ELECTRO-MECHANICAL CHARACTERIZATION of REBCO CONDUCTORS AND JOINTS for use in NHMFL 32 T ALL SUPERCONDUCTING MAGNET


The funding for this research was provided by Florida State University and the Nation Science Foundation.
Characterization of YBCO Coated Conductors is done in support of the design and construction of a 32T all-superconducting magnet at the NHMFL.

The test program serves to;
1. Document the variability in production grade conductors.
2. Confirm the performance and margins of safety.
3. Identify potential problems areas.
OUTLINE

Background
- Magnet and conductor description

Physical Dimension Measurements
- Measurements of thickness and width of conductor with optical microscope

Tensile Tests
- 77K and 4 K Stress-Strain Curves of conductors w/ varying thickness of copper
- $I_c$ vs Axial Strain, Tensile and Fatigue Tests
  - $T = 77$ K, Single conductors and Lap joints.
  - Measure $I_c$ as a function of applied tensile strain.
  - Fatigue Tests to confirm retention of $I_c$ as a function of cyclic stress.

Conclusions and Future Work
BACKGROUND

Magnet system
- 32 T, 4.2 K, 34 mm cold bore
- Uniformity over 1 cm DSV 500 ppm
- Stored energy 8.3 MJ
- Expected cycles/20 years 50,000

Inner coils
- Pancake wind
- Dry wind
- Insulated co-wind steel reinforcement
  - Average current density 193/170 A/mm²
  - Copper current density 428 A/mm²
  - Stress in windings 363/378 MPa
  - REBCO conductor length 10 km

Outer magnet
- 15 T, 250 mm bore, Nb3Sn/NbTi, 7.0 MJ
- Commercial supply

Thickest surround copper available ~100 um corresponds to suitable operating current 170 – 180 A.
MATERIAL:
- Production grade YBCO superconducting composite tape produced by Superpower Inc.
- A series of conductors with variable thickness copper stabilizer (range 40 µm to 100 µm)

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<td>4.13 x 0.13</td>
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<td>SP26</td>
<td>124</td>
<td>4.15 x 0.15</td>
<td>50</td>
<td>2.18</td>
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**Cu thickness = average tape thickness - nominal hastelloy thickness**

End view photo of SP07 conductor shows Surround Cu Stabilizer (SCS) and Hastelloy substrate.
Measurement of conductor thickness profile using inspection microscope

40 um total copper

With 40 µm copper, conductor is relatively flat, minimum dog-bone.

110 um total copper

With 100-110 µm copper, conductor is thick in center by ~ 10%.

Additional copper for protection is found to be accompanied by a distribution in conductor thickness, resulting in a decrease in packing factor, reduced radial thermal conductivity, and reduced structural compactness.
YBCO Tensile Testing

5-10 % increase in strength from 77 K to 4 K.
77K YBCO Reference Stress-Strain Curves

- **T = 77 K**
- **Hastelloy**
  - $E = 210 \text{ GPa}$

- **50:50 Hastelloy:Cu**
  - $E = 165 \text{ GPa}$
  - Calc by ROM

- **Total Cu Thickness**
  - 42\text{µm}
  - 70\text{µm}
  - 100\text{µm}
77K YBCO qualification Stress-Strain Curves

Production Conductor for 32 T
Lap Joint Reference Data

Critical Current (A)

Axial Strain

SP 26 - Ic vs Strain
Self Field, T = 77 K
1 e-6 V/cm criterion
Lap Joint Test Observations

• The 10 to 15 % variation in Ic is approximately the same as observed in any single conductor piece length.

• The ~ 35% difference between the two materials may be more representative of the variation in Ic at 77 K that is likely to occur from piece to piece in production length conductors.

• The average lap joint resistance for the 40 mm lap joints is independent of the axial tensile stress

\[
\begin{align*}
\text{SP07} & \sim 50 \text{ nano-ohms} \\
\text{SP26} & \sim 25 \text{ nano-ohms}
\end{align*}
\]

• A few tests were carried out to fracture and in all cases the fracture occurred at the grip end indicating excellent lap joint axial tensile strength and shear strength.

• The 60 mm long lap joint Ic is about equivalent with single conductor, at around 0.5% strain both start to exhibit degradation.
Lap Joint Tests

The strain is calculated for the region of interest from the applied tensile force.

32 T lap joints are 120 mm long.
Ic vs Strain, Conductor and Lap Joint Fatigue Testing

- Teflon clamp plate - Used for Lap Joint tests
- G-10 Alignment Test Bed
- Bolt-together Cu Grips For Current and Force application
- YBCO Tape Tensile or Lap Joint Specimen

The magnet is designed for a fatigue life of 50 k cycles at 0.4 % Strain.
**FATIGUE RESULTS**

<table>
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<tr>
<th>Spec.</th>
<th>% Design Strain</th>
<th>Max Cyclic Strain, %</th>
<th>Ic at Peak Cycle Strain</th>
<th>Comments</th>
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<td>Single Conductors</td>
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All four single conductors survived 50 k cycles with no sign of degradation.
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Three of four lap joints failed (Ic degradation) prior to 50 k cycles.
CONCLUSIONS

1. R&D efforts at NHMFL, in collaboration with Superpower, enabled the determination of conductor specifications for this challenging magnet project.

2. The critical specifications for the conductor are difficult to achieve and the production grade conductors requires careful inspection and qualification testing.

3. The tensile strength of the production conductors meet requirements.

4. The $I_c$ of the production conductors and joints meets requirements.

5. The conductor’s superconducting and strain performance show no signs of degradation over the expected fatigue life of 50 k cycles at 20% higher strain level than the maximum operating strain.

6. Only one lap joint has been qualified to meet the fatigue life requirement of 50 k cycles at the design strain.

7. Three lap joints have failed after approximately 30 k cycles at 20% higher than the design strain fatigue test.
FUTURE WORK

Conduct more fatigue tests to establish the fatigue life safety margin.

Confirm the electro-mechanical performance of both the conductor and joints at longer fatigue lives. Factor of safety on strain is probably a more severe test than necessary.

Specifically:
Conduct several more 77 K Fatigue tests at Design Strain for $1.0 \times 10^6$ cycles.

THANK YOU FOR YOUR ATTENTION