HTS Activities and Recent Progress at BNL

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July 31, 2015
• HTS magnet R&D over a wide range:
  – High field, Medium field and low field (high temperature)
  – Many geometries – solenoid, racetrack, cosine theta, curve coils

• Number of HTS coils/magnets designed built & tested:
  – Well over 150 HTS coils and well over 15 HTS magnets

• Type of HTS used:
  – Bi2223, Bi2212, ReBCO, MgB₂ – wire, cable, tape

• Amount of HTS acquired:
  – Over 50 km (4 mm tape equivalent)

• Our recent activities have been largely on magnets with ReBCO
Superconducting Magnet Division

Completed HTS Magnet Programs

• 25 mm aperture 16 T HTS solenoid (SBIR)
• 100 mm aperture 9 T HTS solenoid (SBIR)
• 100 mm aperture “12.5 T @27 K” HTS SMES solenoid (arpa-e)
• HTS quadrupole for RIA (Collaboration with MSU)
• Bi2223 HTS tape common coil dipole (funded by DOE)
• Bi2212 Rutherford cable Common Coil Collider Dipole (DOE)
• HTS solenoid for Energy Recovery Linac (BNL project)
• HTS magnet for NSLS (BNL Project)
• Cosine theta dipole with 4 mm YBCO/ReBCO tape (SBIR)
• Cosine theta dipole with 12 mm YBCO/ReBCO tape (SBIR)
• And a few others
Current HTS Magnet Programs

- High Field HTS solenoid for IBS, Korea (Work for Others)
- High field collider dipole (Phase II STTR)
- Curved ReBCO tape dipole (Phase II SBIR)
- MgB$_2$ solenoid (Phase II SBIR)
- High field open HTS midplane dipole (Phase I SBIR)
- High radiation HTS Quadrupole for FRIB (Collaboration)
- HTS solenoid for Energy Recovery Linac (BNL project)

A wide variety of applications and collaborative work is the nature of our HTS magnet program.
A Brief Review of Select HTS Magnet Programs

1. High Field Large Stress (~400 MPa) HTS Solenoids
2. High Radiation/Energy Deposition Quadrupoles

Common Features:
SS tape insulation, either to deal with large stresses or to provide radiation resistant insulation and help in quench protection
Path to a 30-40 T Solenoid

Goal: Develop high field solenoid for Muon Cooling

Several coils (build and test in their own structure, then combine):

a) >12 T HTS solenoid (insert): 25 mm, 14 pancakes, 4 mm tape
b) >10 T HTS (midsert): 100 mm, 24 pancakes, 4 mm tape
c) >10 T LTS (outsert): NbTi and/or Nb₃Sn cable
16T HTS Solenoid
(a wide range of operating temperature)

- Field on axis: 15.7 T
- Field on coil: 16.2 T
  (original target: 10-12T)

Highest field all HTS solenoid

Overall $J_o$ in coil:
>500 A/mm$^2$ @16 T

Insert solenoid: 14 pancakes, 25 mm aperture
Large Aperture High Field HTS Magnet
(a wide range of operating temperature)

PBL/BNL 100 mm HTS Solenoid Test for Muon Collider

Peak Field on Coil at 250 A: ~9.2 T
Coil operated with margin at 250 A

Run stopped at 250 A

Half midsert operated at 250 A @4 K
(6.4 T field on axis, 9.2 T peak field on coil)

Full midsert (24 pancakes)

Half midsert (12 pancakes)

HTS Insert + midsert designed to generate ~22 T and with Nb$_3$Sn outsert ~35 T
High Field HTS SMES Coil
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 ∝ B²)
  ✔ 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

High Risk, High Reward R&D funded by arpa-e

Aggressive parameters:

Field: 25 T@4 K
Bore: 100 mm
Hoop Stresses: 400 MPa
Conductor: ReBCO
• A torus would consist of a large number of solenoid module
• Field becomes parallel => less amount of conductor required
GJ scale GRID storage system that can fit in a room!

- Moreover, a small $B_\perp$ (<0.5 T) for a large $B_{//}$ (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>
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<tbody>
<tr>
<td>Stored Energy</td>
<td>1.7 MJ</td>
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<tr>
<td>Current</td>
<td>700 Amperes</td>
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<tr>
<td>Inductance</td>
<td>7 Henry</td>
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<tr>
<td>Maximum Field</td>
<td>25 Tesla</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>4.2 Kelvin</td>
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<tr>
<td>Overall Ramp Rate</td>
<td>1.2 Amp/sec</td>
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<tr>
<td>Number of Inner Pancakes</td>
<td>28</td>
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<tr>
<td>Number of Outer Pancakes</td>
<td>18</td>
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<tr>
<td>Total Number of Pancakes</td>
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<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>
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<tr>
<td>Inner dia of Outer Pancake</td>
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<td>Outer dia of Outer Pancake</td>
<td>303 mm</td>
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<tr>
<td>Intermediate Support</td>
<td>13 mm</td>
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<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)
HTS Coil Winding
HTS Pancakes

~210 meter i.d., 12 mm tape, 258 turns

• 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

Two Pancakes Connected with Spiral Splice Joint

V-taps for QA
All pancakes are individually pre-tested at 77 K for QA check (a unique benefit of HTS)

Critical current (1 µV/cm)

Two single pancakes powered in series.

Ic and N value at 77 K of single pancake coils
### Adjustment in SS tape thickness and amount of Cu on HTS tape

#### Four types to achieve grading (see slide 12)

**Outer double pancake coils**

- **Type A**: CC(160 μm) + SS (25 μm)
  - Measured value:
  - Beyond range:
- **Type B**: CC(160 μm) + SS (50 μm)
  - Measured value:
  - Beyond range:
- **Type C**: CC(120 μm) + SS (25 μm)
  - Measured value:
  - Beyond range:
- **Type D**: CC(120 μm) + SS (50 μm)
  - Measured value:
  - Beyond range:

#### Two pancakes powered in series

Each pancake powered alone

**Higher \( I_c \) in coil at 77K, doesn’t necessarily translate in to a higher \( I_c \) at 4K**
Double Pancake 77 K QA 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.
Coils, Test Fixtures and Support Structure

Pancake coils: inner and outer
77 K Test Fixture for outer

11 T, 760 A coil and fixture

Outer Support Tube for Outer
Outer Assembly Tube for Outer
Inner Assembly Tube for Inner
Copper Discs
Inner Coils

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

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

**Total:** 46 pancakes
Final Assembly

Outer inserted over inner coil

SMES coil in iron laminations
Low Temperature Test Results
Superconducting Magnet Division

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
Double Pancake Coil Test
(a wide range of operating temperature)

Nominal design current: ~700 A

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

Ramp rate up to 10 A/s
Superconducting Magnet Division

SMES Coil Run on 5/21/14

12.5 Tesla at 27 K

350 Amp
425 kJ
id:102 mm
od:303 mm

27 K possible with liquid Neon

Record field/energy density in a superconducting magnet at a temperature of 10 Kelvin or higher

Current (A)

Time (hh:mm)

14:24 15:36 16:48 18:00 19:12 20:24 21:36
HTS Quadrupole for RIA/FRIB

RIA: Rare Isotope Accelerator
FRIB: Facility for Rare Isotope Beams
To create intense rare isotopes, 400 kW beam hits the production target. Magnets in the fragment separator region are exposed to unprecedented radiation and heat loads. HTS can efficiently remove that at elevated temperatures.

**Exposure in the first magnet itself:**
- **Head Load**: ~10 kW/m, 15 kW
- **Fluence**: $2.5 \times 10^{15}$ n/cm$^2$ per year
- **Radiation**: ~10 MGy/year
Warm Iron Design with Bi2223 HTS
First Generation HTS Quad Test
(operation over a large temperature range)
Second Generation HTS Quad for FRIB Fragment Separator Region

YBCO/ReBCO from two vendors ASC and SuperPower
Large Temperature Margins
(only possible with HTS)

HTS provides robust operation against local and global heat loads.
The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 µA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.
Impact of Irradiation on 2G HTS


I\(_c\) Measurements at 77 K, self field

- SuperPower Sample#1
- SuperPower Sample#2
- SuperPower Average
- ASC Sample#1
- ASC Sample#2
- ASC Average

I\(_c\) of all original (before irradiation) was \(\sim 100\) Amp

100 \(\mu\text{A.hr}\) dose is \(\sim 3.4 \times 10^{17}\) protons/cm\(^2\) (current and dose scale linearly)

YBCO is at least as much radiation tolerant as Nb\(_3\)Sn is
• While the SuperPower and ASC samples showed a similar radiation damage pattern in the absence of field, there is a significant difference in the presence of field (particularly with respect to the field angle).

• HTS from both vendors, however, show enhancement to limited damage during the first 10 years of FRIB operation (good news)!!!
Cryo-cooler based HTS Coil R&D

- Coils reached <40 K (goal was 40 to 50 K)
- 25 W at 50 K can be removed by a number of cryo-coolers
3d and Curved HTS Coils
Cosine (θ) Coil with Complex Ends
PBL/BNL (two) STTR

No measurable degradation
Curved HTS Coil
Quench Protection
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. Co-winding with stainless steel tape helps in quench protection.

Twelve coil test at 4K (~12 T, ~120 KJ)
BNL has worked on a variety of HTS magnets covering a wide range and a variety of geometries with a number of collaborators.

In addition to HTS, BNL has expertise with NbTi and Nb$_3$Sn magnets which will be helpful in developing the entire system.

BNL is the only US laboratory with a large operating superconducting accelerator complex - Relativistic Heavy Ion Collider (RHIC). This gives a very useful perspective and support to superconducting magnet program.

We are looking forward to working with PPPL in this possible ground breaking application of HTS magnets in fusion technology.