High Field HTS SMES Solenoid

Part I : Relevance, Overview & Lessons Learned


Part II : Coil Construction & 77 K Test (Lakshmi)
Relevance of SMES Solenoid to HEP High Field Magnet Program

- High field: 25 T
- Large aperture: 100 mm
- Large stresses: 400 MPa
- Large number of coils: 48
- Significant HTS per coil: 100 m to over 200 m
- Large use of HTS: over 6 km, 12 mm wide
- Associated technology: quench protection, etc.

- There has been no such HTS magnet project in the past
- Aggressive parameters – BNL/SMD appreciated that – but didn’t want to miss the chance of learning from this major opportunity
- Significant portion of the technology developed & lessons learned are directly applicable to very high field magnets for HEP, etc...
### Parameters of HTS Solenoid

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored Energy</td>
<td>1.7 MJ</td>
</tr>
<tr>
<td>Current</td>
<td>700 Amperes</td>
</tr>
<tr>
<td>Inductance</td>
<td>7 Henry</td>
</tr>
<tr>
<td>Maximum Field</td>
<td>25 Tesla</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>4.2 Kelvin</td>
</tr>
<tr>
<td>Overall Ramp Rate</td>
<td>1.2 Amp/sec</td>
</tr>
<tr>
<td>Number of Inner Pancakes</td>
<td>28</td>
</tr>
<tr>
<td>Number of Outer Pancakes</td>
<td>18</td>
</tr>
<tr>
<td>Total Number of Pancakes</td>
<td>46</td>
</tr>
<tr>
<td>Inner dia of Inner Pancake</td>
<td>102 mm</td>
</tr>
<tr>
<td>Outer dia of Inner Pancake</td>
<td>194 mm</td>
</tr>
<tr>
<td>Inner dia of Outer Pancake</td>
<td>223 mm</td>
</tr>
<tr>
<td>Outer dia of Outer Pancake</td>
<td>303 mm</td>
</tr>
<tr>
<td>Intermediate Support</td>
<td>13 mm</td>
</tr>
<tr>
<td>Outer Support</td>
<td>7 mm</td>
</tr>
<tr>
<td>Width of Double Pancake</td>
<td>26 mm</td>
</tr>
</tbody>
</table>

High field and big radius create large stresses (~400 MPa)
Conductor Specifications

12 mm wide

- Formal specs at 77 K
- Informal specs at 4 K (mutually agreed upon)
  - Minimum $I_c (@4K, 8T) : 700$ A (irrespective of angle)
  - Ends of each cut saved for 4 K, in-field measurements

Cu: 65 $\mu$m and 100 $\mu$m
- for electrical and mechanical grading

Hastelloy: 50 $\mu$m

Insulation: SS Tape
- 25 $\mu$m and 50 $\mu$m
HTS is not a production conductor yet and was treated that way

- Conductor inspected physically during the coil winding
- Each coil was tested at 77 K with many v-taps to find weak links

Few issues were discovered and decision was made on the case by case basis

Coil construction and 77 K tests in the next presentation
**Inner and Outer Coils**

**Inner Coil** (28 pancakes)
- 102 mm id, 194 mm od

**Outer Coil** (16 pancakes)
- 223 mm id, 303 mm od

Multiple leads to bypass weaker or defective pancakes

*(plan for the worst case scenario: only one test run)*
High Field HTS Magnet Test Results
100 mm bore, 12 mm ReBCO SMES Coil

2 pancakes
1140 A, 4K

12 pancakes
760 A, 4K, 11.4 T

46 pancakes
350 A, 27K, 12.5 T

Peak fields higher
12 pancakes, each made with 100 meter of 12 mm wide ReBCO Tape

- Reached ~ 11.4 T at 760 A
- Energy extracted and dumped in the external resistor
- 77 K re-test showed no degradation in coil performance
Record field in a superconducting magnet at a temperature of 10 K or higher

350 Amp
12.5 Tesla
@ 27 K

The Event

Large Aperture, High Field Coil
id:100 mm, od:300 mm, >6 km of 12 mm tape
The Event

- We tested the solenoid at several temperatures between 20-80 K, including the 350 Amp (12.5 T) test run

- During one such test, the system tripped due to a data entry error at ~165 A – well below the current reached earlier

- The trip resulted in large resistive voltage in a few sections of the inner coil, together with the loss of most instrumentation

➤ Differences in opinion on what should be the next step
Major issues with the two sections consisted of “leads, splices and pancake coil(s)”
Physical Inspection of the Inner
Lessons Learned
(personal thoughts)

- Technical reviews with subject matter experts are important
- In superconducting magnets (particularly demanding magnets with a new technology), more than one test and iterations are required. They must be part of the program
- The team that constructs the device is usually in the best position, at least in the first round, to debug and fix it before the magnet is out
- Above statements may be obvious but are important. Such reasoning should be understood and explained to collaborators and funding agencies - irrespective of the reasons
- Multiple failures, either real or perceived, in devices made with new material is not good for anyone, and may be detrimental to the field
SUMMARY

- Even though the design goals - high field (25 T), big aperture (~100 mm), new conductor (ReBCO), large hoop stresses (~400 MPa) - were much to aggressive to be achieved in first attempt, the R&D opportunity was beneficial in advancing the technology.

- Demonstration of 12.5 T at 27 K is a significant milestone and is a demonstration of the potential of ReBCO.

- This is the first time that such a large amount of HTS (over 6 km of 12 mm wide tape) has been used in a high field application.

- From a pure scientific perspective, there is still lot to learn from the device made - setbacks are part of R&D, shouldn’t be the end. However, the experience and several aspects of technology developed should be relevant to high field magnets for FCC.