HTS Coils for High Field Hybrid FCC Dipoles

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Overview

• HTS Coils in a Hybrid Design for a ~20 T Dipole

• Technique to Reduce Magnetization Effects in Superconducting Magnets Built with Tapes

  ➢ This could be a game changer for ReBCO

• HTS Coil R&D at BNL and Future Possibilities

• Summary
Hybrid design to minimize cost:

- HTS in high field region for ~4 T
- LTS in low field region for ~16 T

HTS options

- Bi2212
  - Advantages: Round wire, high current Rutherford cable
  - Challenges: Limited production & long term economic viability
    Degradation in performance under large stresses

- ReBCO
  - Advantages: Larger production from multiple vendors
    Can tolerate large stresses as in high field magnets
  - Challenges: Tape form could cause large magnetization
    Lower current without new or complex cable

Focus of this presentation:

Possibility of making ReBCO based hybrid magnets more attractive
  ➢ Both in performance, and in cost …
Magnetization in ReBCO Magnets

• **Issue:**
  – ReBCO is primarily available in tape form
  – Magnetization is large in cosine theta or common coil designs
    ➢ related to tape width: 12 mm for high current conductors

• **Solution #1 : conductor design**
  – Round wire
  – Striated tape

• **Solution #2 : coil design**
  – See what we can do to use and **enhance** the strengths of the conductor

*Next few slides on the technique*
Design Technique to Reduce Magnetization Effects:

- Align the tape conductor (thickness few μm) such that primarily the "narrow side sees the perpendicular field"
- It’s possible to align HTS tape to a good extent in hybrid magnets "by carefully designing the coil"

Effective filament size 12 mm ➔ a few μm in an ideal design ➔ small in a real design, depending on the optimization
Comparing Designs for Magnetization

If persistent current induced harmonics is only the figure of merit

- **Bad** designs for HTS tape
  - large area covered by the perpendicular component of the field

- **Good** designs for tape (small area curved by the perpendicular component of the field)

Technique to Reduce Magnetization Effects in Superconducting Magnets Built with Tapes

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Persistent current induced harmonics should come down dramatically
Goal: Magnetization

- Reduce magnetization to a reasonable amount.
- Try to determine variation in persistent current induced harmonics between coil to coil to determine the “systematic” and “RMS” variations.
- We don’t have to be perfect in making it zero. As long as it is manageable with correctors, etc., it may be good enough.
Other Benefits of Aligned Tape Design (conductor efficiency)

Survey of 20 T Magnet design possibilities

One of many such plots and 1000's of magnet x section designs in total

Courtesy:
J. Van Nugteren
CERN
Other Benefits of Such Designs (2)

- Lorentz forces are primarily on the wide face of the conductor
  \[ I \times B \]
  - ReBCO can tolerate large stresses on the wide side
- Blocks are easy to segment
  - Between HTS and LTS
  - For stress management
A unique opportunity to investigate the idea and to develop the basic technology.
Technique to Reduce Field Errors Due to Magnetization in HTS Tape...
Proof-of-Principle Demonstration Magnet
Optimization of the High Field Accelerator Magnet Design
Coil Ends (practice windings)
Cost Reduction
Commercialization and Technology Transfer to E2P

Previous noteworthy PBL/BNL SBIR/STTR:
Development of high field HTS solenoid and HTS cosine theta coils
➢ Resulted in significant development in HTS magnet technology
(Thank you SBIR/STTR office)
Common Coil Dipole with a large open space

- Coils can be inserted without opening the magnet

A Hybrid HTS/LTS ...High-Field Accelerator Magnets

- STTR Phase II PBL/BNL/E2P (funded)
The coil block made here is similar to what would be needed for testing reduction in magnetization.

No measurable degradation @ 77 K

Similar coils are needed in Phase II.
Also investigated “bonded” or “clad” 12 mm tape from SuperPower.

No measurable degradation@77 K

Fig. 17. Bend test results for bonded tape with the YBCO layer oriented toward the central Cu strip. Degradation in $I_c$ begins between a bending diameter of 75 mm and 25 mm.
Other HTS Magnet Program at BNL

- HTS magnet R&D over a wide range:
  - High field, Medium field and low field (high temperature)
  - Many geometries – racetrack, cosine theta, solenoid
- Number of HTS coils/magnets designed built & tested:
  - Well over 100 HTS coils and well over 10 HTS magnets
- Type of HTS used:
  - Bi2223, Bi2212, ReBCO, MgB$_2$ – wire, cable, tape
- Amount of HTS acquired:
  - ~50 km (4 mm tape equivalent)
- Our recent activities have been largely on magnets with ReBCO
High Field (16T) Demo of HTS Magnet

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

Significant technical demonstration at a low cost

Overall $J_0$ in coil: $> 500$ A/mm$^2$ @16 T

HTS Solenoid: 14 pancakes, 25 mm aperture

PBL/BNL SBIR

Superconducting Magnet Division

BROOKHAVEN NATIONAL LABORATORY

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Ramesh Gupta

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High Field HTS Magnet Test Results
100 mm bore, 12 mm ReBCO SMES Coil

Goal:
~25 T at 4 K

Large Stresses:
>400 MPa

Record Field:
12.5 T at >10 K in the 1st test itself

Significant use of HTS: over >18 km (4 mm equivalent)
**High Field Solenoid for Axion Search**
Funded by Korean research institute
SuNAM has partly delivered and partly on the way to delivery about 5 km (~4 mm equivalent) as a part of this research and/or its contribution to HTS R&D at BNL

**HTS Coils for High Field Hybrid Dipole**
PBL/BNL/E2P STTR

**Base Program**
Very important for performing R&D – not yet funded
No-insulation Nb$_3$Sn Tape Coils
Bill Sampson (before my time)
High Current Conductor/Cable

- Present value of field parallel $I_c$ is over 3 kA for single tape
  - Likely to increase as ReBCO thickness becomes several $\mu$m
- Develop simple multi-tape (bonded, multi-ply, …) conductor
  - This increases kA value of conductor
  - This should make conductor more robust as current may bypass from one tape to another (as in “no-insulation”) in case of local defect or variation
- Explore wide multi-tape robust cable configurations
  - Perform experiments in magnet coils

A dream conductor may be an optimized multi-tape configuration

10-20 kA @ design
8 Coils and 5 Magnets built with Rutherford Bi2212 Cable

Earlier coils <1 kA (~2001)
Later coils 4.3 kA (2003)

Record 4.3 kA in HTS coils

Still a record???
SUMMARY

• It may be possible to develop high field hybrid magnet designs in such a way that the conductor magnetization (persistent current induced harmonics) become manageable, overcoming a major technical issue associated with the tape.

• Such designs can handle large stresses, as present in high field magnets, as they are against the wider side of the tape.

• Requirements of expensive conductor are significantly reduced because of the field orientation (previous design work at CERN).

• Degree of above benefits need to be determined by model calculations and demonstration in actual tests. A demonstration is planned under an STTR with a unique background field common coil magnet available for such testing at BNL.
Bi2212 Coil Experience at BNL
TABLE II
COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. \( I_c \) IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

<table>
<thead>
<tr>
<th>Coil / Magnet</th>
<th>Cable Description</th>
<th>Magnet Description</th>
<th>( I_c ) (A)</th>
<th>( J_e\text{(sf)}[J_e\text{(5T)}] ) (A/mm²)</th>
<th>Self-field, T</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC006 DCC004</td>
<td>0.81 mm wire, 18 strands</td>
<td>2 HTS coils, 2 mm spacing</td>
<td>560</td>
<td>60 [31]</td>
<td>0.27</td>
</tr>
<tr>
<td>CC007 DCC004</td>
<td>0.81 mm wire, 18 strands</td>
<td>Common coil configuration</td>
<td>900</td>
<td>97 [54]</td>
<td>0.43</td>
</tr>
<tr>
<td>CC010 DCC006</td>
<td>0.81 mm wire, 2 HTS, 16 Ag</td>
<td>2 HTS coils (mixed strand)</td>
<td>94</td>
<td>91 [41]</td>
<td>0.023</td>
</tr>
<tr>
<td>CC011 DCC006</td>
<td>0.81 mm wire, 2 HTS, 16 Ag</td>
<td>74 mm spacing Common coil</td>
<td>182</td>
<td>177 [80]</td>
<td>0.045</td>
</tr>
<tr>
<td>CC012 DCC008</td>
<td>0.81 mm wire, 18 strands</td>
<td>Hybrid Design 1 HTS, 2 Nb₃Sn</td>
<td>1970</td>
<td>212 [129]</td>
<td>0.66</td>
</tr>
<tr>
<td>CC023 DCC012</td>
<td>1 mm wire, 20 strands</td>
<td>Hybrid Design 1 HTS, 4 Nb₃Sn</td>
<td>3370</td>
<td>215 [143]</td>
<td>0.95</td>
</tr>
<tr>
<td>CC026 DCC014</td>
<td>0.81 mm wire, 30 strands</td>
<td>Hybrid Common Coil Design 2 HTS, 4 Nb₃Sn coils (total 6 coils)</td>
<td>4300</td>
<td>278 [219]</td>
<td>1.89</td>
</tr>
<tr>
<td>CC027 DCC014</td>
<td>0.81 mm wire, 30 strands</td>
<td>Hybrid Common Coil Design 2 HTS, 4 Nb₃Sn coils (total 6 coils)</td>
<td>4200</td>
<td>272 [212]</td>
<td>1.84</td>
</tr>
</tbody>
</table>

BNL pursued “React & Wind” technology for Bi2212

Eight coils and five magnets were built at BNL with Rutherford Bi2212 Cable (Showa/LBNL)
Magnet Structures for Bi-2212

Common Coil Design