IR Magnets for VLHC

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A very limited amount of work has been done on VLHC Interaction Region (IR) magnets.

Consider all designs preliminary and/or conceptual.

All Cosine theta IR quad designs are from Fermilab.
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)
    - Material and labor cost does not matter
    - Magnet R&D would determine the cost

♠ Perhaps different design principles should apply to two.
Consider energy deposition issue as an integral part of the magnet design. Need feedback before going too far.

Do we need liner? If yes how big?

Does open midplane magnet design help? If yes, how much?

We considered open midplane in an early days of LHC quad design. However, preliminary energy deposition calculations suggested that the secondary bombardment was also serious. Revisit the issue again.

If open midplane helps then how much do we compromise in gradient (specially if significant number of turns are removed from midplane)? What is the impact of that on IR design (optics, geometry and magnets)?
**Stage 1**
Use present conductor technology for determining magnet design except for some small projected improvements (for example, 3000 A/mm$^2$ $J_c$ in Nb3Sn). But feel free to be innovative in magnet design.

**Stage 2**
Stage 2 is 25 years away!
Expect major improvements in superconductor and magnet technology. For example, consider HTS based magnets.

*It is not realistic not to assume progress in this period.*

Design IR accordingly.
But if designs and expected performance are too aggressive; please have a fall back solution, just in case!
The following information is from VLHC Design Study Report.

Main features/requirements of the quadrupole design:

- Design gradient: 300 T/m
- Aperture: ~80 mm
- Maximum beam separation within quad: 12.5 mm

Design gradient: 300 T/m with two layers
- Aperture: 85 mm
- Nb3Sn Jc: 3000 A/mm2
- Mechanical Design: An upgraded version of LHC IR quad design by FNAL
Two type of optics:
Flat beam and round beam.
IR design depends significantly with the optics chosen.

In round beam optics, the magnetic polarity of the first quad must be the same for the two counter-rotating beams.

   Beam can pass through the same quadrupole, but allow beam to separate.

In flat beam optics, the magnetic polarity of the first quad must be opposite for counter-rotating beam.

   This means that we need separate quadrupoles for the two beams.

Separation between the two magnets is an important parameter
   • Determines the field in the first beam splitting dipole
   • Determines the increase in beta function and influences the beam size
   • Determines the field strength needed for all IR dipoles

Worthwhile to look for alternate magnet designs
A Guide to the Maximum Field in the Magnets

Dipole: $B = -\mu_0 J_0 \frac{t}{2}$
Quad: $G = -\mu_0 J_0 \frac{t}{2} \ln(1 + \frac{t}{a})$

$t$ = coil thickness
$a$ = coil radius
Quadrupole Gradient for various coil radius

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

$J_0 = 700 \text{ A/mm}^2$ at the given field.
Need $J_c \sim 2000$ or more.

Important number is field: Gradient $\times$ coil radius = pole-tip field

Note: Legends are coil radius, not aperture
IR Magnets for Round Beam Optics

Stage 2 Interaction Region Magnets

The following information is from VLHC Design Study Report.

IR quadrupoles are double bore magnets with the same cross section as arc quads. Length of the magnet is adjusted to get the desired integral strength.

- Design gradient: 400 T/m
- Aperture: 60 mm

Note: These may not be the final parameters.

First beam splitting dipole (D1) is similar to the second generation IR 80 mm aperture 10 T dipole being built at the University of Twente.
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.
Conductor friendly and better field quality design

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. The conductor configuration (consisted of several blocks) is changed significantly to improve the field quality. Expect system optimization between field field strength, field quality and corrector design.

One design of particular interest is the case when no conductor is 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

**Problems Data**
- Problem name: double4d-full
- Symmetry: YY
- Quadratic elements
- Values of BX

**Units**
- Length: mm
- Flux density: T
- Field strength: A/m
- Potential: V/m
- Conductivity: S/m
- Source density: A/m²
- Power: W
- Force: N
- Energy: J
- Mass: kg
Design Parameters of Insertion Region Magnets for VLHC-2 Flat Beam Optics

Designs based on the Nb$_3$Sn and other materials available today.

Table Irx1: Design parameters of VLHV-2 interaction region magnets

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Field</th>
<th>Gradient</th>
<th>Aperture</th>
<th>Length</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1A</td>
<td>16 T</td>
<td>---</td>
<td>25 mm</td>
<td>12.1 m</td>
<td>1-in-1</td>
</tr>
<tr>
<td>D1B</td>
<td>12 T</td>
<td>---</td>
<td>50 mm</td>
<td>6 m</td>
<td>1-in-1</td>
</tr>
<tr>
<td>D2</td>
<td>12 T</td>
<td>---</td>
<td>50 mm</td>
<td>11.1 m</td>
<td>2-in-1</td>
</tr>
<tr>
<td>Q1A</td>
<td>400 T/m</td>
<td></td>
<td>30 mm</td>
<td>12.4 m</td>
<td>2-in-1</td>
</tr>
<tr>
<td>Q1B</td>
<td>600 T/m</td>
<td></td>
<td>30 mm</td>
<td>12.4 m</td>
<td>2-in-1</td>
</tr>
<tr>
<td>Q2A</td>
<td>600 T/m</td>
<td></td>
<td>30 mm</td>
<td>7.9 m</td>
<td>2-in-1</td>
</tr>
<tr>
<td>Q2B</td>
<td>600 T/m</td>
<td></td>
<td>30 mm</td>
<td>7.9 m</td>
<td>2-in-1</td>
</tr>
</tbody>
</table>

1. D1A has higher field and lower aperture. Lower aperture means less accumulated forces. Can be built with Nb$_3$Sn or “BSCCO, Nb$_3$Sn hybrid”.
2. The gradient in Q1A is lower due to a superimposed non-zero dipole field.
Design Parameters of VLHC-2 Insertion Region Magnets

For doublet optics

Designs based on the Nb$_3$Sn and other materials available today

Table Irx1: Design parameters of VLHV-2 interaction region magnets

<table>
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<tr>
<th>Magnet</th>
<th>Field</th>
<th>Gradient</th>
<th>Peak Field</th>
<th>Aperture</th>
<th>Length</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1A</td>
<td>16 T</td>
<td>---</td>
<td>~16.7 T</td>
<td>25 mm</td>
<td>12.1 m</td>
<td>1-in-1</td>
</tr>
<tr>
<td>D1B</td>
<td>12 T</td>
<td>---</td>
<td>~12.5 T</td>
<td>50 mm</td>
<td>6 m</td>
<td>1-in-1</td>
</tr>
<tr>
<td>D2</td>
<td>12 T</td>
<td>---</td>
<td>~12.5 T</td>
<td>50 mm</td>
<td>11.1 m</td>
<td>2-in-1</td>
</tr>
<tr>
<td>Q1A</td>
<td>400 T/m</td>
<td>~11 T</td>
<td>~11 T</td>
<td>30 mm</td>
<td>12.4 m</td>
<td>2-in-1</td>
</tr>
<tr>
<td>Q1B</td>
<td>600 T/m</td>
<td>~10 T</td>
<td>~10 T</td>
<td>30 mm</td>
<td>12.4 m</td>
<td>2-in-1</td>
</tr>
<tr>
<td>Q2A</td>
<td>600 T/m</td>
<td>~10 T</td>
<td>~10 T</td>
<td>30 mm</td>
<td>7.9 m</td>
<td>2-in-1</td>
</tr>
<tr>
<td>Q2B</td>
<td>600 T/m</td>
<td>~10 T</td>
<td>~10 T</td>
<td>30 mm</td>
<td>7.9 m</td>
<td>2-in-1</td>
</tr>
</tbody>
</table>

Notes:

1. D1A has higher field and lower aperture. Lower aperture means less accumulated forces. Can be built with Nb$_3$Sn or “BSCCO, Nb$_3$Sn hybrid”.

2. The gradient in Q1A is lower due to a superimposed non-zero dipole field.
One may like to consider alternate designs for round beam optics as well.

I believe that the magnet parameters can be pushed upward to help beam optics (Please see the maximum fields on the conductor in the previous table).

- Higher field/gradient?
- Larger aperture?
- Remove a few turns from the midplane?

In particular, a large radiated beam power from IP makes these magnets a natural candidate for HTS.
**Expected Performance of HTS-based Magnets**

- **Performance of 0.8 mm dia wire (as of year 2000)**
  - Nb$_3$Sn (4.2K)
  - NbTi (1.8K)
  - BSCCO2212 (4.2K)

**Expected performance of all Nb$_3$Sn or all HTS magnets at 4.2 K for the same amount of superconductor:**

<table>
<thead>
<tr>
<th>Year 2000 Data</th>
<th>All Nb$_3$Sn</th>
<th>All HTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 T</td>
<td>12 T</td>
<td>5 T</td>
</tr>
<tr>
<td>15 T</td>
<td>15 T</td>
<td>13 T</td>
</tr>
<tr>
<td>18 T</td>
<td>18 T</td>
<td>19 T*</td>
</tr>
</tbody>
</table>

*20 T for Hybrid

<table>
<thead>
<tr>
<th>Near Future</th>
<th>All Nb$_3$Sn</th>
<th>All HTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 T</td>
<td>12 T</td>
<td>11 T</td>
</tr>
<tr>
<td>15 T</td>
<td>15 T</td>
<td>16 T</td>
</tr>
<tr>
<td>18 T</td>
<td>18 T</td>
<td>22 T</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 IR region where large energy is deposited from the decay products.
- Has potential to produce very high magnetic fields.

**Challenges:**
- Large quantities are not available yet
  - But enough to make test coils. The current trends show that longer and longer length are going to be available in future.
- Unknown field quality issues
  - We will be measuring them soon.

One point of view: The performance has reached a level that we can do serious R&D. If short coils/magnets are built and results are promising, it would have a significant impact on IR region design. So far results are encouraging. Consider this option future magnets, but not near future.
Measured Performance of HTS Cable and Tape As A Function of Field at BNL

Note: Tape and wire have about the same area.

Measurement of "**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.

Measurement of "**BSCCO 2223 tape**" wound at 57 mm diameter with applied field parallel (1\( \mu \)V/cm criterion)

- (field perpendicular value is ~60%)

Note: Tape and wire have about the same area.
Two coils were tested in Liquid Nitrogen.

The HTS cables were from two different batches. They behaved differently:
- Different $I_c$
- Different $T_c$

Based on preliminary analysis, no large degradation has been observed.
Performance of Coil #2 in Common Coil Configuration

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

Coil #2 in Common Coil Configuration

µV/cm

I(A)

µV/cm

I(A)
A conceptual magnet design and layout has been developed. Consider this a classical example of close interaction between magnet designers and accelerator physicists.

Most details are yet to be sorted out.

A significant magnet R&D is needed.
In dipoles, conductor amount is proportional to the aperture size (linear).

\[
\text{Dipole: } B = -\mu_0 \frac{J_0}{2} t \\
\text{Quad: } G = -\mu_0 \frac{J_0}{2} \ln(1+t/a)
\]

\(t = \text{coil thickness}\)  
\(a = \text{coil radius}\)

Note: The coil thickness is proportional to the field, but the conductor amount is not proportional to the field. The conductor amount is computed/optimized differently.

\(J_0 = 700 \text{ A/mm}^2\) at the given field. Need \(J_c \sim 2000\) or more.

The curve is computed for \(J_0 = 700 \text{ A/mm}^2\). However, \(J_0\) is a function of the field. The curve scales as \(J_0\).
## Usable current Density in Magnet Design

### 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>885</td>
</tr>
<tr>
<td>4.29</td>
<td>7</td>
<td>6431</td>
<td>1216</td>
<td>856</td>
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<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>
</tr>
<tr>
<td>2.46</td>
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<td>3689</td>
<td>1066</td>
<td>751</td>
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<td>1.09</td>
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<tr>
<td>0.86</td>
<td>15</td>
<td>1289</td>
<td>693</td>
<td>488</td>
</tr>
</tbody>
</table>

Scaled from TWCA

### Insulated

\[ y = -74.64x + 1824.1 \]

\[ R^2 = 0.9956 \]

A Good "Linear Fit"
Support Structure Consuming Expensive Space

Used in early BNL conceptual design. Mechanical designs of other common coil magnets are different; but this ugly feature did not disappear.

Investigate alternate mechanical designs. Do we need it for field quality purpose? See 80% good field aperture in RHIC D0.

Average Field errors $\sim 10^{-4}$ up to 80% of the coil radius