HTS Quadrupole R&D at BNL for FRIB

Ramesh Gupta
(for BNL Superconducting Magnet Division)

October 27, 2015
Overview

- Few slides on the results of IBS/BNL collaboration
  - High field HTS solenoid for CAPP with SuNAM conductor
- **First Generation Radiation Resistant HTS Quad for FRIB**
  - Brief overview
- **Second Generation Quad for FRIB** (most of this presentation)
  - Design
  - Construction
  - Test
  - Quench protection
- **Extra slides**
  - Radiation damage studies
  - Energy deposition studies
**Motivation of High Field Solenoid for CAPP (slides from Yannis Semertzidis)**

**What’s there to improve over ADMX?**

\[
P = \left( \frac{\alpha g_\gamma}{\pi f_a} \right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L
\]

- \( B^2 \), energy density
- \( Q \), resonator quality factor
- B-field/resonator volume \( V \)
- Ampl. noise/physical temperature, S/N

**B-field possibilities**

- Magnetic field \( B \):
  - Develop 25T magnet.
  - 35T magnet based on high \( T_c \).

**(CAPP) Axion dark matter plan**

- We have started an R&D program with BNL for new magnets: goal 25T; then 35T. Currently all axion experiments are using <10T.
- Based on high \( T_c \) cables (including SuNAM, a Korean high \( T_c \) cable company). ~5 year program.

To create state of the art facility, Center for Axion and Precision Physics (CAPP), needs large aperture, high field solenoid (\( B^2 V \))
HTS/LTS hybrid design

- 25 T from HTS and 10 T from LTS
- HTS used only in high field region
- HTS is expensive

LTS Outer solenoid from commercial vendor but HTS must be developed

HTS magnet pose huge challenges

- Large stresses
- Quench protection
- New conductor

Magnet design and technology developed for HTS SMES can be directly applied to CAPP research

- **Field:** 25 T @ 4 K
- **Bore:** 100 mm
- **Stresses:** 400 MPa
Work Performed at BNL for CAPP/IBS

- Conductor Test
- Coil Construction and Test
- Magnet Assembly and Test

**Task:**
Demonstrate 10 T peak field in a 100 mm bore solenoid built with SuNAM HTS, as available at that time.
BNL Measurements of SuNAM conductor at 4K, 4-8T

Sample Holder for in-field $I_c$ Measurements at BNL
Remarkably uniform performance
(specially for conductor delivered in 3 batches)
### Summary of Conductor Measurements

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SuNAM</td>
<td>77</td>
<td>0</td>
<td>634</td>
<td>36</td>
<td>5.7%</td>
</tr>
<tr>
<td>SuNAM</td>
<td>20</td>
<td>4</td>
<td>423</td>
<td>28</td>
<td>6.7%</td>
</tr>
<tr>
<td>BNL</td>
<td>77</td>
<td>0</td>
<td>628</td>
<td>51</td>
<td>8.1%</td>
</tr>
<tr>
<td>BNL</td>
<td>4.2</td>
<td>4</td>
<td>793</td>
<td>28</td>
<td>3.5%</td>
</tr>
<tr>
<td>BNL</td>
<td>4.2</td>
<td>8</td>
<td>524</td>
<td>20</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

**SuNAM:** Measurements at SuNAM (77 K and 20 K, 4T)

**BNL:** Measurements at BNL (77 K and 4 K, 4-8 T)
Pancake coils

V-taps for extensive QA
i.d. = 101.6 mm, o.d. = 192 mm

Spiral Splice for making Double Pancakes
(~300 meter, 12 mm tape)
Double Pancake Coil at Test Station
Three leads to power coils either in single pancake or in double pancake configurations.

Higher field means lower current in a double pancake.
Performance of Six Coils
(Powered Individually as Single Pancakes)
Performance of Six Coils
(Powered two together as Double Pancakes)
Superconducting Magnet Division

Final Solenoid Construction
Six Pancake Solenoid @77 K
(V-I curve of each pancake, powered together)

- Pancake A
- Pancake B
- Pancake C
- Pancake D
- Pancake E
- Pancake F

Bottom: A
Top: F
End pancakes: B⊥
Critical Current Vs. Temperature

10.8 T Peak Field
590 Amp at 4.2 K

Target of 10 Tesla Met
First Generation HTS Quad Design for FRIB

- Short model built with ~5 km of 4 mm wide first generation (1G) HTS tape from American Superconductor Corporation (ASC)
- ~30 K Operation, 10 T/m, 290 mm aperture
For intense rare isotopes, 400 kW beam hits the production target. Several magnets in the fragment separator region are exposed to unprecedented radiation and heat loads.

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

![Diagram of Radiation Tolerant HTS Quad for the Fragment Separator Region of FRIB](image)
HTS magnets in Fragment Separator region over Low Temperature NbTi Superconducting magnets provide:

**Technical Benefits:**
- Provides higher gradient and/or larger aperture than copper magnets (increases acceptance and beam intensity transmitted through the beam line)
- Provides large temperature margin than LTS – HTS can tolerate a large local and global increase in temperature (resistant to beam-induced heating)

**Economic Benefits:**
- Removing large heat loads at higher temperature (30-50 K) rather than that at ~4 K (as in LTS) is over an order of magnitude more efficient.

**Operational Benefits:**
- In HTS magnets, the temperature need not be controlled precisely. This makes magnet operation more robust, particularly in light of large heat loads.

Appears to be a custom made application of HTS magnets
Development of a Significantly New Magnet Technology

- The radiation tolerance requirements in FRIB magnets for fragment separation region are unprecedented.

- In addition to the conductor, all magnet parts (including insulation, cryogenic & support structure) must withstand large radiation loads (10 MGy/year for > 10 years).

- This is perhaps the first time that we have made a superconducting magnet that is built with no organic component in it (including metallic SS insulation).

- In addition to high radiation, the magnet technology developed is able to withstand large energy deposition too.
HTS Coil Winding

A coil being wound in a computer controlled winding machine

HTS Tape

SS Tape
Each single coil uses ~200 meter of tape

13 Coils made HTS tape in year #1

12 coils with HTS tape in year #2

Note: A uniformity in performance of a large number of HTS coils
First Generation HTS Quad

Three magnet structures, built and tested

Mirror cold iron

Mirror warm iron

Warm Iron Design to Reduce Heat Load
Summary of First Generation HTS Quad Tests

Operation over a large temperature range - only possible with HTS
Second Generation
HTS Quad for FRIB

- Higher operating temperature (up to 50 K instead of 30 K in the 1st) and higher gradient (15 T/m instead of 10 T/m in the 1st)

- Full size model built with 12 mm wide 2G HTS tape from two US vendors (SuperPower and ASC)

  ➢ ~9 km equivalent of 4 mm tape
Design
Magnet Design

- Warm iron magnet design to reduce heat loads
- 12 mm ReBCO (2G) HTS Tape from two vendors
- Designed for remote/robotic replacement of coil
## Parameter List of the Second Generation Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole Radius</td>
<td>110 mm</td>
</tr>
<tr>
<td>Design Gradient</td>
<td>15 T/m</td>
</tr>
<tr>
<td>Magnetic Length</td>
<td>600 mm</td>
</tr>
<tr>
<td>Coil Overall Length</td>
<td>680 mm</td>
</tr>
<tr>
<td>Yoke Length</td>
<td>546 mm</td>
</tr>
<tr>
<td>Yoke Outer Diameter</td>
<td>720 mm</td>
</tr>
<tr>
<td>Overall Magnet Length</td>
<td>~880 mm</td>
</tr>
<tr>
<td>HTS Conductor Type</td>
<td>Second Generation (2G)</td>
</tr>
<tr>
<td>Conductor Vendors</td>
<td>Two (SuperPower and ASC)</td>
</tr>
<tr>
<td>Conductor width, SP</td>
<td>12.1 mm ± 0.1 mm</td>
</tr>
<tr>
<td>Conductor thickness, SP</td>
<td>0.1 mm ± 0.015 mm</td>
</tr>
<tr>
<td>Cu stabilizer thickness SP</td>
<td>~0.04 mm</td>
</tr>
<tr>
<td>Conductor width, ASC</td>
<td>12.1 mm ± 0.2 mm</td>
</tr>
<tr>
<td>Conductor thickness, ASC</td>
<td>0.28 mm ± 0.02 mm</td>
</tr>
<tr>
<td>Cu stabilizer thickness ASC</td>
<td>~0.1 mm</td>
</tr>
<tr>
<td>Stainless Steel Insulation Size</td>
<td>12.4 mm X 0.025 mm</td>
</tr>
<tr>
<td>Number of Coils</td>
<td>8 (4 with SP and 4 with ASC)</td>
</tr>
<tr>
<td>Coil Width (for each layer)</td>
<td>12.5 mm</td>
</tr>
<tr>
<td>Coil Height (small, large)</td>
<td>27 mm (SP), 40 mm (ASC)</td>
</tr>
<tr>
<td>Number of Turns (nominal)</td>
<td>220 (SP), 125 (ASC)</td>
</tr>
<tr>
<td>Field parallel @design (maximum)</td>
<td>~1.9 T</td>
</tr>
<tr>
<td>Field perpendicular @design (max)</td>
<td>~1.6 T</td>
</tr>
<tr>
<td>Minimum $I_c$ @2T, 40 K (spec)</td>
<td>400 A (in any direction)</td>
</tr>
<tr>
<td>Minimum $I_c$ @2T, 50 K (expected)</td>
<td>280 A (in any direction)</td>
</tr>
<tr>
<td>Operating Current (2 power supplies)</td>
<td>~210 A (SP), ~310 (ASC)</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>~40 kJ</td>
</tr>
<tr>
<td>Inductance</td>
<td>0.45 H (SP), ~1.2 (ASC)</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>~38 K (nominal)</td>
</tr>
<tr>
<td>Design Heat Load on HTS coils</td>
<td>5 kW/m³</td>
</tr>
</tbody>
</table>

Oct 27, 2015
Magnetic Design

Uses 12 mm tape rather than 4 mm tape

Benefits of 12 mm Tape:

- Minimizes the number of coils and joints
- Current is higher (inductance is lower)
- Relative impact of a weak section is less
Structure for the Body of the Magnet

Partial View of Clamped Coil

Magnet Cross-Section
Coil Assembly with Clamps and End Plates
Cryo-mechanical Structure

R&D Magnet in cryo-stat
(allows independent testing of four HTS coils)

Cut-away isometric view of the assembled magnet
(compact cryo-structure design allowed larger space for coils and reduction in pole radius)
Structure to Facilitate Remote Handling
• The ability of the clamping system to withstand radial and axial Lorentz forces
• All clamp bolts sized and arranged to maintain stress and deflection within acceptable limits
• Analysis results indicate deformation in coils does not exceed 25 microns
• Long clamps made from stainless steel instead of aluminum to reduce deflections

FE Analysis of Long Clamp CS with Coils
FE Analysis of Coil Axial Deflection

Decal unit: inches
Min=4.3e-5 in
Max=0.0008 in (20 micron)

Decal unit: inches
Min=-0.02 in
Max=0.008 in (200 micron)

6.9e-4 in (~17 micron)
Winding of HTS Coils and 77 K Tests in LN$_2$

- All coils tested individually
- All coils tested together in a structure
Winding of HTS Coil with Computer Controlled Universal Coil Winder

4 coils made with ASC:
~210 m double sided
(420 m HTS per coil)
~2x125 turns

4 coils made with SP:
~330 m per coil
~213 turns

Remember: 12 mm tape
(3X the standard 4 mm)

(~9 km of standard 4 mm equivalent used)
Coils Made with ASC HTS

• ~210 m (~125 turns), 12 mm double HTS tape per coil.

• One coil was wound without any splice in the coil

Voltage taps are placed generally after every 25 turns and also on either side of an internal splice.
SuperPower coil uses ~330 m 2G tape (~213 turns) per coil.

Fully wound coil with SuperPower tape with one splice.
Coils Assembled in Quadrupole Support Structure

12/20/2011
Coils Made with HTS from 2 Vendors (SuperPower and ASC)
77 K tests of HTS coils with LN$_2$ provide a useful QA
Performance of ASC Coils (four coils of eight powered)

ASC Tape: 2 plies of HTS and 2 plies of Cu

Field on ASC coils at 100 A

$I_c$ defined at 0.1 $\mu$V/cm

Four SuperPower coils not powered
Performance of SuperPower Coils (four of eight coils powered)

Four ASC coils were not powered

Field on SuperPower coils at 100 A

Internal splice on wrong tape side shows higher resistance. This is not an operational issue as the heat generated is small as compared to the energy deposition. ➢ Therefore, the expensive coil was not discarded.

Location confirmed with Voltage taps that are typically placed after every 25 turns and on either side of an internal splice (slope localized to splice section)
77 K Test in Quadrupole Mode (all eight coils powered)

Currents used for quadrupole mode at 77 K (equal \( J_e \))

<table>
<thead>
<tr>
<th></th>
<th>SP</th>
<th>ASC</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>69.3</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>86.7</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>104</td>
<td></td>
</tr>
</tbody>
</table>

Design (38 K): SP coils ~210 A & ASC coils ~310 A (equal Amp-turns).

- Coils reached about 1/3 of the design current at 77 K itself.
- Extrapolation to 38 K indicates a significant margin.

Note: No iron yoke yet in this structure.
Proud Team Members
Construction and Test of the
FRIB HTS Quad with Iron
at the Operating Temperature
Superconducting Magnet Division

FRIB Quad with Clamps
(in preparation for installing yoke)

12/20/2011
Yoke Iron for FRIB Quad
Coil and Support Structure Partially Assembled inside the Yoke
Coil and Support Structure Fully Assembled inside the Yoke
Aperture of 2G HTS Quad for FRIB
Completed 2G HTS Quad for FRIB
Preparation for Low Temperature Test

8 leads (Helium Gas cooled at the top)
Magnet at the Test Station

Superconducting Magnet Division

HTS Quadrupole R&D at BNL for FRIB

R. Gupta

RISP/IBS

Oct 27, 2015
Superconducting Magnet Division

Final Test: Large Temperature Margins (only possible with HTS)

- Coils from both vendors performed well (easily met the requirements).
- This is an unprecedented temperature margin (thanks to HTS).
- Provides robust operation against local and global heat loads.

Note: Above are not the limits of the coils ($I_c$).
These are the currents to which the coils were energized.

- Design Current @38 K:
  - SuperPower 210 A
  - ASC (double tape) 310 A

Impressive Performance

- (+20% in $I_c$ & +10 K in $T_c$)
- (50K, 375A)
- (+15% in $I_c$ & +20 K in $T_c$)
- (60K, 240A)

Design SuperPower  □ Design ASC  ○ Measured SP#1  ■ Measured SP#2  ▲ Measured ASC#1&#2
Advanced Quench Protection System
Advanced Quench Protection Electronics

Detsects onset of pre-quench voltage at $< 1\text{mV}$ and with isolation voltage $> 1\text{kV}$ allows fast energy extraction.
Magnet Operation and Quench Protection

Superconducting Magnet Division

HTS Quadrupole R&D at BNL for FRIB

R. Gupta      RISP/IBS
Oct 27, 2015
Protection of HTS Magnet During an Operational Accident Near Design Current

Design: 210 A in SP Coils

Vacuum leak made the temperature increase to ~57 K (design temp ~38 K)

Ringing in power supply made situation worse

Slow logger: One point/sec
Event (Quench?) while ASC Coils were held at 382 A (design: 310 A) at ~50 K (design: 38 K)

Coil Voltages (mV)

Slow logger: One point/sec
Operation Well Beyond the Quench Detection Threshold Voltage (~ mV)

Operated at about two order of magnitude beyond the quench detection threshold. No degradation in coil performance observed.

Test temperature: ~67 K
(ASC to 150 Amp; SP to 100A)
Spinoff of FRIB HTS Magnet Technology

SMES magnet was also tested at about the FRIB design operating temperature

HTS Quadrupole R&D at BNL for FRIB

R. Gupta

RISP/IBS

Oct 27, 2015
Inner and Outer Coils
Assembled with Bypass Leads

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

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

Total: 46 pancakes
Preparation for the Final Test
SMES Coil Test @50%
Critical Current Reached at 27 K

12.5 Tesla at 27 K

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

27 K possible with liquid Neon

Current (A)

Time (hh:mm)

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

Summary

• A decade of R&D has developed medium field radiation tolerant HTS magnet technology to a level that it can now be considered for use in a real machine.

• HTS magnets could play a crucial role - a unique solution to large energy deposition and high radiation loads (extra slides).

• A variety of tests have shown that the technology (including quench protection) can withstand operational failure (vacuum leak) and can work well beyond the normal operating conditions.

• This demonstration is a major development in magnet technology. This provides a good base for other applications of HTS magnets.

• BNL is glad to collaborate with IBS – CAPP already, RISP next?
Extra Slides
Radiation Damage
Radiation Damage Measurements @BNL


$I_c$ Measurements at 77 K, self field

$I_c$ of all original (before irradiation) was ~100 Amp

100 μA.hr dose is $3.4 \times 10^{17}$ protons/cm$^2$ (current and dose scale linearly)

Ic Measurements of SuperPower and ASC at 77K in field of 1T

More detail in the following slides
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.
Key Steps in Radiation Damage Experiment

142 MeV,
100 μA protons
Superconducting Magnet Division

Relative Change in $I_c$ due to Irradiation of SuperPower and ASC Samples

**Radiation Damage Studies on YBCO by 142 MeV Protons**
by G. Greene and W. Sampson at BNL (2007-2008)

$I_c$ 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 ~100 Amp

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

SuperPower and ASC samples show very similar radiation damage at 77 K, self field

Ramesh Gupta, BNL 3/2008
The maximum radiation dose was $3.4 \times 10^{17}$ protons/sec (100 $\mu$A.hr) with an energy of 142 MeV. Displacement per atom (dpa) per proton is $\sim 9.6 \times 10^{-20}$. (Al Zeller)

This gives $\sim 0.033$ dpa at 100 $\mu$A.hr for the maximum dose.

Based on 77 K self field studies:
- Reduction in $I_c$ performance of YBCO (from both vendors) is $< 10\%$ after 10 years of FRIB operation (as per Al Zeller, MSU).
- This is pretty acceptable.
- Drop in $I_c$ at maximum dose (of theoretical interest) is $\sim 70\%$.

It appears that YBCO is at least as much radiation tolerant as Nb$_3$Sn is (Al Zeller, MSU).

SuperPower and ASC samples show very similar radiation damage at 77 K, self field.
Change in Critical Temperature ($T_c$) of YBCO Due to Large Irradiation

$I_c$ ($1\mu$V/cm) as a function of temperature

- Radiation has an impact on the $T_c$ of YBCO, in addition to that on the $I_c$.
- However, the change in $T_c$ is only a few degrees, even at very high doses.

Before Irradiation

- ~ $1.7 \times 10^{17}$ protons/cm$^2$
- ~ $3.4 \times 10^{17}$ protons/cm$^2$
• 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)!!!
Energy Deposition
• Energy deposition experiments were carried out at different operating temperature.

• The amount of energy deposited on the HTS coils is controlled by the current in heaters placed between the two coils.
Energy Deposition Experiment During Cool-down at a Constant Helium Flow-rate

Heaters between HTS coils were turned on while the magnet was cooling with a helium flow rate of 135 standard cubic feet (SCF).

Temperature decreased at 19.4 W
Temperature increased at 29.4 W
Heat load for steady state ~26 Watts

Note: HTS coil remained superconducting during these tests when operated somewhat below the critical surface.
Magnet operated in a stable fashion with large heat loads (25 W, 5kW/m³) at the design temperature (~30 K) at 140 A (design current is 125 A).

Stable operation for ~40 minutes.

Voltage spikes are related to the noise.
Quench Protection
Snap Shot of the Event (Quench?) that Triggered the Shut-off

Fast data logger: One point/msec

Large inductive voltage in individual coils (ramp)

No degradation in coil performance after the event

Superconducting Magnet Division

Small quench detection threshold (2 mV) kept during the ramp by monitoring difference voltage

Diff voltage

Voltage (mV) vs. Time (msec)

Voltage (mV) vs. Time (msec)

Voltage (mV) vs. Time (msec)
Snap Shot of the Event in ASC Coils (individual and difference voltages)

Event at (a) 12 K above the design temperature and (b) at 24% above design current

- This and previous event appear to be the sign of flux jump
- This exceeded quench threshold, triggered shutoff & energy extraction

No degradation in coil performance observed