Fermilab

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Flexible REBCO Cables for High-Field Accelerator Magnets

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U.S. DEPARTMENT of ENERGY

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FERMI NATIONAL ACCELERATOR LABORATORY

Flat Flexible REBCO Cables

Scope

Motivation:

- Combine the excellent packing and winding characteristics of LTS cables with the high field potential of HTS (REBCO).

Goal:

- Evaluate the feasibility of flexible, compact, flat REBCO cable **geometry** for use in high-field accelerator magnets.

Timeline and Contributions:

- The Phase-I project started in August 2025
- 7 students have been working on this project
    - M.S. student on electromechanical characterization (Ph.D. Student in Fall 2025), Two Ph.D. student on FEM modeling, Three senior undergrad students on automation of the tape wrapping , One undergrad student on data analysis
- A possible Phase-II project
    - Produce a multi-tape flat cable and fabricate and test a racetrack or a cosine-theta magnet
    - Application on-hold due to unavailable SBIR budget for this year

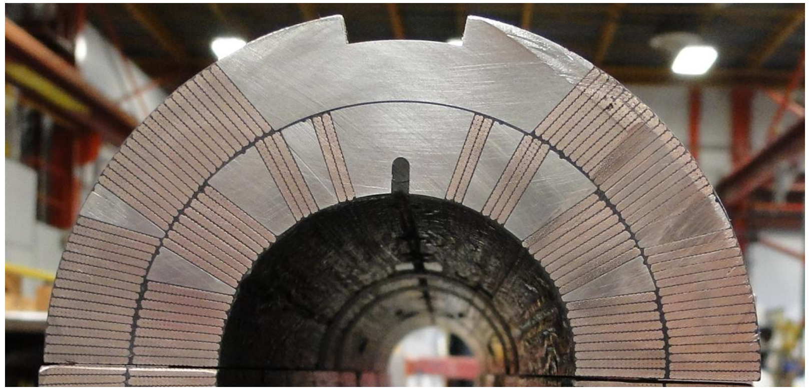
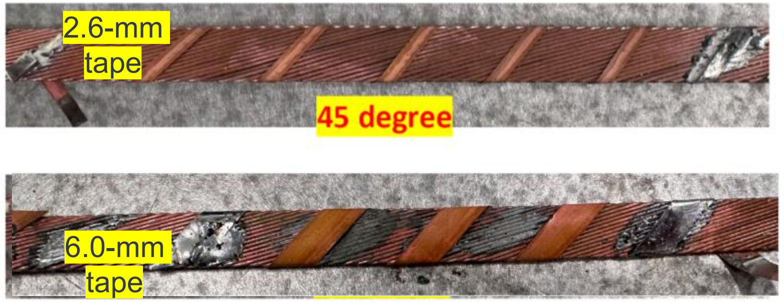


Figure: Cross-section of the Nb3Sn dipole built in collaboration with CERN.

Figure: FReTC cable, developed by M. Takayasu, geometry compared to new proposed cable (schematic provided by C. Navarro)



Flat Flexible REBCO Cables

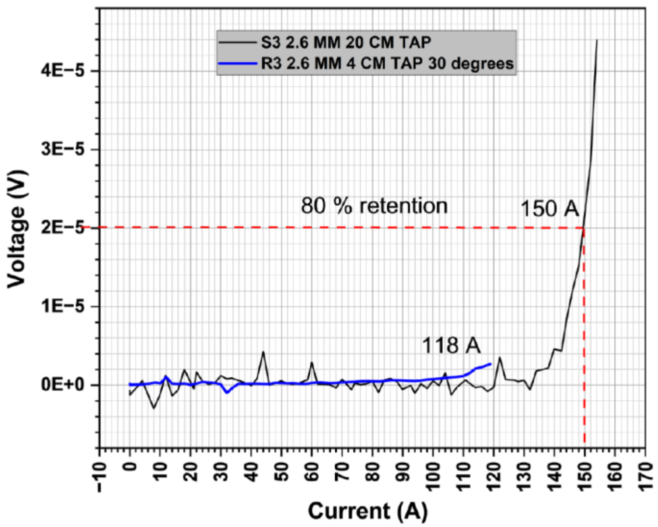
Introduction

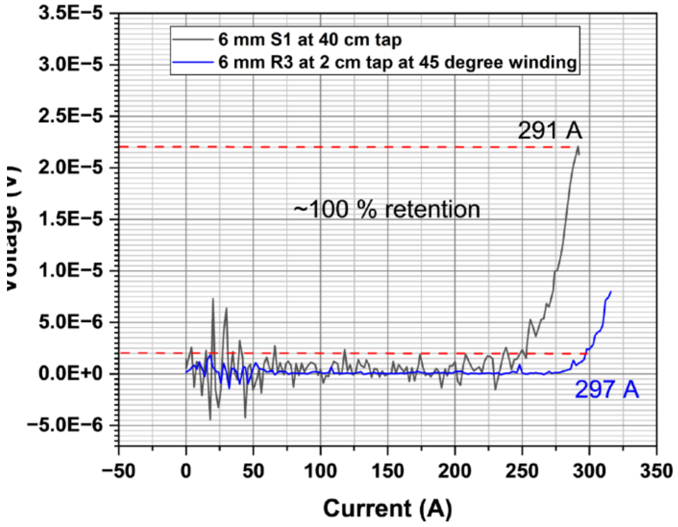
Short-term objective:

- Establish a parameter space (tape width and angle) that produces a target I_c retention (>90%) after wrapping and bending.

Initial Results

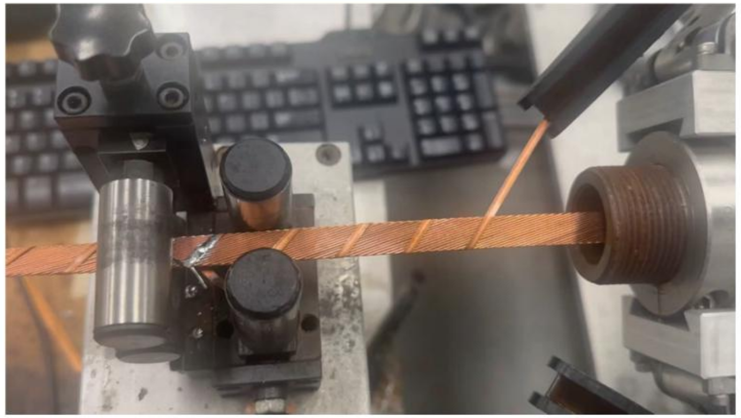
- AMPeers fabricated STAR® tapes in 2-6 mm width range
  - Initial results were encouraging
  - An extensive sample fabrication and testing is in progress at Fermilab





AMPeers

2.6 mm wide
Symmetric tape



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Experimental Setup

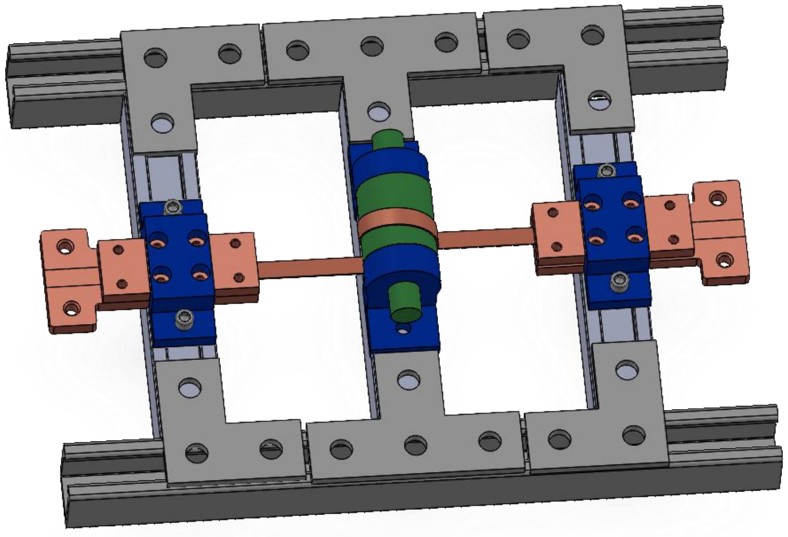

Figure: CAD model for experimental set up in "bent configuration"

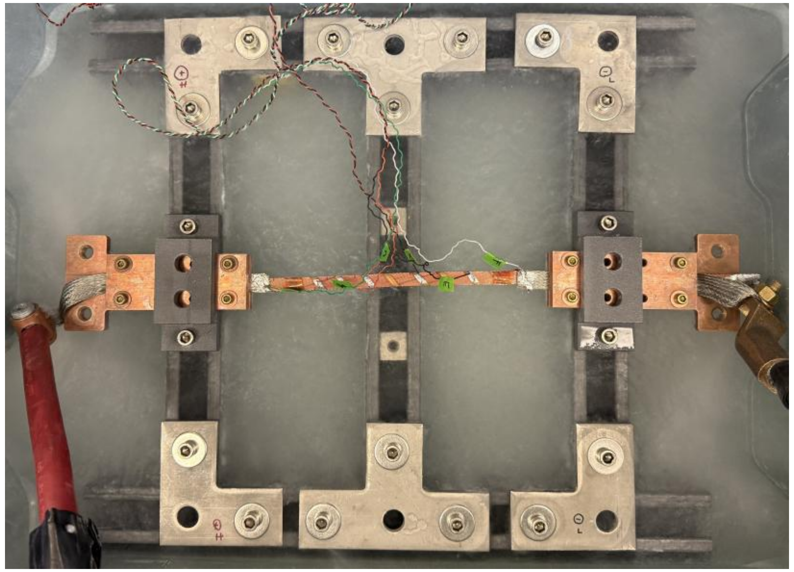

Figure: Experimental setup in the "straight configuration"

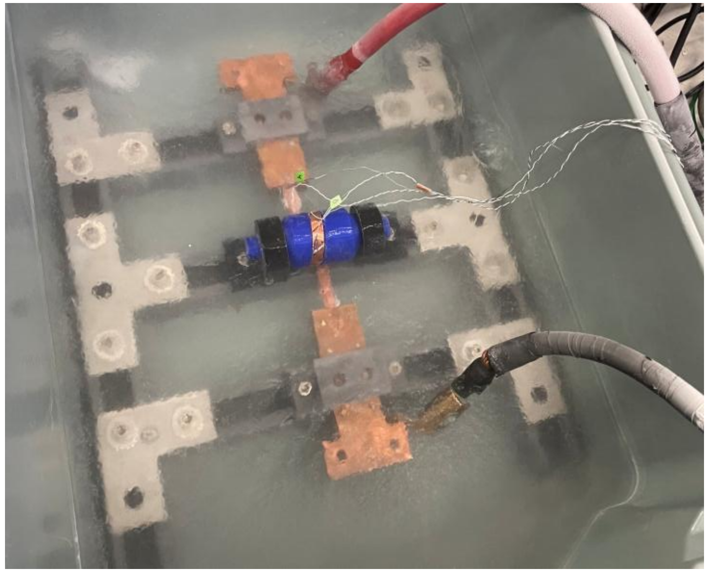

Figure: Experimental setup in the "bent configuration"

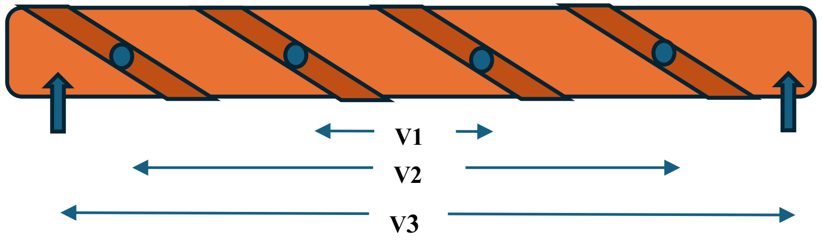

Figure: Experimental setup instrumentation including voltage tap pairs located on the tape (V1 & V2) and the cable (V3)

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Parameters

Table: Expected effect of key parameters to be tested

Parameter	Range	Expected Effect
Tape Width	2, 4, 6 mm *	Wider tape → higher current capacity but more strain.
Lay Angle	30 & 45° *	Lower angle allows for more efficient current transfer, but influences strain distribution.
Bend Diameter	30, 35, 40 mm	Smaller diameter → higher strain.

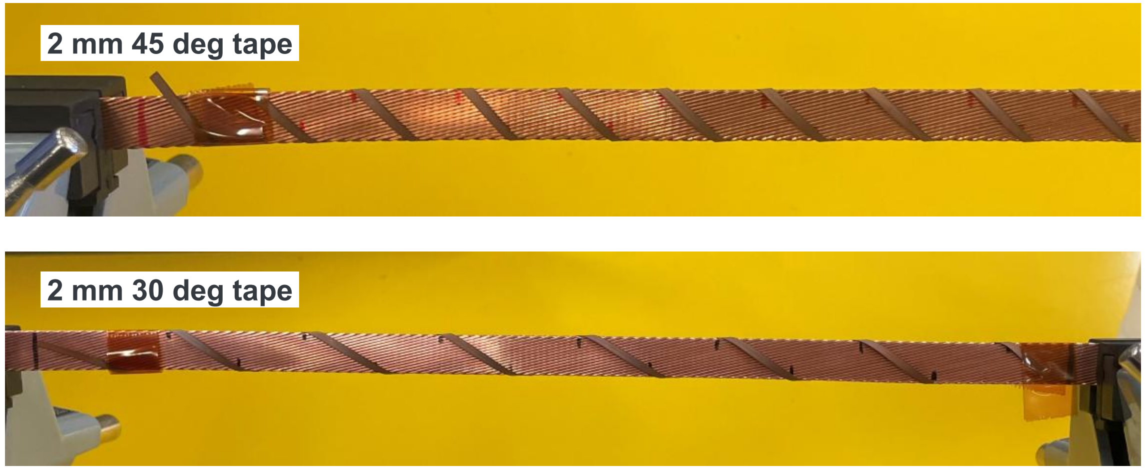

Figure: Sample fabrication of 2mm tapes at 45 deg and 30 deg lay angles

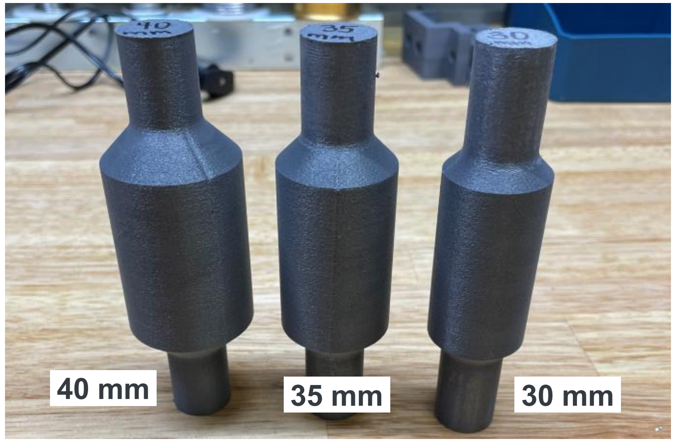

Figure: Size comparison of the 3d-printed cylinders used for sample bending

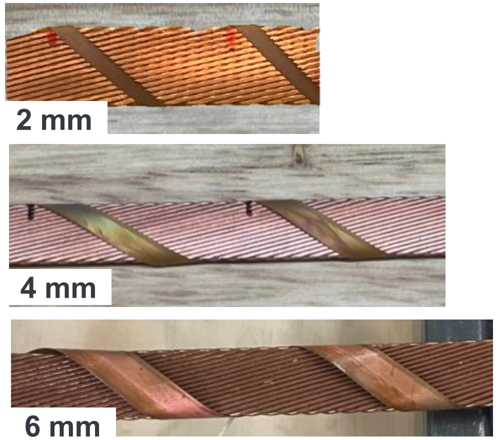

Figure: Sample fabrication of 2, 4, 6mm tapes

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Timeline Update

Test Plan:

- All test, except 2mm at 45deg, were completed.
- Statistical significance:
  - Two rounds of testing will be completed before end of March.
  - Three-four rounds of testing plan to be completed before the end of SBIR Phase I.

Testing issues:

- FEA shows 2mm has most strain, specifically around bends. This is reflected in the AMPeers testing. Could contribute to the delicate nature of 2mm at 45deg test and the struggles.

Tape Width (mm)	Tape Angle (deg)	Bending Diameter (mm)
2	30	straight
		40
		35
		30
	45	straight
		40
		35
		30
4	30	straight
		40
		35
		30
	45	straight
		40
		35
		30
6	30	straight
		40
		35
		30
	45	straight
		40
		35
		30

Figure: Parameter space defining one full round of tests

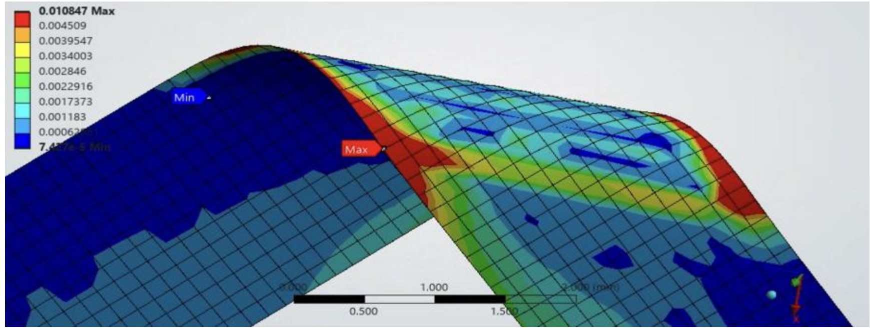

Figure: ANSYS model of 2mm tape wrapped around Rutherford-type core (provided by R. Powers)

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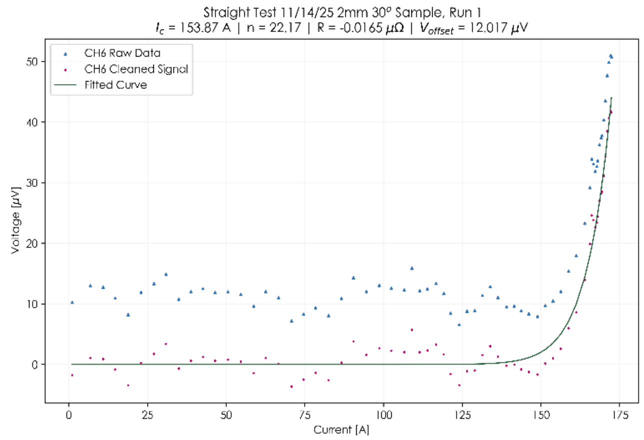
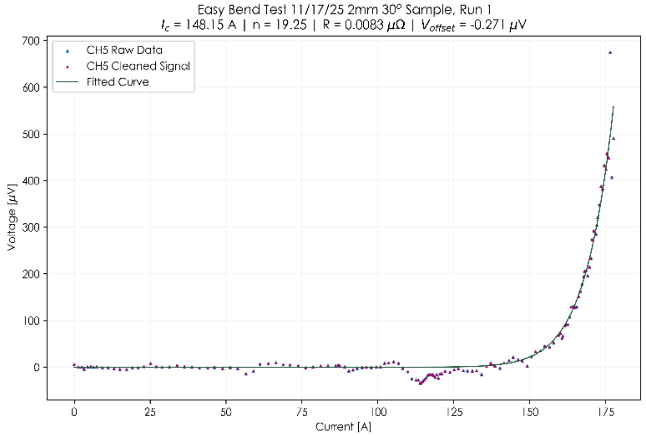
Preliminary Results

Straight, 2mm, 30 deg

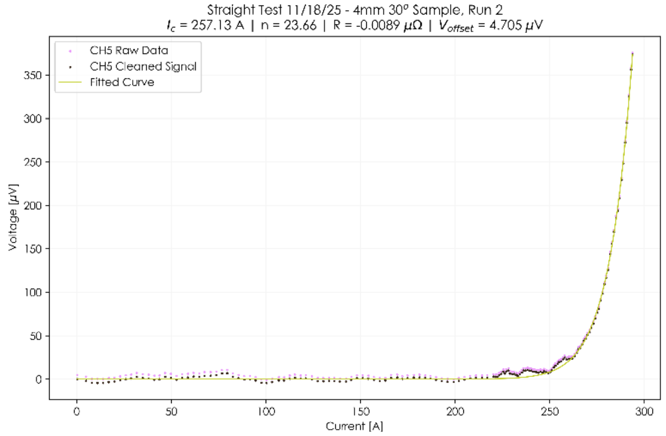


Bent (40mm), 2mm, 30 deg

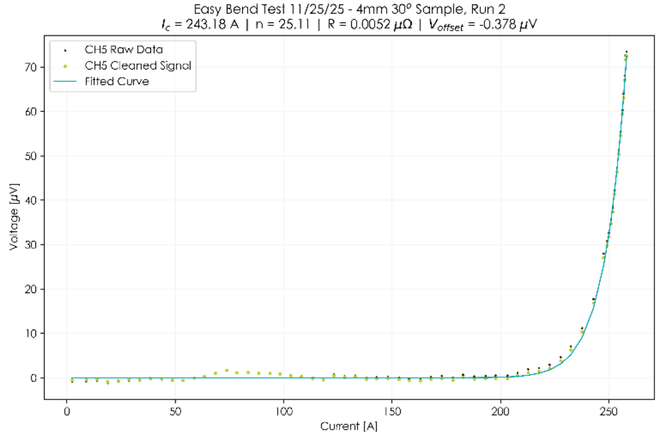


I_c retention = 96.3%

Straight, 4mm, 30 deg

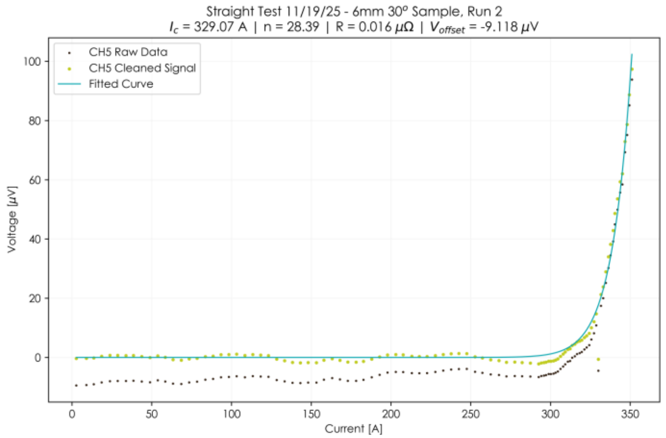


Bent (40mm), 4mm, 30 deg

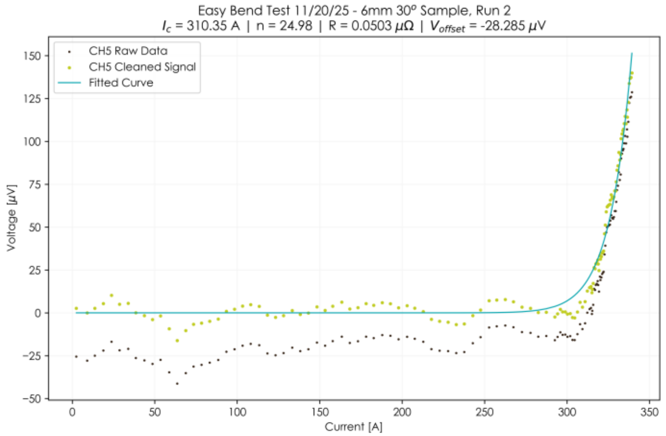


I_c retention = 94.6%

Straight, 6mm, 30 deg



Bent (40mm), 6mm, 30 deg



I_c retention = 94.3%

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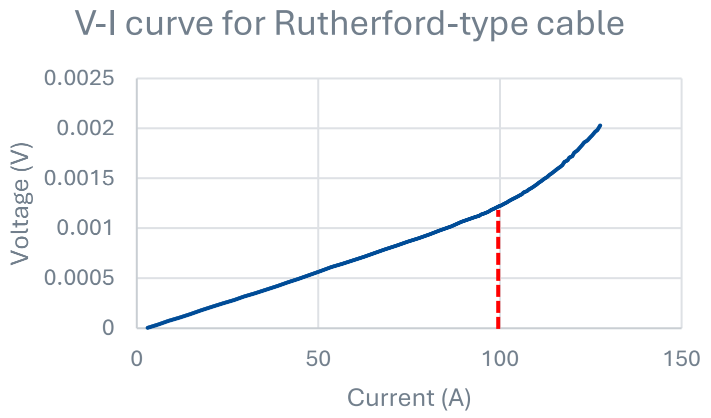
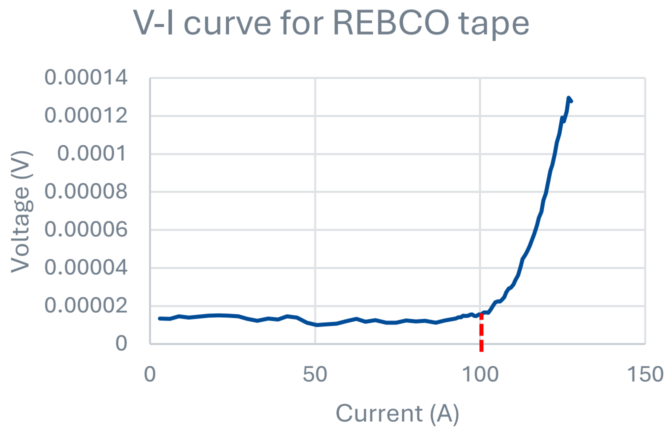
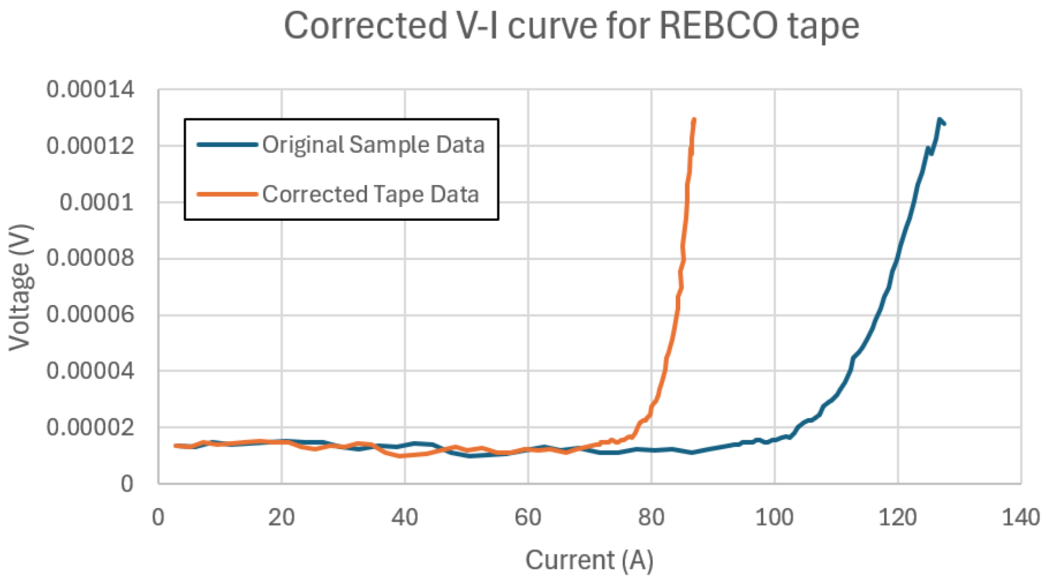
Current Sharing





$$I_{cable} = \frac{V_{cable}}{\rho_{normalize} * \delta_{cable}}$$

$$I_{tape} = I_{tot} - I_{cable}$$



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Alternative Core Testing

Ultra-Fine Superconducting Wires

- Development of Nb_3Sn, Nb_3Al, etc. ultra-thin wires, lead by A. Kikuchi et al.

Subscale Rutherford Cables Using Roped Strands Made from Ultrafine Wires

- Provided by Ian Pong (LBNL)
    - Dummy cable (copper-only)

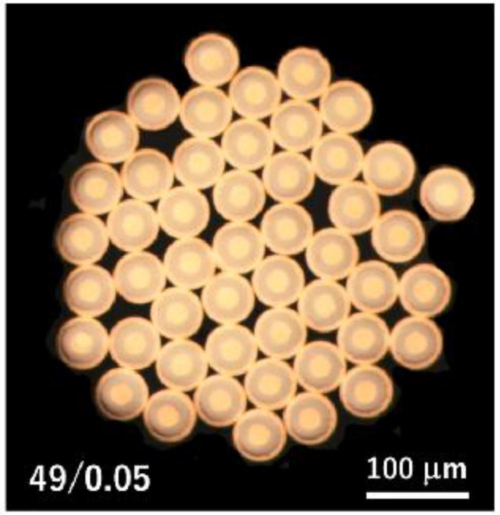

Figure: Nb3Al strand cable cross section [1].

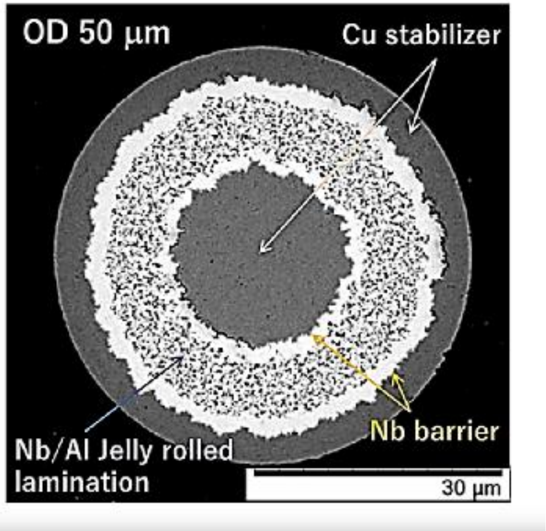

Figure: Cross sections of the Nb3Al wire with jelly rolled lamination [1].

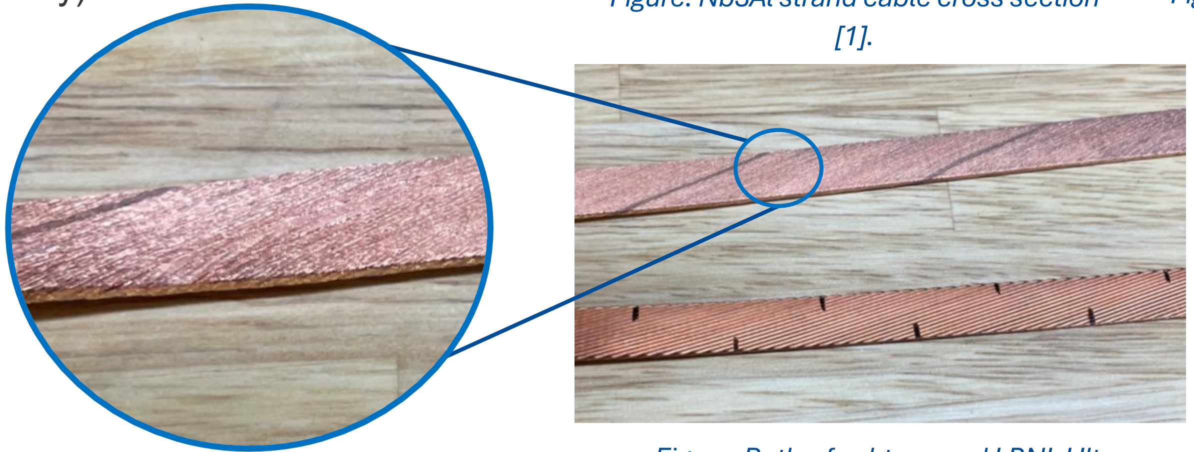

Figure: Rutherford-type and LBNL Ultra-fine cable comparison

Figure: LBNL Ultra-fine cable flexibility "test"

[1] N. Ohuchi, A. Kikuchi, M. Yamamoto, X. Wang, K. Tsuchiya, K. Aoki, Y. Arimoto, T. Oki, and Z. Zong, "Development of Super Fine Strand Nb3Al Cable for SuperKEKB Superconducting Sextupole Magnet System," *IEEE Trans. Appl. Supercond.*, vol. 33, no. 5, pp. 1–5, 2023, doi: 10.1109/TASC.2023.3253073.

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Alternative Core Results

Preliminary Results

- Very easy to handle
- Very promising results compared to Rutherford-type cable

Some Challenges

- Strand/rope separation during handling and compression
- Difficult to wrap tapes with tension (could explain improved results)

Table: Preliminary results comparing Rutherford-type and ultra-fine cable

Tape Width	Tape Angle	Bending Diameter	Ic Retention (Rutherford)	Ic Retention (Ultra-fine)
4	45	40	95.6%	99.1%
		35	94.1%	98.1%
		30	92.7%	97.9%

Figure: Strand and rope separation after compression

Figure: Lack of tension in tapes wrapped around ultra-fine cable

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Next Steps

Deadlines:

- M.S. Thesis defense, March 24th 2026
- SBIR Phase I Final Report, TBD (Extended)

Next Steps:

- Complete testing plan and finetune data analysis:
  - Finalize real I_c calculations and develop data visualization methods.
- Development of process automation for sample fabrication.

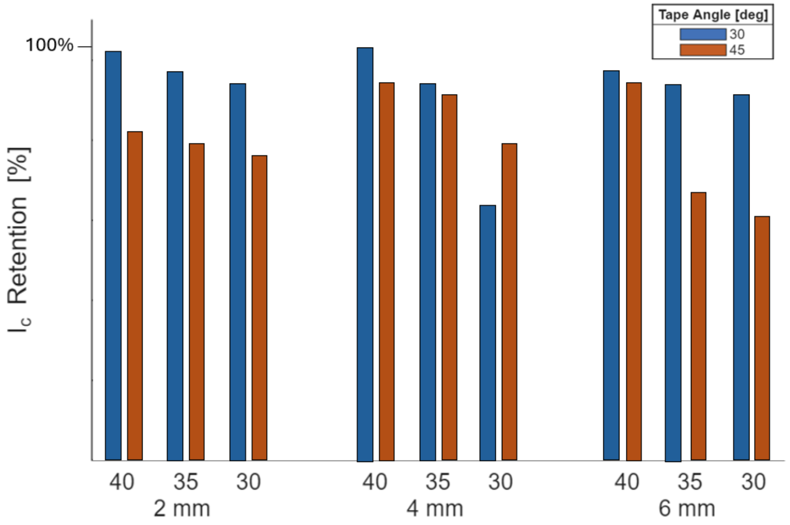

Figure: Histogram graph for data visualization

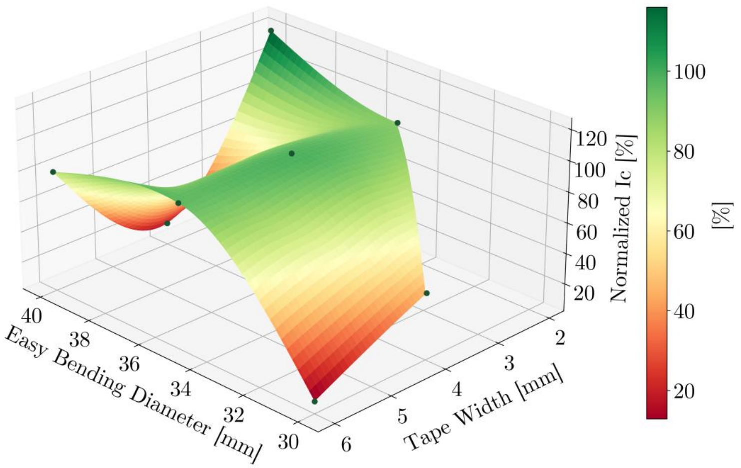

Figure: Three-dimensional graph for data visualization (provided by C. Navarro)

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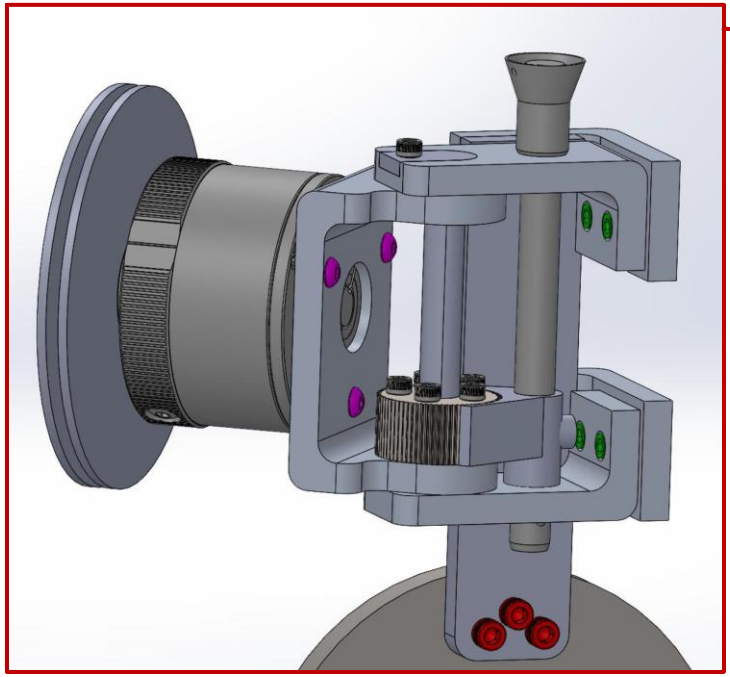
Automation of the REBCO tape wrapping



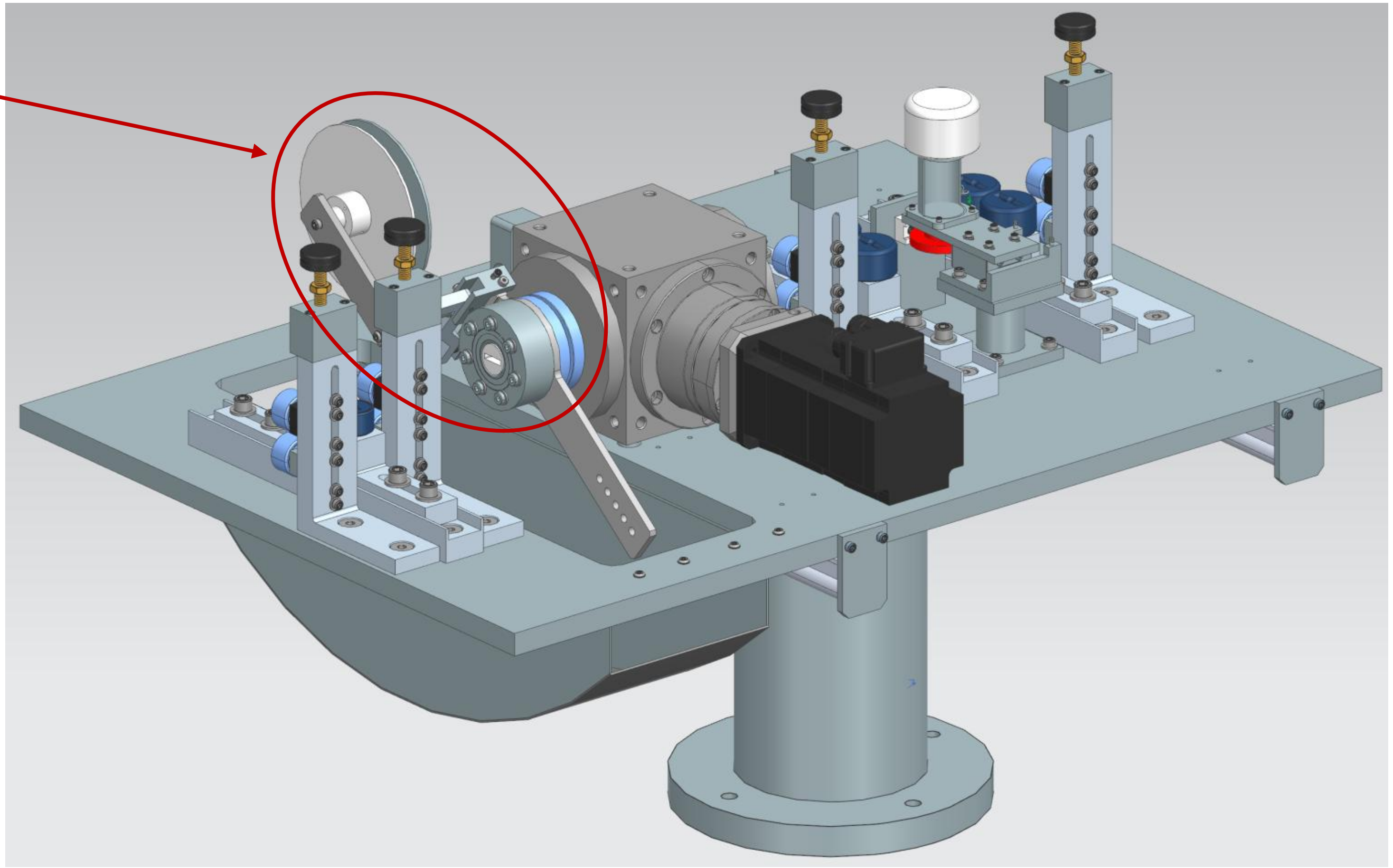
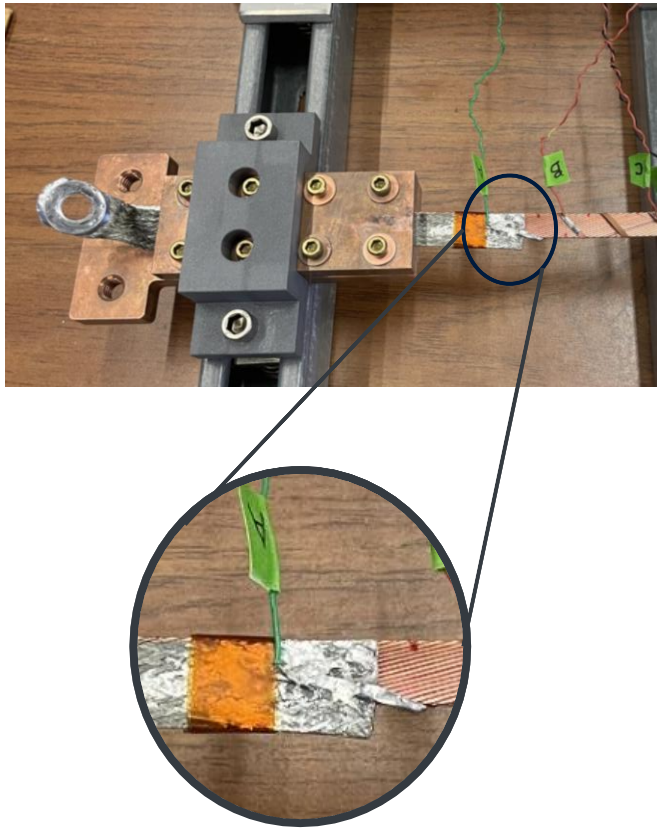
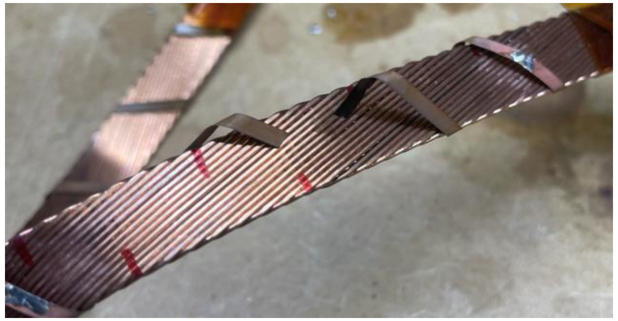


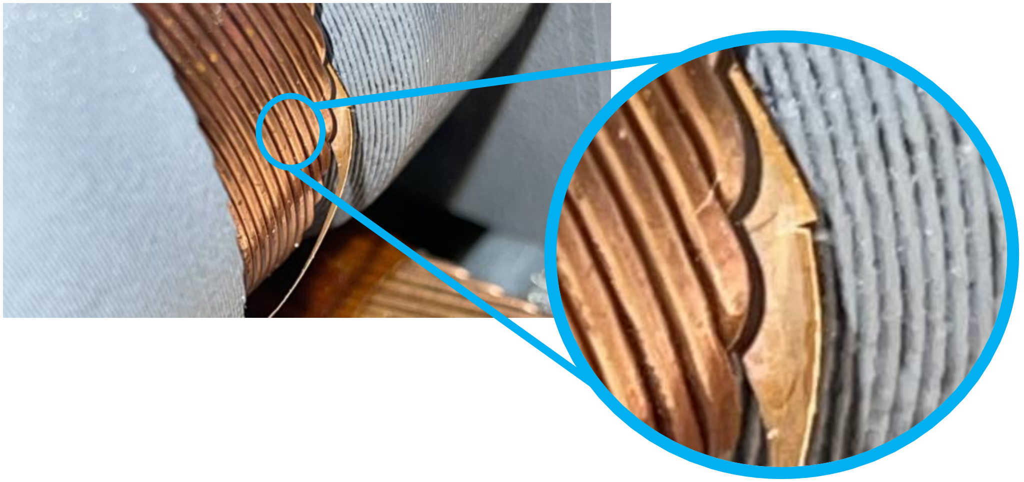
Figure: REBCO Wrapper CAD model for sample fabrication automation (provided by E. Fohlmeister, K. Gillen, J. Oelrichs)

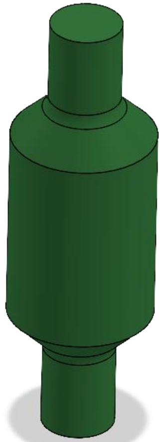
- Modify existing machine designed and built for Mu2e conductor wrapping with Kapton with additional features:
  - simultaneous 4-tape wrapping capability of 2-6 mm tapes
  - 10°−45° wrap angle adjustment
  - 0-13 lbs tape tension adjustment

Troubleshooting (Appendix)





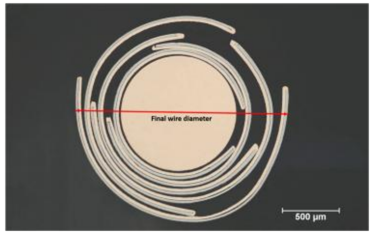


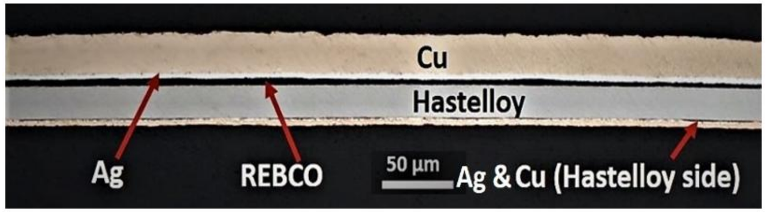


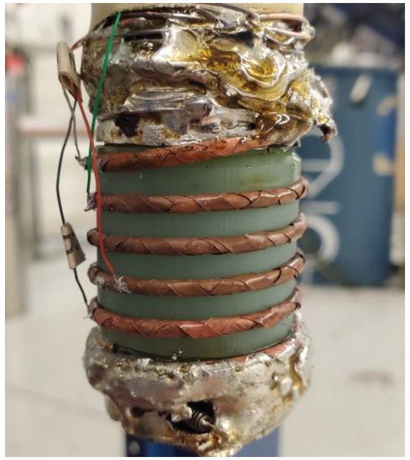
Commercial round REBCO wires (Appendix)

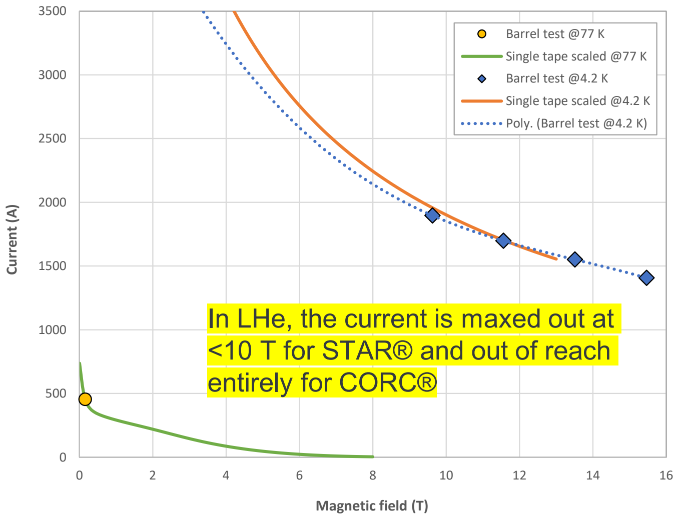
STAR®

- Symmetric Tape Round
- Based on proprietary tape technology
- Smaller wire diameter and more flexible
- Over 2 km of high Ic symmetric tape has been recently manufactured and used in >80 m of 16-tape cable for COMB-STAR project
  - This is the largest STAR® wire production to date!









CORC®

- Conductor on Round Core
- Based on commercially available tapes
- Larger wire diameter and higher critical current, but less bendable
- Had issues with the previous generation of conductors that were degrading by 50% after bending due to the lubricant drying issue, fixed by now