Accelerator Magnet Development Based on COMB Technology with STAR® Wires

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Introduction

• Fermilab is working on superconducting accelerator magnet R&D under the framework of the U.S. Magnet Development Program (USMDP). An integral part of that program is High Temperature Superconducting (HTS) accelerator magnet development to
  - demonstrate HTS self-fields of 5 T or greater
  - be compatible with operation in hybrid LTS/HTS configuration
    • to probe fields beyond 16 T for future High Energy Physics (HEP) experiments
• RE-Ba$_2$Cu$_3$O$_7$−$\delta$ (REBCO) coated conductors are among the most promising HTS materials for accelerator magnets
  - has high critical field and temperature, but sensitive to strain
    • physics requirements (aperture, field strength, et.) place limits on the use of this material
• To address these limitations, Fermilab is developing the Conductor on Molded Barrel (COMB) magnet technology
  - elegant solution for fabrication of dipole, quadrupole and higher-pole coils with round HTS conductors
  - offering stress management and precise turn positioning to control the magnetic field quality
COMB magnet development with STAR® wires

- COMB technology couples well with Symmetric Tape Round (STAR®) wires from AMPeers LLC
  - state-of-the-art multi-tape REBCO conductors
  - offer unrivaled bending performance suitable for high field magnets with the bore size in 50-60 mm range, which will be needed for future HEP experiments

- One of the most pressing questions for REBCO application in accelerator magnets is what kind of the critical current ($I_c$) degradation can occur in the process of winding the conductor into the support structure with a relevant diameter
  - short STAR® wire measurements performed in the past indicated that the critical current retention was as high as 97% for a 30 mm bending diameter
  - however, a general experience with winding other REBCO conductors suggests that the actual $I_c$ retention due to winding the conductor into the structure may be considerably lower than during short (i.e. hairpin) sample tests due to various contributing factors

- A wire winding and testing experiment, described in this presentation, was needed to draw a definitive conclusion on whether the STAR® wires can withstand the coil winding process and retain their performance
**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
- 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

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![Diagram showing the steps of the STAR® wire fabrication process.

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

2. **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.

3. **Symmetric Tape**
   - Cu plating to position REBCO film near neutral plane.

4. **Symmetric Tape Round (STAR®) REBCO wire**
   - Spiral winding Symmetric Tapes on 1 mm diameter Cu wire former.

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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 test 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
  - $I_c$ in 595-606 A range using the electrical field criterion of $0.4 \, \mu V/cm$
  - the n-value between 8-9 for
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 was 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 redistribute 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 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
• Maximum current of 8.8 kA expected at 1.9 K based on the wire $I_c$ measurements
  - corresponding bore field of 3.9 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

- 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 film 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 (Imax), which provided enough data points to measure the resistive transitions
- The magnet was not (intentionally) quenched
  - it was not the objective of liquid nitrogen testing
  - 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
### Magnet testing

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Run #</th>
<th>$I_{\text{max}}$ (A)</th>
<th>$I_c$ (A)</th>
<th>n-value</th>
<th>Peak transfer function (T/kA)</th>
<th>Expected $I_c$ (A)</th>
<th>$I_c$ retention (%)</th>
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- 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 small reduction in n-value after the coil winding.
Magnetic measurements

- Hall probe array in the magnet bore consisted of three probes
  - positioned to measure the dipole field component on the magnet axis
  - one probe placed at the magnet center and the other two +/- 50 mm apart
- Calculated (solid lines) and measured (markers) dipole field on the magnet axis
- 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

• A COMB magnet 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 is an excellent result for any kind of HTS conductor
  - the magnet went through four thermo-cycles and fourteen 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

• Preparations for testing this magnet in liquid helium are under way