Alternate Magnet Options for Muon Collider

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A quick recipe for help choosing reasonable magnet design parameters

Alternate design options for muon collider
To get maximum field keep increasing coil thickness (within practical limit) till you reach the maximum field in the coil where magnet quenches.
Quadrupole Gradient for various coil radius

Dipole: \( B = -\mu_0 J_0/2 \times t \)
Quad: \( G = -\mu_0 J_0/2 \ln(1+t/a) \)
\( t = \) coil thickness
\( a = \) coil radius

\( J_0 = 700 \text{ A/mm}^2 \) at the given field.

Need \( J_c \sim 2000 \text{ or more.} \)

Note: Legends are coil radius, not aperture.

The plot scale linearly with \( J_0 \) (current density in coil).
A reasonable range of \( J_c \) is 400-1000 A/mm².

Important number is pole-tip field = Gradient * coil radius

In large aperture magnets, forces become large.
Usable current Density in Magnet Design

A case study of Nb3Sn Superconductor

<table>
<thead>
<tr>
<th>Cu/Sc Ratio</th>
<th>B(T)</th>
<th>Jsc(A/mm²)</th>
<th>Jwire(A/mm²)</th>
<th>Joverall(A/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.30</td>
<td>5</td>
<td>9454</td>
<td>1295</td>
<td>911</td>
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<tr>
<td>5.18</td>
<td>6</td>
<td>7766</td>
<td>1257</td>
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<td>4.29</td>
<td>7</td>
<td>6431</td>
<td>1216</td>
<td>856</td>
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<td>3.56</td>
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<td>5347</td>
<td>1171</td>
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</tr>
<tr>
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<td>9</td>
<td>4446</td>
<td>1122</td>
<td>790</td>
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<td>2.46</td>
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<td>3689</td>
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<td>3048</td>
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<td>2500</td>
<td>938</td>
<td>660</td>
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<tr>
<td>1.35</td>
<td>13</td>
<td>2031</td>
<td>863</td>
<td>607</td>
</tr>
<tr>
<td>1.09</td>
<td>14</td>
<td>1631</td>
<td>781</td>
<td>550</td>
</tr>
<tr>
<td>0.86</td>
<td>15</td>
<td>1289</td>
<td>693</td>
<td>488</td>
</tr>
</tbody>
</table>

Critical Current Density in Superconductor: $J_{sc}(at\ 4.3\ K)$
Also Wire & Overall Current Densities Normalized for a Given $J_{cu}$

Scaled from TWCA

A Good "Linear Fit"

$y = -74.64x + 1824.1$

$R^2 = 0.9956$
Expected Performance of HTS-based Magnets

**Year 2000 Data**

<table>
<thead>
<tr>
<th></th>
<th>All Nb$_3$Sn</th>
<th>All HTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 T</td>
<td>5 T</td>
<td></td>
</tr>
<tr>
<td>15 T</td>
<td>13 T</td>
<td></td>
</tr>
<tr>
<td>18 T</td>
<td>19 T*</td>
<td></td>
</tr>
</tbody>
</table>

*20 T for Hybrid

**Near Future**

<table>
<thead>
<tr>
<th></th>
<th>All Nb$_3$Sn</th>
<th>All HTS</th>
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<tr>
<td>12 T</td>
<td>11 T</td>
<td></td>
</tr>
<tr>
<td>15 T</td>
<td>16 T</td>
<td></td>
</tr>
<tr>
<td>18 T</td>
<td>22 T</td>
<td></td>
</tr>
</tbody>
</table>

**Cu(Ag)/SC Ratio**

- BSCCO: 3:1 (all cases)
- Nb$_3$Sn: 1:1 or $J_{cu} = 1500$ A/mm$^2$

**Year 2000 data for $J_c$ at 12 T, 4.2 K**

- Nb$_3$Sn: 2200 A/mm$^2$
- BSCCO-2212: 2000 A/mm$^2$

**Near future assumptions for $J_c$ at 12 T, 4.2 K**

- Nb$_3$Sn: 3000 A/mm$^2$ (DOE Goal)
- BSCCO-2212: 4000 A/mm$^2$ (2X from today)
Issues with HTS

**Advantages:**
- Can work at elevated temperature. For example, in muon collider and IR region magnets where a large energy is deposited from the decay products.
- Has potential for producing very high magnetic fields.

**Challenges:**
- Large quantities are not available yet
  - But enough to make test coils and the length of wire available are increasing continuously. Remember HTS is support by other program.
- Unknown field quality issues
  - We will be measuring them soon.
- High cost
  - Needs to come down by the time these magnets are needed. Also compare the overall system cost. Consider special applications where cost matters less.

**Status:**
The performance has reached a level to consider them as a promising candidate.
BNL has started magnet R&D with this challenging material. Results are encouraging. Consider HTS option for magnets that are not required immediately.
Measurement of an earlier “BSCCO-2212 cable” at BNL test facility.

$I_c$ is better by over a factor of 2 now. This was a narrow (18 strand) cable. Standard cable will carry much more. Expect 5000 A up to a high field.

Measurement of “BSCCO 2223 tape” wound at 57 mm diameter with applied field parallel (1 $\mu$V/cm criterion) (field perpendicular value is ~60%).

HTS Cable Test

HTS Tape Test
Common Coil Magnets With HTS Cable

Two coils were tested in Liquid Nitrogen

The HTS cables were from two different batches. They behaved differently:

- Different Ic
- Different Tc

Based on preliminary analysis, no large degradation has been observed.
Results of Coil #2 Tested in Muon Collider and Common Coil Configuration

Muon Collider Configuration - Coil #2

Coil #2 in Common Coil Configuration

- Lead
- Turn#10
- Turn#9
- Turn#8
- Turn#7
- Turn#6
- Turn#5
- Mid-SS
- Turn#4
- Turn#3
- Turn#2
- Turn#1

- Lead-SS
- Turn#10
- Turn#9
- Turn#8
- Turn#7
- Turn#6
- Turn#5
- Mid-SS
- Turn#4
- Turn#3
- Turn#2
- Turn#1
High Field Magnets for Muon Collider and ν Factory Storage Ring

**Design Issues:**

- Must use **brittle** superconductors: $\text{Nb}_3\text{Sn}$, HTS
- Large Lorentz forces
- Large energy deposition
- Cold coils, Warm iron
- Need compact cryostat
- Large heat leak

Conventional cosine $\theta$ design (e.g., RHIC magnets)
Complex 3-d geometry -- not best for high fields

Conductor friendly racetrack coil geometry
Suitable for high field magnets with brittle material
The following design is for ν Factory but the principles are relevant to muon collider also.

Decay products clear superconducting coils.

*Earlier studies on open midplane design by P. McIntyre and by M. Green (with some variations.)

HTS is an interesting possibilities in such magnets.
5 T Dipole for $\nabla$ Storage Ring

5 T central field can be achieved by NbTi

A dipole with no cutout in yoke for a reverse field region. Electrons will hit yoke and create shower

Decay electrons get back towards main aperture by (a) Reverse field and (b) Magnet saggitta which knob to use how much may depend on E & B

In neutrino storage ring, is \(\sim 10\%\) energy deposition acceptable?

Design with a reverse field region in Iron

Electrons deflected back by reverse field

Iron yoke starts here

Muon Storage Ring Magnets

R. Gupta, 7/7/01
Lattice & Magnet Designs for a Compact Ring

- **Skew quadrupole needs **NO** conductor at midplane (B. Parker)**

- In study 1 (50 GeV), ~1/3 space was taken by inter-connect regions

  
  \[
  \text{Quadrupole (Q): Field Gradient}
  \]
  
  \[
  \text{Dipole (D): Field}
  \]

  
  \[
  \text{No space is wasted for interconnect}
  \]

  
  \[
  \text{Shorter cells ⇒ smaller aperture, improved beam dynamics}
  \]

  
  \[
  \text{Interconnect Region}
  \]

  
  \[
  \text{Gets worse at lower energy (50 => 20 GeV in study 2)}
  \]

- **New magnet system design** makes a productive use of all space
Alternate End Design Concept

- Reverse coils to cancel field harmonics in ends (also generate skew quad)

New Magnet System Design
- Good field quality
- Makes ring small

Important for BNL site

Note: Bx & By (normal and skew harmonics) are cancelled but Bz (axial field) is not.
We have got a limited funding under LDRD. With that we are building a series of short coils (length same as in study 2).

The cross section in the magnet under construction belongs to an earlier design; but all design principles remain the same.

The magnet will be made using ITER cable and therefore would reach a lower (~4 T) field.
Racetrack coil magnet designs with open midplane offers an interesting possibility of making high field magnets that can deal with large energy deposition.

HTS is a promising technology for muon collider magnets.