U.S. MAGNET DEVELOPMENT PROGRAM

Experience with CORC® and STAR® conductors

A. Ben Yahia, V. Kashikhin, X. Wang

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Two round wires, similar concept and different features

- CORC® by ACT in Colorado
  - nominal 30 mm bend radius, ~ 4 mm diameter
  - Use commercial REBCO tapes from external vendors
  - 6 kA I_c at 12 T, 4.2 K
  - More experience with several coils made and tested
- STAR® by AMPeers in Texas
  - nominal 15 mm bend radius, < 3 mm diameter
  - Use in-house made tapes, vertically-integrated manufacturing capability
  - We start gaining experience

Input from Anis at BNL

- The cost of the conductor in the quantity needed remains very high and restricts the possible experiments and designs.
- Need a standard to qualify the performance of the various conductors in one consistent framework.
- This is specific to the multi-tape REBCO conductors where the V-I curves are specific to the cable design and interpreting them always carry some post processing of the results.
- Can we set up a standard to characterize the various conductors consistently?

Input from Anis at BNL

- To what extent we can use cheaper (and hopefully more available) tapes and conductors to answer some of the REBCO magnet technological questions?

- Similarly, can we answer some of these questions by testing short samples in He by leveraging existing cable testing facilities (medium background field and high current)?

COMB magnet development with CORC cables

- Extensive studies have been conducted on short CORC® samples prior to winding the coils.
  - It was found that winding the cables into the COMB structure resulted in *a considerable loss of critical current* (I_c)*, often reaching 50%*,
  - It has not been previously observed on uniaxial (hairpin) bent samples.

- Further analysis performed by Advanced Conductor Technologies (ACT) revealed the issues with *drying lubricant used in CORC® production and high surface roughness on latest REBCO tapes*, which hampered the bending performance.

- The next generation of CORC® cables have been optimized by ACT to accept tapes with high surface roughness using new lubricant formula, winding method, and production parameters that allowed to reach *~80%* I_c *retention*. Additional improvement was reported at ASC22.

- CORC-related activities are currently on hold pending procurement of the conductor with improved flexibility:
  - Plans to build a 100-mm bore (120-mm OD) coil and test it stand-alone and as part of a hybrid HTS/LTS magnet system in 2024-25

STAR in COMB SBIR with AMPeers

- Phase-I (ongoing) to be complete by mid-April 2023:
  - STAR wire fabrication by AMPeers LLC – 2x5-m long pieces with 12 tapes and expected self-field I_c of ~1 kA at 77K
  - COMB demonstration magnet with 60 mm clear bore - design and fabrication at Fermilab
  - Testing in LN_2 at Fermilab
  - *Target is >90% I_c retention after winding*, but >70% is considered acceptable (with the expectation of future improvements)

- Phase-II (if approved) 2024-2025:
  - Manufacturing of ~100 m of STAR wire
  - Fabrication of a multi-layer COMB dipole magnet
  - Testing the magnet in liquid helium to demonstrate >5 T field in ~60 mm bore generated by the HTS coil (performance demonstration)
  - Possible hybrid test if supported by MDP

- Round wires
- Process
- People

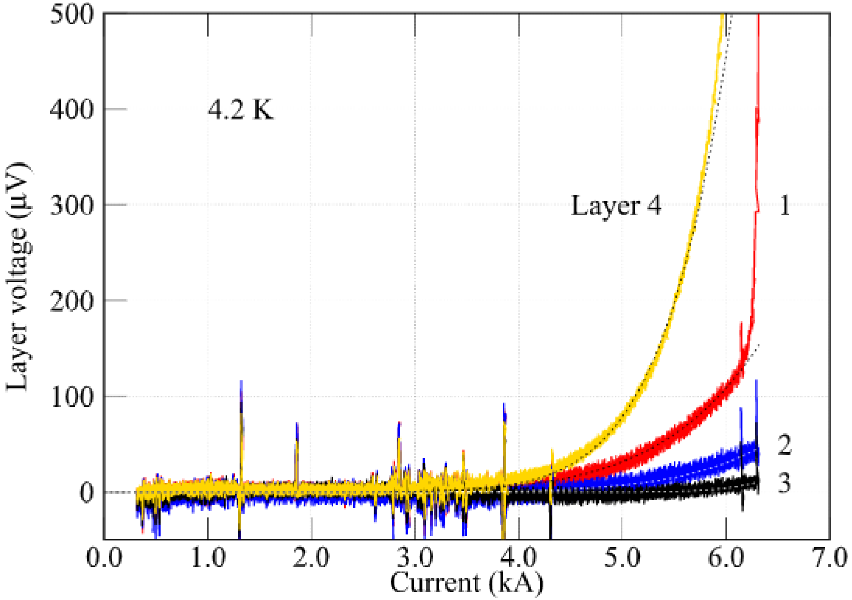
Next magnets need CORC® with higher performance

Parameter	Today	Next targets
I_c at 12 T, 4.2 K [kA]	6	12, 18
Bend radius [mm]	30	20, 15

- Potential path
  - Thinner substrate: 25, 20 micron
  - Narrower tapes: 1.5, 1 mm
  - Better cabling process

C2 magnet suggests that the transport and bending performance not obviously non-uniform along the wire

Layers 1 – 3 transitioned as expected accordingly to the peak field

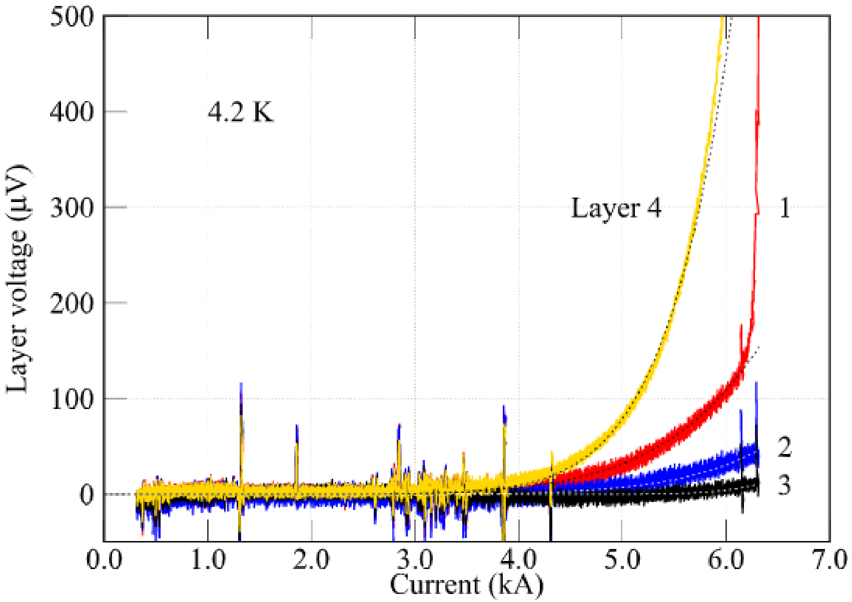


Layer	Length (m)
1	13
2	15
3	20
4	23

Make and test more magnets using longer wires

C2 Layer 4 also suggests that mixing tapes with different I_c may not be desirable

Layer 4 shows earlier transition



- Layer 4 wire composed of tapes with I_c varied by up to a factor of two between tape batches
- Let's see what C3 can tell us

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STAR® wires need more coil tests and experience

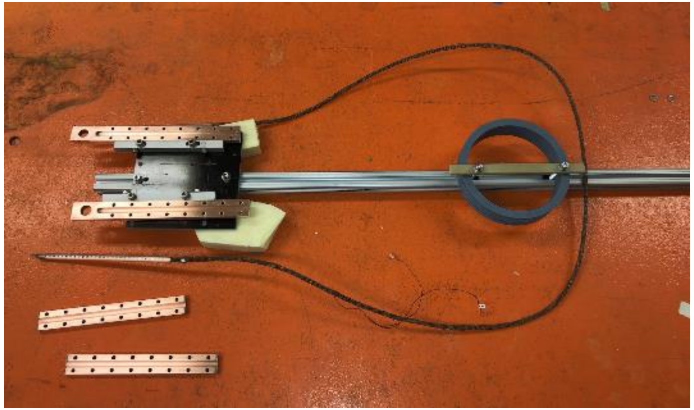
- Positive overall impression based on emerging but very limited experience
- Need to understand better the source of early voltage rise observed in some of the samples
- Learn more as MDP makes more STAR® coils

First 6/1 STAR® cable sample is more robust than we thought

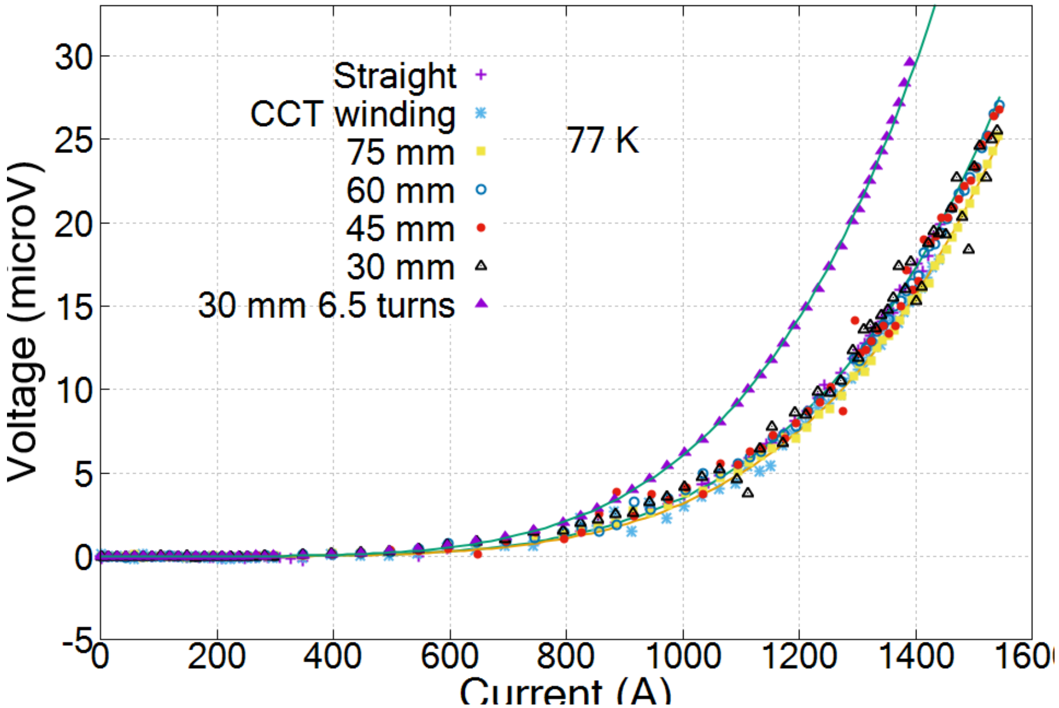
- Six STAR® wires cabled around a Cu core, ~ 50 mm twist pitch length, 1.5 m long between the terminations

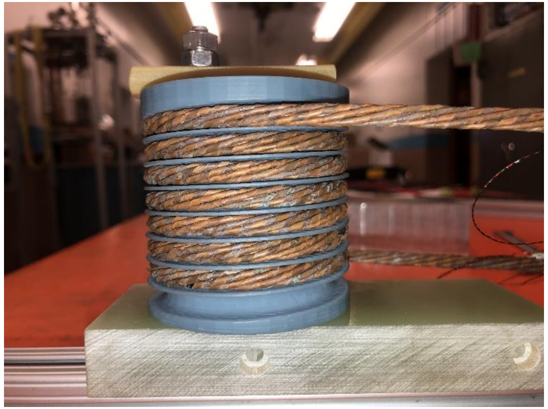
Previously it was wound into a CCT coil form with a minimum bend radius of 75 mm

Then we unwound and tested it at successively smaller bend radii



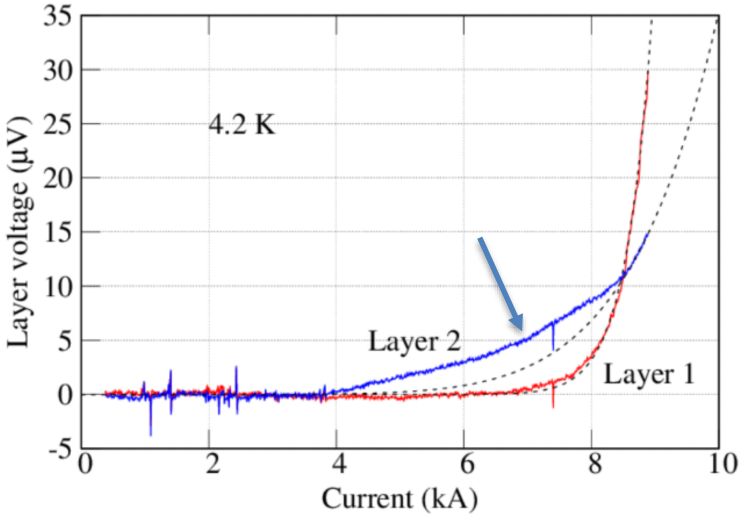
V(I) remained unchanged from straight to half-turn at 30 mm radius; reduced by about 12% in a solenoid form at 30 mm radius



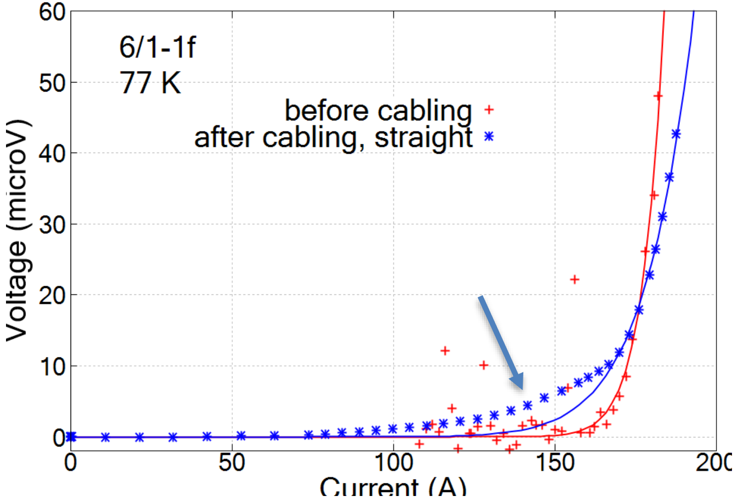


Early voltage rise is concerning. Does it indicate degraded tape(s)?

s0 magnet Layer 2 shows early voltage rise



STAR® wire with 4 tapes, after being cabled into 6/1 configuration



Technical challenges can occur and can be addressed; we need to push the boundaries

- In March 2019, ACT started ordering the HM tapes
  - Specified I_c for the first time. > 350 A at 4.2 K, 6 T
  - 10 km length, 2 mm width, 30 μm thick substrate
- In December 2020, 21 months later, SuperPower started delivering the tapes
- It can take time, patience and some faith to go through and survive
- Don’t wait to push the performance

Cultivate closer and faster feedback loop among conductors, independent characterization, and magnets

- To help C3 reach the 5 T milestone, ACT specified the minimum I_c
- SuperPower responded with the HM formulation in their tapes
- ASC/FSU characterized the sample tapes from all the batches provided by ACT
  - ACT rejected more than one batches based on the I_c data
  - The tape vendor also appreciated the data that calibrated the manufacturing process
- MDP started making C3a coils using the HM CORC® wires
- This feedback loop is critical and need to continue

Who you work with can be more important than what you work on

- REBCO is fortunate to have two great characters as providers: ACT and AMPeers

- How can we put them to generate best work for future REBCO dipole magnets?
  - Show them the money, when we have it