Optimized Quads for Collider IP
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MCTF Thursday

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- Motivation
- Super-conductor properties
- Cos theta quadrupole optimization
- Aside on "block" design
- Grading super-conductor current density (p9)
- Use of exotic magnetic materials
- Application to Collider final focus
- Open mid-plane dipole
- New Collider Parameters
- Conclusion
Motivation

Luminosity

\[ \mathcal{L} = n_{\text{turns}} f_{\text{bunch}} \frac{N^2 \mu}{4\pi \sigma_{\perp}^2} \]

\[ \mathcal{L} \propto \frac{\langle B \rangle \cdot P_{\text{beam}} \cdot N}{\epsilon_{\perp} \cdot \beta^*} \]

- We may have trouble getting \( N = 2 \times 10^{12} \)
- We may have trouble getting \( \epsilon = 25 \times 10^{-6} \) m
- We may have trouble getting 7% cooling transmission
- Beam beam tune shift \( \Delta \nu \) may not be a constraint

- Look for other ways to recover Luminosity
  - More proton power (Chuck)
  - Higher \( \langle B \rangle \) <<<
  - Lower \( \beta^* \) <<<
Advances in SC Quadrupole Design

Design of HQ – a High Field Large Bore Nb$_3$Sn Quadrupole Magnet for LARP


Above magnet now under construction uses conductor performance:

![Graph showing conductor performance](image-url)

LARP Quad Cross section
Reproduce LARP Design

- Gradient found of 194 T/m
c.f. LARP’s 203 T/m
  Good agreement

- Note field at all angles
- So YBCO is not suitable
• Max fields higher in dR/R=2.0, current densities lower, but gradient still higher

• dR/R=0.5: Radial width of conductor (0.5 cm) much less than LARP (3 cm)

• dR/R=2.0: Radial width of conductor (2 cm) still less than LARP (3 cm) but key-stoning is more severe and will need R&D
Search for optimum $dR/R$ for different $R$

- Optimum always near $dR/R = 2$
- But Large $dR/R$ more useful at low radii
$B_{pole}$ and Gradient vs. $R$

- Huge gains if radius reduced
Aside: "Block" Cross Section vs. Cos $\theta$

- Blocks shape easier to wind, but
- 20% loss of gradient using L shape

**Nb3Sn**
- $j$ (A/mm$^2$): 1019
- $B_{\text{max}}$ (T): 10.8
- $\text{Grad}$ (T/m): 723
- Pole B (T): 7.2

**Ni3Sn**
- $B_{\text{max}}$ (T): 10.76
- $\text{Grad}$ (T/m): 870
- Pole B (T): 8.63
- $j$ (A/mm$^2$): 1103
Grading super-conductor current densities

- Tables show fraction of short sample currents by block
- Without ‘grading’ inner blocks run far below maximum
- Adjusting densities by choice of cable thickness brings all blocks to same level
- Field and gradient gain is 10 %
- Small further gain with more, or better, block choices
Fields vs radius with/without grading

- 10% gain appears independent of radius
Use of exotic materials for pole tips

Holmium
only becomes ferromagnetic below 20K and saturates at about 4 Tesla.
http://en.wikipedia.org/wiki/Holmium
http://www.stanfordmaterials.com/ho.html
Phys. Rev. 109 (1958) 1547
http://prola.aps.org/pdf/PR/v109/i5/p1547_1

Dysprosium
Becomes ferromagnetic below 85K and saturates at maybe 3.5 Tesla
Physica B211 (1995) 345 "Magnetically aligned polycrystalline dysprosium as ultimate saturation ferromagnet for high magnetic field polepieces"
http://dx/doi.org/10.1016/0921-4526(94)01059-A

Gadolinium
Saturates at 3.2 T at 80 deg K
http://en.wikipedia.org/wiki/Gadolinium $130/kilogram
The Curie point is described as a phase transition.
http://en.wikipedia.org/wiki/Ferromagnetic
Argonne super-conducting quad using Holmium

NIM A313 (1992) 311;
http://accelconf.web.cern.ch/AccelConf/p95/ARTICLES/FAQ/FAQ09.pdf

Rad=1.5 cm  Bpole=5.25 T  Grad-350 T/m
Use of Exotics for our use

- Because of decay electron halo, we will need some shielding - assumed 2 cm
- Having ferromagnetic poles passing through this shielding would add significantly to the gradient
- The shielding, and poles, can not be at 4 deg for the heat load
- 70-80 degrees is probably ok
- That rules out Holmium, but leaves Gadolinium and Dysprosium as possibles
- They saturate at 3.2-3.5 T and should add about 2 T to the pole tip field, in addition to that directly from the coils
- Since the final focus quads will be inside the detector solenoidal field, they will need bucking solenoids to shield them
• The Gadolinium. or Dysprosium will be fully saturated along its length
• It will bring flux from the outer conductor to the pole face
• There will be a negligible effect on the field due to the nearer conductors: most of the direct field
• There will be an additional $\approx 2$ T pole tip field from the ferromagnetic pole
• Support of pole material at 80 degrees will be unstable and tricky
Gradients vs Rad

- No shield
- Dots with grading
- Shield and Pole
- Shield
- ANL
- LARP
Collider Final focus design

- Yuri and Eliana’s Dipole First design
- $\beta_{\text{max}} = 175^2 \text{ m} \approx 30 \text{ km}$
- Aim to keep $\beta_{\text{max}} \leq 30 \text{ (km)}$, but with lower $\beta^*$ for higher luminosity
Final focus with high grad quads, shield, $\beta^*=10$ mm

<table>
<thead>
<tr>
<th>$\sigma$ Ebeam (TeV)</th>
<th>0.75 shield (cm)</th>
<th>2.0 Btip (T)</th>
<th>0.0 fac</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>beta IP (mm)</td>
<td>10.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pole tip field</td>
<td>Nb3Sn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>emit (micron)</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>beta max (km)</td>
<td>9.2</td>
<td>0.10</td>
<td>4.20</td>
<td>2.27</td>
</tr>
<tr>
<td>beta max (km)</td>
<td>9.3</td>
<td>0.20</td>
<td>2.10</td>
<td>2.29</td>
</tr>
<tr>
<td>thetas</td>
<td>-7.252212E-05</td>
<td>5.349454E-05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- For the same $\beta^*$: $\beta(max) \approx 1/3$ Yuri/Eliana’s (9.2 vs. 30 km)
With 2 cm shielding, Exotic Pole, and $\beta^* = 5$ mm

<table>
<thead>
<tr>
<th>sigmas 4 Ebeam (TeV)</th>
<th>0.75 shield (cm)</th>
<th>2.0 Btip (T)</th>
<th>2.0 fac</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>beta IP (mm) = 5.0</td>
<td>G(m) = 1.00</td>
<td>L(m) = 1.15</td>
<td>R(cm) = 0.81</td>
<td>284</td>
</tr>
<tr>
<td>pole tip field Nb3Sn</td>
<td>emit (micron) = 25</td>
<td>0.10</td>
<td>1.20</td>
<td>1.61</td>
</tr>
<tr>
<td>beta max (km) 12.3</td>
<td>0.10</td>
<td>3.90</td>
<td>2.63</td>
<td>-250</td>
</tr>
<tr>
<td>beta max (km) 12.5</td>
<td>0.20</td>
<td>1.92</td>
<td>2.65</td>
<td>250</td>
</tr>
</tbody>
</table>

thetas: -1.381856E-04, -4.800754E-05

- $\beta_{max} \approx 1/3$ Yuri/Eliana’s (12.2 vs. 30 km)
- Poles assumed to follow changing beam dimensions
• With 2 cm shield: \( \beta^* = 3.5 \text{ mm vs. } 10 \text{ mm for same } \beta_{\text{max}}=30 \text{ km} \)
  \( \beta^* = 5 \text{ mm has } \beta_{\text{max}} = 20 \text{ (km)} \)

• With shield & pole: \( \beta^* = 2.5 \text{ mm vs. } 10 \text{ mm for same } \beta_{\text{max}}=30 \text{ km} \)
  \( \beta^* = 5 \text{ mm has } \beta_{\text{max}} = 13 \text{ (km)} \)

• Hopefully ok without dipole first (for which there is no room)
HTS/Nb$_3$Sn Open Mid-Plane Dipole (Gupta)

- HTS Dipoles should allow ave bending field $\approx 10$ T
- It makes no sense to stay with LTSC dipoles
- 13 T design with Nb$_3$Sn 15 T with HTS
## Possible New Parameters

<table>
<thead>
<tr>
<th></th>
<th>Current Base</th>
<th>New Ideal</th>
<th>Compromise</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity</strong></td>
<td>1.0</td>
<td>4.0</td>
<td>1.0</td>
<td>$10^{34}$ cm$^2$ sec$^{-1}$</td>
</tr>
<tr>
<td>Beam-beam Tune Shift</td>
<td>0.1</td>
<td>0.1</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Muons/bunch</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Ring \textless bending field\textgreater</td>
<td>5.2</td>
<td>10.4</td>
<td>10.4</td>
<td>T</td>
</tr>
<tr>
<td>Beta at IP = $\sigma_z$</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>rms momentum spread</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>%</td>
</tr>
<tr>
<td>Muon survival</td>
<td>0.07</td>
<td>0.07</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>12</td>
<td>12</td>
<td>17</td>
<td>Hz</td>
</tr>
<tr>
<td>Proton Driver power</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>MW</td>
</tr>
<tr>
<td>Trans Emittance</td>
<td>25</td>
<td>25</td>
<td>35</td>
<td>pi mm mrad</td>
</tr>
<tr>
<td>Final solenoids</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td>T</td>
</tr>
<tr>
<td>Long Emittance</td>
<td>72,000</td>
<td>72,000</td>
<td>36,000</td>
<td>pi mm mrad</td>
</tr>
<tr>
<td>6D Emittance</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>$10^{-12}$ (m rad)$^3$</td>
</tr>
</tbody>
</table>

- 6 D emittance the same
- 15 T open mid-plane dipoles (Gupta)
- 5 mm beta* using high grad quads
- 0.2 % rms mom spread
- Reduced transmission (5% vs. 7%)
- Cooling in 40 T solenoids to 35 $\mu$m
- Fewer Muons per bunch (1 vs 2 $10^{12}$)
- Same momentum spread (0.1 % rms)
Conclusion

- 200 T/m Nb\textsubscript{3}Sn Quad under construction by LARP
- Using this material: Gradients much higher than assumed now
- Need for tungsten shields lowers gradients
- Grading the sc gives relatively small gain
- Exotic magnetic materials gives large gain
- Use of such quads could lower $\beta^*$ in collider ring
- Also reasonable to use 15 T HTS open mid-plane dipoles in ring
- Allows either
  1. Four times luminosity, or
  2. Easier parameters for same luminosity (Chuck)

- To Do
  - Magnet simulations using code like OPERA for magnet material saturation
  - MARS study of needed shielding
  - Plasma (for $\mu^-$) and e beam (for $\mu^+$) focusing