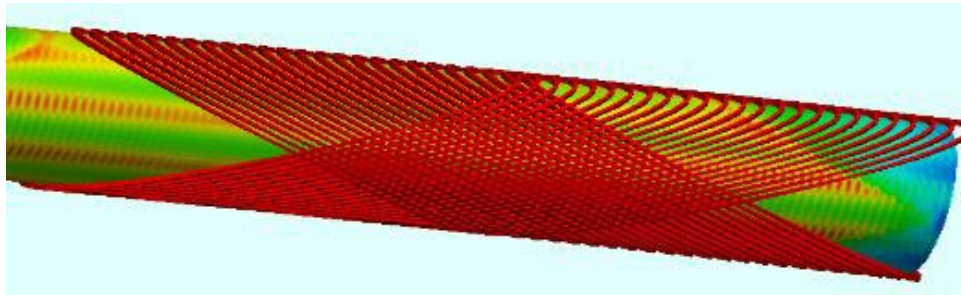


STAR® Wires and REBCO Tapes for Magnet Applications

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

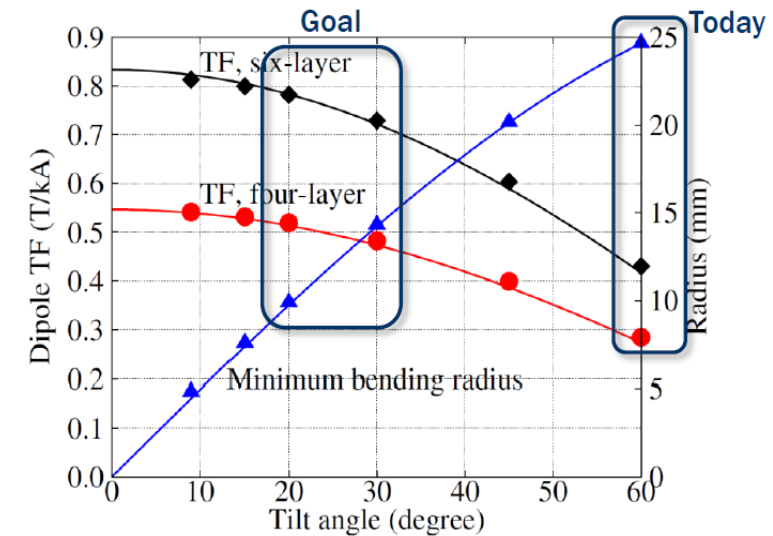
Canted Cosine Theta (CCT) coil



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).

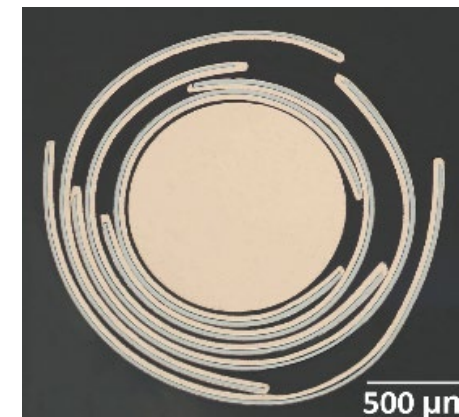
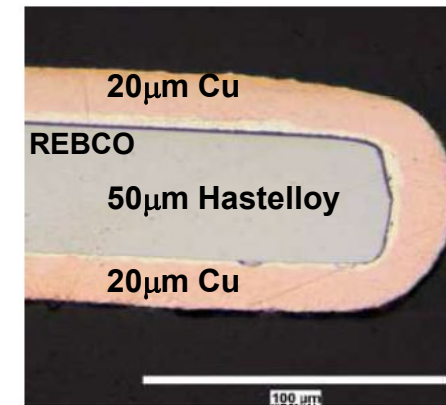
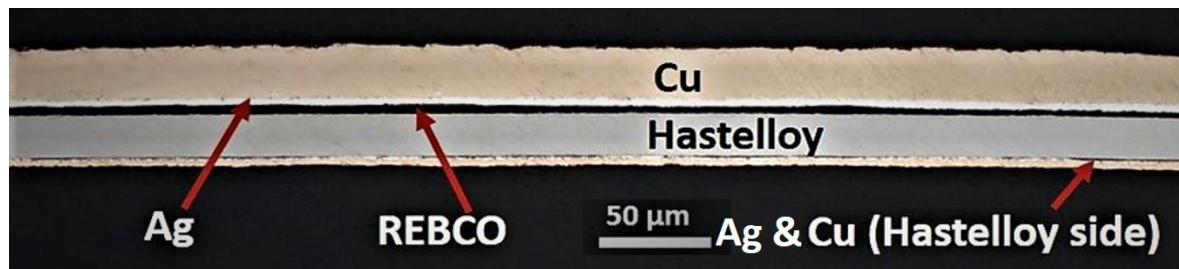
Symmetric Tape Round (STAR®) REBCO wire to achieve 15 mm bend radius

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.



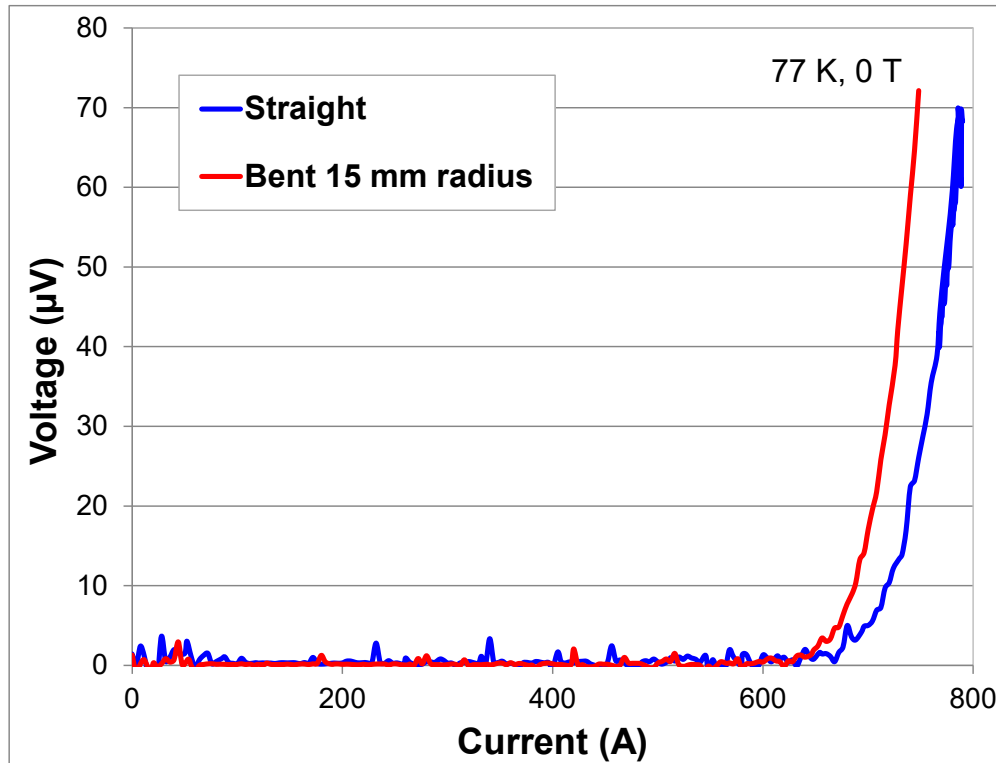
Symmetric REBCO tapes used to make round REBCO wires on 0.6 – 0.8 mm diameter copper former

IEEE Trans. Appl. Supercond. 27, 6603204 (2017),

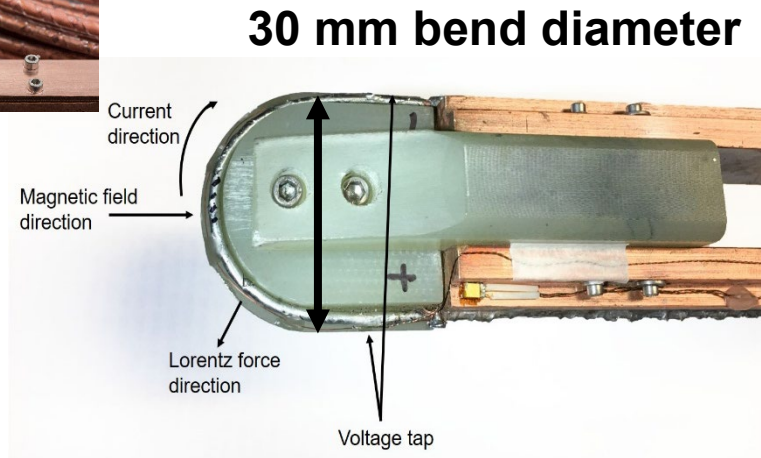
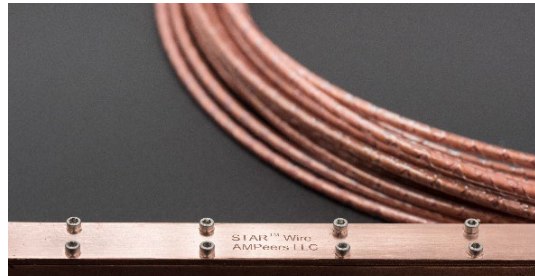
IEEE Trans. Appl. Supercond. 27, 6602705 (2017), *Supercond. Sci. Technol.* 3, 04LT01 (2018)

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

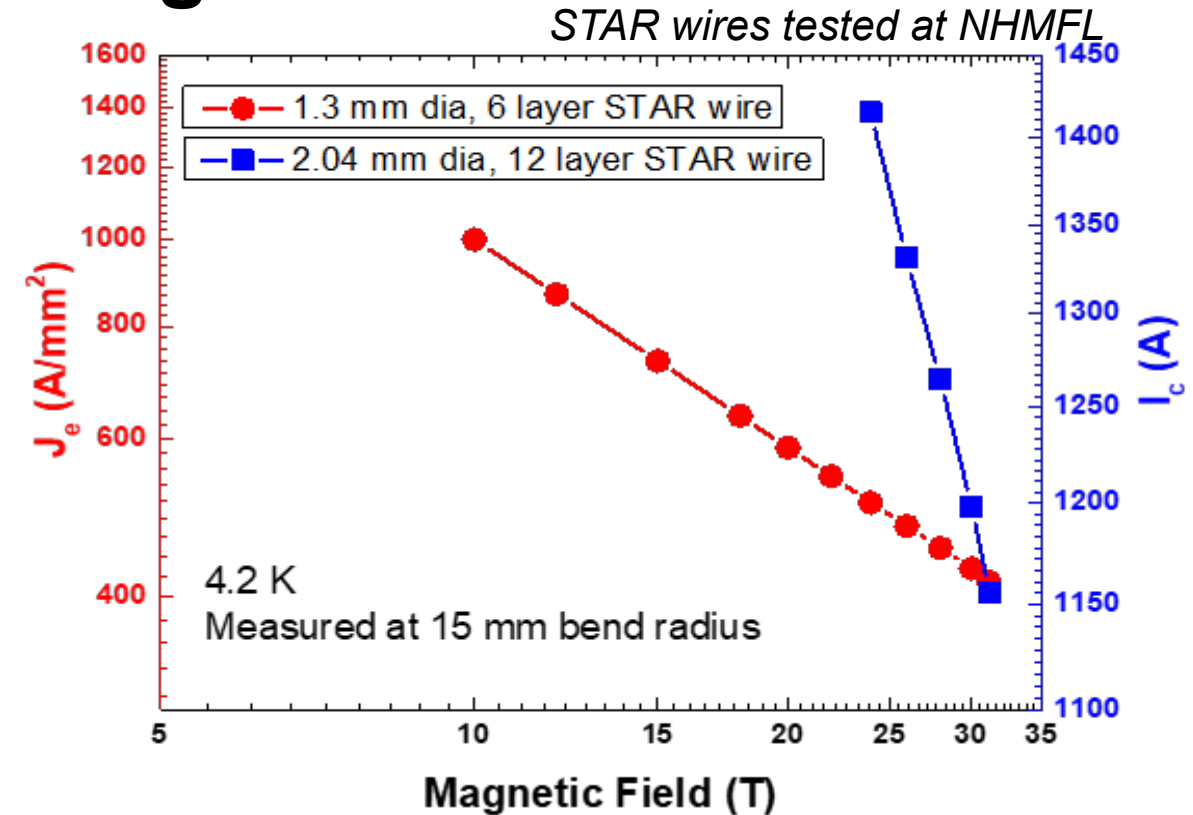
- 2.29 mm diameter STAR® wire on 0.81 mm former (11 symmetric tape strands)
- I_c in straight form = 728 A at 77 K, self-field
- I_c when bent to 15 mm radius = 690 A (**95% retention**)



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

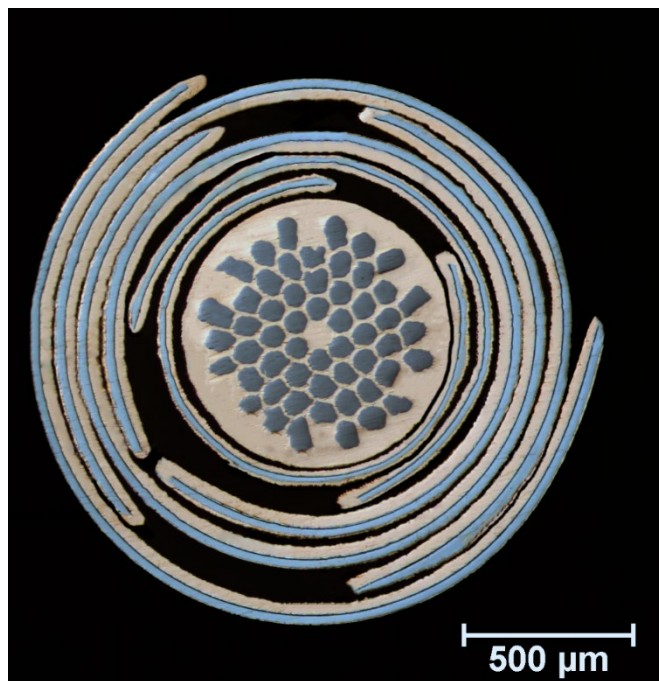


1.67 mm diameter STAR wire bent to a radius of 15 mm



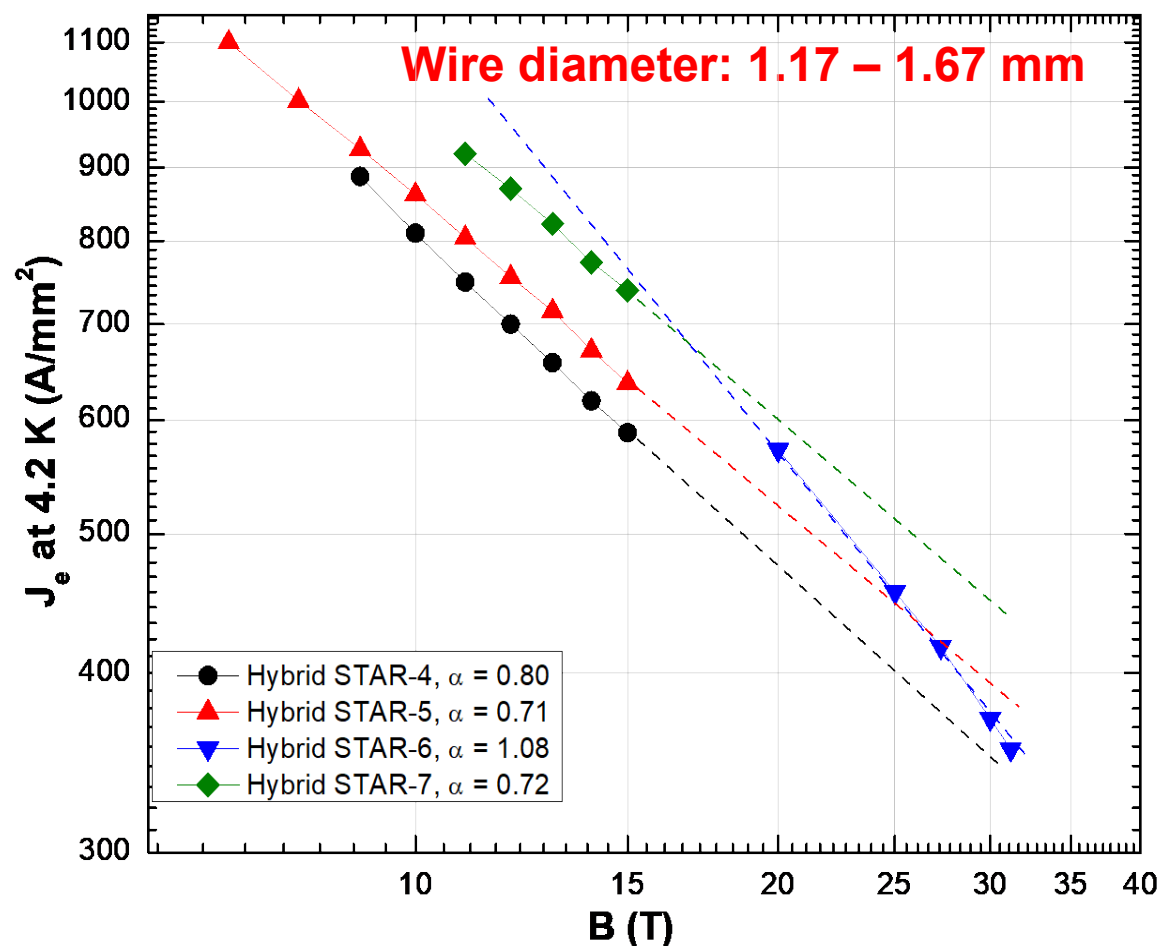
At a **bend radius of 15 mm**, using REBCO tapes with 1.7 μ m thick films,
 J_e of 1.3 mm diameter STAR wire : **729 A/mm² at 15 T** and **586 A/mm² at 20 T**
 I_c of 2 mm diameter STAR wire : **1400 A at 24 T**

Hybrid STAR[®] wire with superconducting Nb-Ti former



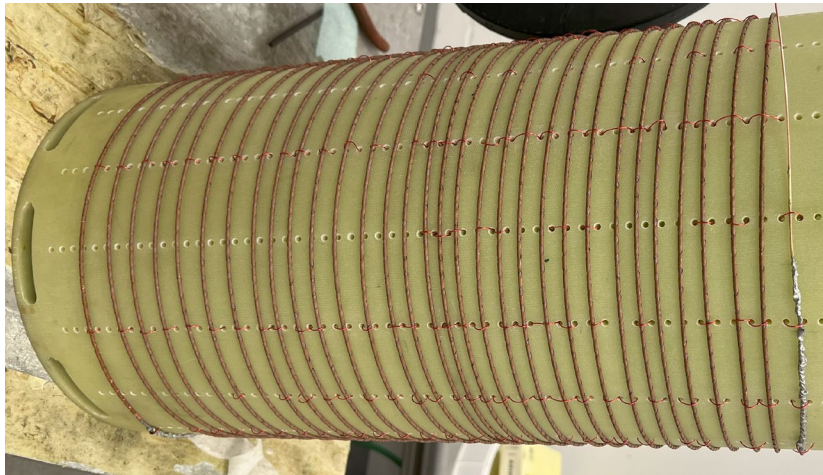
NbTi/Cu (*Luvata*) former
(NbTi:Cu = 1:1.25)
54 filaments

NbTi $I_c > 700$ A at 4.2 K, 4T

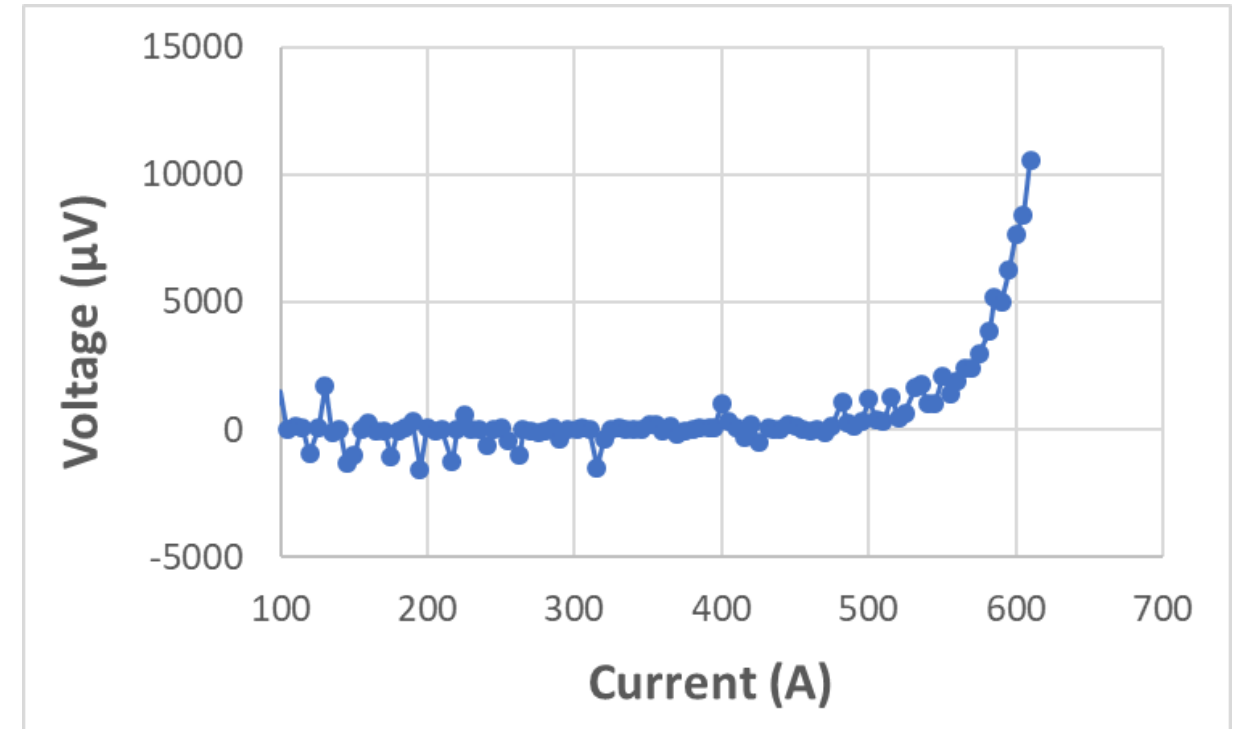


J_e at 4.2 K, 15 T = 739 A/mm²; projected J_e at 4.2 K, 20 T = 600 A/mm².

24 m long, 2.1 mm diameter STAR® wire end-to-end critical current of 575 A



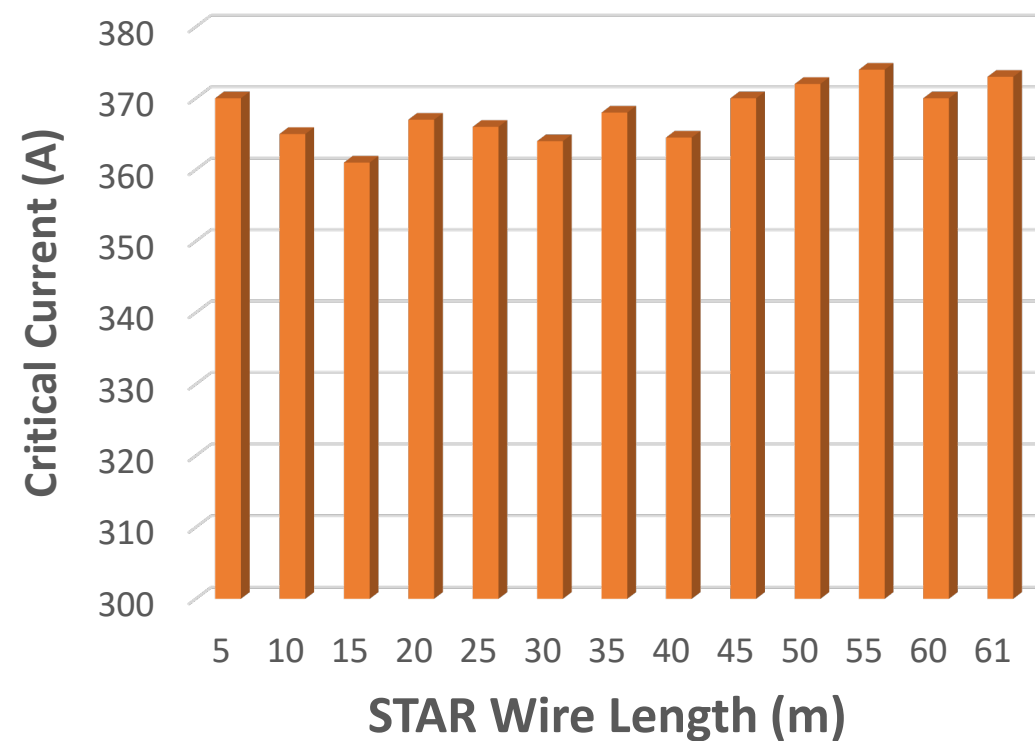
Metric	Value
Wire length	24.25 m
Wire diameter	2.1 mm
# Strands	8
Former diameter	1.024 mm
Critical current at 77 K, self-field	575 A
N-value	19



Scaled up STAR[®] wire to 61 m



1.84 mm diameter

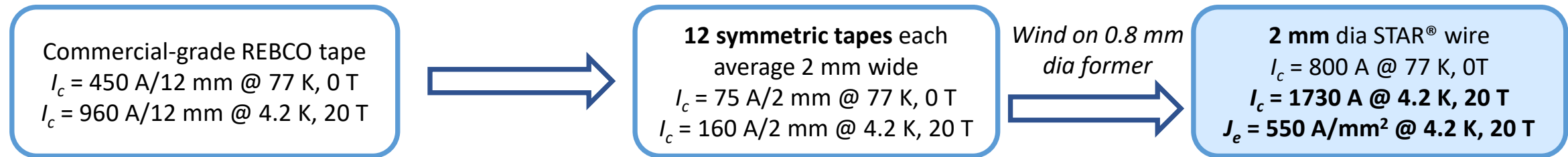


61 m STAR wire with $I_c \sim 368$ A @ 77 K

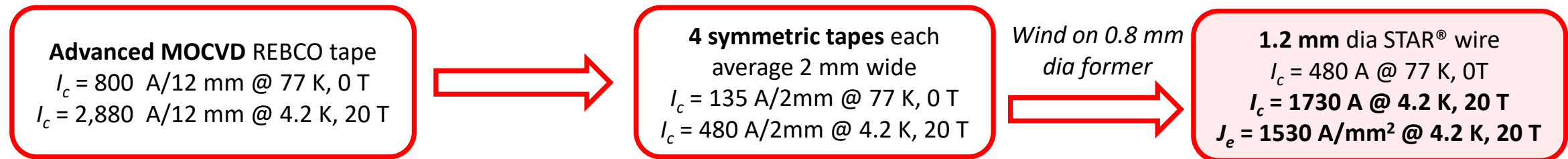
Reducing cost of STAR[®] wires

- Cost of individual tape strands is the major component of STAR[®] wire cost.
- Using 3x higher I_c tape \rightarrow 3x fewer tape strands \rightarrow >2.8x lower cost

STAR[®] wires now made with commercial-grade REBCO tapes:

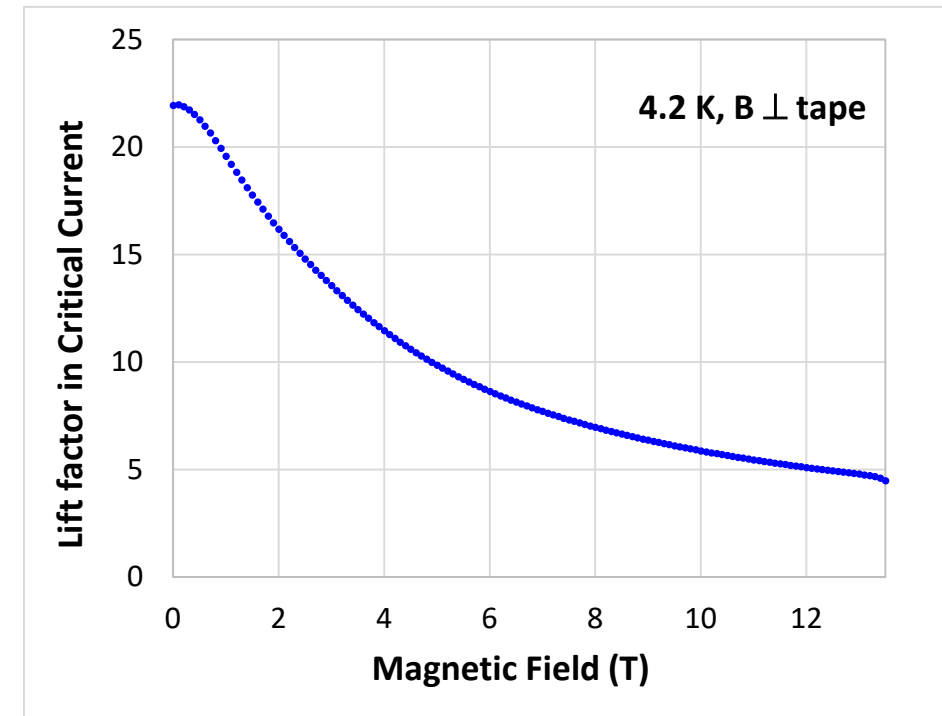
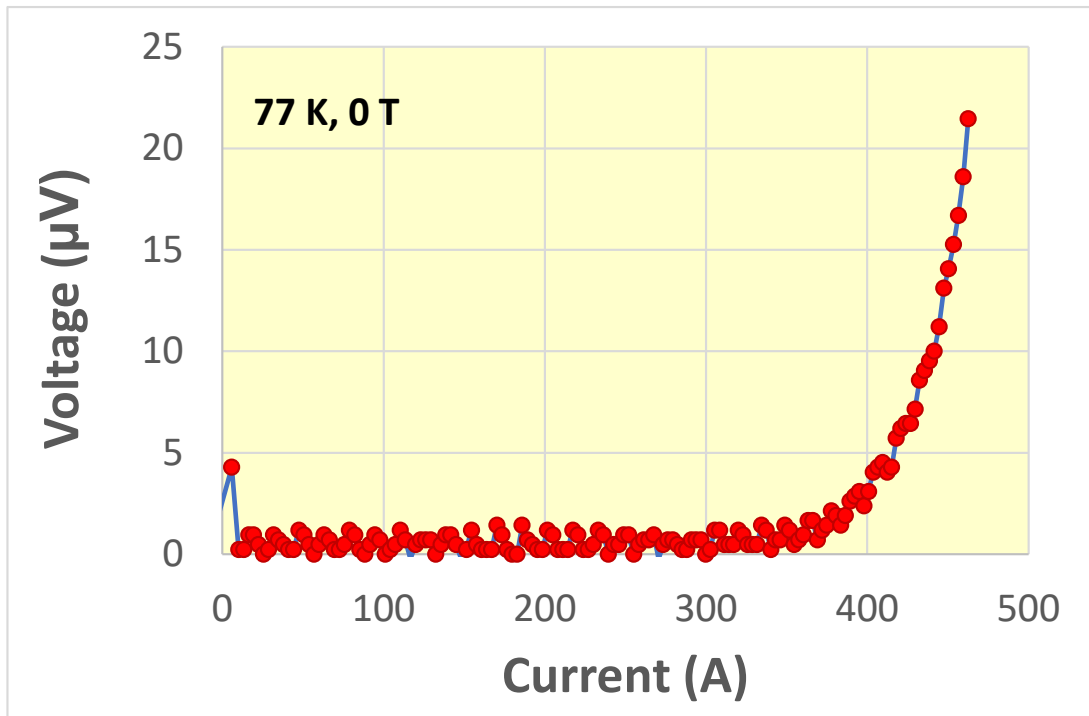


STAR[®] wires with Advanced MOCVD REBCO tapes:



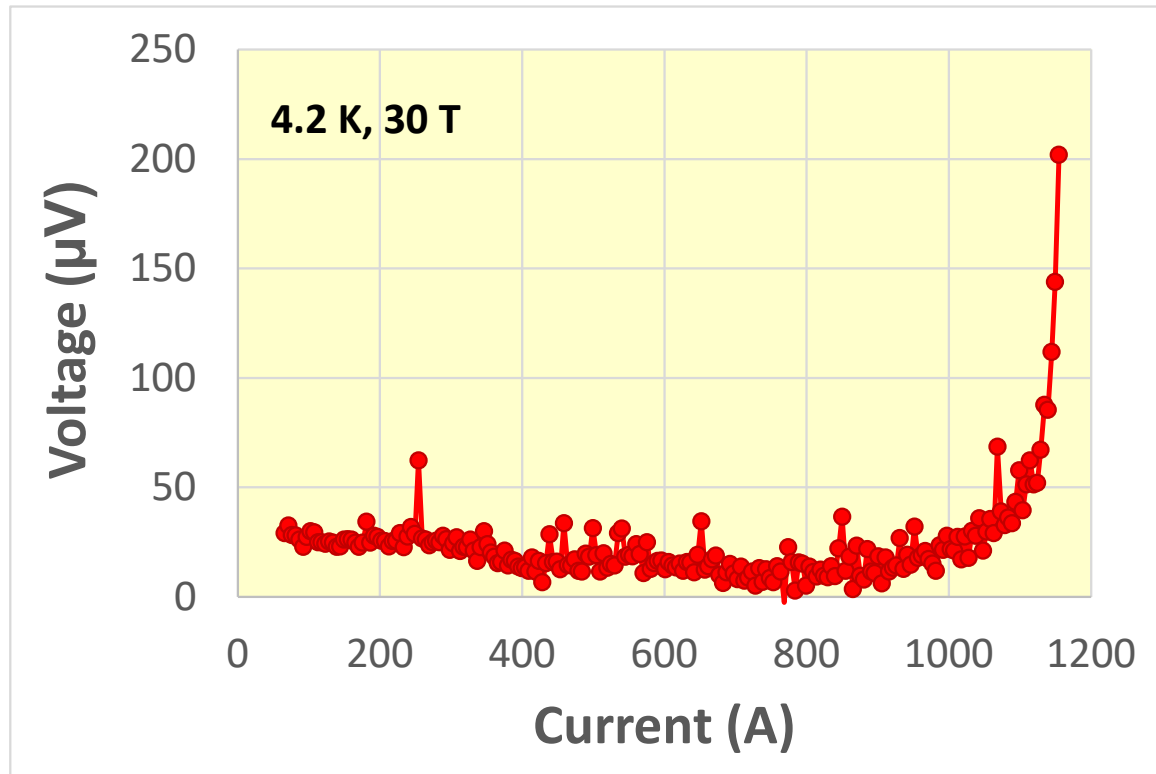
1.51 mm STAR[®] wire with only 4 symmetric tape strands with high-performance Advanced MOCVD tape

- 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;
 $J_e = 597 \text{ A/mm}^2$

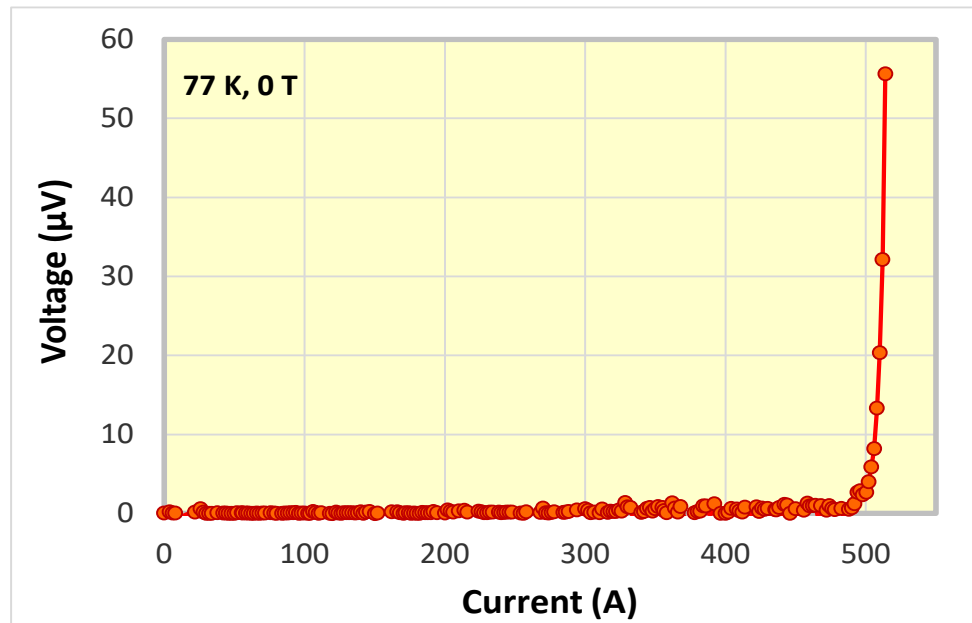


- Measured I_c of STAR[®] wire at 4.2 K, 30 T matches exactly the expected I_c based on lift factor in I_c of tapes used in STAR[®] wire.
- Lift factor in I_c of tapes used in STAR[®] wire at 4.2 K, 20 T = 3.46
- Expected I_c of STAR[®] wire at 4.2 K, 20 T = 1,455 A
- Expected J_e of STAR[®] wire at 4.2 K, 20 T = 812 A/mm²

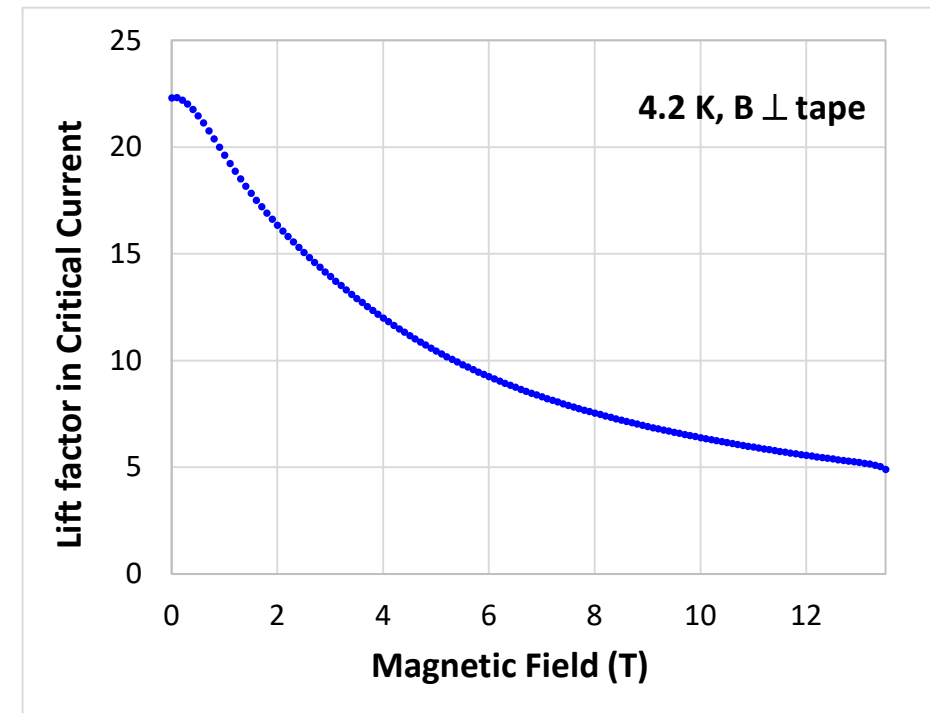
1.49 mm STAR wire with only 4 symmetric tape strands with high-performance Advanced MOCVD tape



- STAR wire I_c at 77 K, 0 T = 506 A

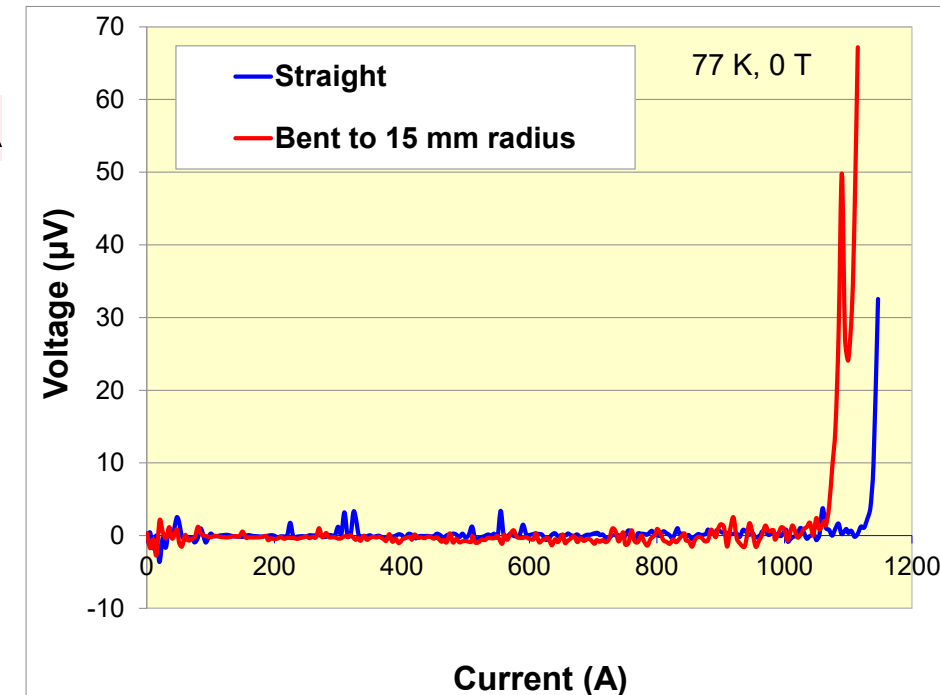
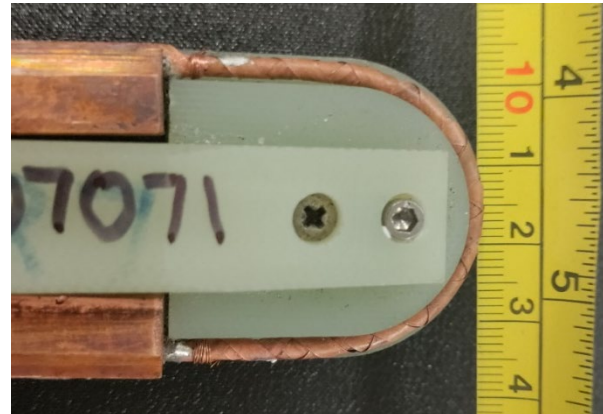
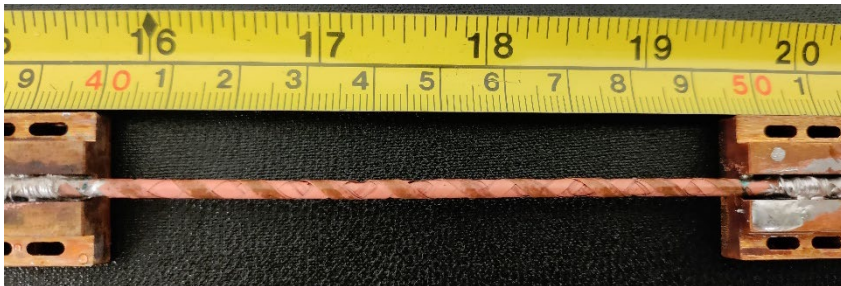


- Alpha value of tapes used in STAR wire = 0.716
- Lift factor in I_c at 4.2 K, 20 T ~ 3.88
- Expected STAR wire I_c at 4.2 K, 20 T $\sim 1,960$ A
- Expected J_e of wire at 4.2 K, 20 T = 1,126 A/mm²**



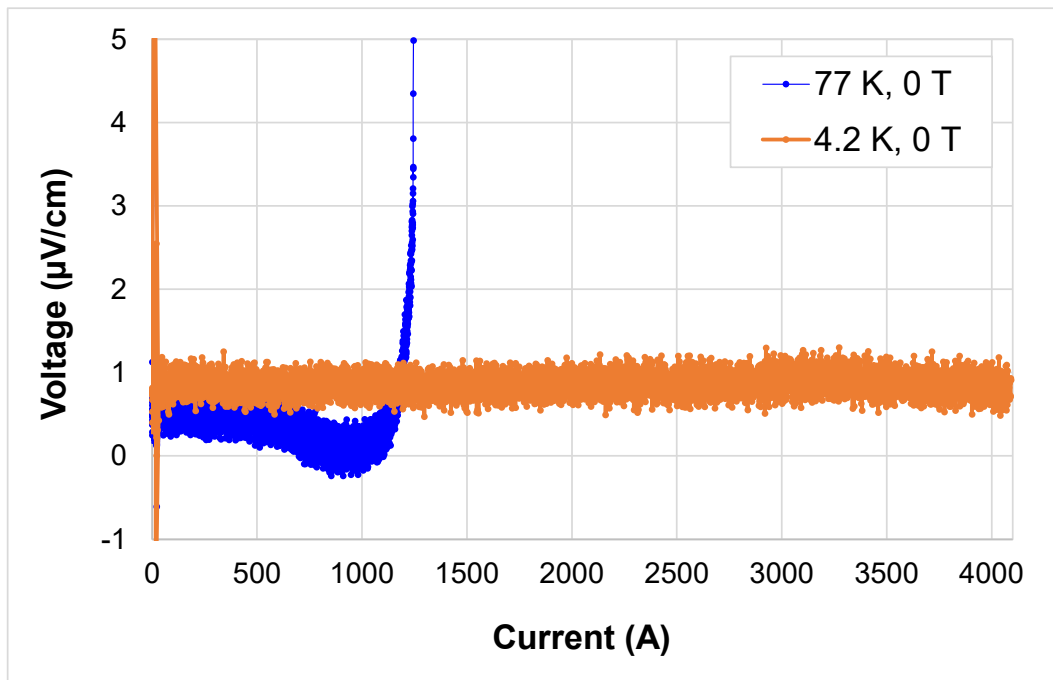
$J_e > 1,000 \text{ A/mm}^2$ at 4.2 K, 20 T with STAR[®] wires made with high I_c Advanced MOCVD REBCO tape strands

- 2.52 mm diameter STAR[®] wire on 0.81 mm former (12 symmetric tape strands)
- I_c in straight form = **1140 A** at 77 K, self-field
- I_c when bent to 15 mm radius = **1090 A** at 77 K, self-field (**95% retention**)
- Lift factor of tape used in wire = 4.72 at 4.2 K, 20 T
- Expected I_c of 2.52 mm STAR[®] wire at 4.2 K, 20 T = **5,140 A** (at 15 mm bend radius) $\rightarrow J_e = 1,030 \text{ A/mm}^2$

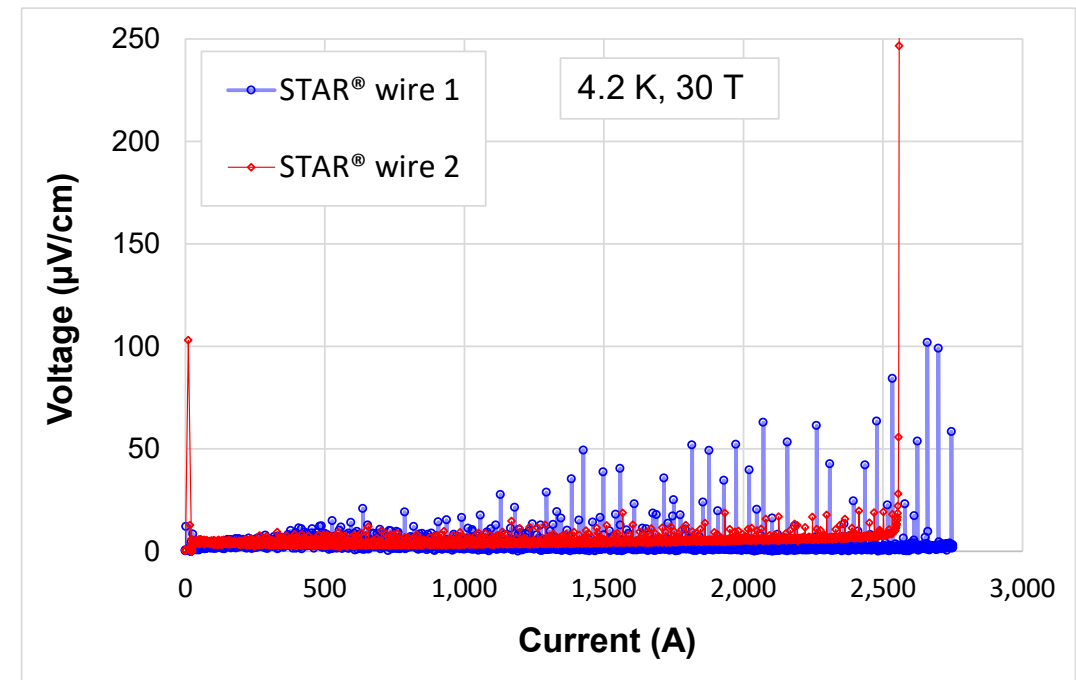


2.52 mm diameter STAR[®] wires made with high I_c Advanced MOCVD REBCO tape strands tested > 2.5 kA at 4.2 K, 30 T

- 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; $J_e > 500 \text{ A/mm}^2$ at 4.2 K, 30 T.



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

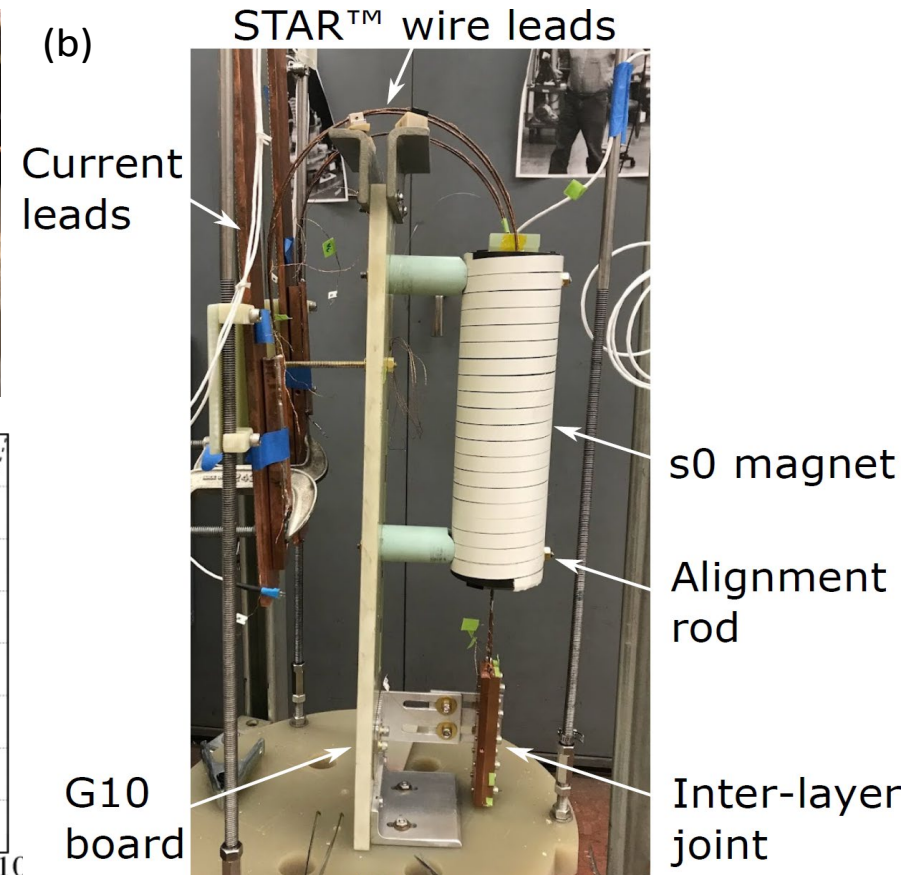
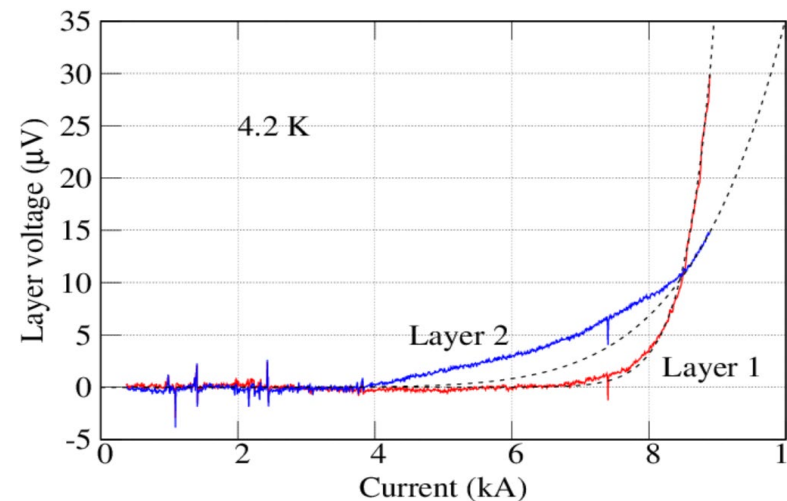
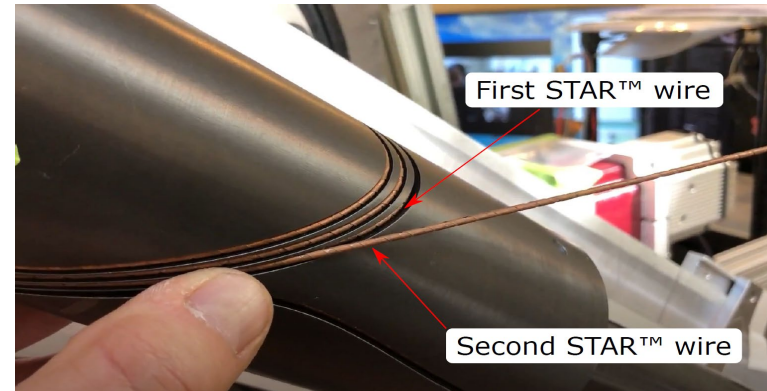


Measurement at CNRS, Grenoble

Applications of STAR[®] wires and STAR[®] cables in magnets

Subscale CCT magnet demonstrated at LBNL with 1.8 mm diameter STAR[®] wires

- Two layers and three turns in each layer.
- Minimum bending radius = 15 mm at the pole region of the magnet.

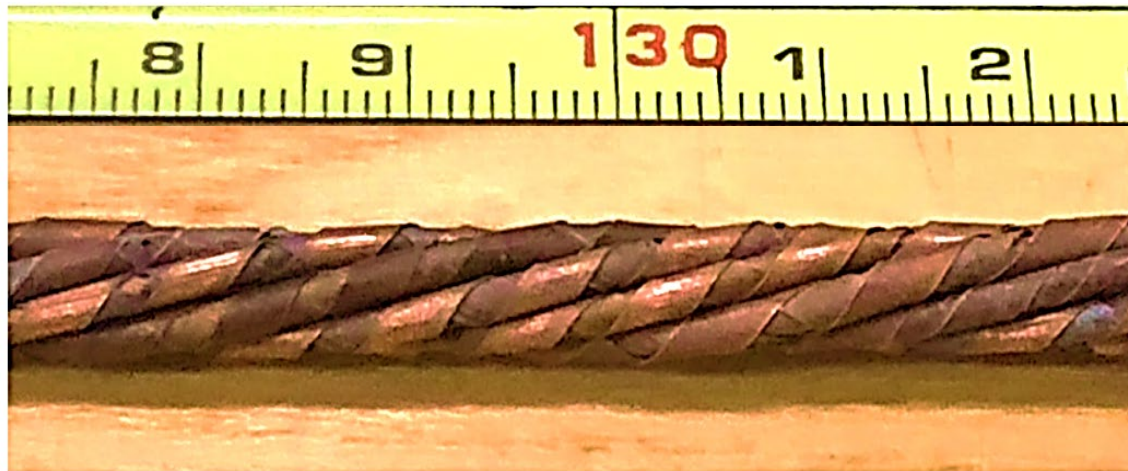


Magnet showed a maximum transport current of 8,500 A at 4.2 K, with no wire degradation after winding, even at the 15 mm bend radius.

Developing compact, multi-strand REBCO cables for accelerator magnets

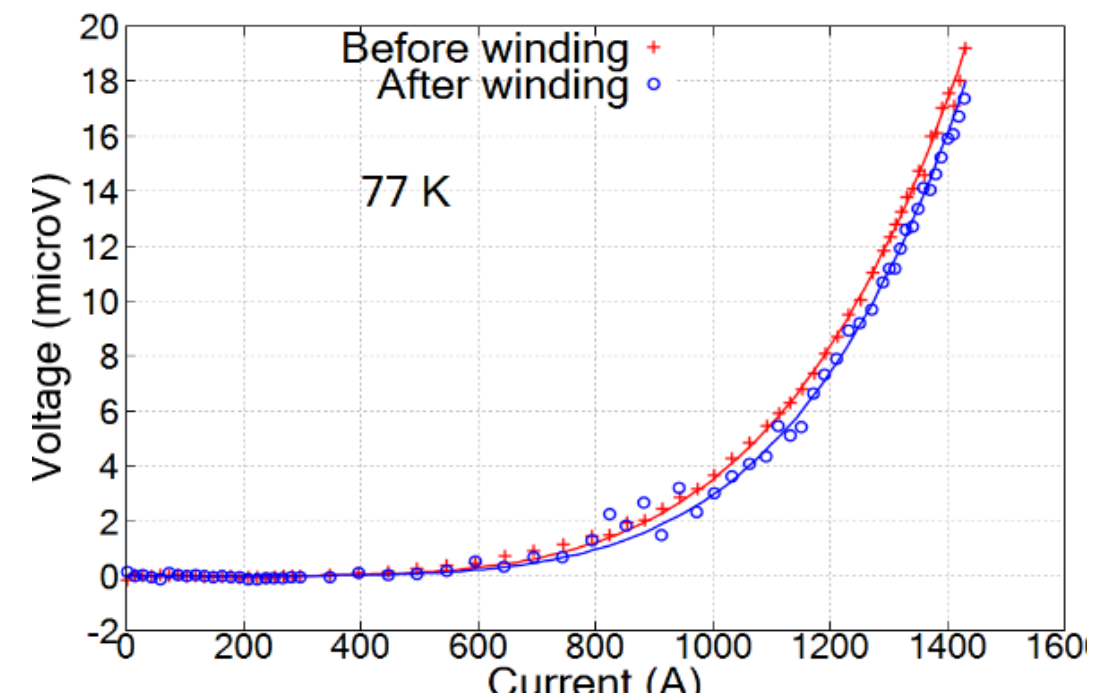
- Substantial flexibility that enables compact coils with small bending radius.
- Twisted geometry that can reduce losses during ramping and perturbations of the magnetic field.
- Possible current sharing between wires.
- Fewer turns compared to a coil made with a single wire → reduces the required strand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

2-m-long, 5.6 mm diameter 6-around-1 cable demonstrated by LBNL with 6 STAR[®] wires (1.8 ± 0.1 mm diameter)



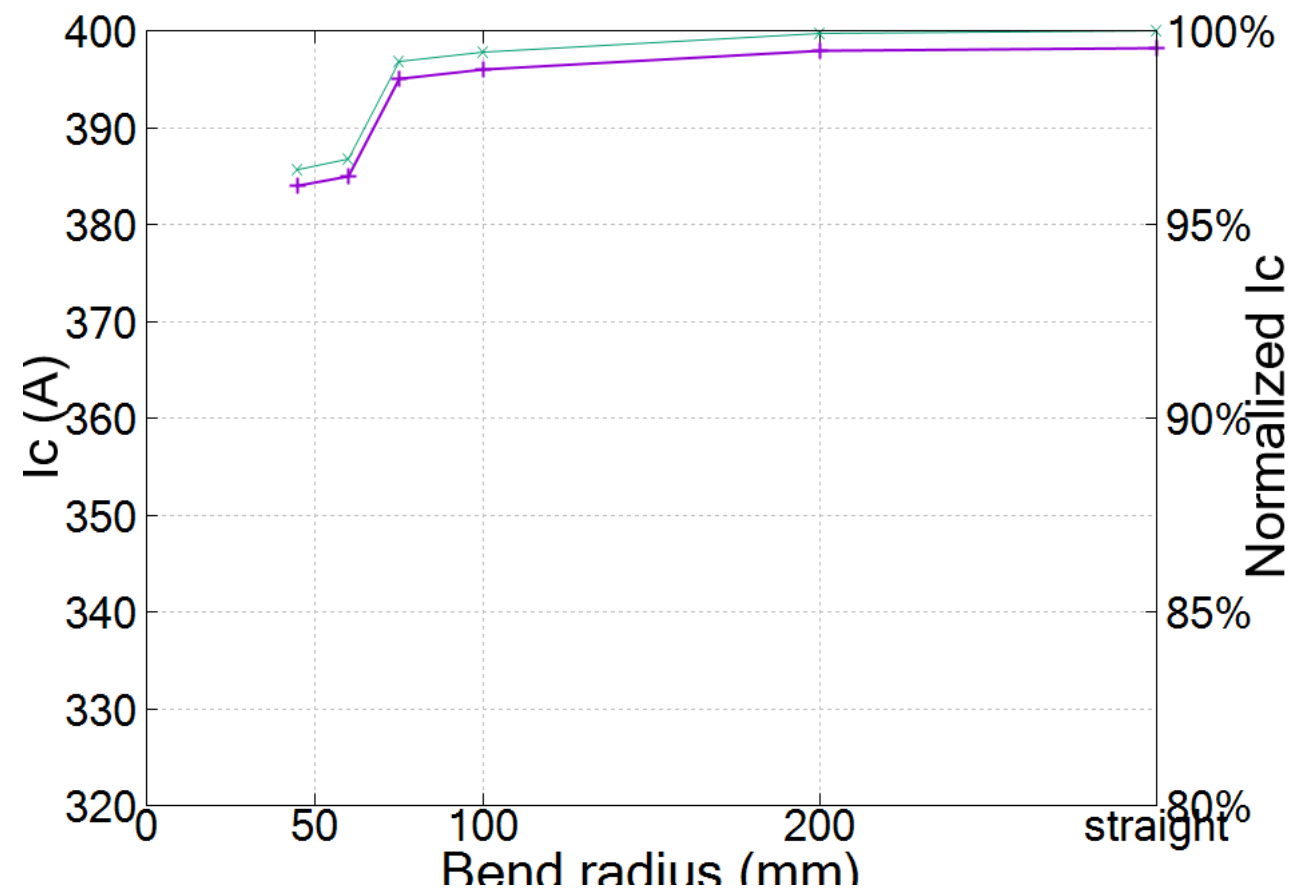
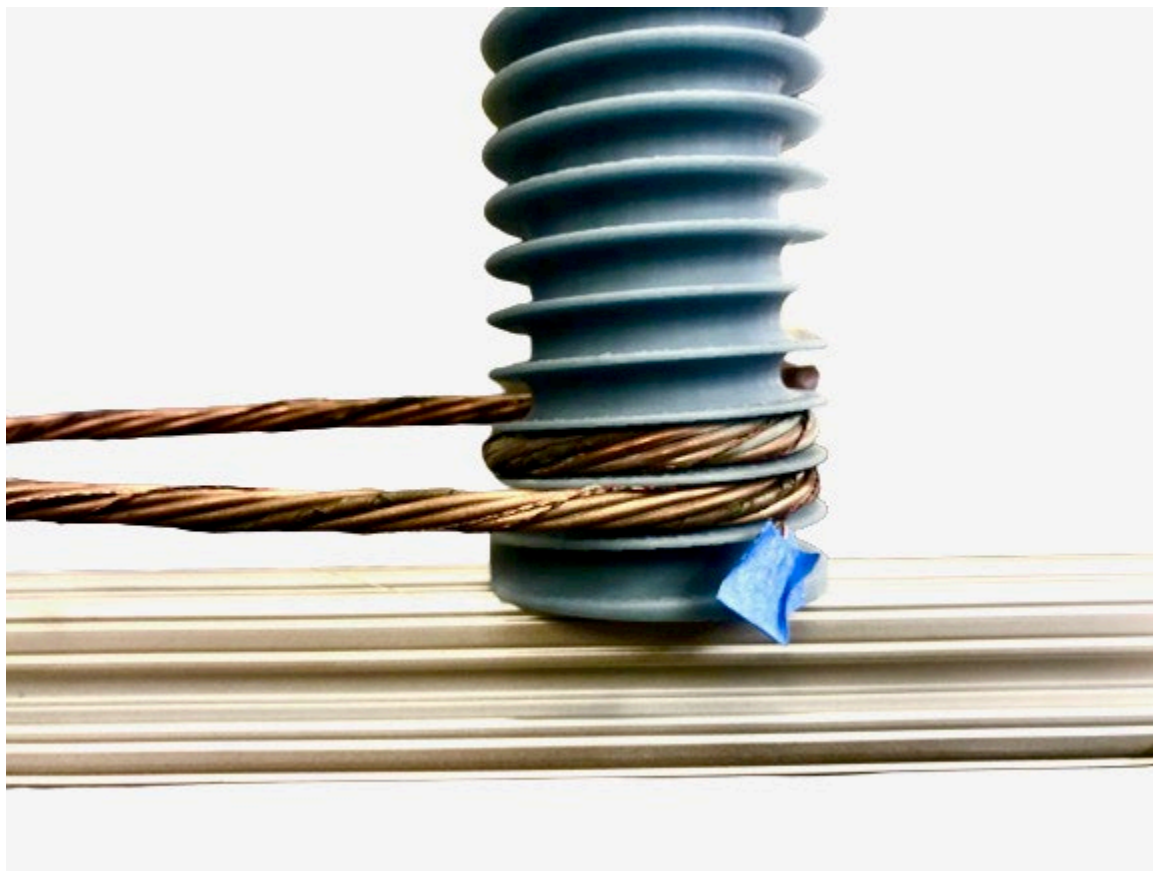
I_c of compact multi-strand STAR[®] cable = 1,444 A at 77 K, self-field
→ 80% of sum of I_c of individual STAR[®] wires

6-around-1 compact multi-strand STAR[®] cable wound into CCT magnet

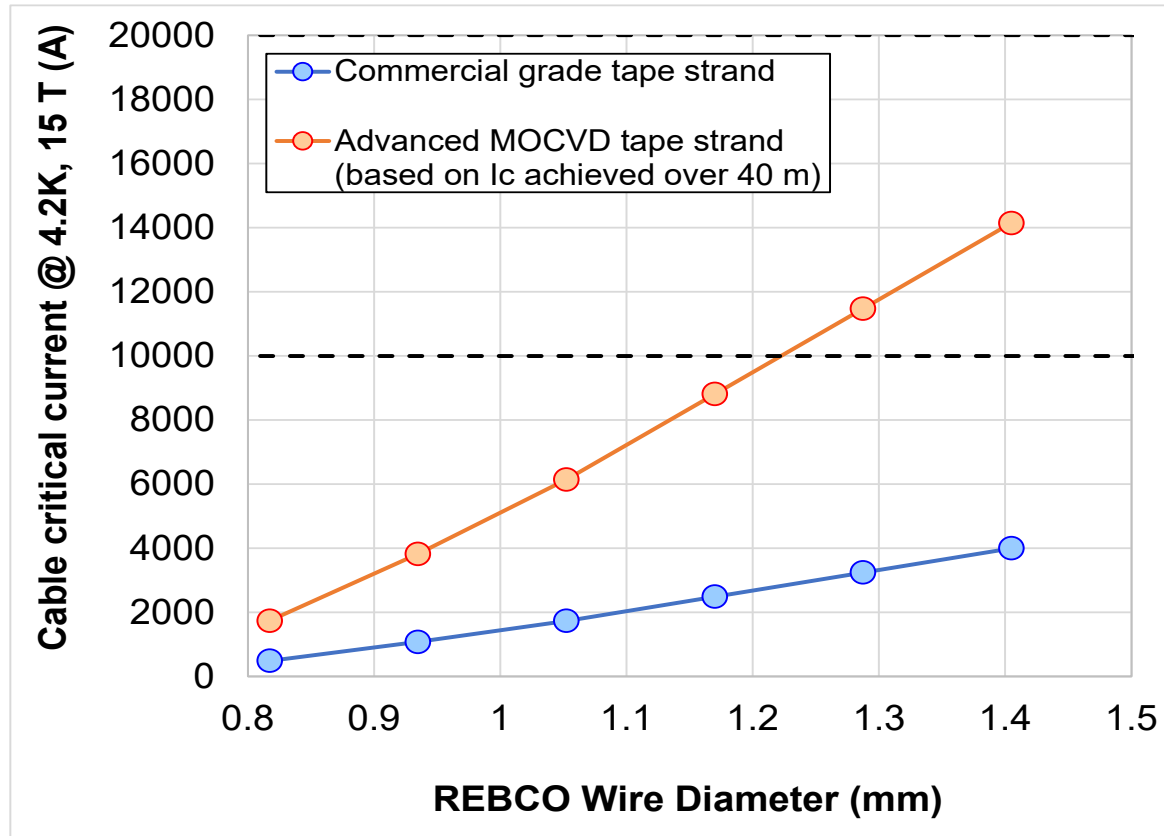


I_c of STAR[®] cable after winding = 1,462 A @ 77 K, self-field \rightarrow no degradation in I_c and n value after winding the cable into the CCT dipole magnet mandrel

6-around-1 compact multi-strand STAR[®] cable retains high critical current even at 45 mm bend radius



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



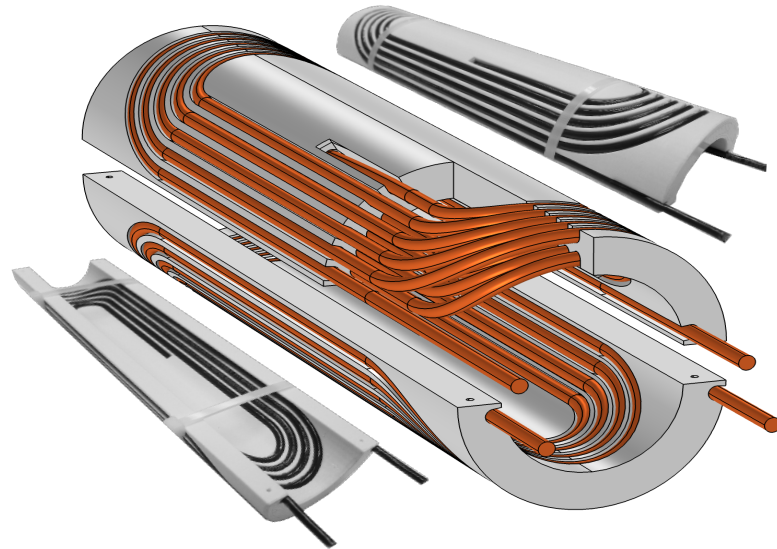
Expected I_c of 6-around-1 cable using six STAR wires.

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.

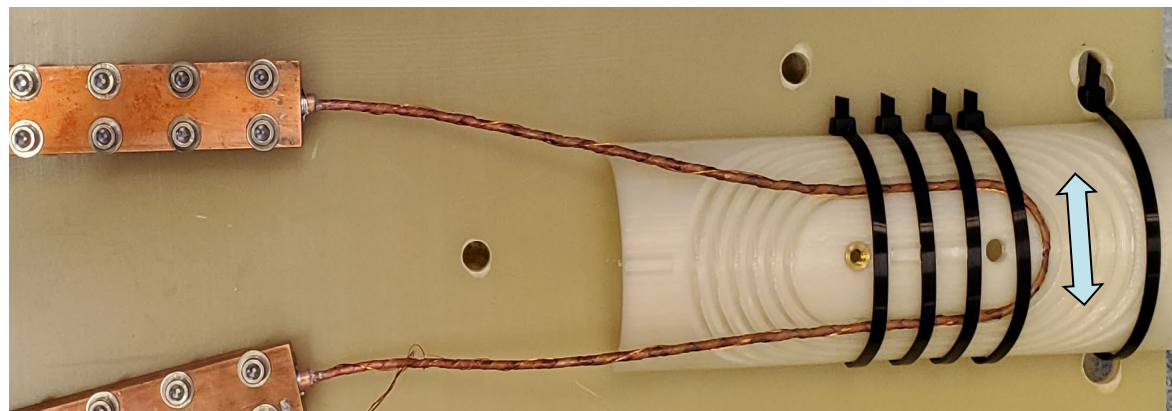
Conductor on Molded Barrel (COMB) magnet

- One solid structural part holds all the turns in two layers of the cable. This eliminates the disconnected pieces that must fit together with a high precision.
- Fewer parts → coil winding less labor intensive.
- No splice in between the layers – especially important for HTS.



Conductor should be bendable around poles with diameter of 25 – 30 mm with a minimal degradation of the critical current to fabricate dipole coil with 50-60 mm aperture, which is the optimum range for a future hadron collider.

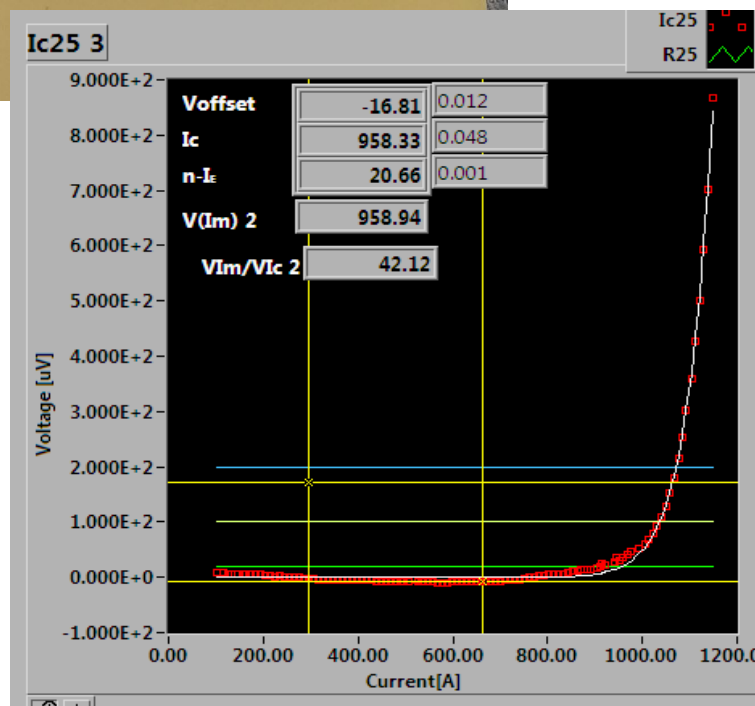
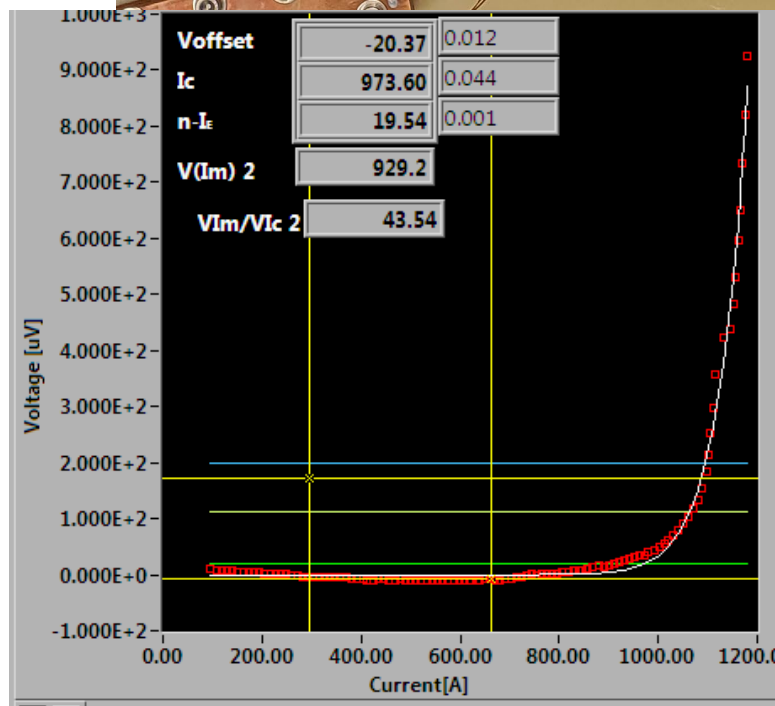
STAR® wire with high-current tape strands films wound on 33 mm diameter for COMB magnet with 98% I_c retention



STAR® wire made with 12 tape strands with 4-μm-thick films

33 mm bend diameter

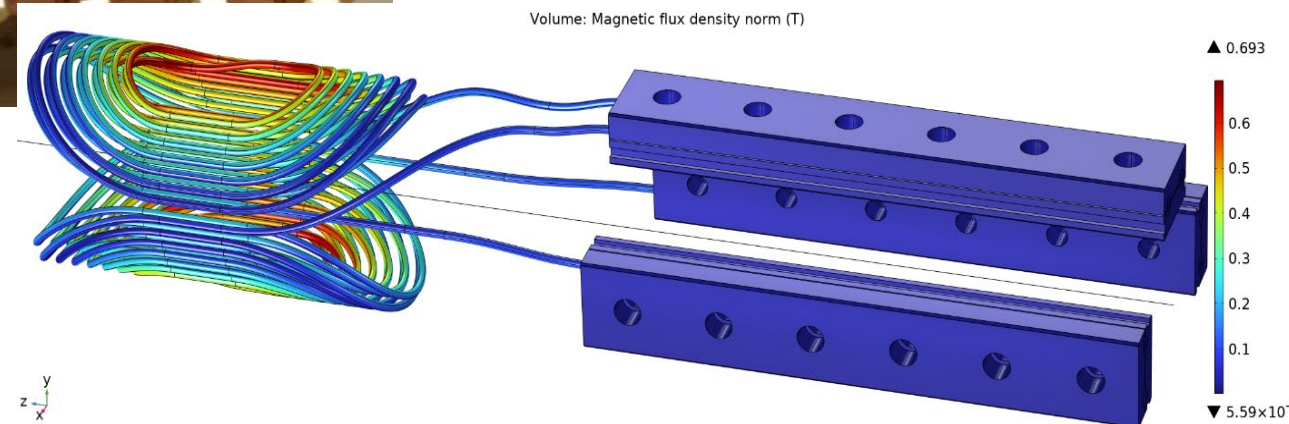
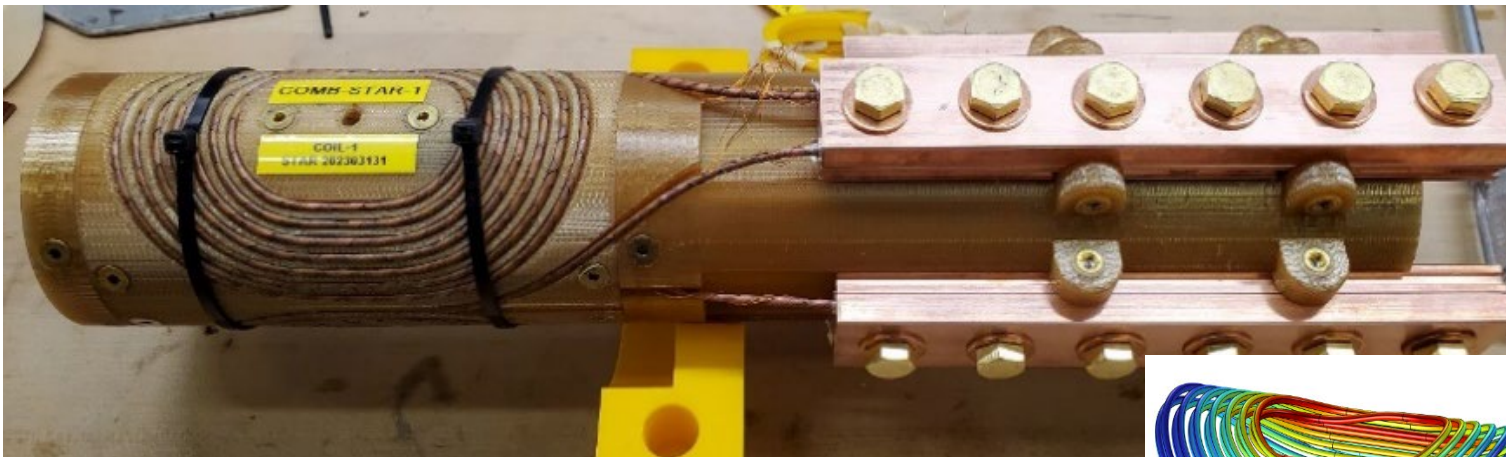
I_c of STAR® wire in straight form = 973 A at 77 K.



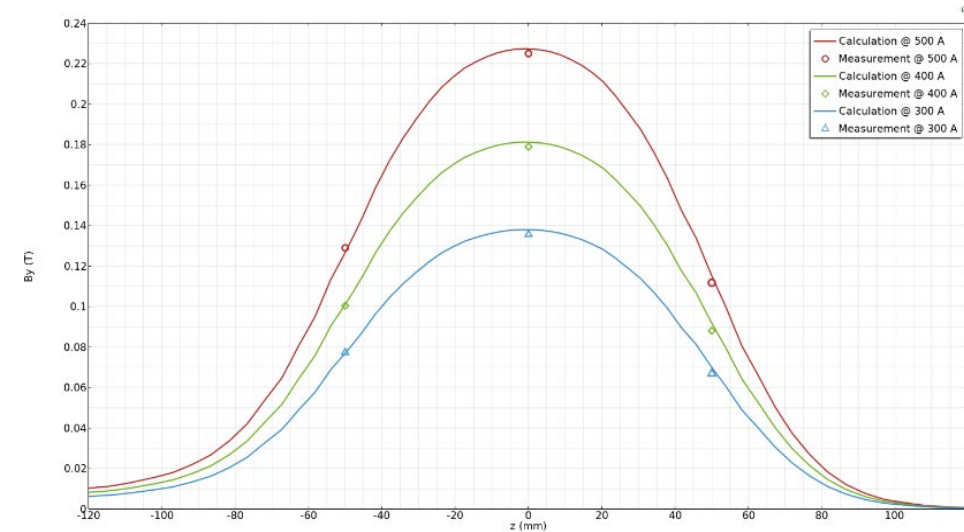
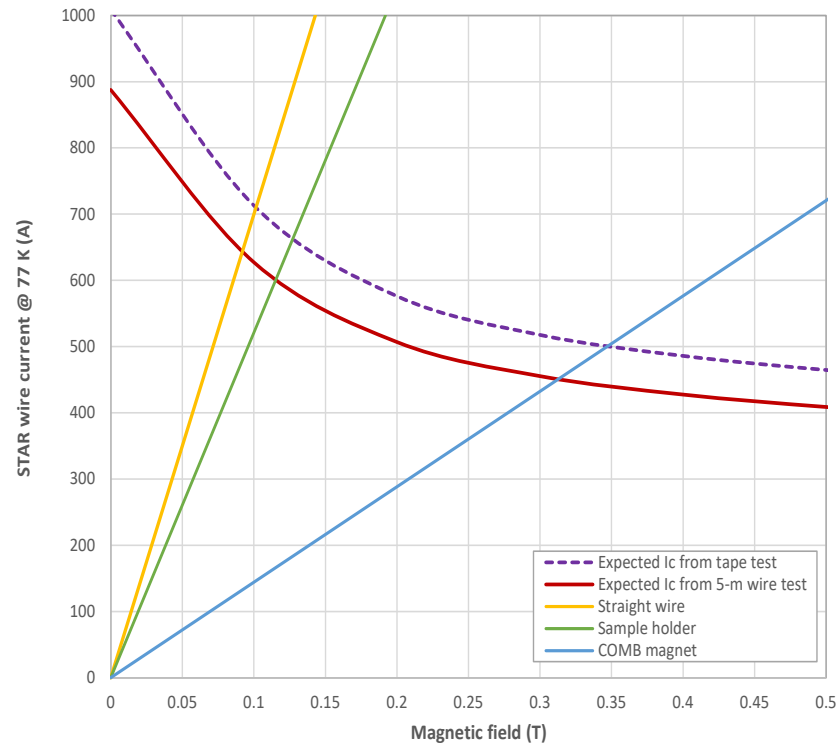
I_c of STAR® wire bent on COMB mandrel to 33 mm diameter = 958 A at 77 K.

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.



STAR® wire with high current tape strands retains 94 – 99% of I_c in COMB magnet with 33 mm bend diameter

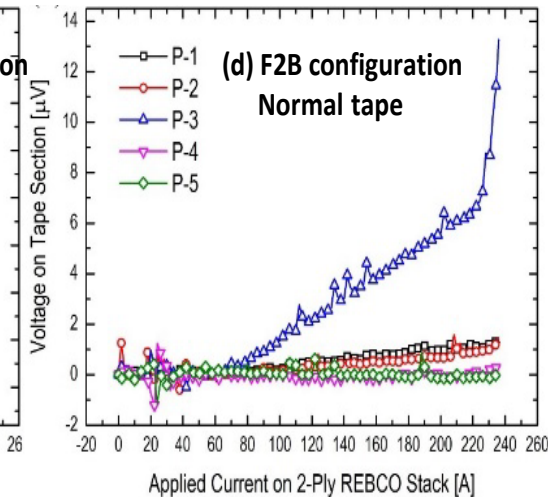
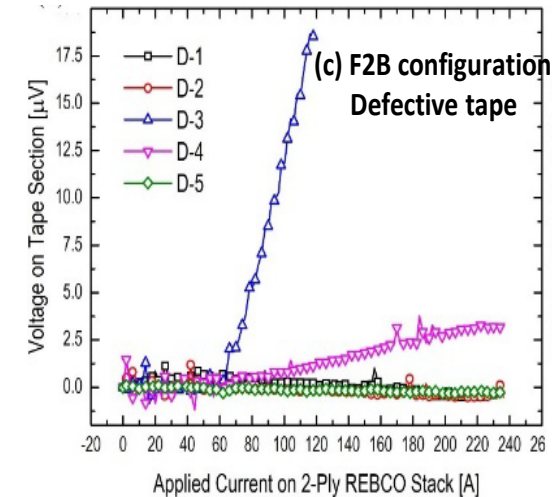
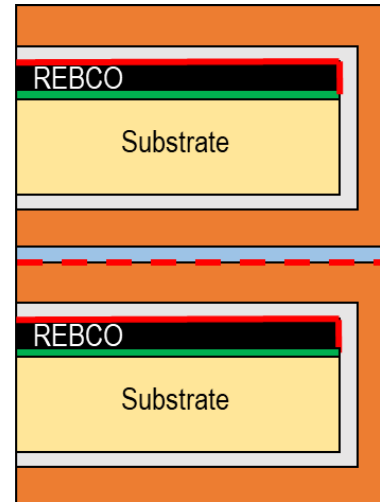
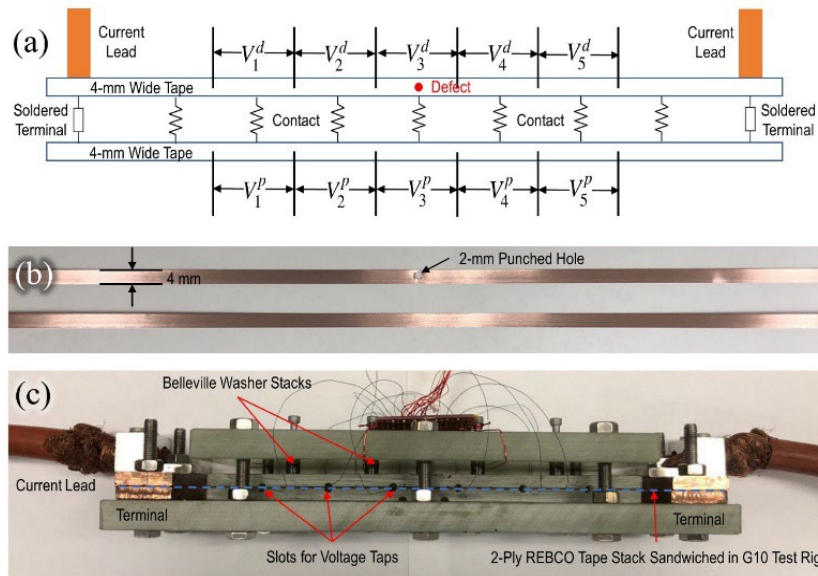


77 K, self field tests	STAR® wire # 131	STAR® wire # 151
Standalone STAR® wire I_c (A)	594.6	606.3
Expected COMB magnet I_c (A)	446	450
STAR® wire in COMB magnet I_c (A)	442.9	421.6
I_c retention of STAR® wire in COMB magnet	99%	94%

Defect-Tolerant High-Temperature Superconductor for Coil Applications

Defect-tolerant REBCO tape architectures

- Our concept is based on reducing contact resistivity to improve current sharing between tapes.



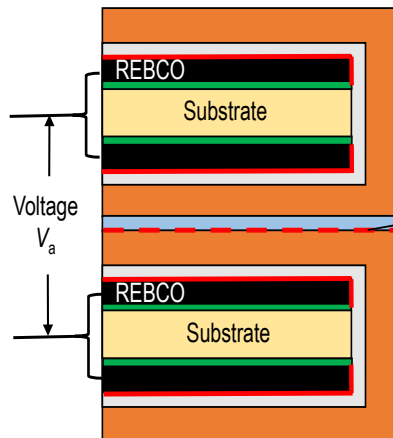
Experiment to test current sharing

- Superconducting devices consist of tapes layered in a face-to-back (F2B) arrangement.

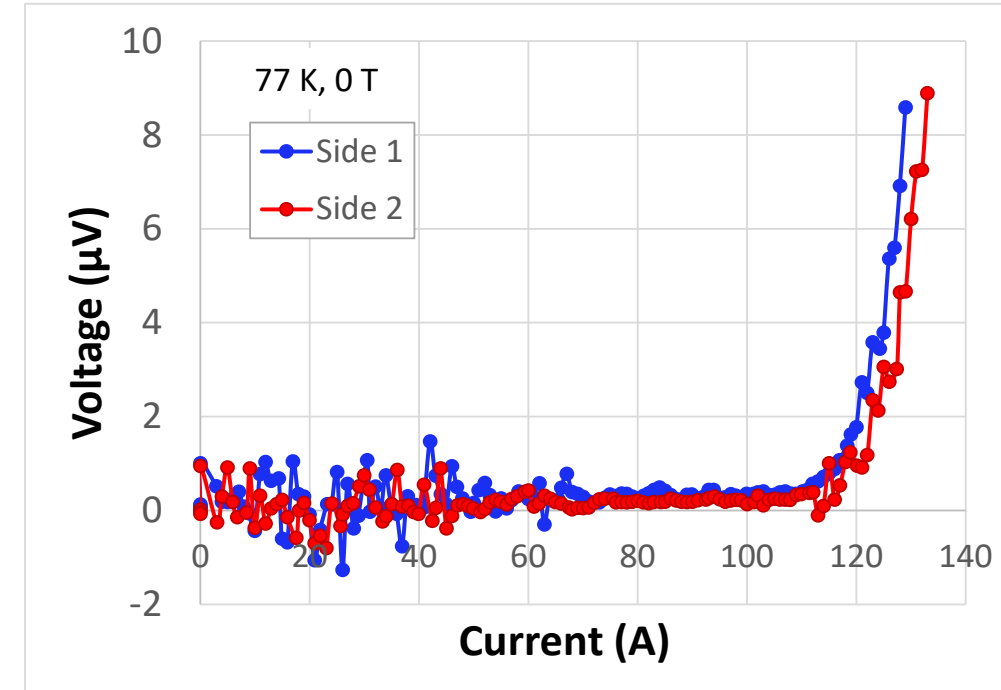
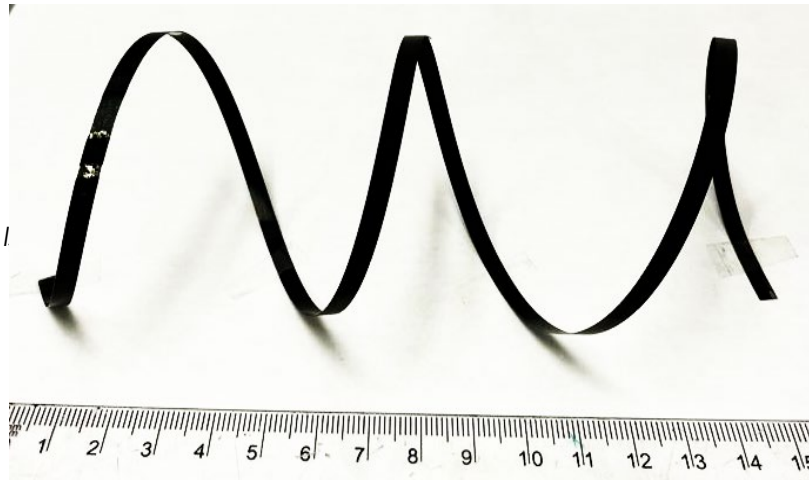
Higher energy dissipation, starting at lower current value, occurs in the F2B configuration during current transfer from the defective tape. Such high energy dissipation can pose a threat of uncontrolled quench and damage.

Fabricated defect tolerant REBCO tape architectures:

Double-sided REBCO tapes

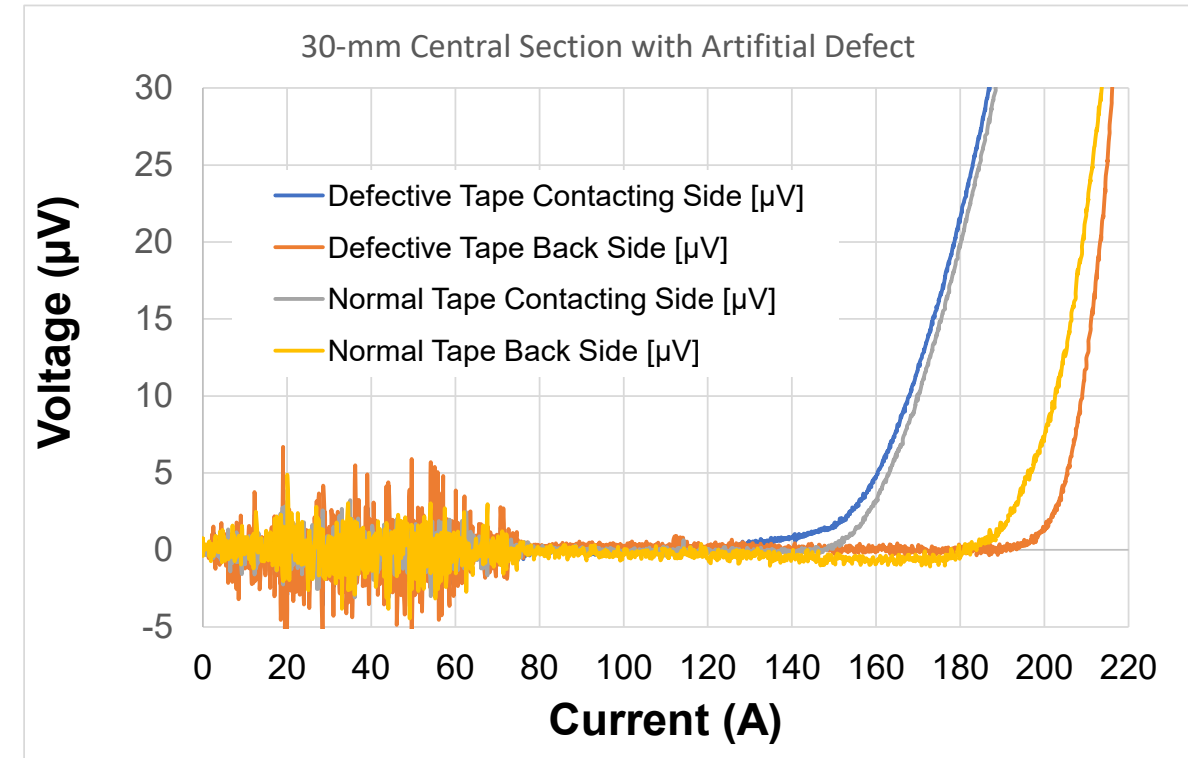
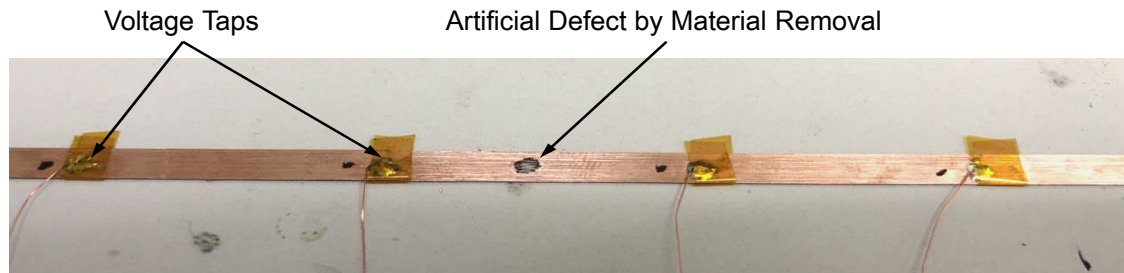
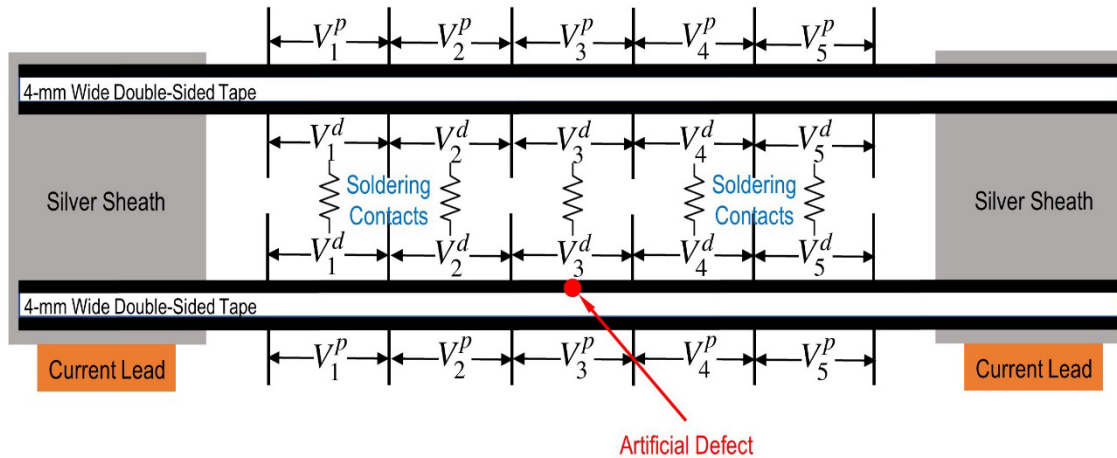


Integration
for Current I



- Face-to-face (F2F) arrangement yields 5x lower contact resistivity.
- Double-sided tapes provide an automatic F2F arrangement.
- Double-sided REBCO tapes fabricated with equal critical current on two sides.

Excellent current sharing obtained in double-sided tape architecture



- Clear evidence of good current sharing between defective and normal double-sided tapes.

Acknowledgments

- N. Mai, A. Chavda, U. Sambangi, A. Arjun, J. Peram, J. Sai Sandra, M. Paidpilli, C. Goel, Y. Li, S. Chen, R. Jain, V. Yerraguravagari, B. Sarangi, Y. Li, G. Majkic, R. Schmidt of **University of Houston**
- Magnet and cable fabrication and testing at **Lawrence Berkeley National Laboratory** by X. Wang and H. Higley.
- COMB magnet fabrication and testing at **Fermilab** by V. Kashikin
- Support for high-field measurements at **NHMFL, Tallahassee** provided by J. Jaroszynski, G. Bradford and D. Abraimov
- High-field measurements at **CNRS, Grenoble** by X. Chaud and J. Song.

Funding:

- SBIR projects DE-SC0021689, DE-SC0022900, DE-SC0020717, DE-SC0015983 funded by the U.S. Department of Energy Office of High Energy Physics.
- STTR project N68335-21-C-0525 funded by U.S. Naval Sea Systems Command.