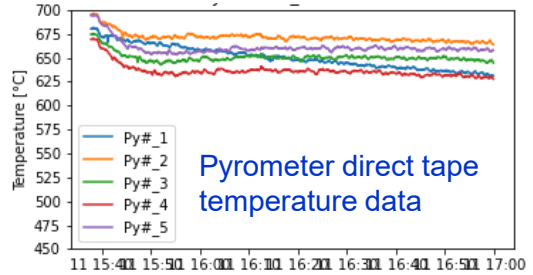
Advanced MOCVD

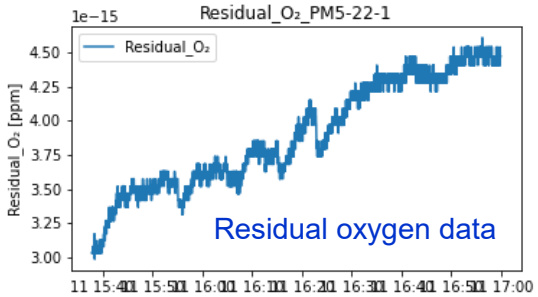


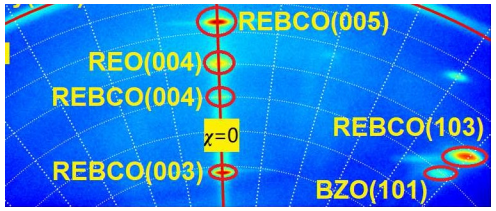


Generate

Multimodal Sensor Data



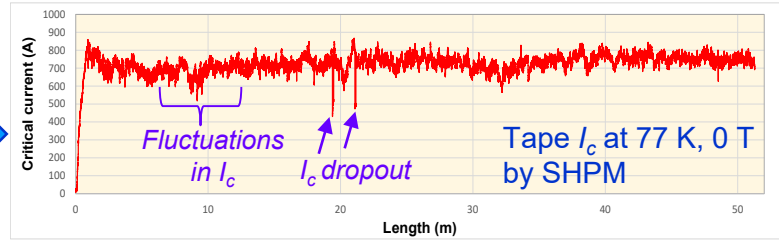


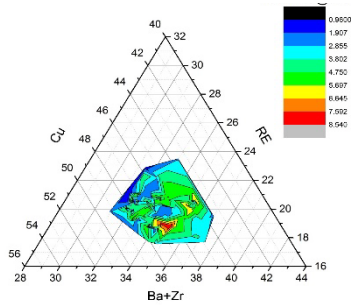


In-line 2D-XRD data

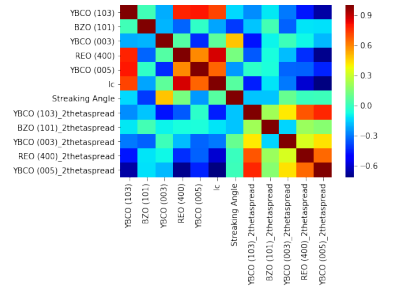
Affect

Property measurements

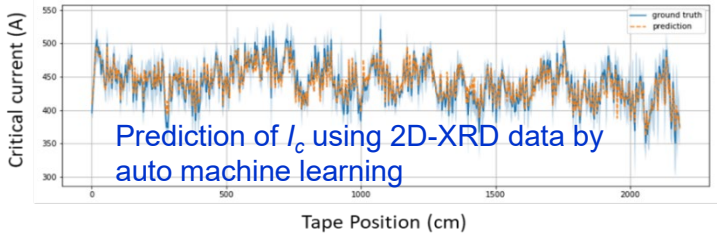




J_c @ 4.2K, 13T & film composition



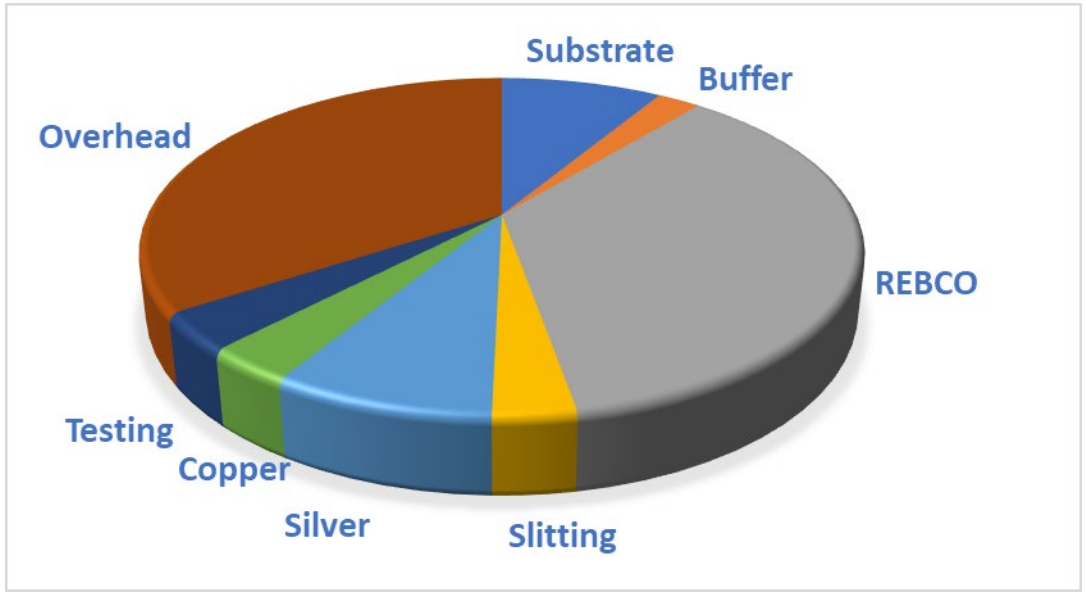
Heat map of correlation between 2D-XRD features & I_c

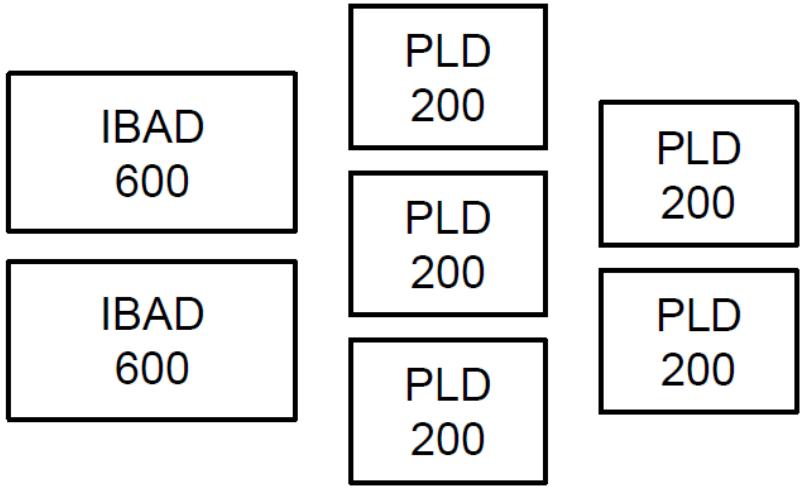


Real-time process feedback and control

Need to increase production capacity per REBCO deposition tool

- Throughput and production capacity is limited by REBCO deposition process.
- Current approach of increasing production capacity by multiplying the same production tools is not sustainable.
- REBCO deposition and capital equipment depreciation contribute a majority of conductor cost.





A. Molodyk "Industrialisation of 2G HTS wire at SuperOx" 2022 Applied Superconductivity Conference

Increasing production rate of REBCO deposition can overcome both capacity and cost bottlenecks.

Pathway to increase production capacity per REBCO deposition tool by 10x

REBCO deposition technology	Growth rate (nm/s)	Deposition area (m^2)	Annual production per tool[1] (km)	Tape Cost ($/m)	Ic (A/4mm)		Tape Cost ($/kA-m)	
					77 K, self field	20 K, 20 T	77 K, self field	20 K, 20 T
Industry PLD	25	0.01	200	30	150	150	200	200
Industry MOCVD	3	0.1	200	30	150	150	200	200
Advanced MOCVD	20	0.15	**2000**	**6**	750	750	**8**	**8**

10x increase in production capacity with 5x critical current will be a breakthrough to utilize REBCO tapes in most applications

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

REBCO R&D Opportunities

- Production volume
  - Increase production capacity per tool by 10x (large-area deposition, high growth rates).
- Cost
  - Increase efficiency of raw material conversion to film.
  - High critical current tapes for lower $/kA-m.
- Piece-length and uniformity along length of tape
  - In-line quality control with intelligent feedback.
  - New reel-to-reel metrology techniques.
- Mechanical strength
  - More robust tape architecture.
  - Increase tensile strength beyond Hastelloy limit.
- Geometry
  - Cost-effective technologies to convert flat tape to round, transposed, multifilament geometry.