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Status of STAR Wires Tailored for High-Field Magnets

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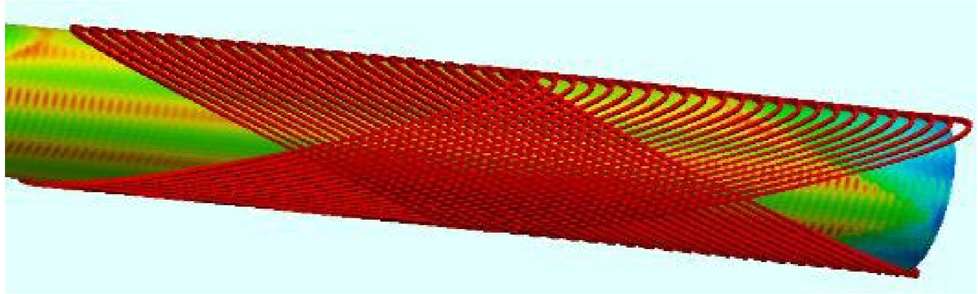
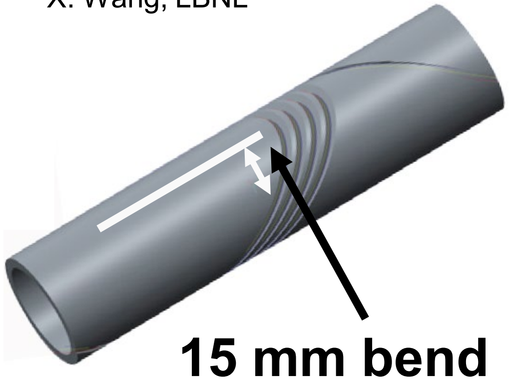
*VS has financial interest in AMPeers

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

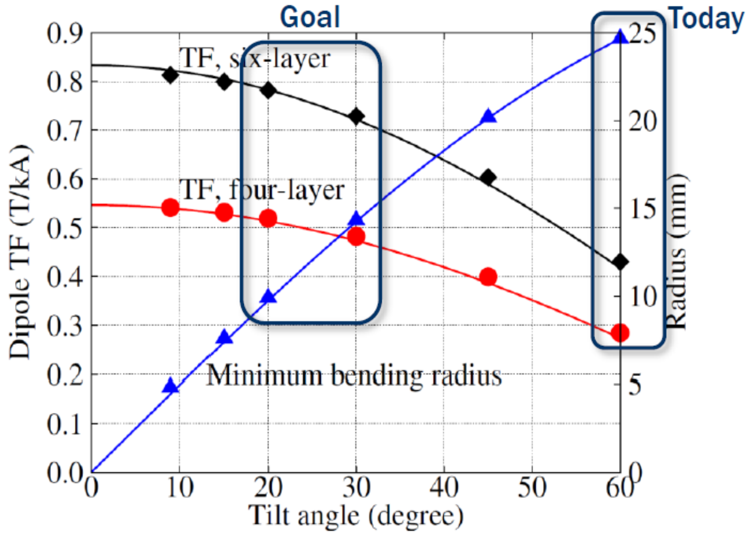
Canted Cosine Theta (CCT) coil



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).

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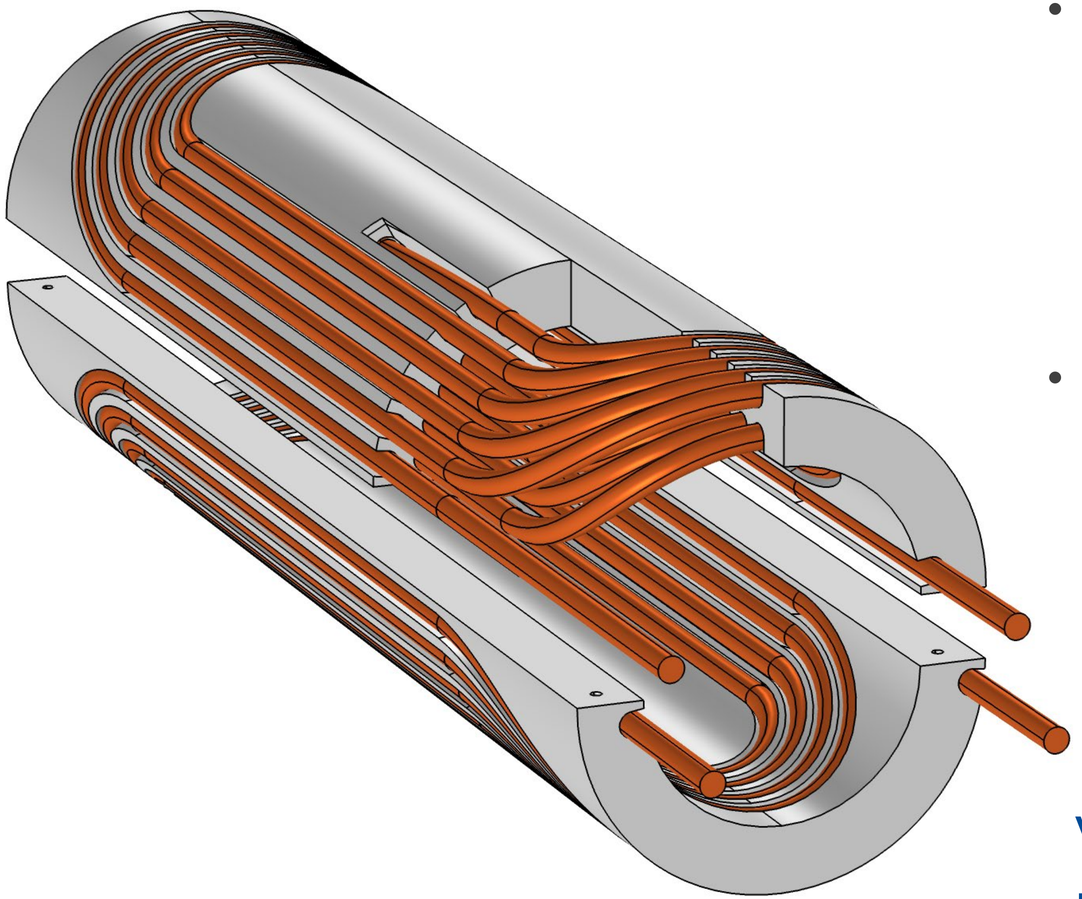
Conductor On Molded Barrel (COMB) magnets require REBCO wires with high J_e at 25 – 30 mm bend diameter

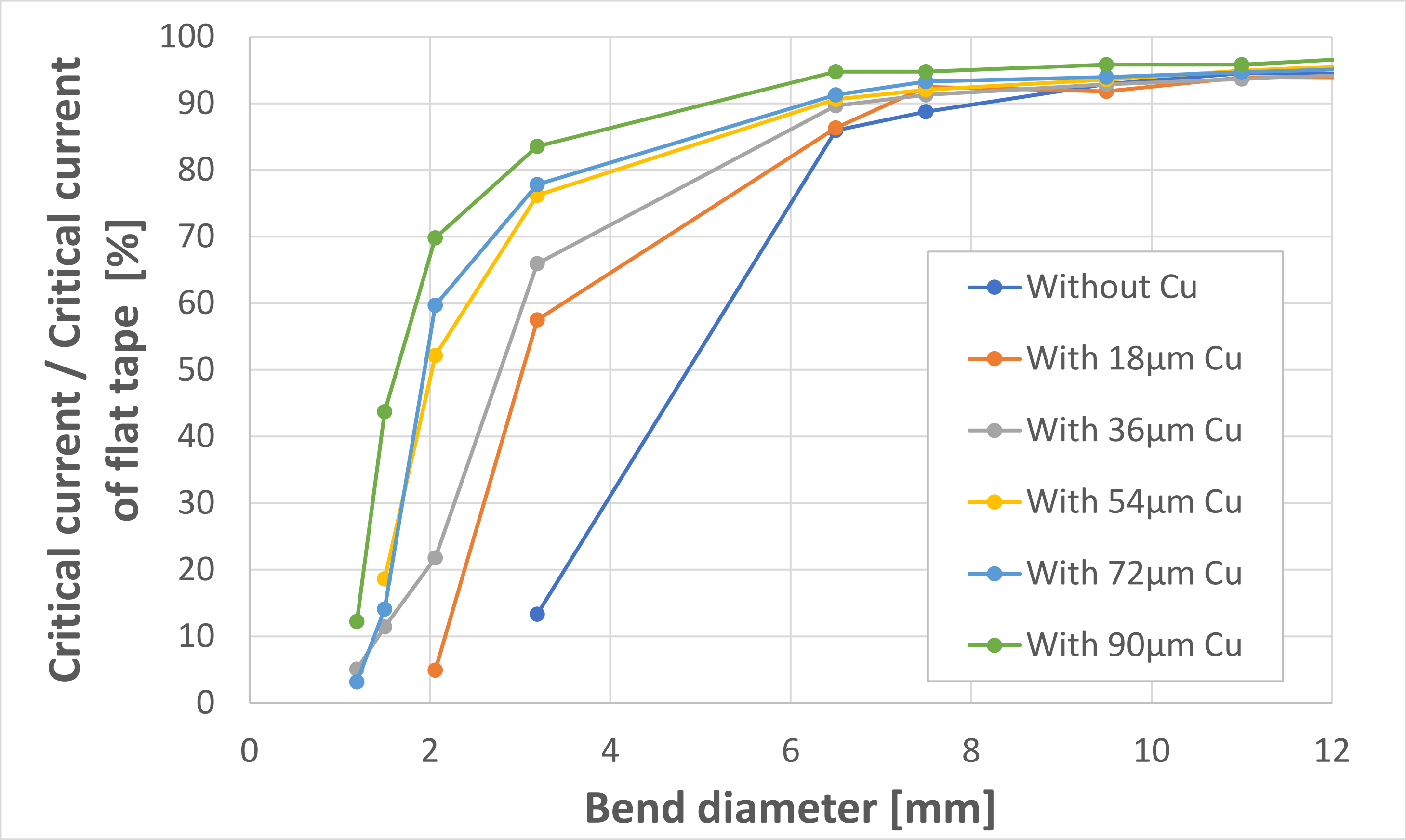


- Cable strain sensitivity:
  - For the aperture of the next collider of ~50 mm, the cable should be bendable around 25-30 mm diameter poles with preferably no more than 20% degradation.
- To produce a 5 T insert in a 15 T background field, the reference J_e(20 T, 4.2 K) (after all degradations are taken into account) should be:
  - At least 400 A/mm^2 for an 8-layer design;
  - But preferably in 550-850 A/mm^2 range to enable 4-6 layer designs;

Vadim Kashikhin, Vito Lombardo
MDP Collaboration Meeting
March 2, 2021

Fermilab

Standard REBCO tapes fail at bend diameter < 2 mm



Standard REBCO tapes cannot be used to fabricate small diameter wires (< 2 mm)

Bend radius of round wires made with standard REBCO tapes limited to > 25 mm.

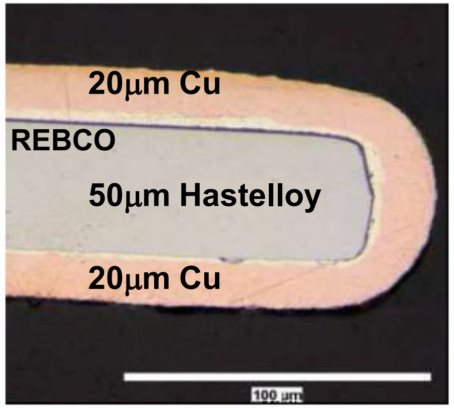
Symmetric Tape Round (STAR) REBCO wire to achieve 15 mm bend radius

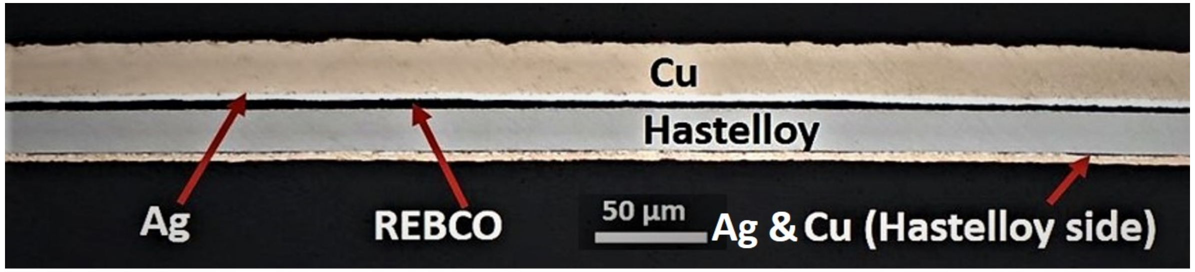
Standard REBCO Tapes:

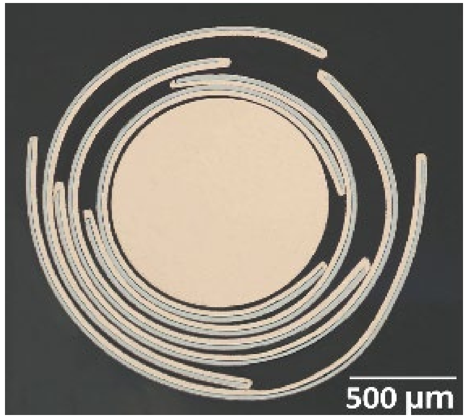
- REBCO asymmetrically positioned far away from neutral plane

Symmetric REBCO Tape:

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



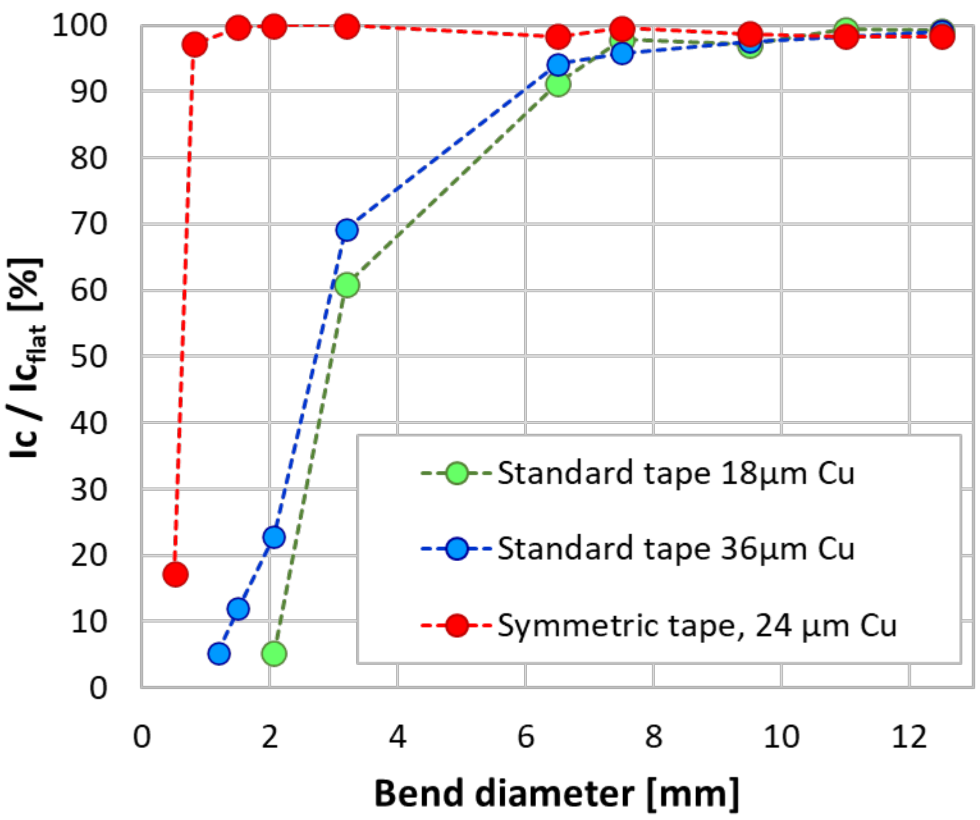


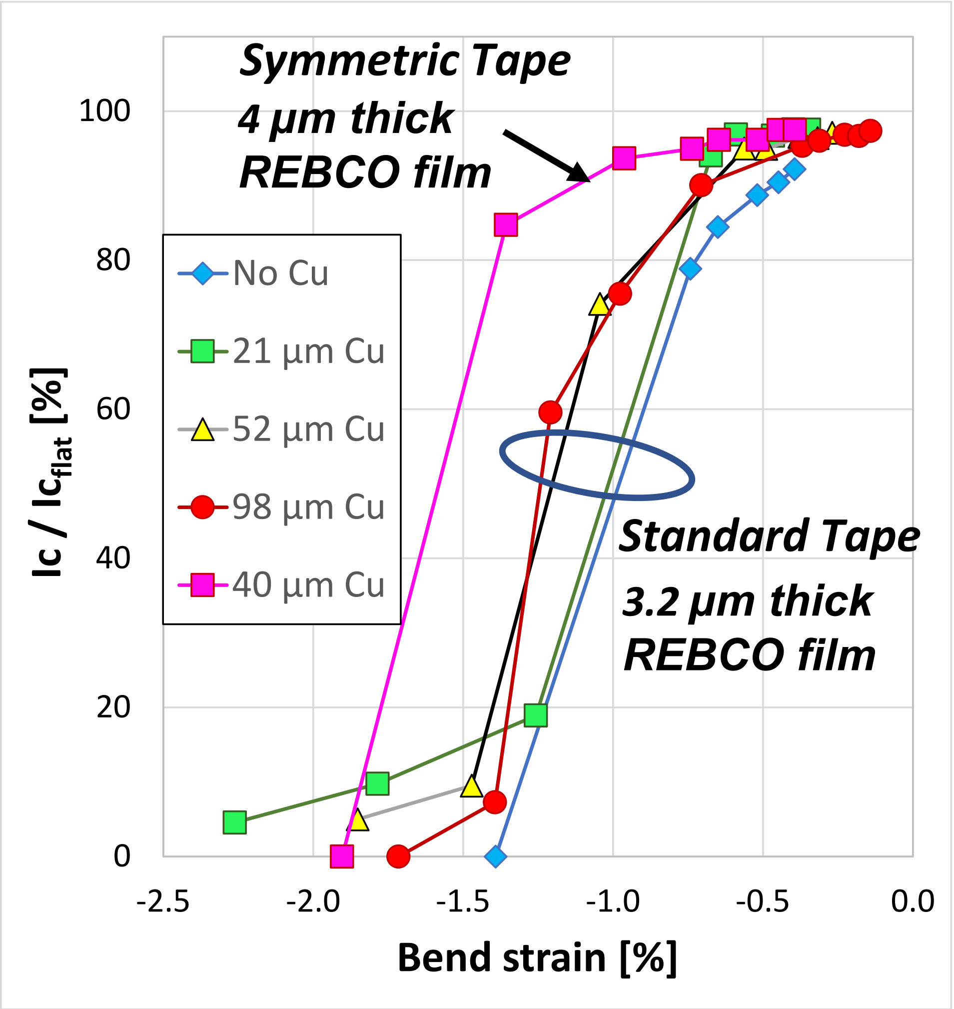


Symmetric REBCO tapes used to make round REBCO wires on 0.8 and 1 mm diameter copper former

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

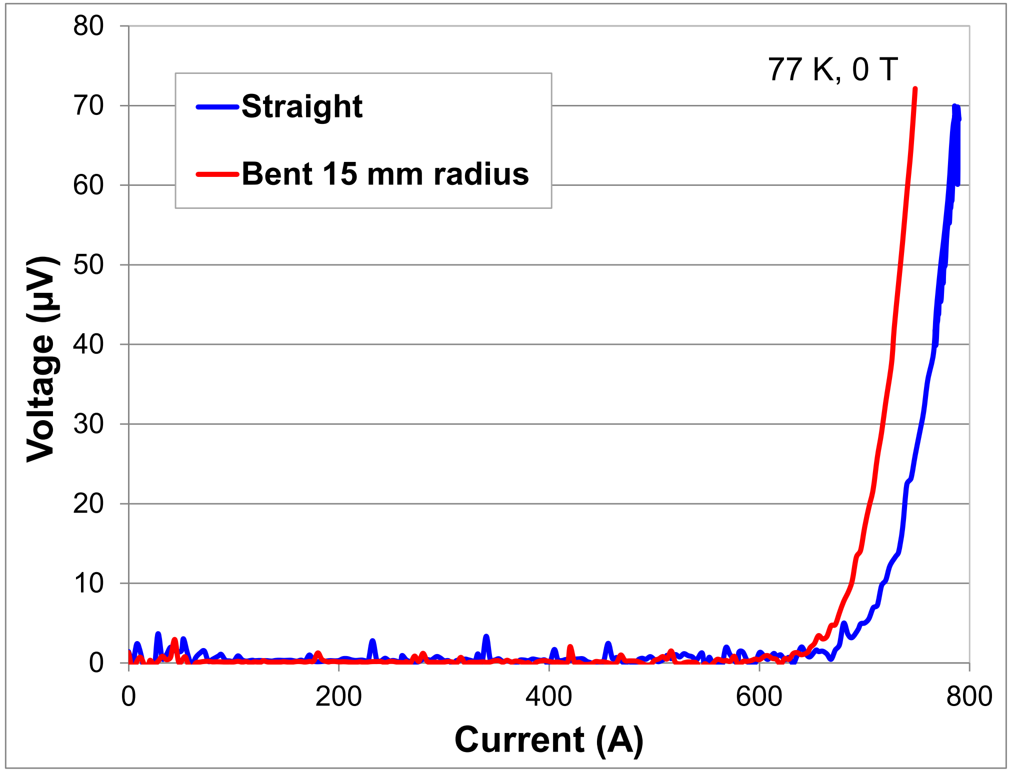
Symmetric REBCO tapes retain > 95% I_c even at bend diameter of 0.8 mm; enable high I_c retention even with 4 µm thick films





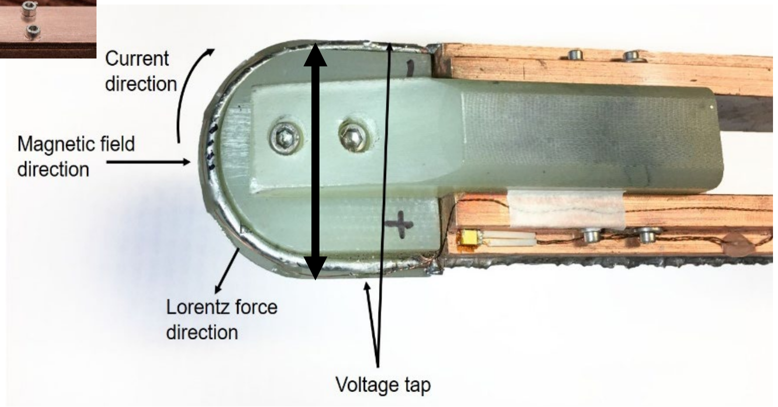
STAR wires retain over 90% of critical current even at 15 mm bend radius

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



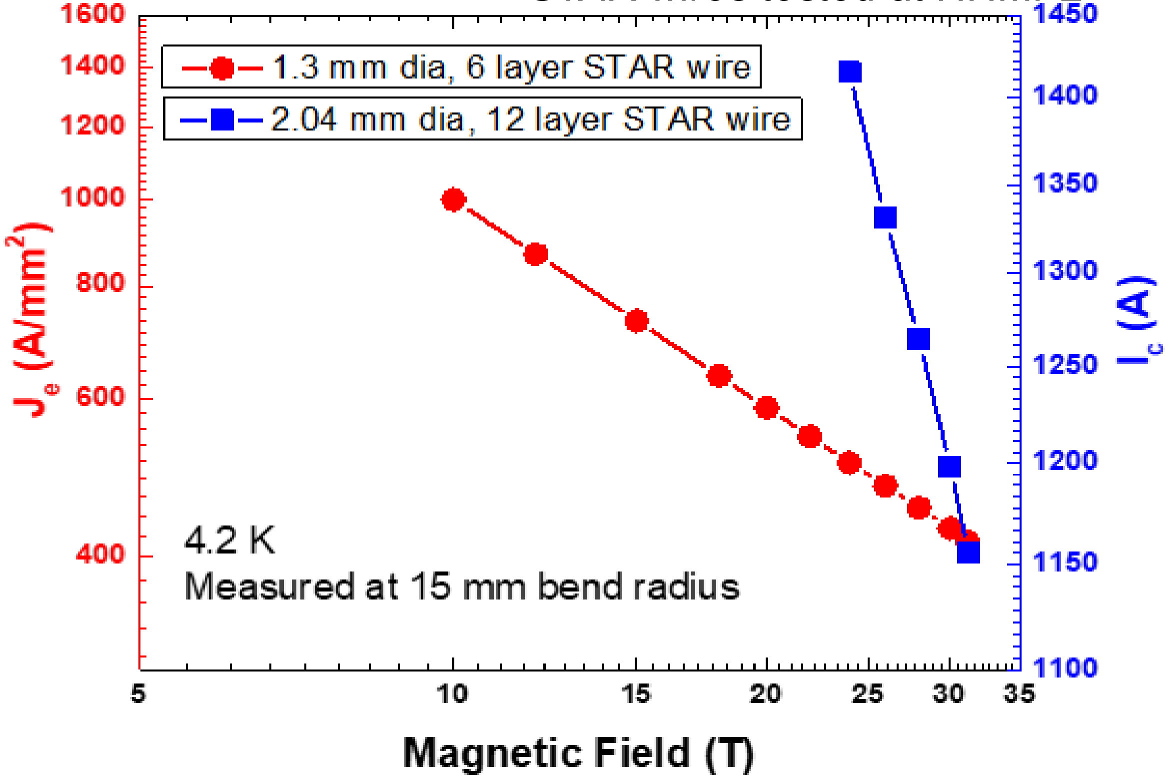
1.3 – 2 mm diameter STAR REBCO wires exhibit excellent performance in high magnetic fields

30 mm bend diameter



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

STAR wires tested at NHMFL

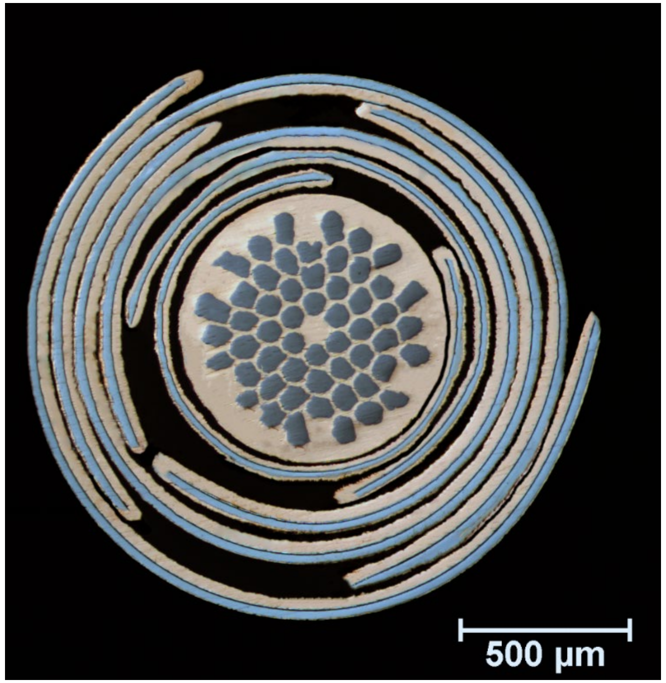


At a **bend radius of 15 mm**, using REBCO tapes with 1.7µm thick films,

J_e of 1.3 mm diameter STAR wire **: 729 A/mm^2 at 15 T and 586 A/mm^2 at 20 T**

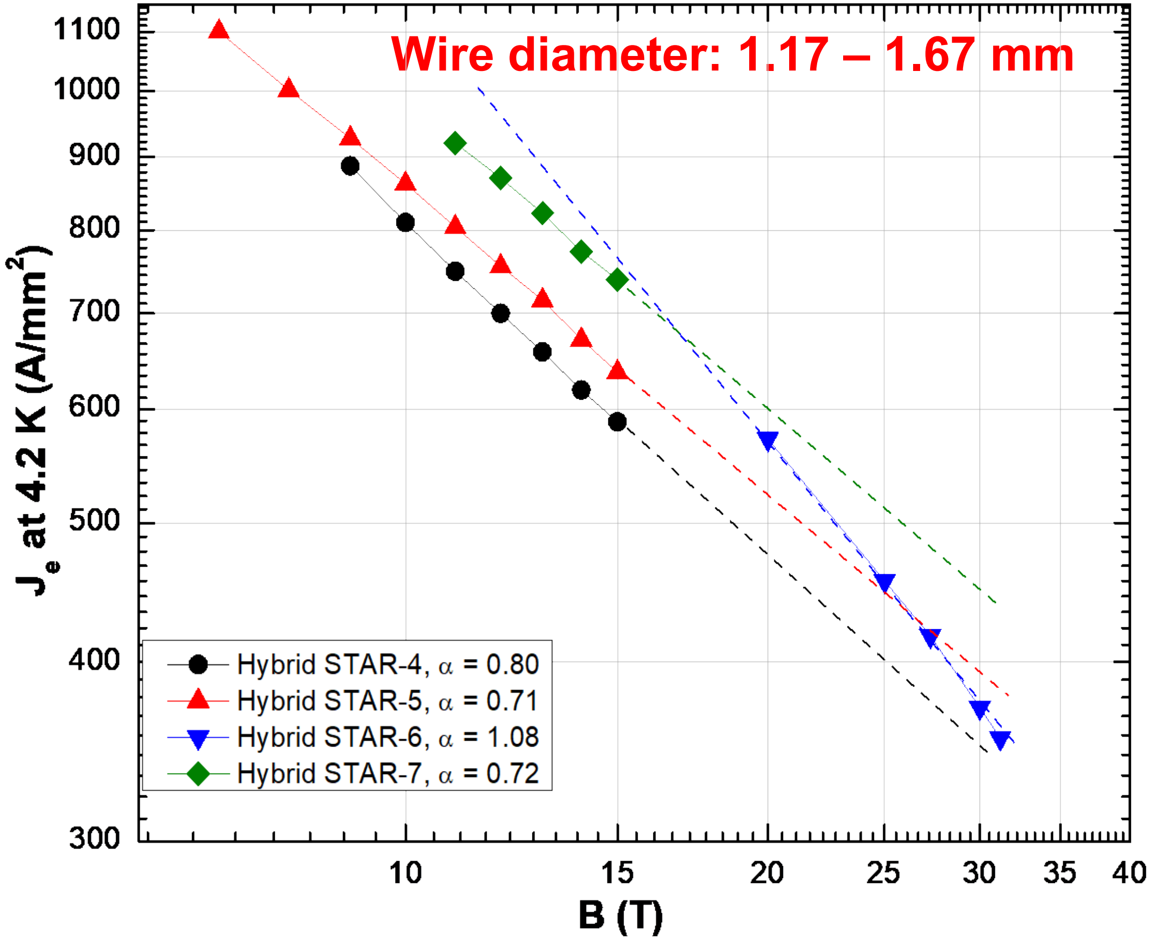
I_c of 2 mm diameter STAR wire **: 1400 A at 24 T**

Hybrid STAR wire with superconducting Nb-Ti former



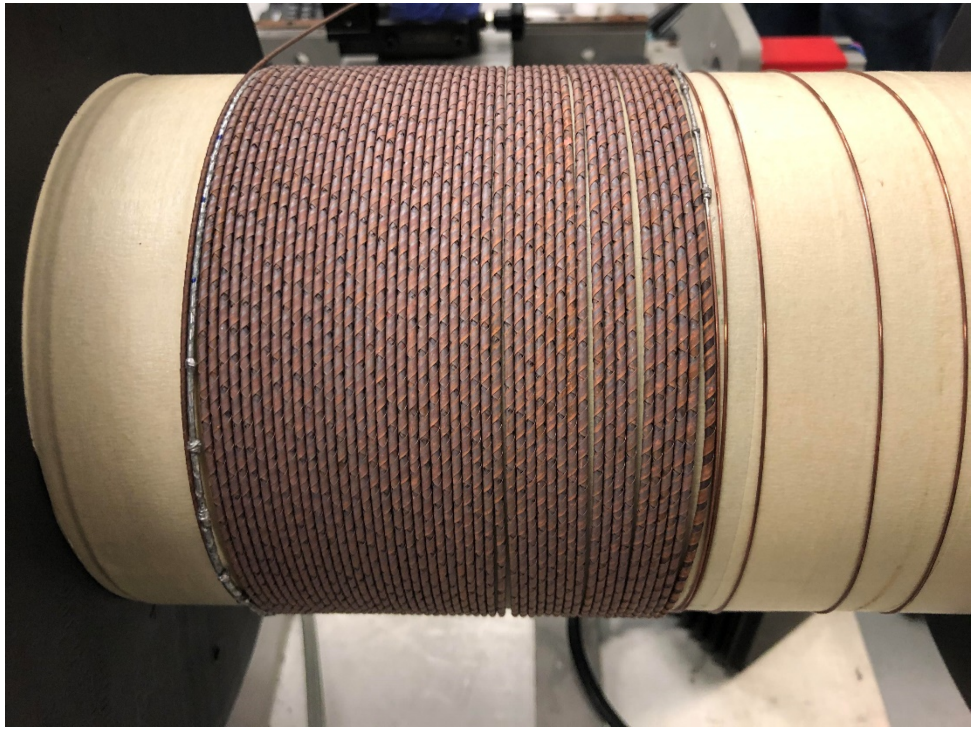
NbTi/Cu (*Luvata*) former
(NbTi:Cu = 1:1.25)
54 filaments

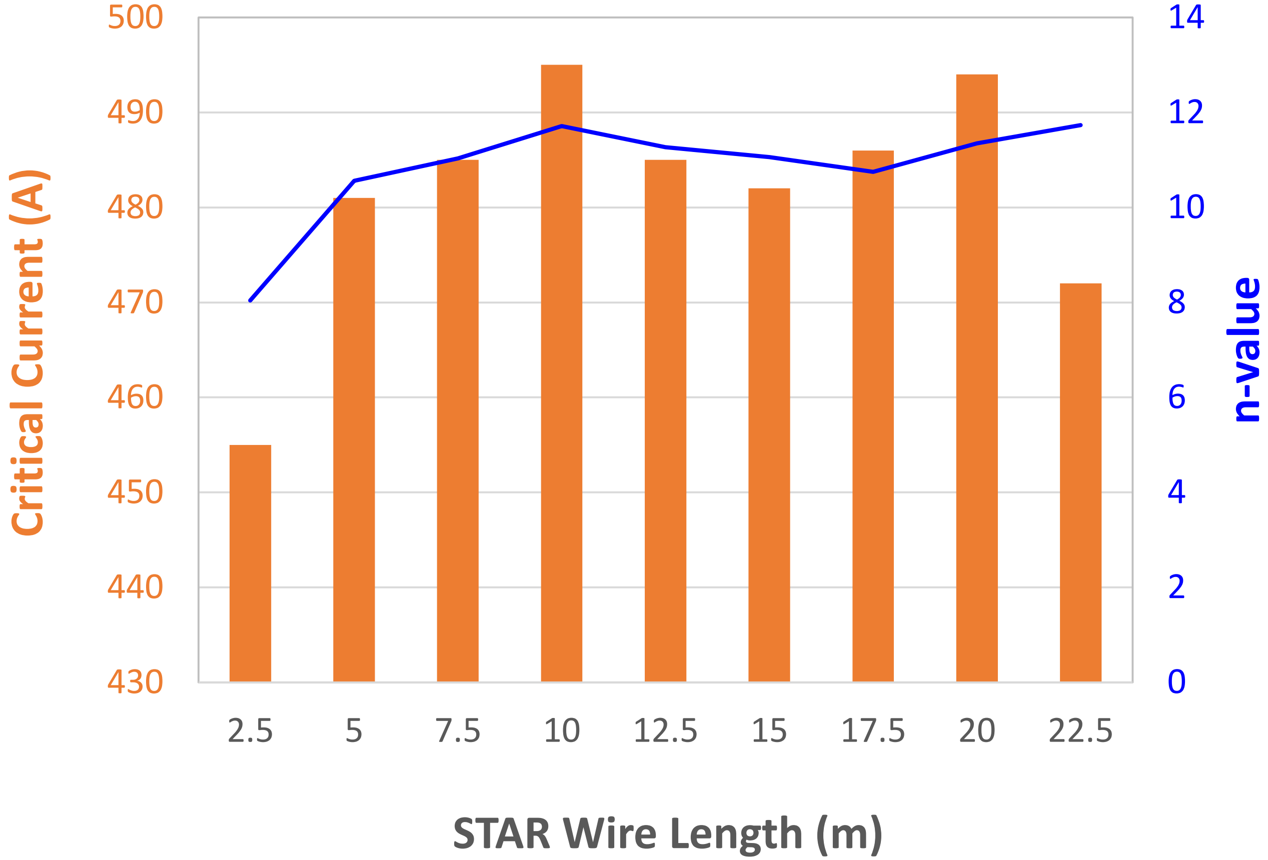
NbTi I_c >700 A at 4.2 K, 4T



J_e at 4.2 K, 15 T = 739 A/mm^2; projected J_e at 4.2 K, 20 T = 600 A/mm^2.

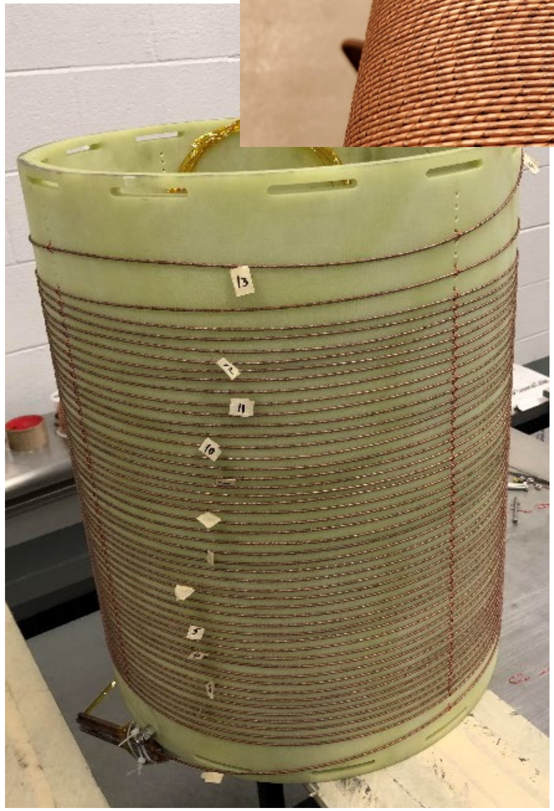
23 m long, 1.95 mm diameter STAR wire with average critical current of 481 A

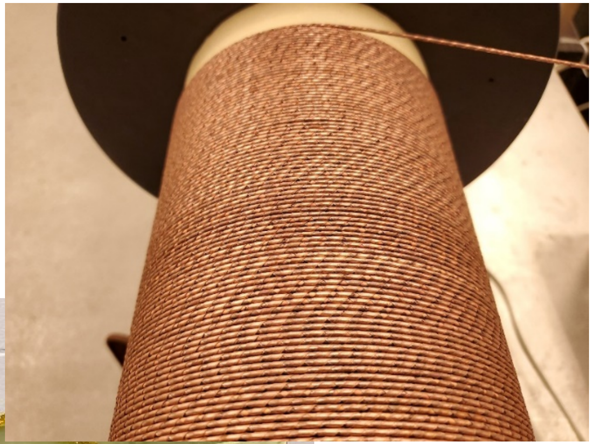


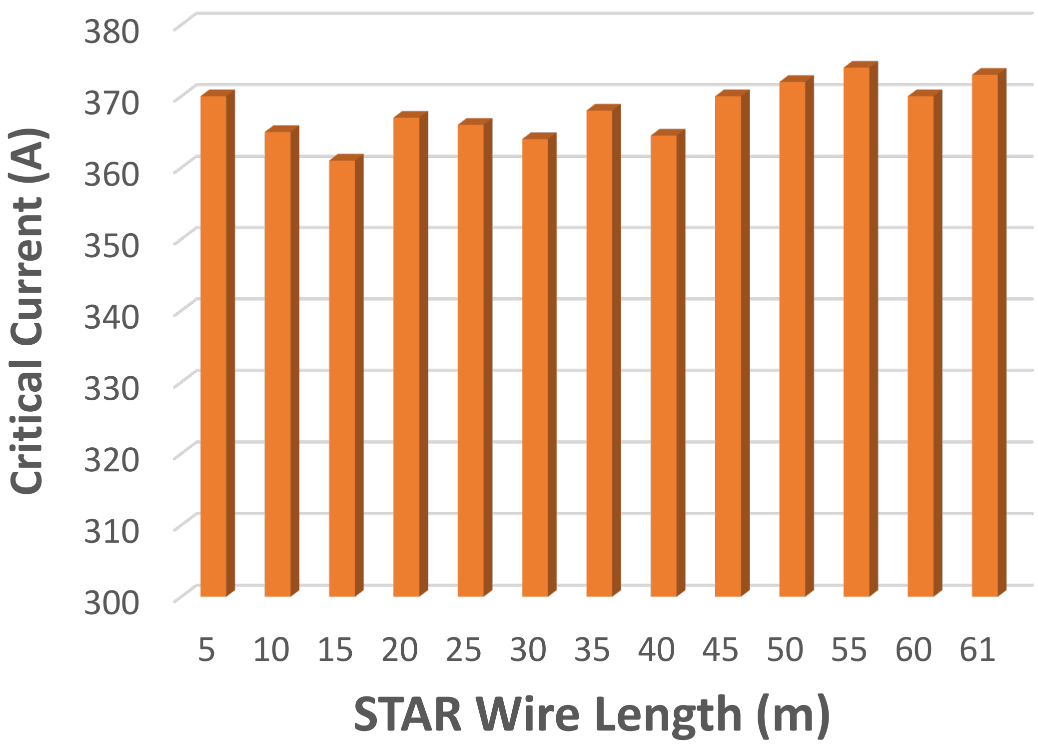


Scaled up STAR wire to 61 m

1.84 mm diameter







61 m STAR wire with I_c ~ 368 A @ 77 K

Reducing cost of STAR wires

- All round HTS wires are expensive.
- Cost of individual tape strands is the major component of STAR wire cost.
- Using 3x higher I_c tape → 3x fewer tape strands → >2.8x lower cost

STAR wires now made with commercial-grade REBCO tapes:

Commercial-grade REBCO tape
I_c = 450 A/12 mm @ 77 K, 0 T
I_c = 960 A/12 mm @ 4.2 K, 20 T

→

12 symmetric tapes each average 2 mm wide
I_c = 75 A/2 mm @ 77 K, 0 T
I_c = 160 A/2 mm @ 4.2 K, 20 T

→ *Wind on 0.8 mm dia former*

2 mm dia STAR wire
I_c = 800 A @ 77 K, 0T
I_c = 1730 A @ 4.2 K, 20 T

STAR wires with Advanced MOCVD REBCO tapes:

Advanced MOCVD REBCO tape
I_c = 800 A/12 mm @ 77 K, 0 T
I_c = 2,880 A/12 mm @ 4.2 K, 20 T

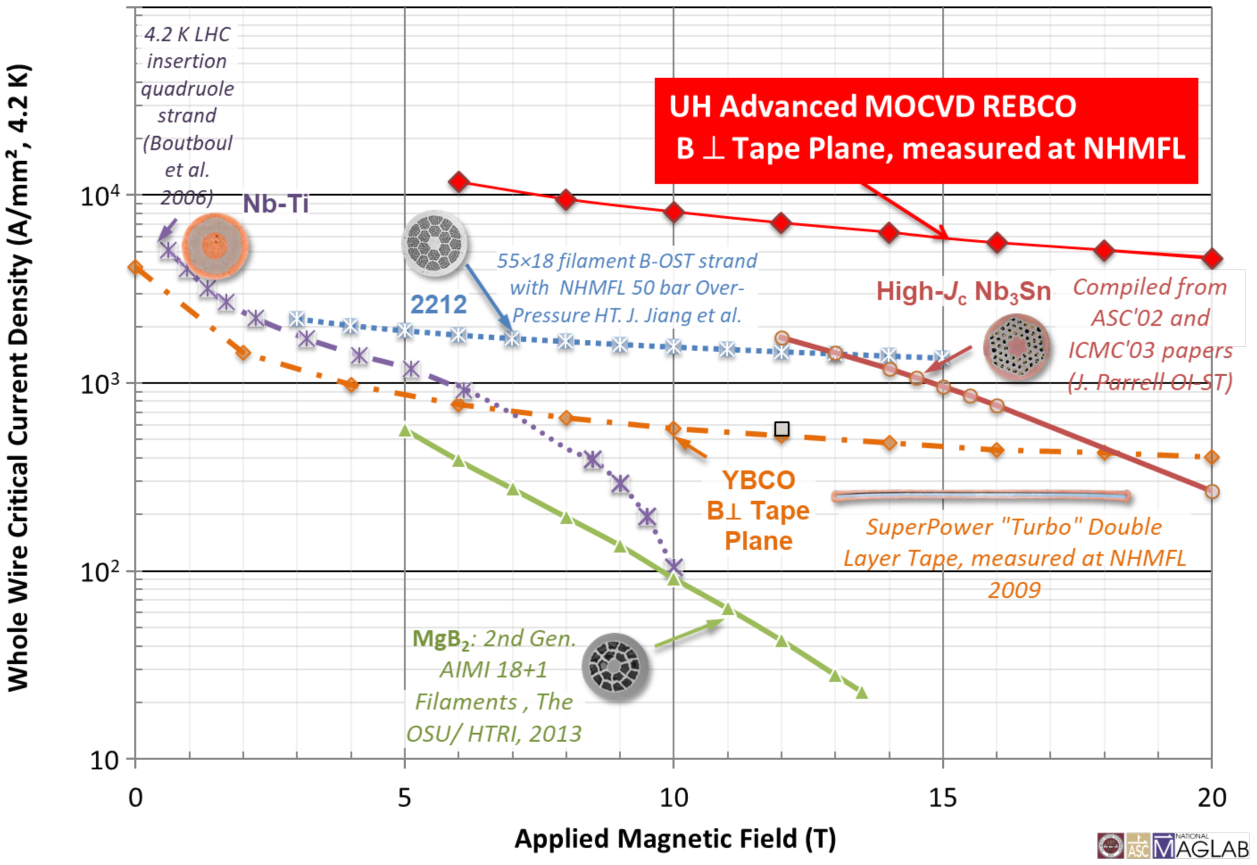
→

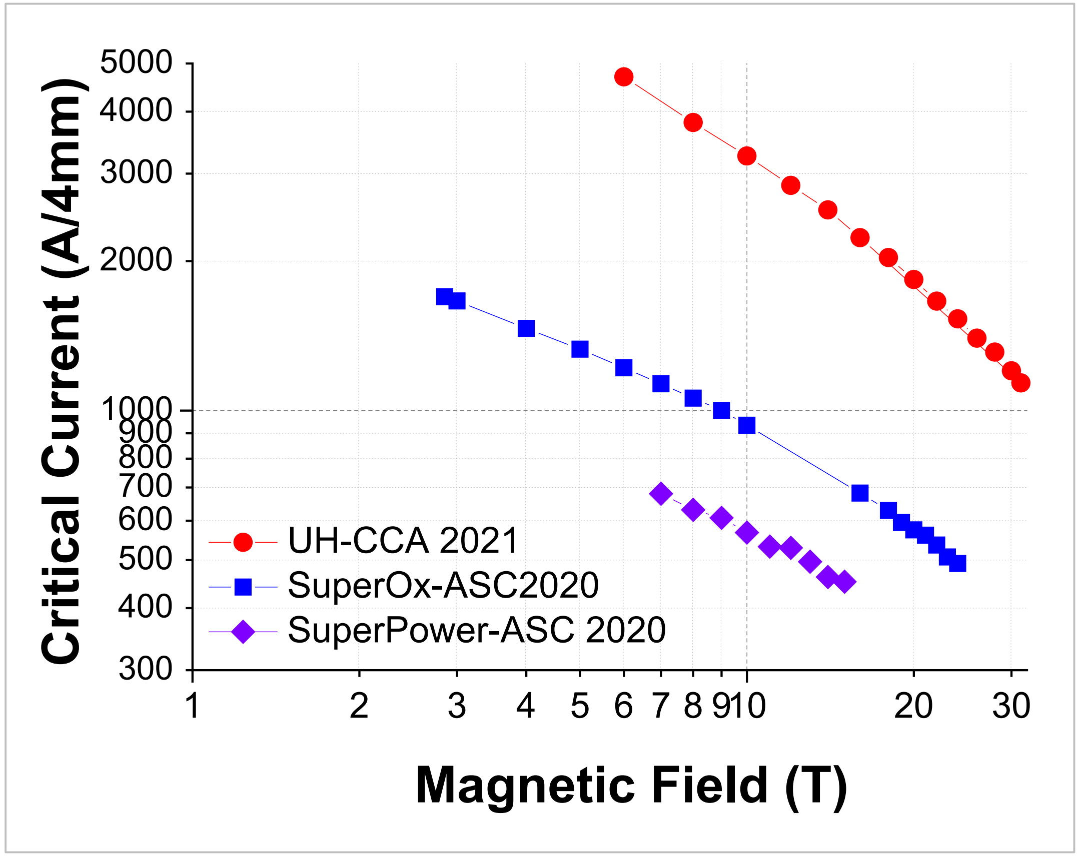
4 symmetric tapes each average 2 mm wide
I_c = 135 A/2mm @ 77 K, 0 T
I_c = 480 A/2mm @ 4.2 K, 20 T

→ *Wind on 1 mm dia former*

1.5 mm dia STAR wire
I_c = 480 A @ 77 K, 0T
I_c = 1730 A @ 4.2 K, 20 T

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, 16 T = 5,575 A/mm^2
7.3x Nb_3Sn @ 16 T

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

Advanced MOCVD REBCO tape selected by US DOE for CABLE Conductor Manufacturing Prize

Conductivity-enhanced materials for Affordable, Breakthrough Leapfrog Electric and thermal applications (CABLE) Conductor Manufacturing Prize

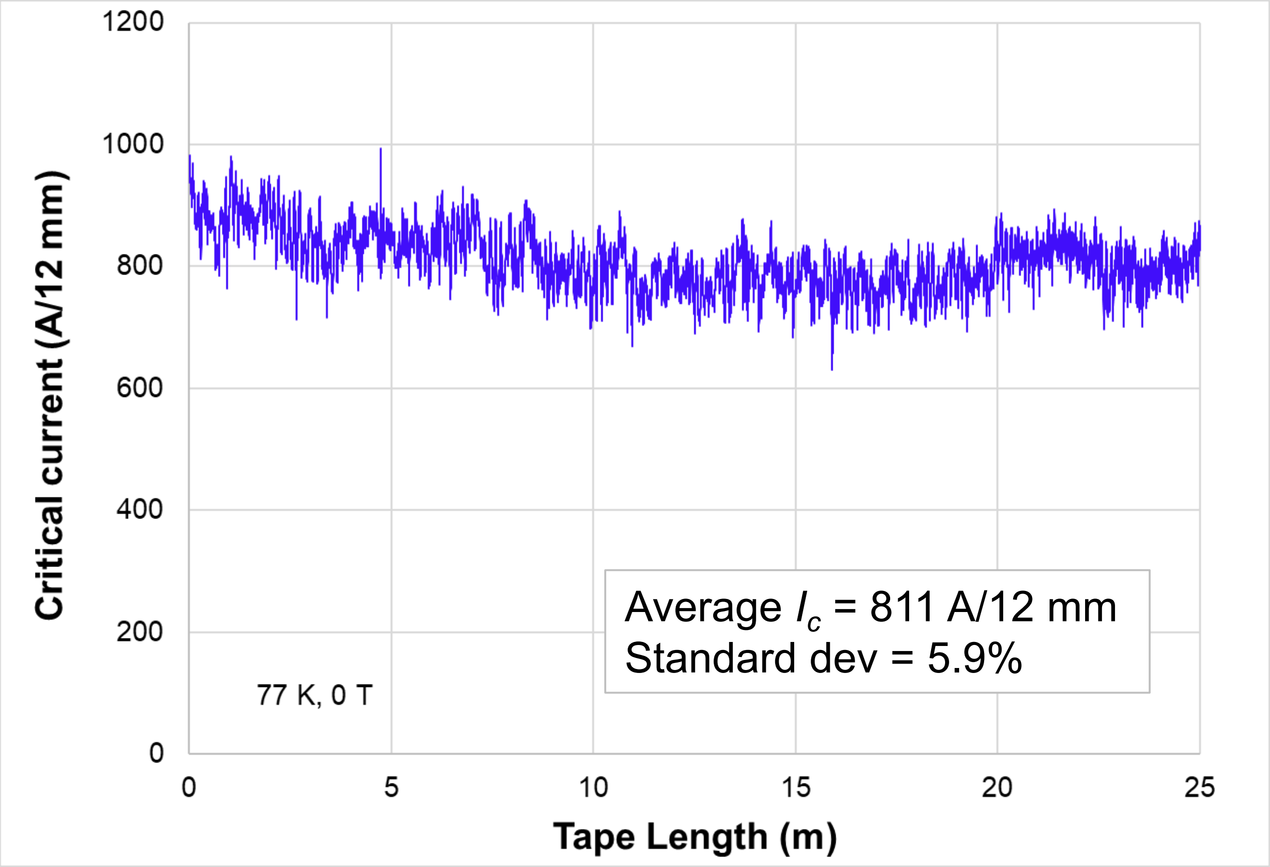
Office of Energy Efficiency & Renewable Energy

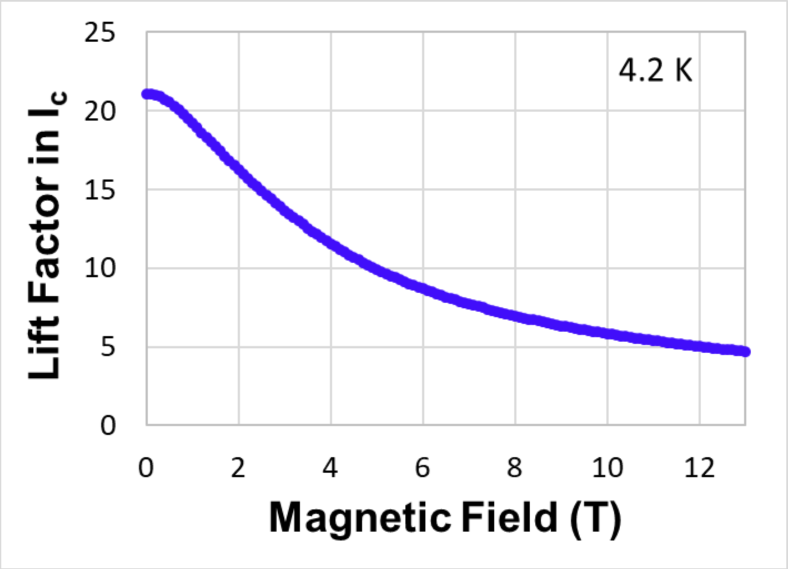
Department of Energy Announces CABLE Conductor Manufacturing Prize Winners

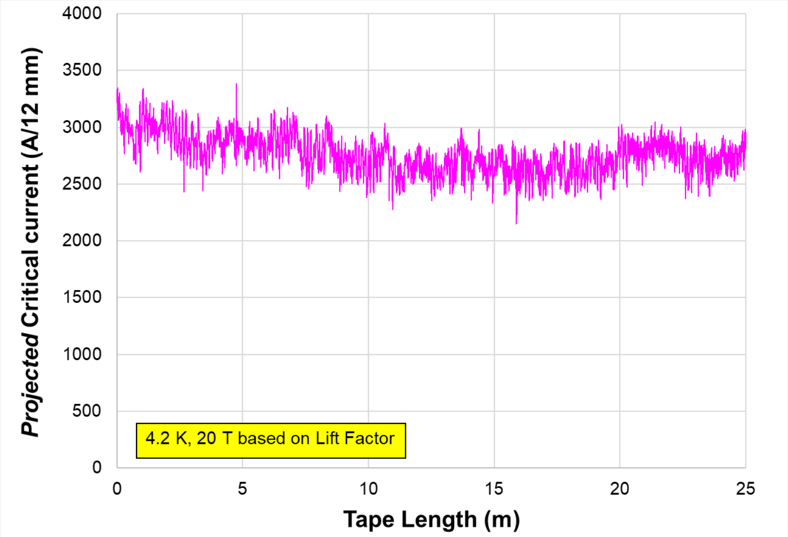
OCTOBER 8, 2021

https://www.energy.gov/eere/amo/conductivity-enhanced-materials-affordable-breakthrough-leapfrog-electric-and-thermal

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

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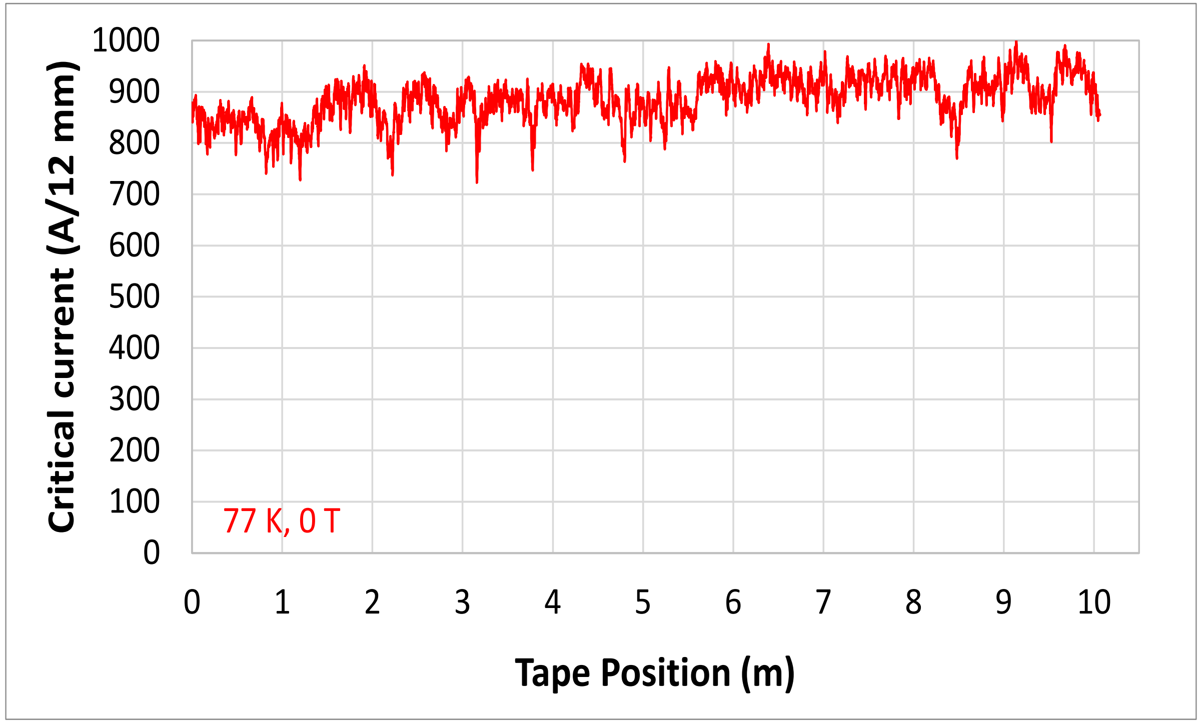
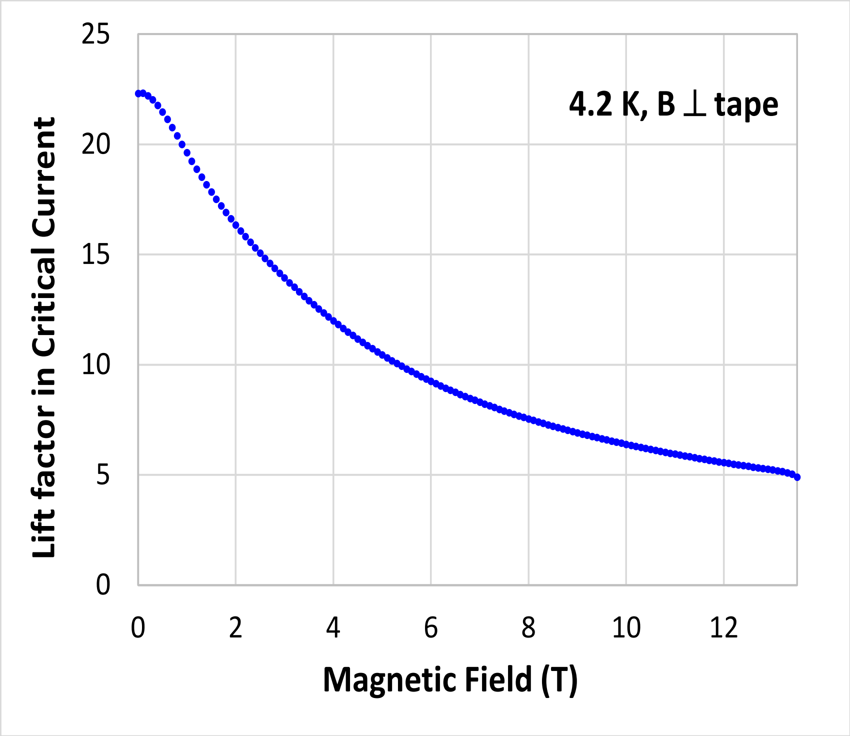
10 m long Advanced MOCVD tape made for STAR wires





- Average I_c = 886 A/12 mm at 77 K, 0 T over 10 m.
- Lift factor in I_c at 4.2 K, 13 T = 5.22 → lift factor in I_c at 4.2 K, 20 T ~ 3.88.
  (compares with ~2.15 for commercial REBCO tape)
- Expected I_c at 4.2 K, 20 T = 3437 A/12 mm (**3.55x I_c of commercial tape at 4.2 K, 20 T**).

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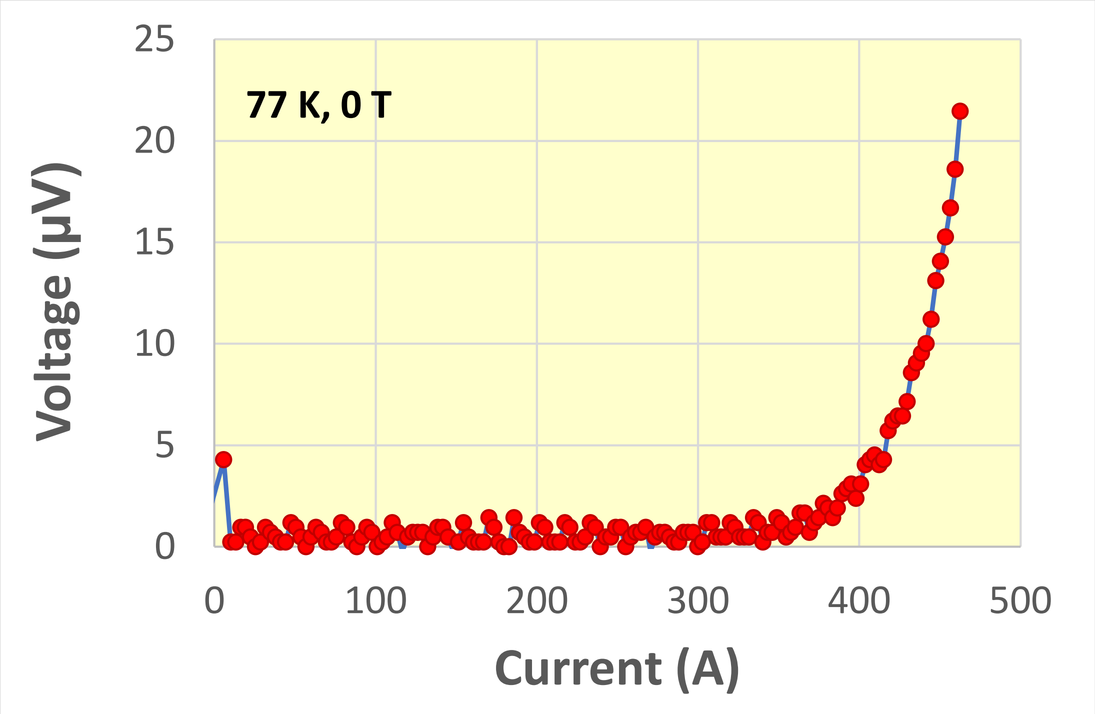
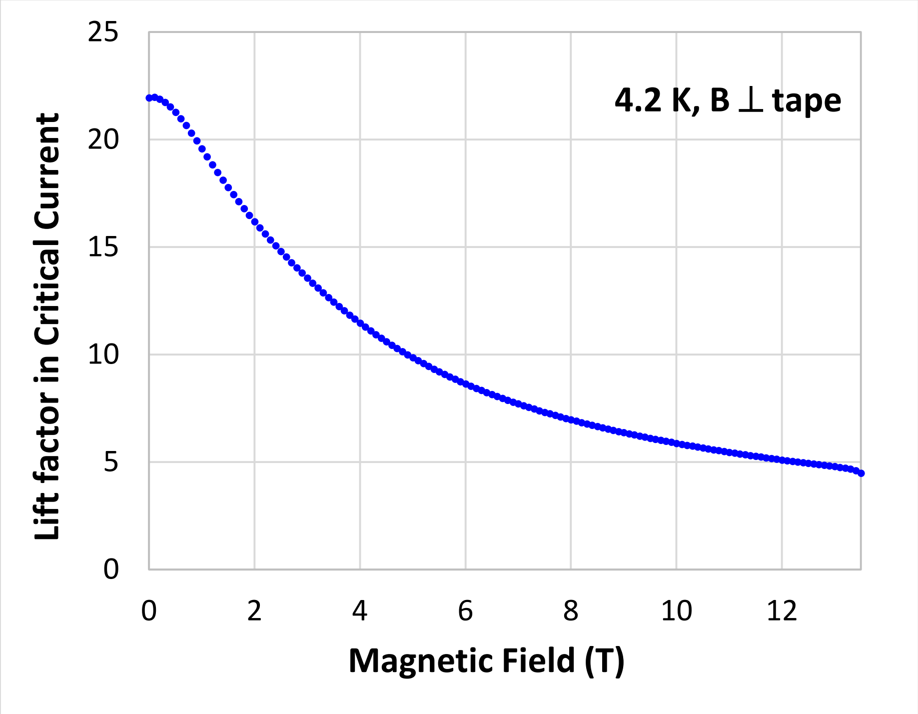
1.51 mm STAR wire with only 4 symmetric tape strands with high-performance Advanced MOCVD tape

- STAR wire I_c at 77 K, 0 T = 420 A

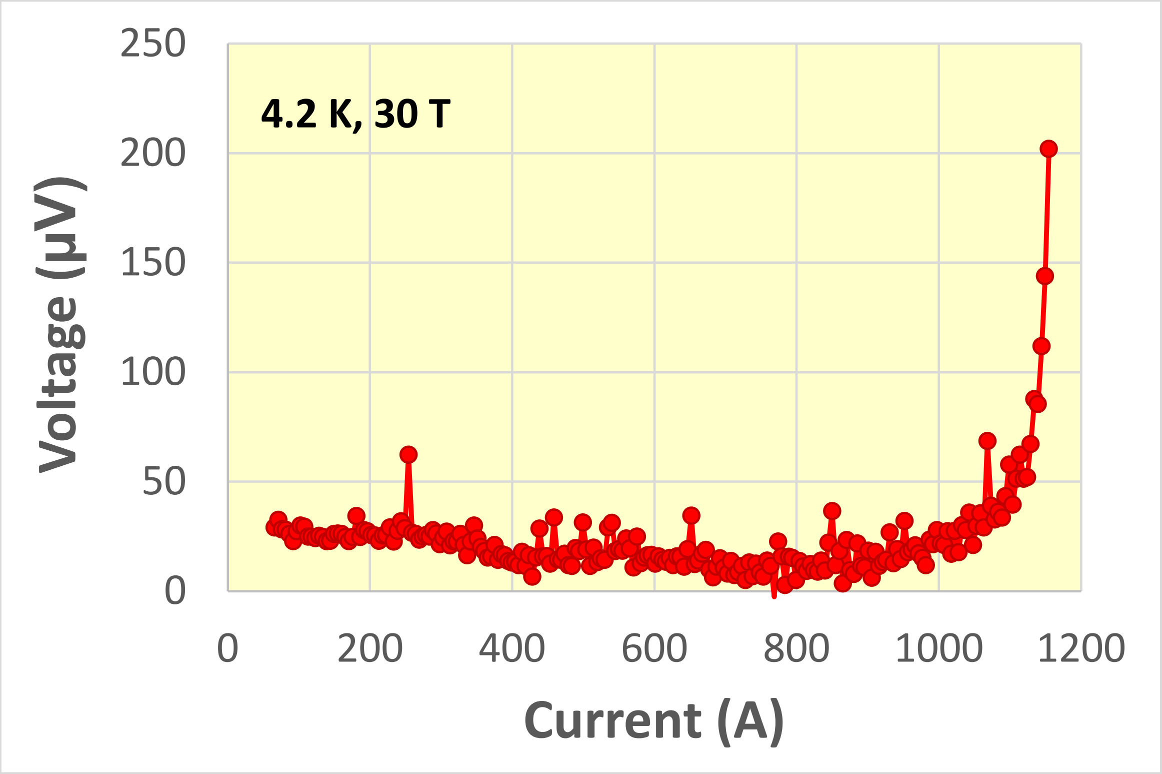
- Alpha value of tapes used in STAR wire = 0.759
- Lift factor in I_c expected at 4.2 K, 30 T ~ 2.55
- Expected STAR wire I_c at 4.2 K, 30 T ~ 1,070 A





1.51 mm STAR wire with only 4 symmetric tape strands with high-performance Advanced MOCVD tape

- **STAR wire I_c measured at 4.2 K, 30 T = 1,070 A; J_e = 597 A/mm^2**



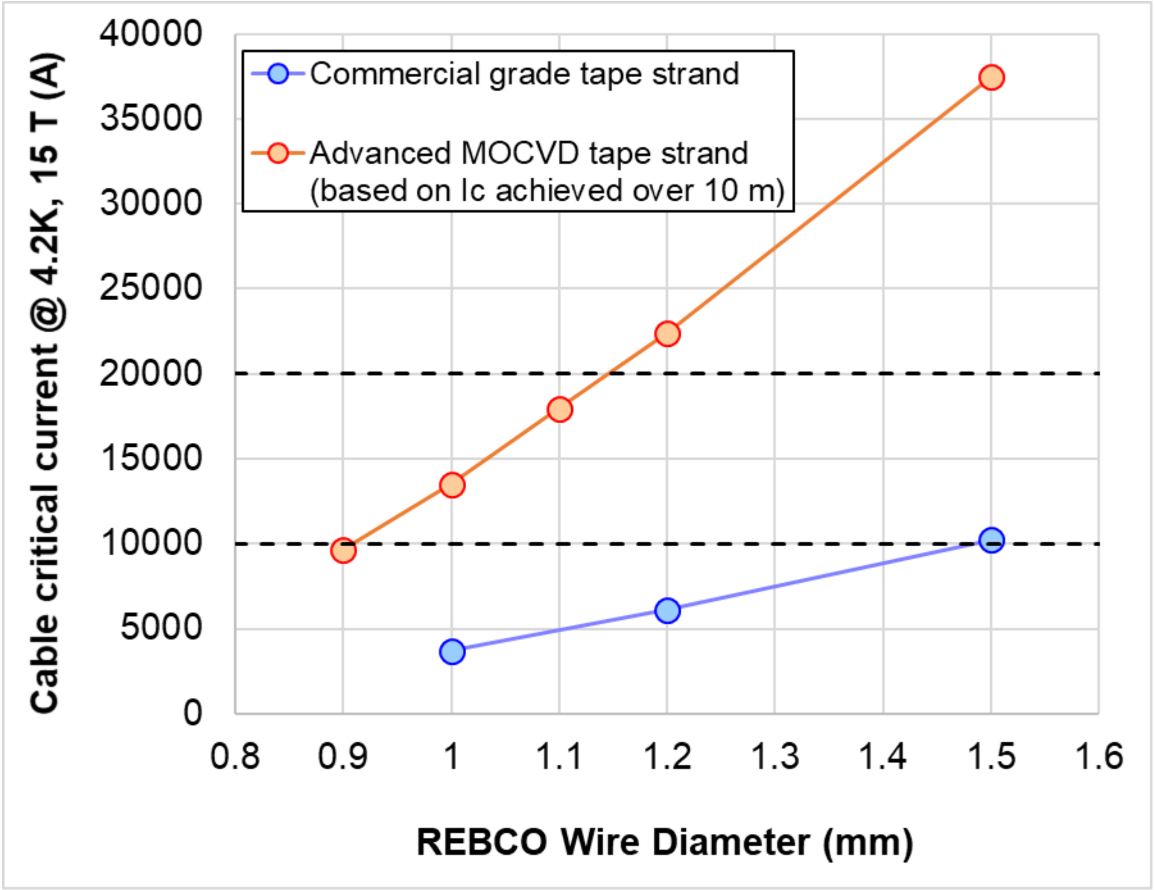
- **Measured I_c of STAR wire at 4.2 K, 30 T matches exactly the expected I_c based on lift factor in I_c of tapes used in STAR wire.**

Developing compact, multi-strand REBCO cables for accelerator magnets

- Substantial flexibility that enables compact coils with small bending radius.
- Twisted geometry that can reduce losses during ramping and perturbations of the magnetic field.
- Possible current sharing between wires.
- Fewer turns compared to a coil made with a single wire → reduces the required strand length as well as lowers magnet inductance → decreases voltages during magnet ramping and enables a faster discharge of current during quench.

Compact, multi-strand cable with STAR wires

6-around-1 cable†



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

Each wire made with symmetric REBCO tapes on 0.6 mm former.

† Figure courtesy of Xiaorong Wang, LBNL

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Status and prospects of STAR wires

- 1.5 – 2.5 mm diameter STAR wires with bend radius capability of 15 mm available now in 50+ m lengths.
- 2 mm diameter STAR wire available now with I_c @ 4.2 K, 20 T ~ 1,700 A (J_e ~ 540 A/mm^2)
- 5 mm diameter, 6-around-1 cable expected with I_c = 10kA @ 4.2 K, 15 T
- Using only 4 Advanced MOCVD tape strands,
  I_c of 1.5 mm STAR wire 4.2 K, 30 T = 1,070 A
- Using Advanced MOCVD tape strands,
  3x less tape strands → 2.8x cost reduction.
  With throughput increase → 5x overall cost reduction.
- Using Advanced MOCVD tape strands,
  2 - 3 mm diameter, 6-around-1 cable expected with I_c = 10 – 20 kA @ 4.2 K, 15 T