Superconducting Magnets for Particle Accelerators

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OVERVIEW

• Superconductivity and Superconducting Magnets
• Review of SC Magnet Design for Accelerators
• HTS Magnets and their Applications
• Summary
Superconductors

- Discovered 100 years ago
- Essentially zero electrical resistance
- Facilitate electro-magnets with high fields that are not practical with magnets made with copper coils while conserving electrical power

Conventional Superconductors

- Most applications require operation at ~4K (-269 C, liquid helium)
  - Thus also called Low Temperature Superconductors (LTS)

High Temperature Superconductors (HTS)

- Materials that are generally superconducting at ~77 K (-196 C, liquid nitrogen)
Conventional Low Temperature Superconductors (LTS) and New High Temperature Superconductors (HTS)

Low Temperature Superconductor (1911)

Resistance of Mercury falls rapidly at very low temperature

High Temperature Superconductors (1986)

New materials (ceramics) loose their resistance at NOT so low temperatures (Liquid Nitrogen)!
Critical Surface

The surface on 3-d (J,T,B) volume within which the material remains superconducting.

Figure 2.11: Sketch of the critical surface of NbTi. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.

In a magnet, the operating point must stay within this volume with a suitable safety margin!

Courtesy: Schmuser/Wilson
Type I and Type II Superconductors

Type I:
Also known as “soft superconductors”.
Completely exclude flux lines (Meissner Effect).
Allow only small field (<< 1 T).
Not good for accelerator magnets.

Type II:
Also known as “hard superconductors”.
Completely exclude flux lines up to $B_{c1}$
but then part of the flux enters till $B_{c2}$
• Important plus: Allow much higher fields.
• These are the one that are used in building accelerator magnets.

Figure 10: Magnetisation of type I and type II superconductors as a function of field.

Courtesy: Schmuser
Critical Field as a Function of Temperature in Low Temperature Superconductors

**Figure 12:** (a) The phase diagram of a type II superconductor.

- **Bc₂ vs. Tc**

- All present accelerator magnets are made with NbTi.

- MgB₂ is LTS with high Tc (perhaps highest possible).

*(Courtesy: Wilson)*
**Critical temperatures ($T_c$) of popular superconductors:**

**LTS**
- NbTi: $\sim 9$ K
- Nb$_3$Sn: $\sim 18$ K

**HTS**
- BSCCO2223: $\sim 110$ K
- BSCCO2212: $\sim 85$ K
- YBCO/ReBCO: $\sim 90$ K
- MgB$_2$: $\sim 39$ K
Critical Current Density as a Function of Field in LTS & HTS

Current Density Across Entire Cross-Section

- YBCO: Tape || Tape plane
- YBCO: Tape | Tape plane
- Bi2223: B || Tape plane
- Bi2223: B | Tape plane
- 2212: Round Wire 28% SC
- Nb3Sn: Internal Sn RRP®
- Nb3Sn: High Sn Bronze
- Nb-Ti: LHC 1.9 K
- MgB2: 19Fil 24% Fill

Critical Current Density as a Function of Field in LTS & HTS

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Superconducting Magnets for Particle Accelerators

Ramesh Gupta, BNL
Copper and Superconducting Magnets

Room Temperature Magnets:
Current density in copper coils of conventional magnets:
- Air cooled (max) \( \sim 1 \, \text{A/mm}^2 \)
- Water cooled \( \sim 2-10 \, \text{A/mm}^2 \)
Typical fields: \( \sim 1.2 \, \text{T} \)

Superconducting Magnets:
Current density in coils of superconducting magnets:
- 100-1000 \( \, \text{A/mm}^2 \)
Typical fields:
- Iron dominated: 2-3 T
- Conductor dominated: 3 - 10 T
- R&D for even higher fields
Even though the superconductor may be capable of carrying a current density of 3000 A/mm$^2$ or so, only a fraction of that is available to power the magnet.

**Here is why?**

- There should be enough copper within the wire to provide stability against transient heat loads and to carry the current in the event the superconductor turns normal (quench).
- Usually the % of copper is more than % of superconductor. In medium field NbTi production magnets, the maximum current density in copper is generally <1000 A/mm$^2$ at the design field.
- The coil consists of many turns. There must be a turn-to-turn insulation taking ~15% of the volume.
- Thus with all included, in most cases Jo could be ~500 A/mm$^2$ (much less than 3000 A/mm$^2$).
Major reasons for using superconducting magnets in the accelerators:

**Cost advantage**

- Superconducting magnets reduce the size of and often cost of advanced machine.
- Superconducting magnets also lower the power consumption and hence the cost operating cost.

**Performance advantage**

- A few high field magnets may significantly enhance the performance of the machine.
- Thus even if the cost of a few magnets is high, the overall return of the investment to experimentalists may be impressive and highly cost-effective.
- Some time there is no option but to use high field superconducting magnets to obtain the desired performance.
Without “energy saving” superconducting magnets, the power bill of many accelerators would have been so large that they would not have been built.

Without “powerful” superconducting magnets, the size of those machines would have been so large that it may hardly have fit in the space available.

Without “high gradient” superconducting magnets, the desired luminosity would not have been possible (RISP in Fragment Separator, included).

Relativistic Heavy Ion Collider (RHIC) at BNL
Variety of Superconducting Magnets in RHIC (all magnets in RHIC are superconducting)

Conductor dominated (cosine theta) and iron dominated (super-ferric) magnets

Fig. 1-16. Cross section of the trim quadrupole cold mass. All lamination dimensions outside the pole area are identical to those in the sextupole lamination.
Cosine Theta (conductor dominated)
Magnets for RHIC, SSC and LHC

RHIC dipole coldmass during assembly
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Superconducting Magnets for Particle Accelerators

Ramesh Gupta, BNL

Slide No. 16

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Super-ferric (iron dominated) Magnets in RHIC

RHIC uses Super-ferric Trim Quadrupole and Sextupole Magnets

FRIB (and hopefully) RISP will also use super-ferric Magnets
Magnet Aperture

- Usually comes from accelerator physicists
- However, an interaction between accelerator physicists and magnet scientists may produce a more optimized system design.

Design Field

- Higher fields may improve the performance of machine and/or reduce cost. However, higher field also make magnets more complicated
- The value of field determines the choice of conductor
• The magnet should be designed in such a way that the conductor remains in the superconducting phase with a comfortable margin.

• Superconducting magnets should be well protected. If the magnet quenches (conductor loses its superconducting phase due to thermal, mechanical, beam load, etc.), then there should be enough copper in the cable to carry the current to avoid burn out.

• The cryogenic should be able to cool and maintain the low temperature (roughly at 4 K in LTS, higher in HTS). It should be able to handle heating caused by the beam, either by radiation or by decay particles.
• The magnet cost should be minimized.

• There are large Lorentz forces in superconducting magnets. The coil should be contained in a support structure that can handle these large forces and minimize the conductor motion.

• The magnets should be designed in such a way that it is easy to manufacture (very important).

• It must meet the field quality (uniformity) requirements.
Designing Conductor Dominated Superconducting Magnets
Breaking news (last week):
Two solenoid systems (each consisting of many coils) were recently built and tested at BNL with >10% margin.
Computer Models of a Solenoid

3d Model

Field on iron and coil

Coil with field superimposed

2d Model

Field on iron and coil

2d Model (more accurate and faster calculations in many cases)
• A good mechanical structure is the key to the success of a superconducting magnet.
• An advanced support structure developed after the conceptual and a detailed engineering design analysis.
• In this case, the mechanical structure is consisted of stainless steel outer support tube and intermediate stainless steel plates to contain complex Lorentz forces.

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Solenoid Wire and Magnet Performance
(Load Line and Peak Field)

**Design Field:**
6 Tesla

**Stored Energy:** ~1.4 MJ,
**Inductance:** ~14 Henry

**Computed Magnet Performance:**

<table>
<thead>
<tr>
<th>Temp</th>
<th>Bss</th>
<th>Bpk</th>
<th>I(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 K</td>
<td>7.1 T</td>
<td>7.65 T</td>
<td>545 A</td>
</tr>
<tr>
<td>4.5 K</td>
<td>6.8 T</td>
<td>7.35 T</td>
<td>523 A</td>
</tr>
</tbody>
</table>

**Field margin@4.5 K:** ~13%

Peak field line corresponds to the maximum field on the conductor
determines how much current one can put in), and Load line refers
to the field in the aperture (determines field available to beam)
Total MIITs in the circuit:
\[ \int I^2 \, dt : \sim 1.5 \, \text{MIITs} \]

(for \( I = \sim 500 \, \text{A}, \, L = \sim 14 \, \text{H}, \, R_{\text{dump}} = \sim 1.2 \, \Omega \);
giving time constant: \( \tau = \sim 12 \, \text{sec} \))

Diodes are across segments of the coil
to limit the energy deposited in the coil
segment (\(< 0.5 \, \text{MIITs})

Bus & diodes are designed to handle a
much higher MIITs than the coil
conductor (\(> 1.5 \, \text{MIITs}).

Energy extraction is used to limit the
maximum MIITs in the bus & diodes

This is safe as temperature remains well below 350 K

Energy extraction and quench protection diodes are used to
control temperature rise in the
coil in the event of a quench

E-Lens Main Solenoid Temp vs MIITS

Keep temperature < 350 K (0.5 MIITs)

Courtesy Joe Muratore
George Ganetis
Coil Designs for High Field Dipoles
Magnets of Modern Accelerators

- All magnets use NbTi Superconductor
- All designs use cosine theta coil geometry
Optimizing Coil Geometry

Coil geometry is optimized with special codes to minimize field errors and maximize the operating fields (parameters - wedges and turns).

Such coil geometry is commonly referred to as “cosine theta geometry”.

The conductor placement error should generally be within 50 \( \mu m \).
The field is high in the pole block and lower on other blocks, particularly on the outside.
Non-linear properties of iron can create field errors at high field even if they were not present at low fields. Magnet designs for more uniform saturation are important issues in super-ferric magnets. 

\[ B = \mu H \]
Designing Iron Dominated Superconducting (Super-ferric) Magnets
Magnetic Modeling

The primary purpose of the magnet modeling at early stage of the program is to:

• Produce designs that meet or exceed the machine requirements
• Give feedback to machine physicists on what errors to expect, and also what is the level of our confidence in those calculations, so that they can use this information in designing the machine
- Pole bumps are used for field shaping.
- Adjust width and height of the bump to obtain a good field quality.
- Vertical size of the bump is kept small to minimize a decrease in the pole gap.

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**2-d Magnetic Design of Dipole**

- Pole bumps are used for field shaping.
- Adjust width and height of the bump to obtain a good field quality.
- Vertical size of the bump is kept small to minimize a decrease in the pole gap.

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**Homogeneity of BMOD w.r.t. value**

- $0.397105307$ at $(50.0,0.0)$
- $3.09163E-05$
- $8.36111E-05$
Needed good field quality (a few part in $10^4$) in +/-20 mm (40 mm total width); above design has a range of 50 mm
Field harmonics are normalized to fundamental harmonic and are given in the units of $10^{-4}$. $b_2$ is quadrupole.

All harmonics are very small (given in units of $10^{-4}$). They are only a few parts in $10^5$ even at 20 mm reference radius. Therefore, the good field requirements are met both in terms of harmonics (see above) and in terms of the good field region (last slide).
Iron Yoke Optimization - Dipole

- Pole shape must be optimized to minimize field errors at low fields.
- Cutout/holes can be used to minimize field errors at high fields when iron properties become non-linear (similar to that as in conductor dominated magnets).

From IPAC2012 Paper

High Radiation Environment Nuclear Fragmentation Separator Dipole Magnet
Stephen A. Kahn¹ and Ramesh C. Gupta²
¹Muons, Inc., Batavia, IL 60510, ²Brookhaven National Laboratory, Upton, NY 11973
Iron Yoke Optimization - Quadrupole

- Space needed for cryostat minimized by carefully designing a cryo-mechanical structure.
- Space yoke in neck area is maximized to minimize iron saturation at high currents.
- Cutout for good field quality at all fields.
- In addition, both quadrupole and dipole yokes are also optimized for reducing peak field (in particular, perpendicular field)

Second Generation HTS Quadrupole for FRIB

Brookhaven National Laboratory

A. Zeller, Senior Member IEEE
Michigan State University

Superconducting Magnets for Particle Accelerators  Ramesh Gupta, BNL
R&D Magnet in cryostat
(allow independent testing of four HTS coils)

Cut-away isometric view of the assembled magnet
(compact cryostat allowed larger space for coils and reduction in pole radius for higher gradient)

From ASC 2010 Paper
This is ¼ (90°) model of the sextupole.

As such only 1/12 (30°) model is needed, since cutout on the outer edge can be neglected as the return yoke is far from saturation.

Non allowed harmonics at low fields are good measure of computational errors.
Use quadratic elements. This increases accuracy of calculations significantly in quadrupoles and sextupoles. Linear elements are OK in dipoles where vector potential changes linearly.

Higher mesh density in the region where higher relative accuracy is needed for computing field harmonics.
Six points (position) and two radii were used in optimizing pole profile to obtain low allowed harmonic while satisfying geometric constraints.
3-d Modelling of the Sextupole

Ends are chamfered to minimize integral harmonics.
Simplifying the Model

Simplifying certain details of iron structure does not decrease the accuracy of the calculations of the interference harmonic but significantly reduces the computational time.
Understanding Errors in Field Computations (2d)

Relative field errors on a circular arc are computed with respect to its value at $x=R$.

- Smooth variation (parts in $10^4$) may be due to inherent harmonics in the model.
- Noise (a few parts in $10^5$) may be due to errors in field calculation.
- This suggest that the calculations should be reliable to a few parts in $10^5$.

This seems to be a reasonably good model giving reasonably good results.
Relative Error in Field Calculations (3d)
Magnitude of Field Parallel to z-axis

For most part relative error is 1 part in $10^4$.
This is unusually good for 3-d for chosen mesh density.
Questions???
HTS Magnets and their Applications

A quick overview – detailed can be discussed off-line
New Possibilities with HTS in Superconducting Magnet Technology

**HTS can function at high temperature**

- That makes helium free superconducting magnets operating at high temperature possible as never before (> 20 K)

**HTS can carry substantial currents at high fields**

- That makes very high field superconducting magnets possible as never before (>20 T)

Even one of above is sufficient to revolutionize the field

➤ Here we have two !!
Magnets Made with HTS (offer a range of possibilities)

- High temperature, low field
  - Already in use in R&D programs at BNL

- Medium field, medium temperature
  - Potential for large scale cryogen-free applications
  - Solving critical problem of large heat loads as in RISP

- Very high field magnets
  - Dipoles for energy upgrade of particle accelerators
  - Quadrupoles for interaction region upgrade
  - Solenoids (>30 T) to make Muon Collider possible
HTS Solenoid for Superconducting Electron Gun

Produces intense electron beams with focusing from HTS solenoid

- No room for LTS solenoid in Liquid Helium
- Copper solenoid would generate ~500 W heat as against the ~5 W heat load of the entire cryostat
- Temperature between baffles ~20 K – NO LTS
- HTS solenoid provides a unique solution

Courtesy: Ben-Zvi, Kewisch

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Testing at ~77 K in LN$_2$ is much cheaper than testing at ~4 K in LHe.

HTS provided an economically better (design + build + test) and technically superior solution.

Conductor cost: ~ a few k$

Compact size

Low current (<20 A) operation with household wiring
HTS solenoid is placed in cold to warm transition region after the superconducting cavity where neither LTS or copper solenoid would work.

A unique BNL solution that other labs are adopting.
Medium Field HTS Magnet Programs

1. General Purpose (for accelerators & medical applications)
   - Must compete with two established technologies:
     - Magnets powered with water-cooled copper coils
     - Super-ferric magnets with conventional superconductors (NbTi)

2. Special Purpose Magnets:
   - HTS magnets solve critical technical problems
   - Example: Large energy deposition in FRIB, RISP, etc.
HTS and Cryo-coolers
(a promising marriage)

Evening: Switch ON; Morning: Fully COLD
HTS Magnet Development Program for Facility for Rare Isotope Beams (FRIB)

Will create rare isotopes in quantities not available anywhere

- Michigan State University

HTS Magnets for RISP:
Discussed in details in the HTS/RISP seminar
Technical Advantage of HTS Magnets in FRIB

- High power beam (~400 kW) hits the target to create intense rare isotope beams
- Magnets are exposed to very high radiation and heat loads (~15 kW in the first)
- HTS magnets remove this heat more efficiently at 30-50 K than LTS at ~4 K
- HTS magnets have a large temperature margin, can tolerate a large local increase in temperature and allow a robust cryogenic operation in presence of large heat loads
• The most demanding program yet
• High fields create large forces, large stored energy, etc., etc., etc.
• Will test the limit of the conductor and of structure

Two ambitious programs:

- 24-30 T HTS solenoid for magnetic energy storage
- 30-40 T HTS+LTS (hybrid) solenoid for cooling in muon colliders

Both would be the highest field HTS magnets ever built!
• Ambitious R&D to develop SC magnet technology for 35-40 T

• Significant demonstrations so far:
  - Highest field (>15 T) HTS magnet ever built
  - Large use (1.2 km) of HTS in a high field magnet
High Field HTS Solenoids for MAP

Two significant construction and tests

Conductor:
High strength 2G HTS from SuperPower with ~45 μm Copper

SBIR with PBL
RISP, ISB, Korea, August 22, 2012
High Field HTS Test Results (magnet #1)

Field on axis:
- over 15 T

Field on coil:
- over 16 T

Real demo of 2G HTS to create high field

Highest field in an all HTS solenoid (previous best SP/NHMFL ~10.4 T)

Overall $J_o$ in coil:
- >500 A/mm² at 16 T
  (despite anisotropy)

24 pancake coils with ~25 mm aperture

SBIR with PBL
Test Results of ~100 mm HTS Coil (magnet #2 - half length midsert)

Proof That A Large Number of 2G HTS Coils Can be Built and Tested without Degradation

- Intermediate test with 12 pancakes
- Full solenoid will have 24 pancakes (each coil built with 100 m SP HTS)
Test Results of $\frac{1}{2}$ Midsert Solenoid

Measured Critical Current As a function of 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

250 A ==> 6.4 T on axis
9.2 T on coil

Coil could have reached above 10 T, but we decided to hold back to protect our electronics

SBIR with PBL
• 25 mm and 100 mm solenoids will be merged together and should be ready for test in a few months

• Expected field: 20-25 T (would be a remarkable result)
  – Highest field in an all HTS magnet (beating 15 T just achieved)

• Proposal to build a NbTi outsert to above to enhance the field to over 25 T when all powered together.

• Proposal to add more modular coils to enhance the combined to ~35 T as needed for Muon Accelerator Program (MAP)
TABLE II  
COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. Ic 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>Ic (A)</th>
<th>Jₑ(4K)[Jₑ(5T)]</th>
<th>Self-field, T</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC006</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>DCC004</td>
<td></td>
<td>Common coil configuration</td>
<td>900</td>
<td>97 [54]</td>
<td>0.43</td>
</tr>
<tr>
<td>CC007</td>
<td>0.81 mm wire, 18 strands</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DCC004</td>
<td></td>
<td>Common coil configuration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC010</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>DCC006</td>
<td></td>
<td>74 mm spacing Common coil</td>
<td>182</td>
<td>177 [80]</td>
<td>0.045</td>
</tr>
<tr>
<td>CC011</td>
<td>0.81 mm wire, 2 HTS, 16 Ag</td>
<td>Hybrid Design 1 HTS, 2 Nb₃Sn</td>
<td>1970</td>
<td>212 [129]</td>
<td>0.66</td>
</tr>
<tr>
<td>DCC006</td>
<td></td>
<td>Common coil configuration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC012</td>
<td>0.81 mm wire, 18 strands</td>
<td>Hybrid Design 1 HTS, 2 Nb₃Sn</td>
<td>3370</td>
<td>215 [143]</td>
<td>0.95</td>
</tr>
<tr>
<td>DCC012</td>
<td>1 mm wire, 20 strands</td>
<td>Hybrid Design 1 HTS, 4 Nb₃Sn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DCC014</td>
<td></td>
<td>Hybrid Design 1 HTS, 4 Nb₃Sn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC026</td>
<td>0.81 mm wire, 30 strands</td>
<td>Hybrid Common Coil Design</td>
<td>4300</td>
<td>278 [219]</td>
<td>1.89</td>
</tr>
<tr>
<td>DCC014</td>
<td></td>
<td>2 HTS, 4 Nb₃Sn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC027</td>
<td>0.81 mm wire, 30 strands</td>
<td>coils (total 6 coils)</td>
<td>4200</td>
<td>272 [212]</td>
<td>1.84</td>
</tr>
</tbody>
</table>

Earlier coils  
<1 kA (~2001)  

Later coils  
4.3 kA (2003)  
Still a record?  

Racetrack HTS coil  
with Bi2212
Thank you for your attention.

Questions?