Development and test of the first COMB-STAR magnet

Vadim Kashikhin
MDP meeting
2 August 2023

In partnership with:

SBIR with AMPeers highlights

- Phase-I (completed by now):
  - STAR® wire fabrication by AMPeers LLC – 2x5-m long pieces with 11 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
    - Ultimate target is 90% I_c retention after winding, but >70% is considered acceptable (with the expectation of future improvements)
- Phase-II (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 a 60-mm bore generated by the HTS coil (performance demonstration)
  - Possible hybrid test, if supported my MDP

STAR® wire fabrication

- AMPeers fabricated two 12-mm wide and 50-m long tapes using their advanced MOCVD process
  - laser slit to 2- and 2.6-mm widths
  - copper plated to put the REBCO layer near neutral plane
- Two 5-m long STAR® wires were fabricated by helically winding the tapes around copper former
  - the wires had designations STAR202303131 and STAR202303151
    - will be further referred to as STAR® wires 131 and 151
  - the diameters of STAR® wires 131 and 151 were 2.40 mm and 2.34 mm respectively

REBCO tape with ultrathin substrate

- Advanced MOCVD tape with ~ 4-µm-thick REBCO film and 18-µm-thick substrate.

Narrow ultrathin tape

- Laser slit 12 mm tape to 2 and 2.6 mm width.
- 2 mm for first 3 layers; 2.6 mm for next 8 layers.

Symmetric Tape

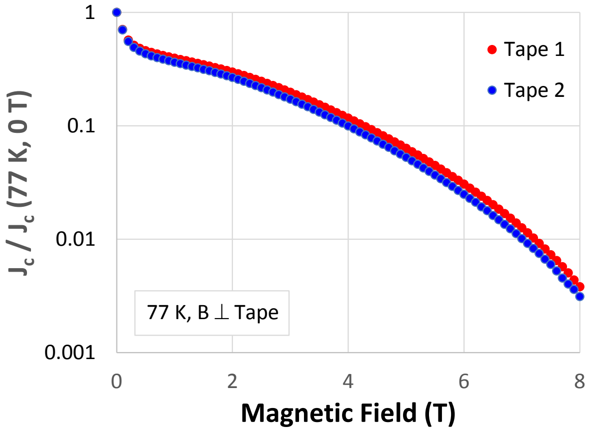
- Cu plating to position REBCO film near neutral plane.

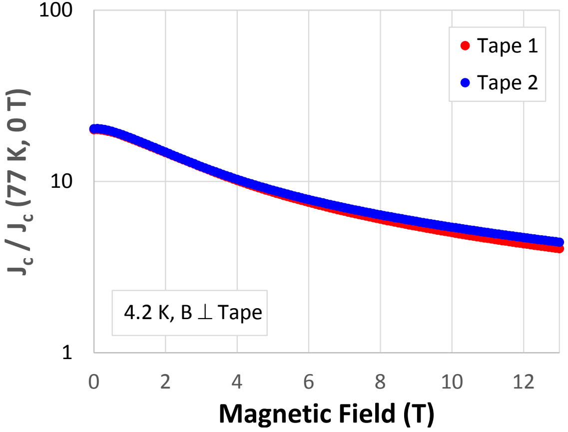
Symmetric Tape Round (STAR®) REBCO wire

- Spiral winding Symmetric Tapes on 1 mm diameter Cu wire former.

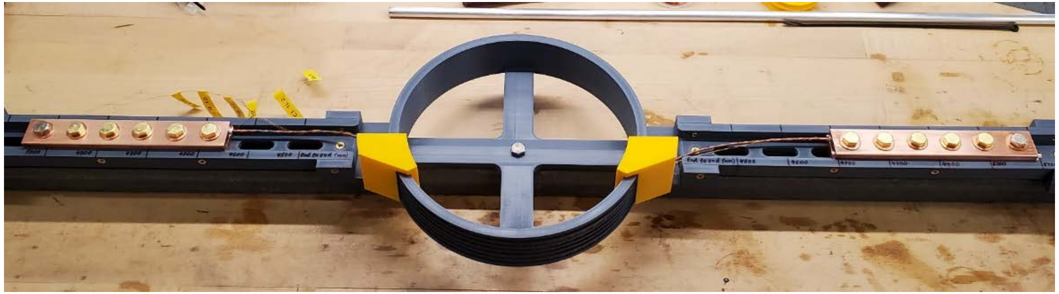
STAR® tape testing

- The critical current of the tapes was measured by reel-to-reel Scanning Hall Probe Microscopy (SHPM)
  - this data was used later to determine the expected critical current STAR® wires made with the Advanced MOCVD REBCO tape strands, in a flat form, after winding on a sample holder and after winding into a COMB magnet
- At 4.2 K, 13 T, the lift factor in critical current of Tapes 1 and 2 was similar at 4.06 and 4.43 respectively
  - the critical current of Tape 1 and Tape 2 at 4.2 K, 13 T are then 1,266 A/4mm and 1,245 A/4mm respectively
- These values are 2.5x the critical current of typical commercial REBCO tapes at 4.2 K, 13 T

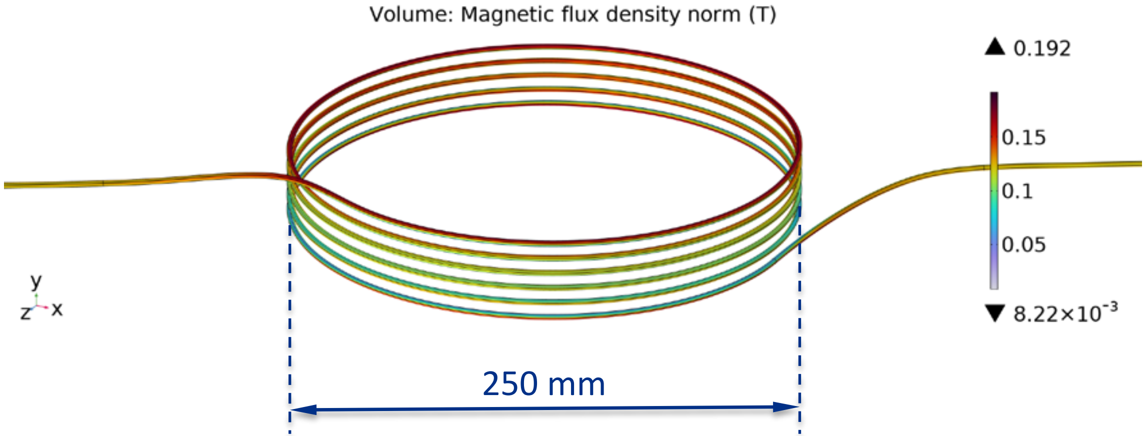


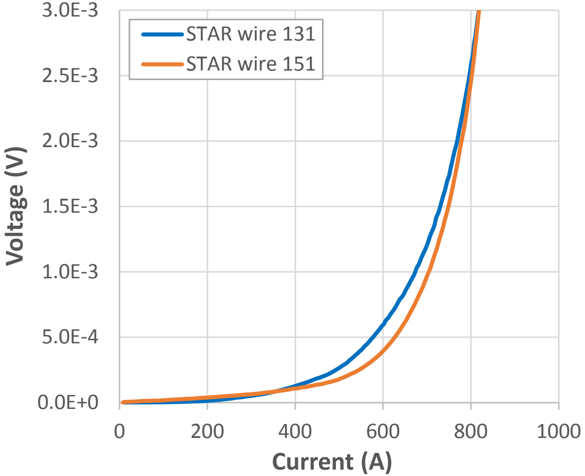


Long STAR® wire testing

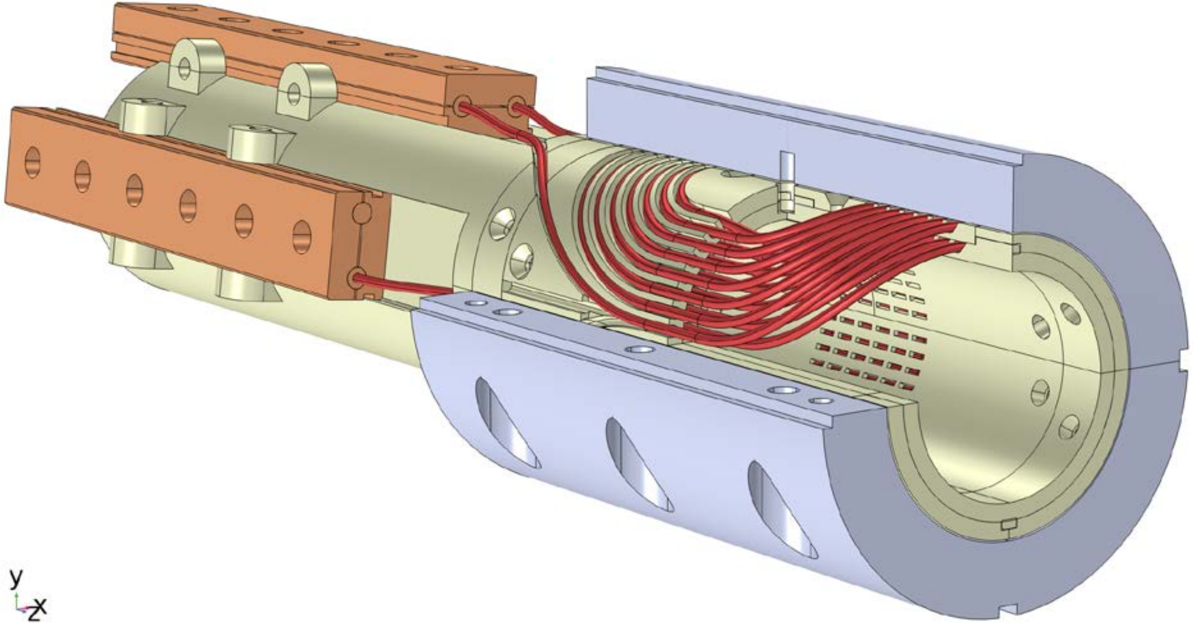


- The 5-m long STAR® wires were tested in liquid nitrogen prior to the coil winding
  - established the reference I_c in 595-606 A range using the electrical field criterion of 0.4 μV/cm
  - the n-value between 8-9





COMB magnet design

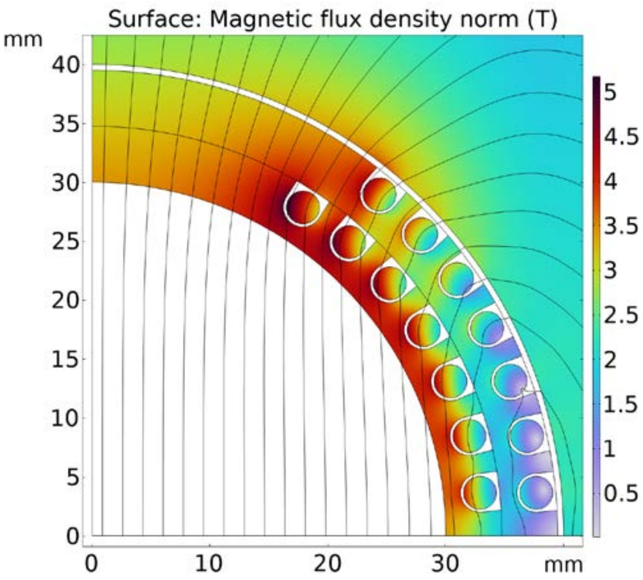


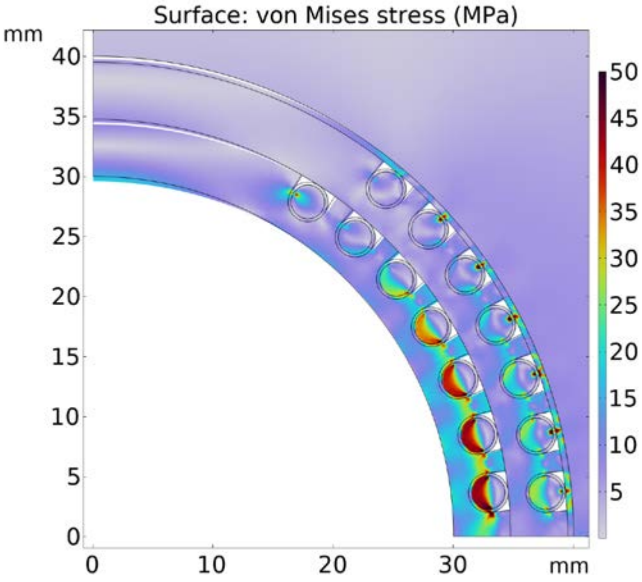
- 60 mm clear bore
- Two half-coils made with two layers of STAR® wire
  - total length of the cable per half-coil is 4.76 m including the leads
  - conductor is wound into a continuous channel without internal splices
- Three copper adapters
  - connect the half-coils together and to the power supply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

COMB coil support structure and mockups

- It was decided not to insulate the STAR® wires to avoid locking in the tapes and to allow them to re-distribute during coil winding
  - electrically insulating structure from ULTEM™ 1010
  - oversized channel to allow the thermal contraction during the cool-down without straining the wire
  - fabricated by Fused Deposition Modelling (3D-printing) with a nearly 100% fill factor
- Although the scope of this project was limited to testing the magnet in liquid nitrogen, the support structure was designed for considerably larger Lorentz forces in liquid helium as this test is foreseen in near future
- Several coil mock-ups were made using a dummy (copper) wire to go through all the steps prior to using the real HTS conductor

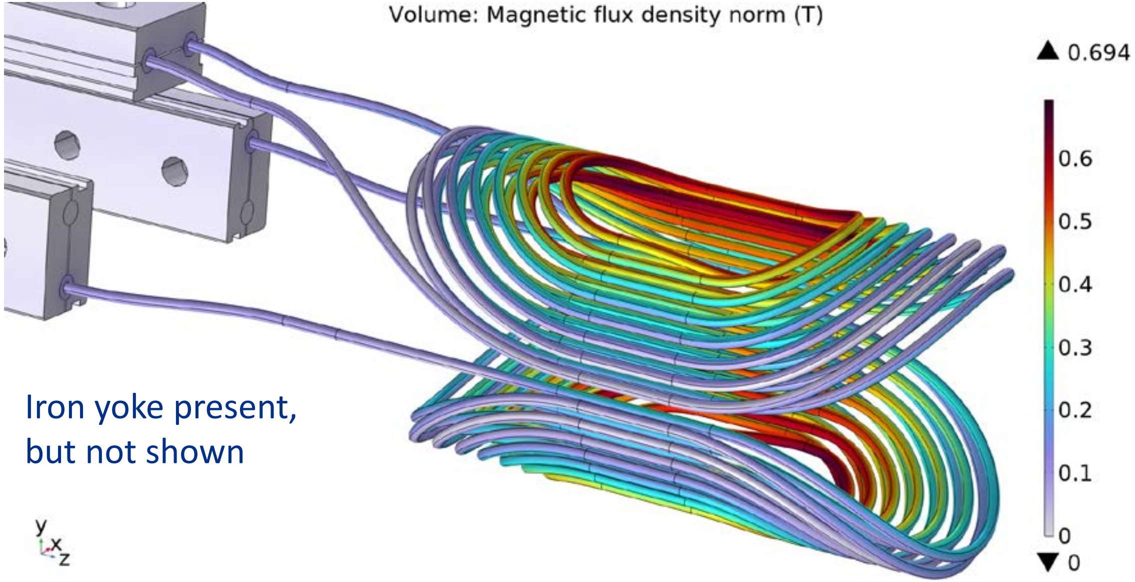
2D magnetic and structural analysis



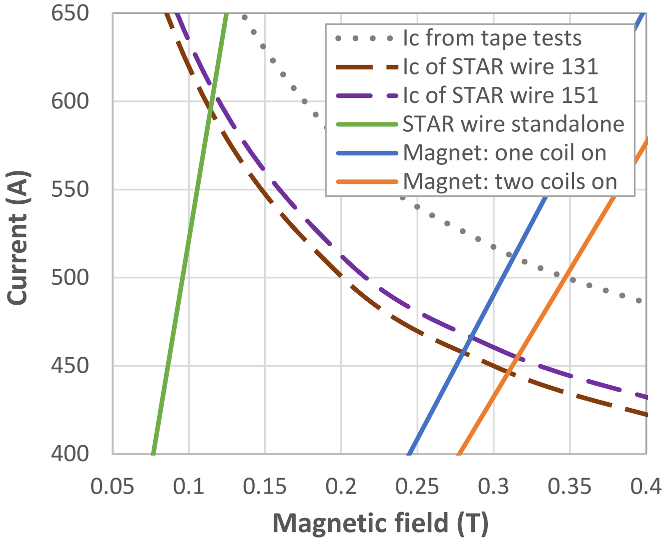


- Maximum current of ~9 kA expected at 1.9 K based on the wire I_c measurements
  - corresponding bore field of ~4 T
  - the peak equivalent stress in the structure is around 50 MPa, in the conductor about 46 MPa
  - the maximum displacement of the pole turn due to the structure deformation under the Lorentz Forces is 0.2 mm

3D magnetic analysis

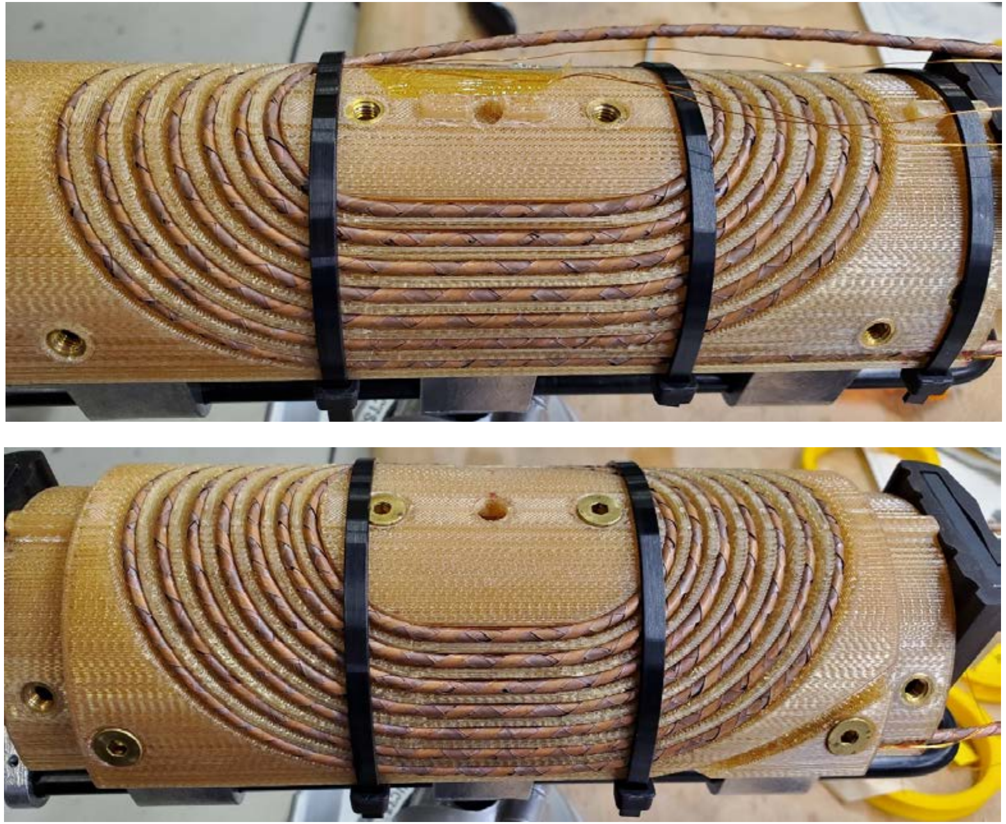


Iron yoke present, but not shown



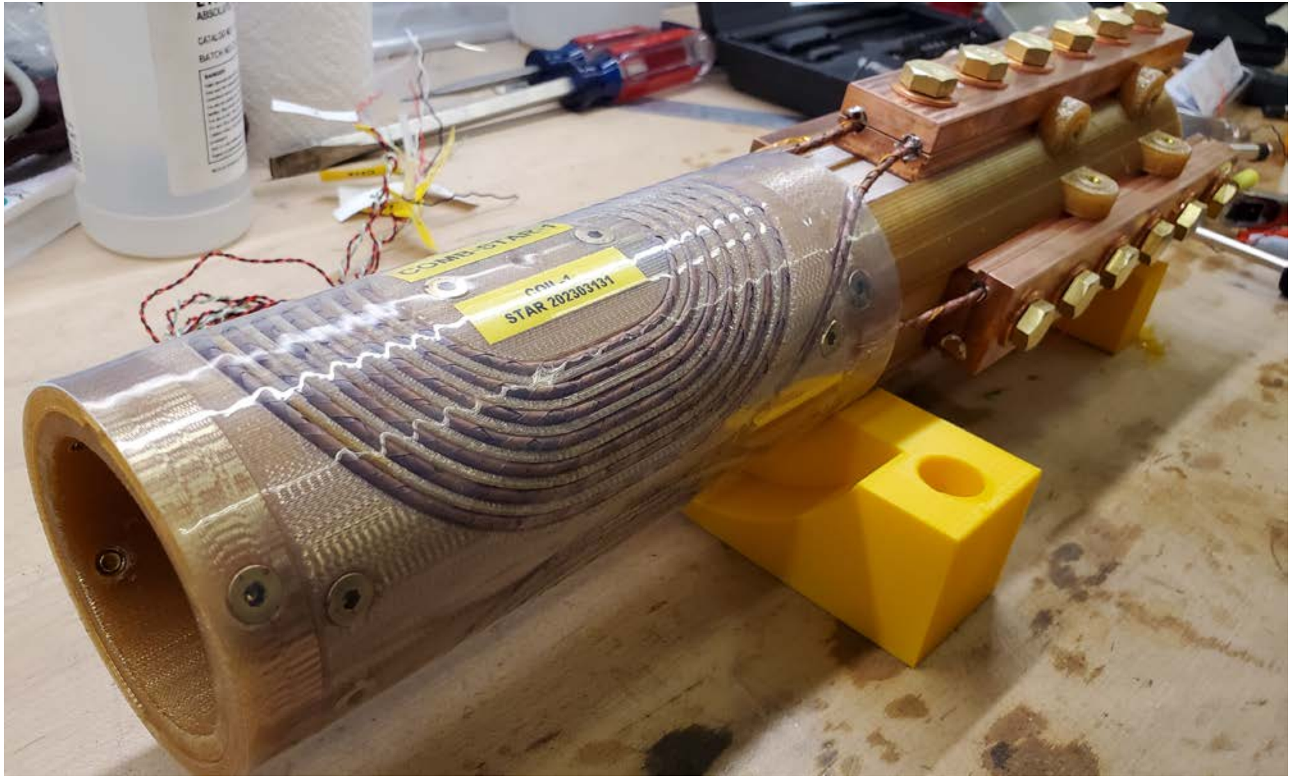
- A complete 3D magnetic model was created as knowing the peak magnetic field on the conductor was necessary for the purposes of this project
  - intersection of the magnet load line with the measured wire characteristic gives the I_c of about 450 A during the magnet test in liquid nitrogen

Magnet fabrication: coil winding



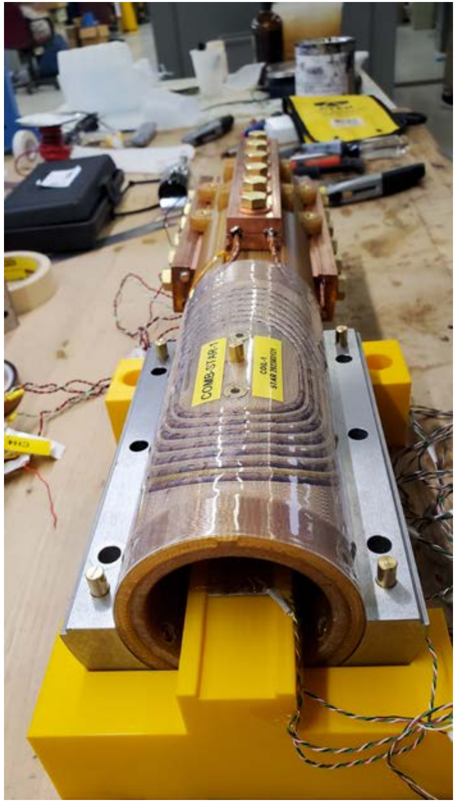
- The magnet fabrication started from manually winding the voltage taps into the support structure of the inner layer of half-coil 1
- It was then followed by manually winding the STAR® wire 131 into the same channel, securing the second layer structure on top of the inner layer and proceeding with the 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

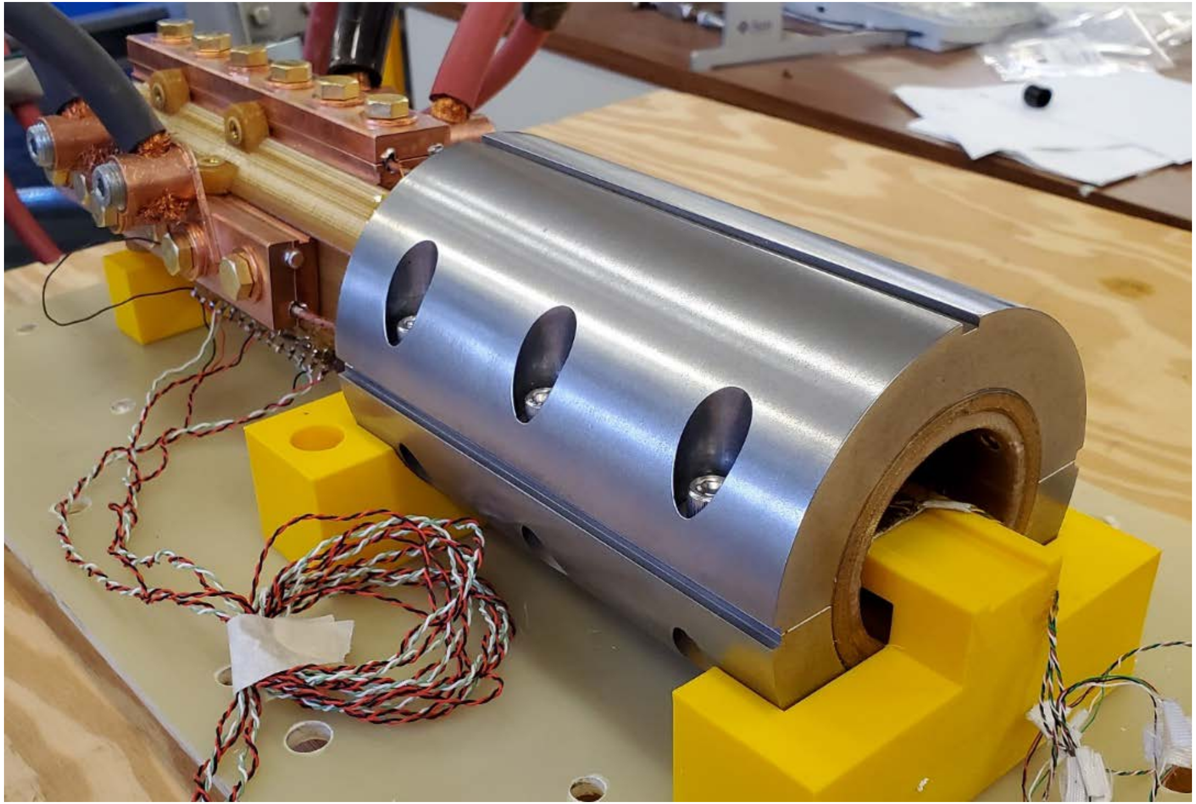
Magnet fabrication: ground insulation and lead support



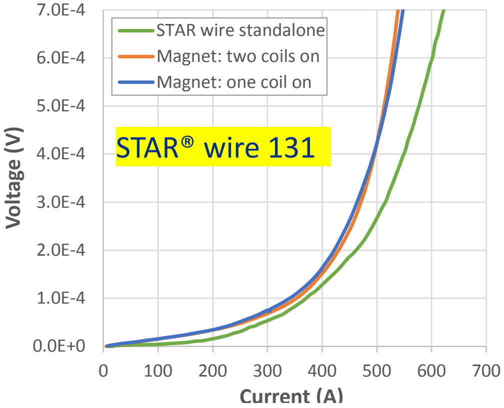
- The two half-coils were assembled with the lead support structure on one end and the retaining ring on the other
- The ground insulation consisted of ~0.5 mm thick polyester was installed around the coils
- The tubes terminating the leads were secured inside of the copper adapters installed in the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

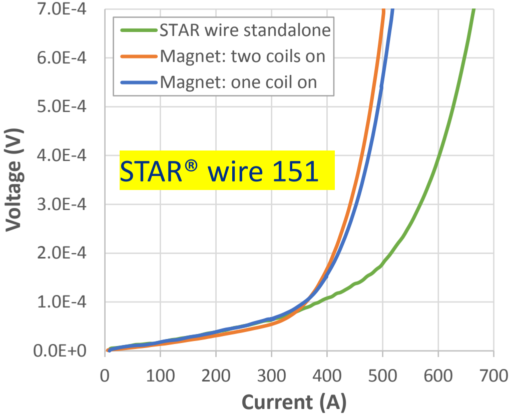
Magnet fabrication: iron yoke and Hall probe array





Magnet testing





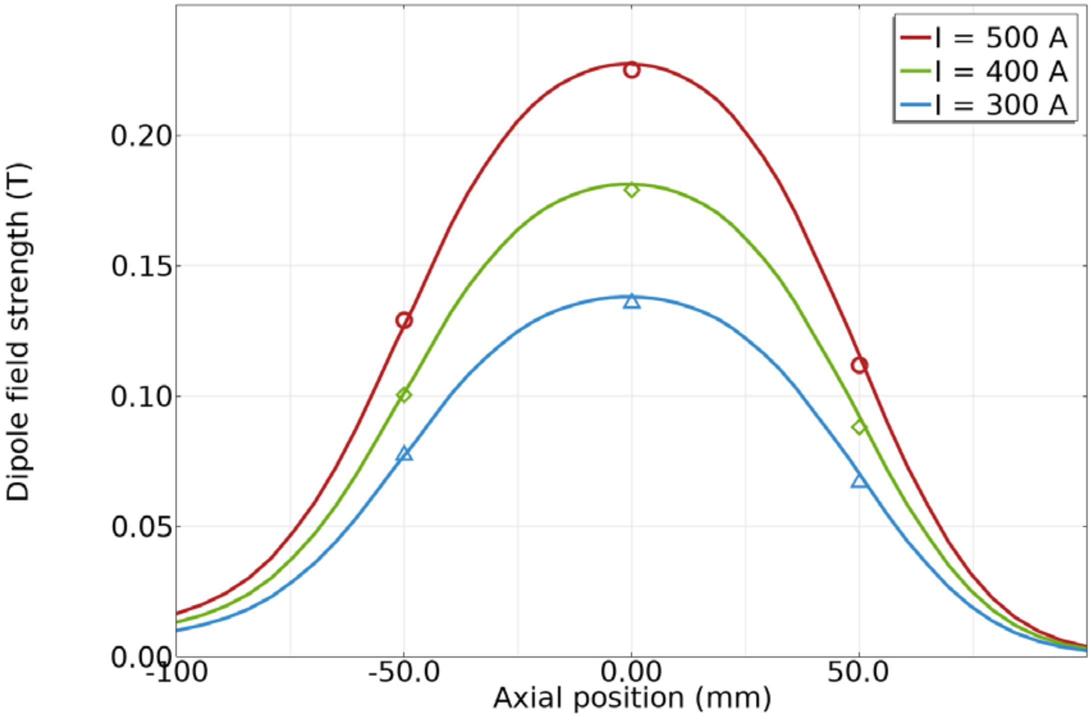
- The magnet testing consisted of four cool-downs from room to liquid nitrogen temperature, ramping the current to measure the resistive transitions and magnetic field measurements
  - first and second cool-downs: the half-coils were powered in series
  - third and fourth cool-down: each half coil was 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			

- STAR® wire 151 performed slightly better in terms of I_c than STAR® wire 131 during the standalone wire testing, however this behavior reversed during the magnet testing
- The measured minimum critical current retentions were 99% and 93% for STAR® wires 131 and 151 correspondingly during the magnet testing
  - STAR® wire 151 demonstrated a slightly higher I_c retention of 95% during the individual coil testing
  - STAR® wire 131 performed similarly during the magnet and coil testing, demonstrating 99% I_c retention
- The n-value of the wire #151 was higher than that of the wire #131 both during the standalone and the magnet testing
  - both wires experienced a reduction in n-value

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

- 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