Impact of HTS Magnets on IR Layout and Design

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Design Considerations

There are two classes of magnets:

- **Main ring magnets**
  
  Large number
  
  Design should be driven by cost
  
  Cost is determined by material and labor

- **Insertion region magnets**
  
  Small number
  
  Design should be driven by performance (we can allow bigger cost per magnet)
  
  The material and labor cost of final magnets will be a small fraction of overall cost that includes cost of R&D.

⇒ Different design principles should apply to two!

HTS magnets with brittle conductors and high “labor & material costs” may be too demanding for whole machine but OK for IR's.
Are we ready to build HTS accelerator magnets?

No, not yet!

Given the time frame of upgrade, the right questions to ask are:

Is there a possibility to demonstrate the viability of HTS magnets in time for making a technology choice for luminosity upgrade?

Based on short HTS coils (yes we have built and tested a few), it’s promising. But it’s too early to tell without more R&D and proof.

What is the impact of HTS on overall IR upgrade design?

HTS magnets with very high fields may be enabling technology for some designs (layouts). But, the benefits must be examined in all lattices to see how each can benefit. Modification in strategy?

What is the impact of HTS on high luminosity operation?

HTS can tolerate several degrees (even up to 5-10) increase in temperature. That changes many design principles.
Expected performance of all Nb₃Sn or all HTS magnets at 4.2 K for the same amount of superconductor:

<table>
<thead>
<tr>
<th>Year 2000 Data</th>
<th>All Nb₃Sn</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

<table>
<thead>
<tr>
<th>Near Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Nb₃Sn</td>
</tr>
<tr>
<td>12 T</td>
</tr>
<tr>
<td>15 T</td>
</tr>
<tr>
<td>18 T</td>
</tr>
</tbody>
</table>

These are quench fields, operating fields may be 10% or more lower.

Cu(Ag)/SC Ratio
- BSCCO: 3:1 (all cases)
- Nb₃Sn: 1:1 or \( J_{cu} = 1500 \text{ A/mm}^2 \)

Performance of 0.8 mm dia wire

- Nb₃Sn (4.2K) (BSCCO2212)
- NbTi (4.2K)
- NbTi (1.8K)

Year 2000 data for \( J_c \) at 12 T, 4.2 K
- Nb₃Sn: 2200 A/mm²
- BSCCO-2212: 2000 A/mm²

Near future assumptions for \( J_c \) at 12 T, 4.2 K
- Nb₃Sn: 3000 A/mm² (DOE Goal)
- BSCCO-2212: 4000 A/mm² (2X today)

Investment in 2212 has been much less than in 2223, there may be room for relatively more improvement.
Engineering (Operating) Current Density in Magnet Designs

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

<table>
<thead>
<tr>
<th>Cu/Sc Ratio</th>
<th>B(T)</th>
<th>$J_{sc}(A/mm^2)$</th>
<th>$J_{wire}(A/mm^2)$</th>
<th>$J_{overall}(A/mm^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.30</td>
<td>5</td>
<td>9454</td>
<td>1295</td>
<td>911</td>
</tr>
<tr>
<td>5.18</td>
<td>6</td>
<td>7766</td>
<td>1257</td>
<td>855</td>
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<tr>
<td>4.29</td>
<td>7</td>
<td>6431</td>
<td>1216</td>
<td>856</td>
</tr>
<tr>
<td>3.56</td>
<td>8</td>
<td>5347</td>
<td>1171</td>
<td>825</td>
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<tr>
<td>2.96</td>
<td>9</td>
<td>4446</td>
<td>1122</td>
<td>790</td>
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<tr>
<td>2.46</td>
<td>10</td>
<td>3689</td>
<td>1066</td>
<td>751</td>
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<tr>
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<td>708</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>
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<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>

Scaled from TWCA

$y = -74.64x + 1824.1$
$R^2 = 0.9956$

Example $Nb_3Sn$
The increase in pole tip field is linear with coil thickness in dipole, but not so in quadrupole. The situation gets worse as we go to high gradients.

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

High current density at high fields is much more useful in high gradient quadrupoles than in high field dipoles.
BNL has built many test coils (14) and magnets with HTS cable and tape.
Today’s HTS cable can carry large currents. This was a narrow cable. LHC size cable will carry much more. Moreover, $I_c$ is better by over a factor of two now.

**Measurement of “**BSGCO-2212 cable”\** Showa/LBL/BNL collaboration**

Cable Test

Tape Test

**Measurement of “**BSGCO 2223 tape”\** wound at 57 mm diameter with applied field parallel (1µV/cm)\n(field perpendicular value is ~60%)
Remember: HTS is also a High Temperature Superconductor!

A few degree increase in temperature, either from energy deposition of decay particles, or from mechanical motion, has a small effect on critical current. HTS magnets will not quench easily, they can tolerate much more beating!
DCC006: 2nd HTS CC Cable Dipole
74 mm Aperture for Field Quality Measurements

A versatile structure to test single or double coils in various configurations

Voltage taps on each turn

Heaters on the magnet to make controlled change in magnet temp

4 thermometers on the coils

HTS Cable Leads to make high temp measurements

74 mm aperture to measure field quality
Field Quality Measurements

DC loop Data (+200A) in DCC006 Dipole Mode

- Normal Sextupole (T.m/kA at 25 mm)

- Mixed strand cable (2 BSCCO 2212, 16 Ag)

Difference between up and down ramp values is within measurement errors. Max field on conductor was only ~550 Gauss. Expect a relatively smaller measurement error when the total current is high in an all HTS cable.
Interaction region magnets for the next generation colliders can benefit a lot from:

- the ability to produce very high fields
- the ability to deal with large energy deposition
- the ability to operate at elevated temperatures that need not be uniform

→ For these IR magnets, the performance, not the material cost is the issue.
→ IR quadrupoles in LHC may be replaced a few years after first experiment.
Optics and magnet requirements (field & aperture) depends crucially on the minimum spacing in the first 2-in-1 IR Quadrupole (doublet optics).

23KW of beam power radiated from the IP makes this a natural for HTS.
VLHC-2 Interaction Region Magnet Design Concept

Conventional 2-in-1 cosine theta design

Panofsky 2-in-1 quad design

Modified Panofsky Quad with no spacing

Spacing depends on the conductor and support structure requirements

Support structure and middle conductor is removed/reduced. This reduces spacing between two apertures significantly.
We have investigated several variations of the design shown in previous slide. Expect system optimization between field field strength, field quality and corrector designs.

A design of particular interest (for neutrals) is the case when there is nothing present at the midpoint of two apertures.

Decay products from IR clear the superconducting coils
Fields in the Proposed Double-Quad Design

Field contours and field lines

Aperture

Aperture
Only a decade ago, HTS was treated as a material of curiosity for such applications. Now we are taking it more seriously. Fermilab and CERN use it in HTS leads.

It is available in much more than a few meter length
- BNL recently purchased wire from Showa that was 1.5 km long.
- LBL has made HTS cable that was ~100 meter long.

It carries much more than a few Ampere current
- Even today, LHC size cable should carry ~5 kA current at high field.

…and we have made a number (14) small coils with it
- Despite being very brittle, it has been shown that it can be handled.
- So far, in the limited test, we have not seen a significant degradation.

However, for making magnets, there is a long way to go!
HTS has a potential to make a significant impact on IR Design

- Can generate high fields
- Can work at elevated temperature
- Can simplify cryogenic system

A reasonable effort in HTS magnet R&D should be directed now to make sure that we don’t miss out a potential opportunity

- This is a “High Risk, High Reward R&D”
- Machine people are requested to explore all benefits of it.