Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Magnet R&D Status Reports (MDP/non-MDP): FNAL REBCO Program

Vadim Kashikhin

REBCO Round Table Meeting

November 2, 2023

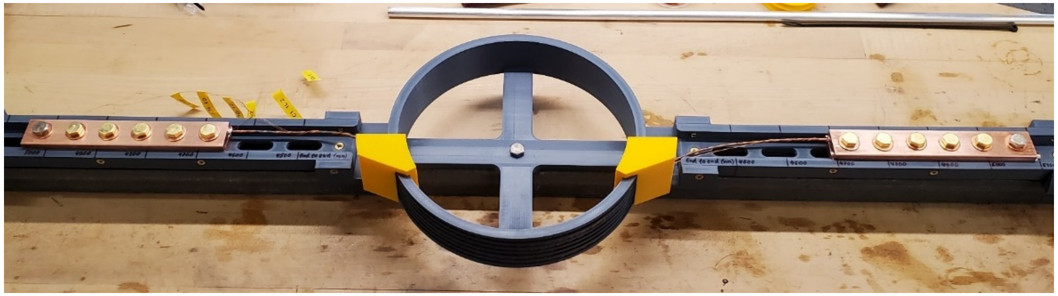
Overview

- COMB magnet development with STAR® wires under SBIR with AMPeers
  - Phase I (completed)
    - Built and tested a 2-layer dipole magnet in LN_2
  - Phase II (setting up the subcontract)
    - LHe test of the Phase-I magnet
    - Fabrication of a 4-layer magnet and test in LN_2/LHe
- COMB magnet development with CORC® cables under MDP
  - Studies on short cable samples
    - Problems with large degradation (~50%) discovered while bending them to 50-60 mm diameters
    - New cable with an improved flexibility is procured
      - Will repeat the bending experiments on new cable before coil fabrication
  - Fabrication and test of the coil fitting into 120-mm bore of a Nb_3Sn magnet
    - Standalone magnet test in LN_2 and LHe
    - Hybrid test as an insert in Nb_3Sn magnet

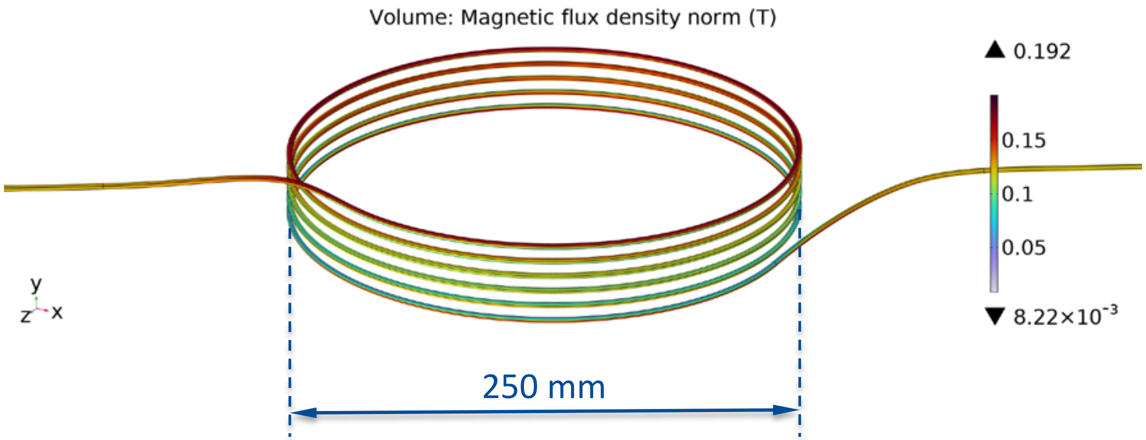
SBIR with AMPeers: highlights

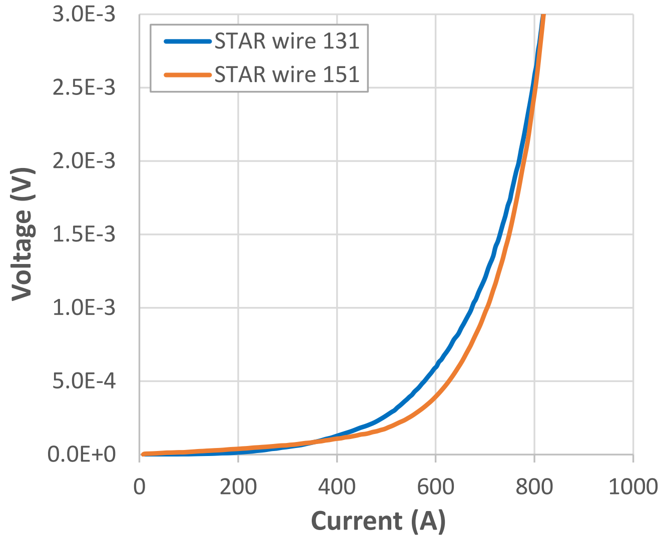
- Phase-I (completed in 2023)
  - STAR® wire fabrication by AMPeers LLC – 2x5-m long pieces with 11 tapes and the self-field I_c of ~600 A at 77 K
  - Design and fabrication of a COMB demonstration magnet with 60 mm clear bore
  - Testing in LN_2
    - Ultimate target was 90% I_c retention after winding; 93-99% I_c retention achieved
- Phase-II (2024-25)
  - LHe test of the Phase-I magnet (end of 2023)
  - Manufacturing ~100 m of STAR® wire (2024)
  - Design and fabrication of a 4-layer COMB dipole magnet (2024-25)
  - Testing the magnet in liquid helium to demonstrate >5 T field in a 60-mm bore generated by the HTS coil (2025)
    - Possible hybrid test, if supported my MDP

Long STAR® wire testing

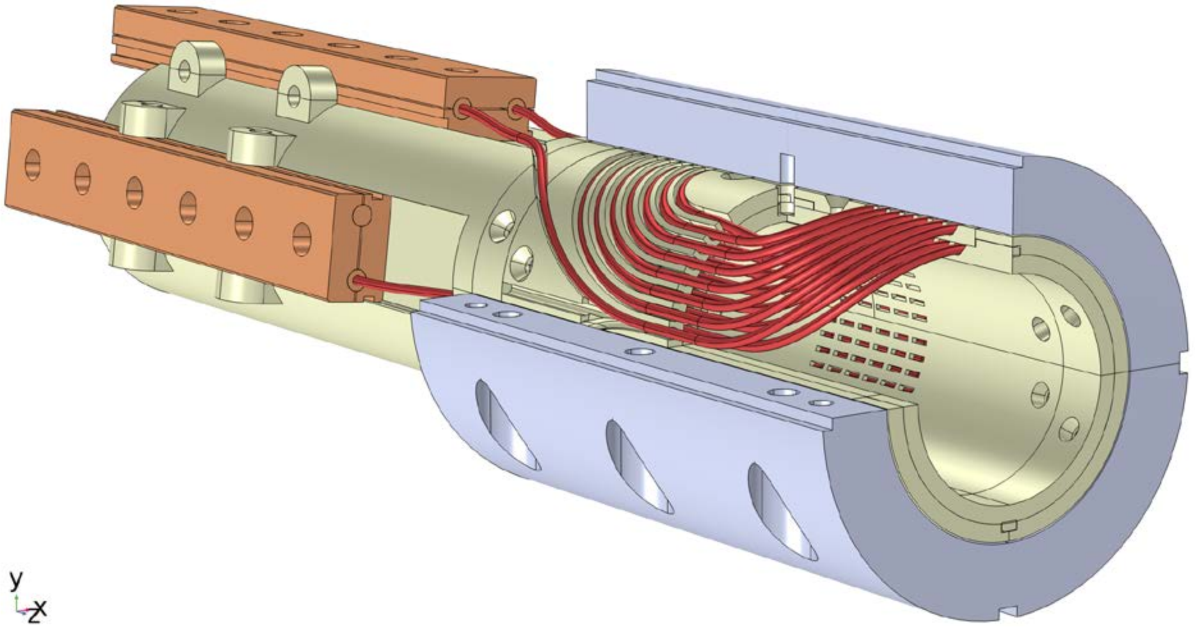


- The 5-m long STAR® wires were tested in liquid nitrogen prior to the coil winding
  - established the reference I_c in 595-606 A range using the electrical field criterion of 0.4 μV/cm
  - the n-value between 8-9



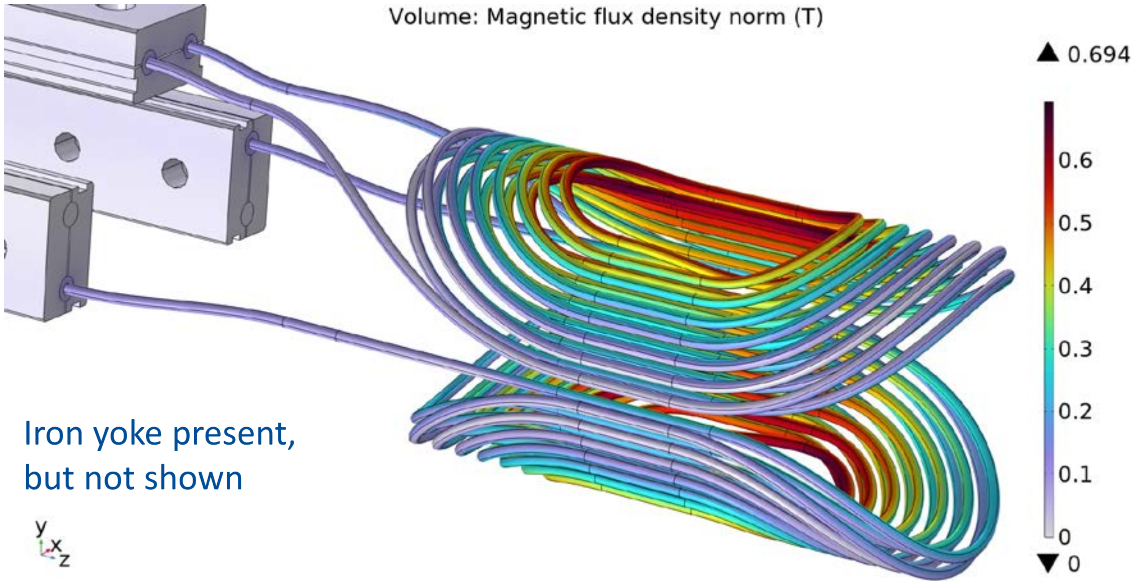


COMB magnet design

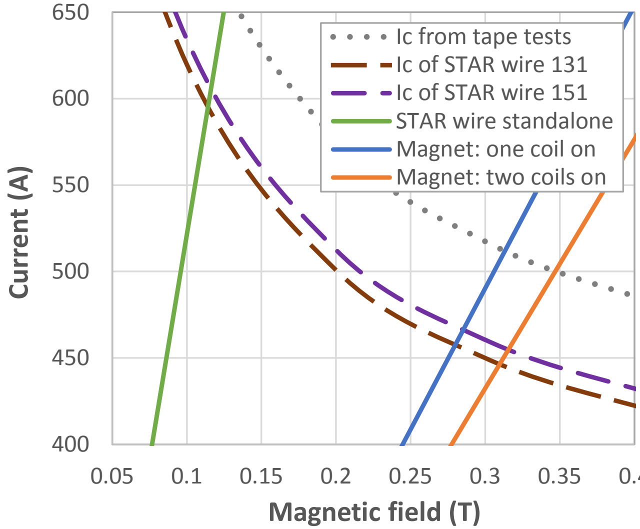


- 60 mm clear bore
- Two half-coils made with two layers of STAR® wire
  - total length of the cable per half-coil is 4.76 m including the leads
  - conductor is wound into a continuous channel without internal splices
- Three copper adapters
  - connect the half-coils together and to the power supply
  - each half coil can be powered individually
- Redundant voltage taps at each wire end

3D magnetic analysis



Iron yoke present, but not shown



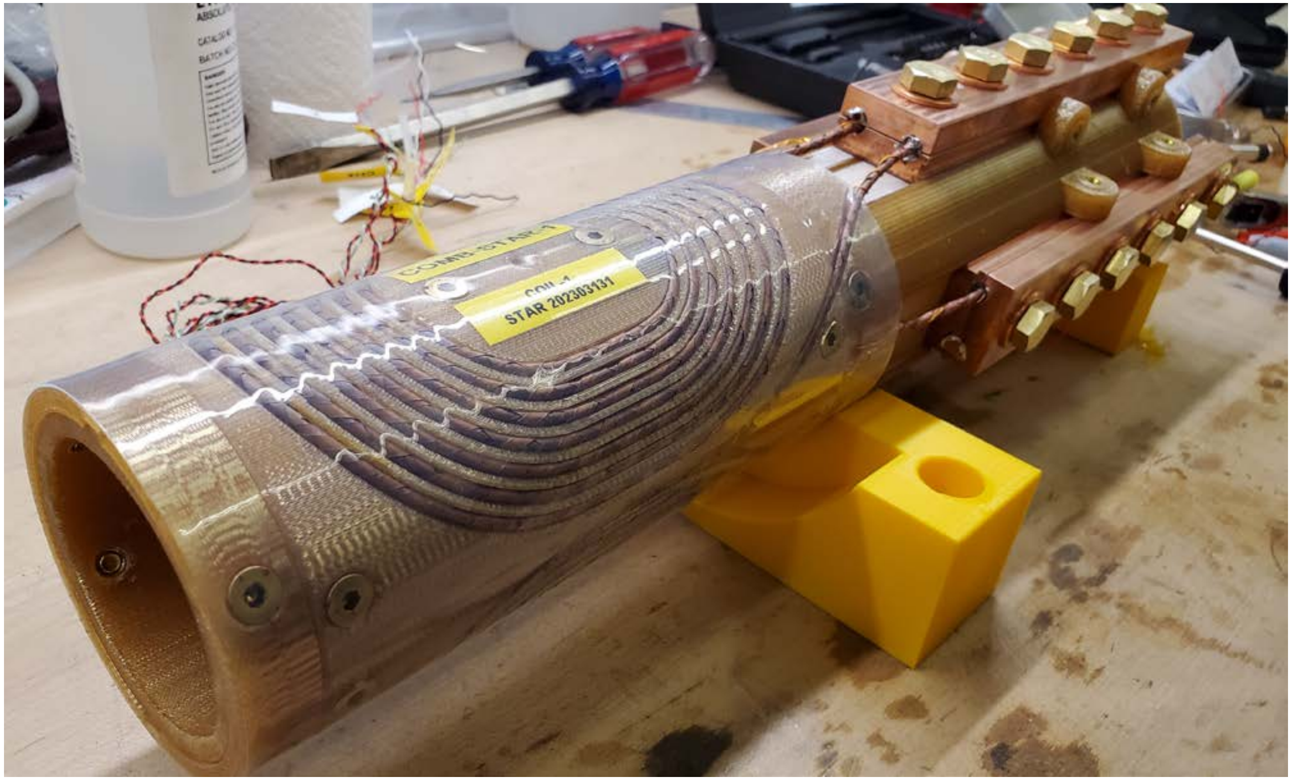
- A complete 3D magnetic model was created as knowing the peak magnetic field on the conductor was necessary for the purposes of this project
  - intersection of the magnet load line with the measured wire characteristic gives the I_c of about 450 A during the magnet test in liquid nitrogen

Fermilab

Magnet fabrication: coil winding

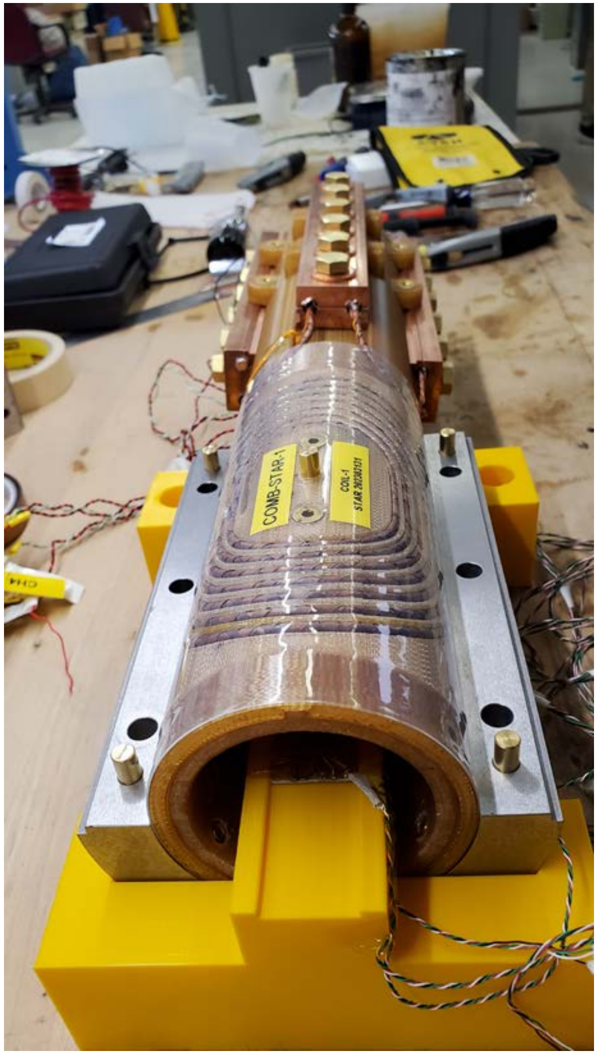
- The magnet fabrication started from manually winding the voltage taps into the support structure of the inner layer of half-coil 1
- It was then followed by manually winding the STAR® wire 131 into the same channel, securing the second layer structure on top of the inner layer and proceeding with the voltage taps and conductor winding procedure for that layer
- The same steps were repeated for the half-coil 2 wound from the STAR® wire 151

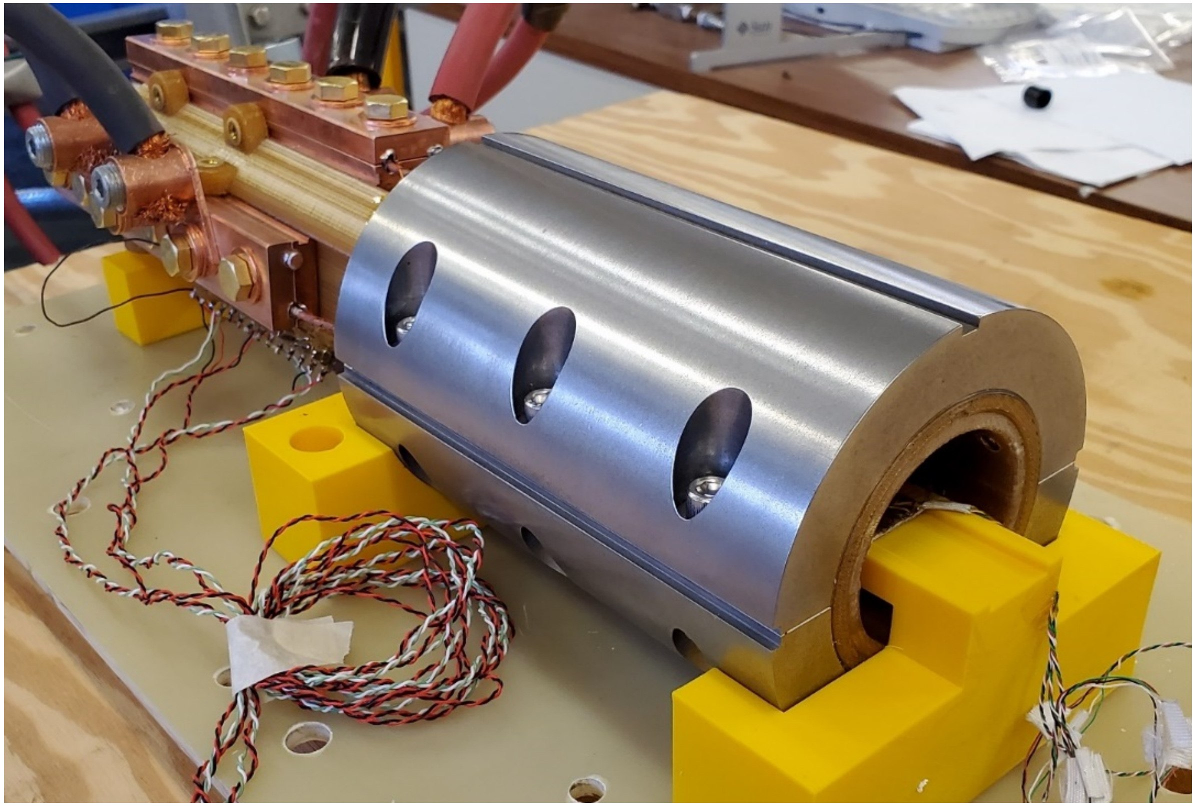
Magnet fabrication: ground insulation and lead support



- The two half-coils were assembled with the lead support structure on one end and the retaining ring on the other
- The ground insulation consisted of ~0.5 mm thick polyester was installed around the coils
- The tubes terminating the leads were secured inside of the copper adapters installed in the lead support

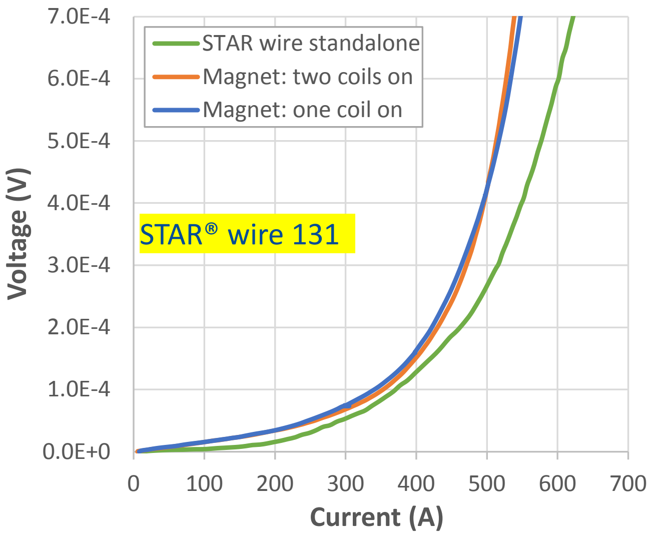
Magnet fabrication: iron yoke and Hall probe array

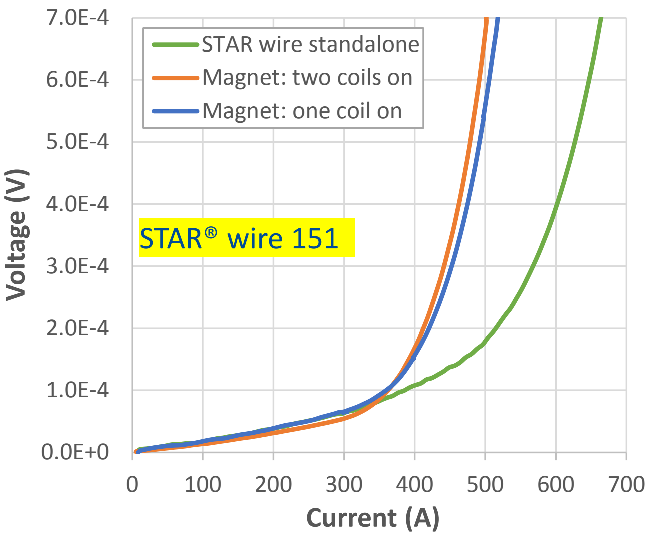




Fermilab

Magnet testing



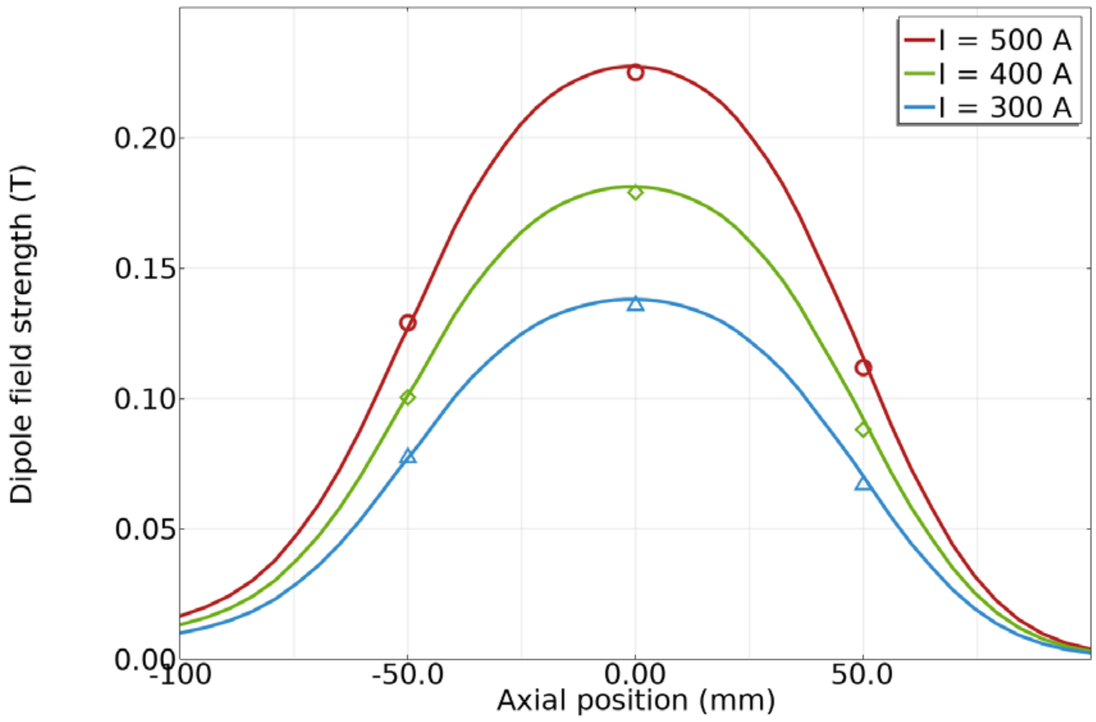


- The magnet testing consisted of four cool-downs from room to liquid nitrogen temperature, ramping the current to measure the resistive transitions and magnetic field measurements
  - first and second cool-downs: the half-coils were powered in series
  - third and fourth cool-down: each half coil was powered individually
- The current was ramped with 5-10 A/s ramp rate to the maximum of ~550 A (I_{max}), which provided enough data points to measure the resistive transitions
- The magnet was not (intentionally) quenched as it was not the objective of liquid nitrogen testing (and the DAQ system would not allow to properly detect and characterize the quenches)
  - these studies are planned for the liquid helium tests with a different system (VMTF)

Magnet testing

Test condition	Run #	I_{max} (A)	I_c (A)	n-value	Peak transfer function (T/kA)	Expected I_c (A)	I_c retention (%)
STAR® wire 131 standalone	2	681	599	8.1	0.192	(595) reference value	(100) reference value
	3	776	595	7.6			
	4	819	600	8.0			
	5	851	600	8.1			
	6	834	596	7.9			
	Minimum	776	595	7.6			
STAR® wire 151 standalone	1	806	620	9.3		(606) reference value	(100) reference value
	2	836	617	9.1			
	3	836	611	9.0			
	4	801	606	8.7			
	Minimum	801	606	8.7			
STAR® wire 131 two coils on	1	502	455	6.4	0.694	446	99.3
	2	551	459	7.6			
	3	510	452	6.4			
	4	531	445	6.6			
	5	531	443	6.4			
	Minimum	531	443	6.4			
STAR® wire 151 two coils on	1	502	425	9.5		455	92.7
	2	551	436	9.0			
	3	510	425	7.6			
	4	531	423	7.6			
	5	531	422	7.5			
	Minimum	531	422	7.5			
STAR® wire 131 one coil on	1	550	453	6.4	0.612	457	99.1
	2	552	454	6.3			
	Minimum	550	453	6.3			
STAR® wire 151 one coil on	1	532	447	9.4		466	95.2
	2	531	444	8.0			
	Minimum	531	444	8.0			

Magnetic measurements



- Array of three Hall probes in the magnet bore
  - positioned to measure the dipole field component on the magnet axis
  - one probe was placed at the magnet center and the other two +/- 50 mm apart
- Calculated (solid lines) and measured (markers) dipole field on the magnet axis are shown
- There is a good correlation between calculated and measured data, which means all the turns retained their geometry after the cool-down and energization

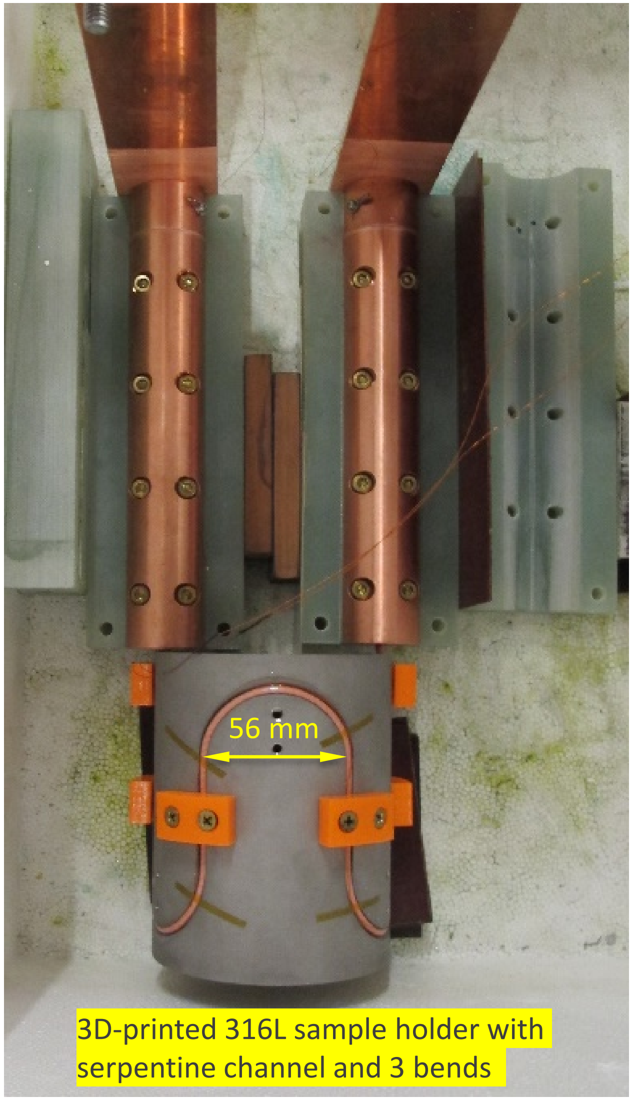
Summary of Phase-I SBIR with AMPeers

- HTS magnet based on COMB technology with a 60-mm clear bore was designed, fabricated and tested in liquid nitrogen at Fermilab using STAR® wires produced by AMPeers
  - the measured critical current retentions for the coils were in 93-99% range, which exceeded the ultimate project target
  - the magnet went through four thermo-cycles and multiple energization cycles without degradation of electrical nor structural properties
- It was the first experimental demonstration of a multi-layer COMB magnet fabricated with ~10 m of REBCO conductor
  - the results indicate that the COMB magnet technology is compatible with the STAR® wires and allows fabrication of magnets with aperture dimensions relevant for future high energy physics applications
  - the FY23 MDP milestone (COMB demonstration with STAR® wires) is complete
- The magnet will get re-assembled with a larger iron yoke and tested in LHe

R&D with CORC® cables: highlights

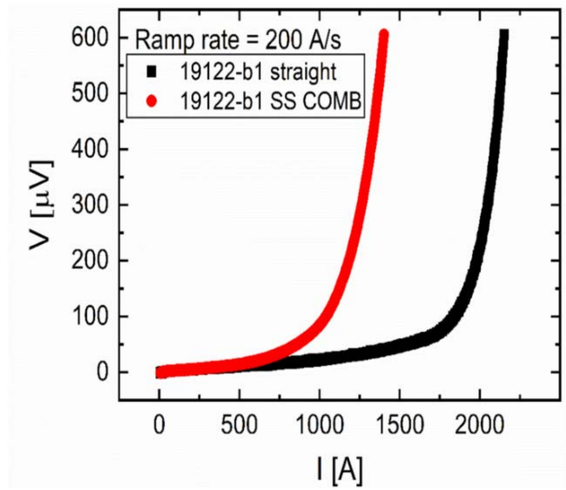
- Extensive studies on short cable samples
  - Problems with large degradation (~50%) discovered while bending them to 50-60 mm diameters in the COMB structure
    - It has not been previously observed on uniaxial-(hairpin)-bent samples
  - Further analysis performed by ACT revealed the issues with drying lubricant and high surface roughness on latest REBCO tapes from Superpower, 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
  - A 25-m long CORC® cable with improved flexibility has been procured
    - Will repeat the bending experiments on short samples before magnet fabrication
- Fabrication and test of COMB coils fitting into 120-mm bore of a Nb_3Sn magnet
  - Standalone magnet test in LN_2 and LHe (2024) with a goal is to reach 5 T in 100-mm bore
  - Hybrid test as an insert in a Nb_3Sn magnet (2025) with a goal is to demonstrate a hybrid HTS/LTS operation

Studies on short CORC® cables

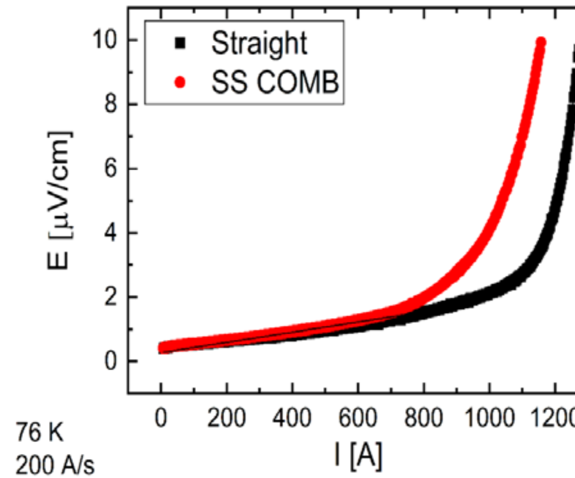


Data courtesy of
Advanced Conductor Technologies
www.advancedconductor.com

Early CORC cables



Later CORC cables



- Critical current of CORC® cables before and after winding into the COMB structure with 100 mm bore:
  - ~56% I_c retention in the early CORC® designs
  - Improved to ~80% I_c retention in the next generation cables