High Field HTS SMES Coil


Brookhaven National Laboratory, NY, USA

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From our sponsor:

... ARPA-E’s mission is to catalyze and accelerate the creation of transformational energy technologies by making high-risk, high-reward investments in their early stages of development.

This presentation summarizes an aggressive R&D where we demonstrated a higher field and a higher operating temperature energy storage coil than proposed before ...

- 12.5 T SMES coil operating at 27 K
Superconducting Magnet Energy Storage System with Direct Power Electronics Interface

Project Goal:
- Competitive, fast response, grid-scale MWh superconducting magnet energy storage (SMES) system

Team member major contributions:
- ABB: Power electronics, Lead
- BNL: SMES coil and Superconducting switch
- SP: 2G HTS manufacture and improved production
- UH: Wire manufacturing process research
Focus of the Presentation

Technology for High field HTS SMES coil

– Design, construction and test results

- For economic viability of a large scale energy storage system, cost of coated conductor must come down significantly (smart designs can help)

- The technology developed could already be applied to special purpose storage system and other applications
SMES Options with HTS

- High Temperature Option (~65 K): Saves on cryogenics (Field ~2.5 T)
- High Field (~25 T) Option: Saves on Conductor (Temperature ~4 K)

Previous attempts:
- LTS: up to ~5 T
- HTS: few Tesla (high temp. to save on cryo)

Our analysis on HTS option:
- Presently conductor cost dominates the cryogenic cost by an order of magnitude

High field HTS could be game changer:
- Very high fields: 25-30 T (E $\propto$ B$^2$)
- Only with HTS (high risk, high reward)

Also: A medium field and medium temperature option
(a new record 12.5T@27K demonstrated, thanks to arpa-e)
The Basic Demo Module

Aggressive parameters:

- **Field**: 25 T @ 4 K (more than ever)
- **Bore**: 100 mm (large)
- **Hoop Stresses**: 400 MPa (>2X)
- **Conductor**: ReBCO (evolving)
**Conductor – ReBCO Tape**

**Superconducting Magnet Division**

**SuperPower Inc.**

A Furukawa Company

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**HTS tape: angular dependence**

*Measurements at NHMFL (earlier sample)*

- **SMES specs (12 mm):**
  - >700 A @ 4K
  - (at any angle)

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**12 mm wide ReBCO tape with high strength hastelloy substrate**
A torus would consist of a large number of solenoid module
Field becomes parallel => less amount of conductor required
Large Scale SMES Concept (2)

Radius: 5 meter, height ~5 meter
Consists of double pancakes – same as in demo
10 rings, each consisting of ~1000 double pancakes

GJ scale GRID storage system that can fit in a room!

- Moreover, a small $B_\perp$ ($<0.5$ T) for a large $B_{\parallel}$ (30 T) means a major reduction in conductor cost (~1/5 with an optimized HTS)
### Design Parameters of BNL Demonstration Coil

<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)
Cross-section of Coil and Support Tube

Conductor used (ReBCO from SP):
- Well over 6 km (12 mm wide tape)

Inches [mm] units

Stainless Steel Support Tubes

Inner Stainless Steel Tubes for Assembling Pancakes
Grading to Optimize Magnetic and Mechanical Design

Adjusted for grading:
- Cu thickness in HTS tape (65 and 100 μm)
- SS tape thickness (65 and 100 μm)
  (more copper in ends; more SS in center)

End Result:
✓ Improved performance
➢ Better mechanical structure and reduced Bperp

Number of turns per pancake (for same coil i.d. and o.d.)

Initial 1.7 MJ Design
Optimized 1.7 MJ Design
HTS Single Pancake

- High strength HTS tape, co-wound with SS tape (for insulation and added strength)
- Thickness of SS tape and copper on HTS adjusted to optimize the performance

Outer: ~210 meter 12 mm tape (258 turns)
Two Pancakes Connected with Spiral Splice Joint
Inner and Outer Coils Assembled

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

Outer Coil
(223 mm id, 303 mm od)
18 pancakes

Total: 46 pancakes
Coils, Test Fixtures and Support Structure

Pancake coils: inner and outer

11 T, 760 A coil and fixture

77 K Test Fixture for outer

Outer Support Tube for Inner

Outer Assembly Tube for Outer

Inner Assembly Tube for Inner

Copper Discs

Outer Support Tube for Outer
Inner and Outer Coils

Inner (in support tube)  Outer (prior to support tube)
Final Assembly

Outer inserted over inner coil

SMES coil in iron laminations

High Field HTS SMES Coil
R. Gupta, ..., BNL
CCA2014, Jeju, S. Korea, Dec. 1, 2014
Test Results

Invited Presentation given at CCA 2014, Jeju Island, Korea, Nov. 30 - Dec. 03, 2014.
Critical current (1 µV/cm)

Two single pancakes powered in series.
**77 K Test of a Series of Double Pancakes (outer)**

Two pancakes powered in series

[Graph showing data for outer double pancake coils]

<table>
<thead>
<tr>
<th>Type</th>
<th>Measured Value</th>
<th>Beyond Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - CC(160 μm) + SS (25 μm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B - CC(160 μm) + SS (50 μm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C - CC(120 μm) + SS (25 μm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D - CC(120 μm) + SS (50 μm)</td>
<td></td>
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</table>

Four types to achieve grading (see slide 12)

Single pancakes powered alone

[Graph showing data for single pancake coils]

Higher $I_c$ in coil at 77K, however, doesn't necessarily translate into a higher $I_c$ at 4K (present conductor)

MT23, Lakshmi, et al

Double Pancake 77 K Test

2 pancakes with similar critical currents

2 pancakes with very different critical current

one pancake good and other pancake defective

Note: Thorough 77 K test of each pancake was an important part of a series for QA
High Field HTS SMES Coil High Field Tests

- 2 pancakes, 1140 A, 4K
- 12 pancakes, 760 A, 4K, 11.4 T
- 46 pancakes, 350 A, 27K, 12.5 T

Peak fields higher
Nominal design current: ~700 A

The option of operating over a large range (the benefit of HTS)

Nominal design current: ~700 A

Ramp rate up to 10 A/s
12 Pancake Coil Test

Charge

Quench

11.4 T in 100 mm bore

- Energy (~125 kJ) extracted and dumped in the external resistor.
- 77 K re-test (after quench) showed that the coil remained healthy.
Preparation for the Final Test

High Field HTS SMES Coil  R. Gupta, ..., BNL  

Invited Presentation given at CCA 2014, Jeju Island, Korea, Nov. 30 - Dec. 03, 2014.
Record field/energy density in a superconducting magnet at a temperature of 10 Kelvin or higher
Status of ARPA-E SMES Coil

• The design goal was: 1.7 MJ at ~700 A with 25 T at 4 K.
• We tested the unit at several temperatures between 20-80 K, including the 350 Amp (12.5 T) test at 27 K.
• During one such test, the system tripped due to a data entry error at ~165 A – well below the earlier magnet test current.
• This trip resulted in damage to a few current leads in the inner coil. It appears that there was arcing, perhaps during shut-off.
• Since the test was not limited by the field performance, the SMES coil still has the potential to reach higher field after repair.
BNL HTS Quench Protection Strategy

A multi-pronged strategy developed and used at BNL in various HTS programs:

- Detect early and react fast with an advance quench protection system

1. Developed an advanced low-noise electronics and noise cancellation scheme to detect pre-quench voltage (phase) where HTS coils can operate safely
2. Fast energy extraction with electronics to handle high isolation voltage (>1kV)
3. Use inductively coupled copper discs for fast energy extraction

- Drawback: additional energy loss during charging and discharging

Twelve coil test at 4K (~12 T, ~120 KJ)

![Graph showing voltage versus current for a HTS coil test.](image)
Copper Discs for Energy Extraction

Inductively coupled cooper discs between two double pancakes

This fast extraction provides initial margin at the critical time

Most action in milliseconds


**SUMMARY**

- Even though we didn’t reach the aggressive design goal of 25 T, in a big aperture (~100 mm) superconducting magnet with large hoop stresses (~400 MPa) in the first attempt, we did learn several things in the process beside creating new records.

- This provided a significant experience in using a large amount of coated conductor (over 6 km of 12 mm wide tape) in a demanding 4K, high field and a high stress application.

- Demonstration of a 12.5 T SMES coil at 27 K is a promising application of the coated conductor. The earlier most ambitious proposal was for 11 T at 20 K by Chubu Electric and Furukawa.

- The experience and technologies developed should also be useful in other applications, such as in NMR, ADMX, accelerators, etc.