Fabrication and testing at 77 K of large-aperture REBCO pancake coils for a high-field SMES solenoid

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Presentation outline

• Specification of REBCO tape
• Coil Parameters
• Fabrication of the single pancake coils
• Preparation of the double pancake assembly
• Test results of double pancake coils at 77 K
• Summary
Evaluation of REBCO tape

- **Type**: SCS12050-AP
- **Total length of the tape**: ~ 7 km
- **Width of the tape**: 12.1 mm
- **Thickness of Hastelloy substrate**: 50 μm
- **Thickness of copper stabilizer**: 65 μm or 100 μm
- **Thickness of the tape**: 0.12 mm or 0.16 mm (depending on the thickness of the copper stabilizer)
- **Piece length**: 50 m to 400 m (may include multiple number of factory-made splices)
- **Transport properties at 77 K, self field**: Minimum $I_c > 300$ A; Average $I_c > 320$ A
Coils are graded to improve maximum field strength and mechanical stability margin.

Conductor + SS ribbon combination (in a single pancake coil)

Type A: Cu in HTS (65 μm) + SS (25 μm)
Type B: Cu in HTS (65 μm) + SS (50 μm)
Type C: Cu in HTS (100 μm) + SS (25 μm)
Type D: Cu in HTS (100 μm) + SS (50 μm)

High current density (conductor with lesser Cu) + high mechanical strength (thicker SS)
### Coil parameters

#### Inner pancake coil
- **Inner diameter**: ~101 mm
- **Outer diameter**: ~194 mm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
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<tbody>
<tr>
<td>Number of inner coils</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Type of the coil</td>
<td>B</td>
<td>D</td>
</tr>
<tr>
<td>Thickness of Cu in the tape (µm)</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Thickness of SS ribbon (µm)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Number of coils</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>Nominal number of turns per coil</td>
<td>270</td>
<td>215</td>
</tr>
<tr>
<td>Nominal length of tape per coil</td>
<td>125</td>
<td>100</td>
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</table>

#### Outer pancake coil
- **Inner diameter**: ~223 mm
- **Outer diameter**: ~297 mm

<table>
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<th>Parameter</th>
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<th>Value 2</th>
<th>Value 3</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>Type of the coil</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Thickness of Cu in the tape (µm)</td>
<td>65</td>
<td>65</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Thickness of SS ribbon (µm)</td>
<td>25</td>
<td>50</td>
<td>25</td>
<td>50</td>
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<tr>
<td>Number of coils</td>
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<td>4</td>
<td>4</td>
<td>4</td>
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<td>Nominal number of turns per coil</td>
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<td>220</td>
<td>208</td>
<td>182</td>
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<tr>
<td>Nominal length of tape per coil</td>
<td>211</td>
<td>180</td>
<td>170</td>
<td>149</td>
</tr>
</tbody>
</table>
Pancake coil winding

- In each pancake coil, the HTS layer of the tape faces inward towards the winding bobbin.
- Spools of REBCO tape and SS ribbon were loaded with low tension during the winding process.
- Tape was visually inspected during the coil winding (first measure of quality assurance of the coils).
- Multiple voltage taps (after first 10 turn and then after 25, 50, 75 turns etc..) were installed for the detailed diagnostics of the coil sections at 77 K.
- Thin layer of epoxy painted on the top and bottom coil surfaces keeps the coil layers physically intact.
Demonstrated a technology for low resistance REBCO splices for application to HTS magnets

Implemented it in the construction of the pancake coils and in the magnet assembly
Preparation of a double pancake coil

Double pancake coil assembly (after installing spiral shaped splice)

- Mylar spacer (~127 μm thick) provides an electrical insulation between the pancake coils
- Spiral shaped splices placed on the inner surface connects a pair of coils in the double pancake coil assembly
- Splice overlap length: 15 cm (inner double pancake assembly)
  : 20 cm (outer double pancake assembly)
Preparation for the 77 K test

Double pancake coil assembly (clamped between a pair of G-10 discs)

- DPC unit is mounted to an electrically insulated SS tube
- 3 mm thick Cu disk placed on the top and bottom of the DPC enables thermal conduction

Double pancake coil assembly (after securing multiple voltage taps)
Test results at 77 K: double pancake coils

Two pancake coils are connected in series

- \( I_c \) of the companions coils range from 70 A to 100 A for the inner DPC assemblies and 75 A to 110 A for the outer DPC assemblies.
Test result at 77 K of a series of outer single pancake coils

- No correlation exists between the $I_c$ of the coil and the tape(s) constituting coil at 77 K.
Highlights of the 77 K test results

**Type 1:**
Companion coils with identical electrical characteristics at 77 K

**Type 2:**
Performance of a DPC is limited by one of the companion coils.

Higher $I_c$ at 77 K of the coils does not translate into an identical coil performance at 4 K
Significance of 77 K test of SMES coils

Type 3:
Inferior performance of the DPC is due to the bad sections in one of the companion coil.

Detailed diagnosis of the coil sections played a critical role to ensure the quality of tapes and the winding and assembly process of the pancake coils.
Test results at 77 K of the spiral splices

- Resistance per splice is less than 7.5 nano-ohms
- Splice resistance is seemingly sensitive to the surface conditions of tapes of different production batches and contact resistance between the layers constituting the tape.
- Splice resistance is practically not sensitive to the resistance of the stabilizer layer
Summary

- Forty six pancake coils, including twenty eight inner coils and eighteen outer coils were built.
- These coils were assembled into twenty three double pancake coil units and tested successfully at 77 K.
- 77 K tests played a crucial role in the QA process for the prototype ~ 24 T solenoid magnet.
- The technology for the low resistance lap joint and spiral shaped splices has been demonstrated and successfully implemented in the construction of the coils.
- The detailed diagnosis of the coil sections provides an additional check on the quality of tapes, winding and assembly process of the coils.
Acknowledgement

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