HTS Quadrupole for FRIB

Design, Construction and Test Results

R. Gupta, M. Anerella, J. Cozzolino, P. Joshi
W. Sampson, P. Wanderer, BNL, NY USA
A Zeller, FRIB, MI, USA
Why HTS magnets for the Facility for Rare Isotope Beams (FRIB)?

- FRIB is a major US facility under construction at MSU

Brief overview of the significant HTS magnet R&D for over last ten years (~4M$)

- Primary focus: the test results
To create 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: \(\sim 10 \text{ kW/m}, 15 \text{ kW}\)
- Fluence: \(2.5 \times 10^{15} \text{ n/cm}^2 \text{ per year}\)
- Radiation: \(\sim 10 \text{ MGy/year}\)
Benefits of HTS Magnets Against Large Energy Deposition

Technical Benefits:

- HTS magnets provide a large temperature margin.
  - HTS magnets can withstand large (10 K or more) local and global increase in temperature.

Economic Benefits:

- Removing such large heat loads at 38 K (with HTS) is over an order of magnitude more efficient than at ~4 K (with LTS).
Radiation Tolerant
HTS Magnet Design

- All material used in the magnet can withstand large radiation loads (10 MGy/year for > 10 years)
- Most parts used are metallic
  - Turn-to-turn insulation, often the weak-link in the magnet, is stainless steel
- Experiments performed on 2G HTS at BNL show that it can withstand these doses

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

- Measurements at 77 K, self field
- $I_c$ of all original (before irradiation) was ~100 Amp

HTS Quad is now the baseline design of FRIB FS
First Generation Design

- Short model built with ~5 km of ~4 mm wide first generation (1G) HTS tape from ASC
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
Warm Iron Design to Reduce Heat Load

Three magnet structures, built and tested

Mirror cold iron

Mirror warm iron

6 feet

1.3 m
Summary of First Generation HTS Quad Tests

Operation over a large temperature range - only possible with HTS
Second Generation Design

- Full size model built with 12 mm wide 2G tape from two vendors (SuperPower and ASC)
  - ~9 km equivalent of 4 mm tape
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
<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>
4 coils made with ASC:
- ~210 m double sided
- (420 m HTS per coil)
- ~2\times125 turns

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

Note: This is a 12 mm tape
(3X the standard 4 mm)

(~9 km of standard 4 mm equivalent used)
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 FRIB Coils @77 K
(4 made with SuperPower and 4 with ASC)

I_c defined at 0.1 μV/cm

Actual current is coils made with double HTS from ASC HTS was twice
Completed 2G HTS Quad for FRIB
Lower Temperature Tests with Helium
Large Temperature Margins
(only possible with HTS)

Provides robust operation against local and global heat loads.
Advanced Quench Protection Electronics

Detects onset of pre-quench voltage at < 1mV and with isolation voltage > 1kV allows fast energy extraction
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
Snap Shot of the Event (Quench?) that Triggered the Shut-off

Fast data logger: One point/msec

Large inductive voltage in individual coils (ramp)

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

No degradation in coil performance after the event
Event (Quench?) while ASC Coils were held at 382 A (design: 310 A) at ~50 K (design: 38 K)

Coil Voltages (mV)

Current (A)

Shut-off

Events prior to Shut-off

Slow logger: One point/sec
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
Operated at about two order of magnitude beyond the quench detection threshold. No degradation in coil performance observed.
Spinoff of FRIB HTS Magnet Technology

Significant development of HTS magnet technology at BNL was funded by DOE/NP to provide a unique solution for the magnets in the fragment separator region of the Facility for Rare Isotope Beams (FRIB), which is currently under construction at Michigan State University in East Lansing, Michigan. The same coil technology (HTS tape co-wound with stainless steel tape) is used in high field (∼24 Tesla) superconducting magnetic energy storage (SMES) solution that can withstand the high stresses that are present in high field magnets. This technology has already been successfully applied in creating the record 16 T field in an all HTS magnet. High fields significantly reduce the amount of conductor for the same stored energy in SMES. This is mainly because the stored energy increases essentially as the square of the field. In addition, because HTS SMES can operate at high temperatures, the high efficiency cryo-coolers can now replace the more expensive and precious liquid Helium cryogen.

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

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

• FRIB could be the 1st major accelerator with HTS magnets playing a crucial role - a unique solution to unprecedented energy deposition and radiation loads.

• A variety of tests have shown that the technology (including quench protection) can withstand several failure mode scansion 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.
Major Topics NOT Covered due to Lack of Time

- Details of magnet design
- Details of magnet constructions
- Several other magnet tests
- Quench protection
- Energy deposition experiments
- Radiation damage experiments