High Field HTS Solenoid for a Muon Collider
Demonstrations, Challenges and Strategies

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One key challenge:

Very High field solenoids (30-50 T)

- Resistive magnets would consume enormous power (hundreds of MW)
- HTS (4K) offers a superconducting solution

Other Applications of High Fields: NMR, SMES, User Facilities
Overview of the Design
Several significant coils (build and test in their own structure):

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 Nb$_3$Sn, cable (design phase)

- Work initially started with a series of Small Business Innovation Research (SBIR)
- Currently supported by Muon Accelerator Program (MAP)
Basic Design and Construction

- Pancakes coils are made with high strength 2G HTS from SuperPower, Inc.
- HTS tape is co-wound with insulating stainless steel tape to reduce hoop stress and to help in quench protection
- Copper discs are used between the double pancakes to reduce thermal gradient during cool-down of large assembly
- No epoxy impregnation (only surface painted)
- A large number of v-taps for extensive 77 K QA testing
Noteworthy Demonstrations
High Field (16T) Demo of HTS Magnet

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

Highest field all HTS solenoid

Overall $J_0$ in coil: $>500$ A/mm² @16 T

Insert solenoid: 14 pancakes, 25 mm aperture
PBL/BNL 100 mm HTS Solenoid Test for Muon Collider

- Half midsert operated at 250 A @4 K
  - (6.4 T field on axis, 9.2 T peak field on coil)
- Design value for full midsert: 220 A for 10 T

Peak Field on Coil at 250 A: ~9.2 T
Coil operated with margin at 250 A
Run stopped at 250 A
Challenges and Strategies

• Quench Protection
• High Field Conductor
• Coils/Magnets
Quench protection of high field HTS magnets is a major challenge!

• We take a multi-prong approach to overcome this challenge:
  – Advanced quench detection system to detect onset of “pre-quench” phase and start action while it is still safe to operate for some time
  – Special electronics to tolerate high isolation voltage (> 1 kV) to allow fast energy extraction once the pre-quench phase is detected
  – Inductively coupled copper discs to reduce current instantaneously
  – Spread heating across the coil faster because of SS tape insulation
  – Also possible: quench heaters as used in LTS magnets (NHMFL)
Advanced quench detection system detects onset of small “pre-quench” voltage (<1 \( \mu \text{V/cm} \)) in the presence of large noise and inductive voltage.

Detection at \( \sim 100 \mu \text{V level} \) (1 \( \mu \text{V/cm} \) in 100 m => 10 mV)

Detection while ramp rate is changing.
Advanced Quench Detection System with Fast Energy Extraction

- Fast energy extraction in larger magnets creates high voltages as “L” increases
- Develop electronics that can tolerate high isolation voltage (>1 kV)
- Divide coils in several sections

Cabinet #1 (32 channels, 1kV)
Cabinet #2 (32 channels, 1kV) (expandable to 64 and 3kV)
Instantaneous (<100 µsec) Drop in Current (as soon as the energy extraction started)

- **Bo = ~15.6 T**
- **Bo = ~5.3 T**

**25 mm 14 coils**

- Inductively coupled Cu discs
- Partial current transferred from coil to disc (simulation show reasonable agreement)
- Partial energy extracted
- Extra margin at critical time
- Cu discs heat up to 50-70 K
Conductor and Coils
• HTS vendors typically measure performance at 77 K and self-field
• Magnets need at operating temperature and operating field
• We observe large variations in in-field scaling of coil and conductor

**Correlation - conductor and coil (77 K)**

- A potential to improve in-field performance & to make it more uniform
- A production conductor requires spec at operating conditions (4K,8T?)
- We may also need to specify/tighten various mechanical spec

**Measured Bperpendicular scaling(4K) at BNL**

- High Field HTS Solenoid for a Muon Collider – Demonstrations, Challenges and Strategies - Ramesh Gupta, … 7/19/13
• HTS Insert (14 pancakes, ran at 16 T peak field) and Midsert (24 pancakes, 12 ran at 9 T peak)
• Expected on axis field at 4 K: > 22 T (design)
• All worked well during 77 K Pre-test
Several pancakes got degraded during one @77 K test with LN$_2$

- All coils have been tested successfully several times before this event.
- No further degradation seen after repeated test after this event.
- Likely cause: excessive thermo-mechanical strain during system testing.
Several pancakes (half) could be repaired by simply removing inner-most turn and making a new splice between two single pancakes.
Strategies for Way Forward

• Extended copper discs, etc. to provide better cooling

• Slower cooling to reduce thermal gradient within coil

• A more robust conductor

• Interesting, currently more issues are being seen and reported during the 77 K testing rather than the 4 K high field testing where the conductor is supposed to be exposed to large Lorentz forces.

• Developing a better defined test procedure may help in interim.
Summary

• Record high fields (~16 T) demonstrated in an all HTS coil
• Multiple strategy help in quench protection – particularly the use of copper discs and advanced electronics
• HTS coils are sensitive to thermo-mechanical strain. A more robust conductor and magnet design will help
• High strength ReBCO has demonstrated the potential for creating high field magnets suitable for many applications. The target field of >22 T in an all HTS and >30 T in all superconducting magnet seems within reach
• As with any ambitious R&D program, one has to be prepared for some surprises and some systematic R&D
Extra Slides
Original Design Parameters
(as presented at ASC2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>Target Design field (optimistic)</td>
<td>~22 T</td>
<td></td>
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<tr>
<td>Number of coils (radial segmentation)</td>
<td>2 self supporting</td>
<td></td>
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<tr>
<td>Stored Energy (both coils)</td>
<td>~110 kJ</td>
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<tr>
<td>Inductance (both in series)</td>
<td>4.6 Henry</td>
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<tr>
<td>Nominal Design Current</td>
<td>~220 A</td>
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<tr>
<td>Insulation (Kapton or stainless steel)</td>
<td>~0.025 mm</td>
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<tr>
<td>$J_e$ (engineering current density in coil)</td>
<td>~390 A/mm²</td>
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<tr>
<td>Conductor</td>
<td>2G ReBCO/YBCO</td>
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<tr>
<td>Width</td>
<td>~4 mm</td>
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<tr>
<td>Thickness</td>
<td>~0.1 mm</td>
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<tr>
<td>Stablizer</td>
<td>~0.04 mm Cu</td>
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Midsert

**Outer** Solenoid Parameter
- Inner diameter: ~100 mm
- Outer diameter: ~160 mm
- Length: ~128 mm
- Number of turns per pancake: ~240 (nominal)
- Number of Pancakes: 28 (14 double)
- Total conductor used: 2.8 km
- Target field generated by itself: ~10 T

**Inner** Solenoid Parameter
- Inner diameter: ~25 mm
- Outer diameter: ~90 mm
- Length: ~64 mm
- Number of turns per pancake: ~260 (nominal)
- Number of Pancakes: 14 (7 double)
- Total conductor used: 0.7 km
- Target field generated by itself: ~12 T

External Radial support (overband): Stainless steel tape

- This was thought to be a very ambitious proposal!!!
- We have achieved >60% (6+ T) with only half outer
- We have already exceeded inner by over 25% (15+ T)
77 K QA Test of 100 mm Pancakes

A Large Number of 2G HTS Pass Extensive Initial Testing in LN$_2$

Total conductor: 2.4 km (supplied by SuperPower)

Field @40 A: Bparallel $\sim$0.5 T and Bperpendicular $\sim$0.3 T