LCLS S-band Structure Coupler

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LCLS S-band L01/L02 Coupler Review
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Overview

• Motivation
• Modeling tools
• Multipole field analysis of SLC structure coupler
• Dual-feed coupler design for LCLS
• New coupler dimensions
• Summary
Motivation

- Low emittance beam is required for the LCLS.
- Beam is low in energy and large in beam size in L01 & L02 structures whose couplers have single feeds.
- The existing design has been corrected for amplitude asymmetry but not the phase so could affect beam emittance.
- We study the head-tail effects of dipole & quadrupole fields in the couplers via full 3D field analysis to determine if Re-design is necessary.
SLC Structure Couplers

- Both input/output couplers use single feed
- Dipole field minimized with racetrack cell profile & center offset
- Quadrupole field is not corrected
- RF phase term is not fully compensated – important for both dipole and quadrupole components
Blue Book Estimation of Dipole Field

\[
E_z = E_{z0} \left[ 1 + \frac{\Delta E}{E_{z0}} \frac{x}{2a} \right] e^{j(\omega t - k_z + \Delta \Phi) \frac{x}{2a}}
\]

John Schmerge

\[
\mathbf{e}_{n-\text{final}} = \sqrt{\mathbf{e}_{n-\text{initial}}^2 + \frac{\sigma_{11}}{4} \left( \frac{\Delta p_x}{mc} \right)^2}
\]

\[
= \mathbf{e}_{n-\text{initial}}(1 + \frac{\mathbf{e}_n \beta / \gamma}{8\mathbf{e}_{n-\text{initial}}^2} \left( \frac{\Delta p_x}{mc} \right)^2)
\]

Head-tail angle~0.24mrad

Head-tail emittance dilution
Head-tail requirements for 2% emittance growth (Cecile)
10-ps bunch (with option for 20-ps bunch)

- Quad: 0.0375 rad/m
- Dipole: 0.06 mrad
- Dipole field is found to be too large
- Full field analysis and re-design needed
Simulation Tools

- **S3P** (3D Parallel S matrix solver) used in Coupler Design and generates 3D field maps for particle tracking
- Beam dynamics analysis of head-tail effects by tracking particles in S3P fields to find multipole moments in transverse momentum
SLC S-Band Coupler – S3P Model

- Dimensions directly from SLC drawings
- Input coupler reflection from S3P is about 0.05

3.9mm offset
For field symmetry
Field Asymmetry In Coupler

- On-axis $E_y$ and $B_x$ are non-zero in the coupler region
- Head-tail effects expected
Beam Dynamics Analysis

• Equation of motion:

\[ \frac{d(\gamma \vec{\beta})}{dt} = \frac{e}{m_0 c} (\vec{E} + c \vec{\beta} \times \vec{B}) \]

• Transverse momentum:

\[ \Delta \vec{P}_{m\perp} = -\frac{je}{\omega} \nabla_\perp \int E_z(r, \theta, z, m) e^{j\omega t - j\zeta z} \, dz \, d\zeta \]

\[ E_z(r, \theta, z, \zeta_z) = \sum_{m=0}^{\infty} A_m J_m(\eta_r r) \cos(m\theta) e^{-j\zeta_z z} + \sum_{m=0}^{\infty} B_m J_m(\eta_r r) \sin(m\theta) e^{-j\zeta_z z} \]

where \( \eta_r^2 + \zeta_z^2 = \frac{\omega^2}{c^2} \)

• To first order:

\[ \Delta \vec{P}_\perp = -\frac{je}{\omega} \left( -\frac{\eta_r^2 A_0}{2} (x\hat{x}_0 + y\hat{y}_0) + \frac{\eta_r A_1}{2} \hat{x}_0 + \frac{\eta_r B_1}{2} \hat{y}_0 + \frac{\eta_r^2 A_2}{4} (x\hat{x}_0 - y\hat{y}_0) + \frac{\eta_r^2 B_2}{4} (y\hat{x}_0 + x\hat{y}_0) \right) \]

\[ \begin{align*}
\text{focusing} & \quad \text{dipole} & \quad \text{quad} & \quad \text{skew quad}
\end{align*} \]
γ Dependence Of Momentum Multipoles

- $1/\gamma$ dependence for azimuthal focusing (back-to-back couplers in full structure for our case)

\[
\gamma(\infty)\beta_r(\infty) = \gamma(-\infty)\beta_r(-\infty) \left(1 + \frac{I_{01}}{\gamma} + \frac{I_{02} - I_{03}}{\gamma^2}\right) - r(a) \left(\frac{I_{11}}{\gamma} + \frac{I_{12} - I_{13} + I_{14}}{\gamma^2}\right)
\]

where $I_{mn}$ are integrals of $E_z$ field

- Dipole and quadrupole terms are $\gamma$ independent.
Multipole Field Analysis

- Use S3P to obtain 3D fields in a symmetric model
- Calculate change in particle momentum through the input coupler
- Multipole decomposition to obtain dipole & quadrupole contributions
Dipole & Quad Fields in Original Couplers

<table>
<thead>
<tr>
<th>Bunch ±5° in RF phase, on crest, E_{acc}=20MV/m</th>
<th>Input coupler</th>
<th>Output coupler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (γ)</td>
<td>~10</td>
<td>~130</td>
</tr>
<tr>
<td>Dipole: Δ(γβ⊥)</td>
<td>2.6×10^{-3}</td>
<td>1.0×10^{-3}</td>
</tr>
<tr>
<td>Quad: Δ(γβ⊥)/m</td>
<td>7.8×10^{-1}</td>
<td>4.4×10^{-1}</td>
</tr>
<tr>
<td>Dipole head-tail angle Δθ (rad)</td>
<td>2.6×10^{-4}</td>
<td>7.7×10^{-6}</td>
</tr>
<tr>
<td>Quadrupole head-tail angle Δθ (rad/m)</td>
<td>7.8×10^{-2}</td>
<td>3.4×10^{-3}</td>
</tr>
</tbody>
</table>
SLC structure

- Constant gradient for uniform input
- Gradient profile follow SLED (field) pulse shape
- Input: 0.76*E_{ave}
- Output: 1.24*E_{ave}
- Head-tail estimated assuming constant gradient along structure
Head Tail Effects In L01 & L02

For dipole fields:

\[
\varepsilon_{n\text{-final}} = \sqrt{\varepsilon_{n\text{-initial}}^2 + \frac{\sigma_{11}}{4} \left( \frac{\Delta p_x}{mc} \right)^2} = \varepsilon_{n\text{-initial}} \left( 1 + \frac{\sigma_{11}}{8\varepsilon_{n\text{-initial}}^2} \left( \frac{\Delta p_x}{mc} \right)^2 \right)
\]

\[
\sigma_{11} = \sigma_x^2 = \varepsilon_n \beta / \gamma
\]

<table>
<thead>
<tr>
<th>Location</th>
<th>(\gamma)</th>
<th>Lattice (\beta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L01 Input</td>
<td>12</td>
<td>1.4</td>
</tr>
<tr>
<td>L01 Output</td>
<td>123</td>
<td>20</td>
</tr>
<tr>
<td>L02 Input</td>
<td>123</td>
<td>34/18</td>
</tr>
<tr>
<td>L02 Output</td>
<td>270</td>
<td>13/39</td>
</tr>
</tbody>
</table>

- Head-tail emittance dilution is quadratic to beam size and head-tail angle
- L01 input needs dual feed to minimize both dipole and quad
- L01 output likely does not need dual feed because (compared to L01 input)
  - Factor of 2.6 smaller head-tail angle due to geometry
  - Similar beam size
- L02 input needs dual feed because (compared to L01 input)
  - 10 time high beam energy
  - 30% higher gradient
  - 20 times higher beta function
Dual-feed Coupler Design

Designs considered:
- Dual-feed with cylindrical cell
- Dual-feed with slot compensation
- Dual-feed with racetrack cell profile

• Only vary dimensions of the coupler cell to match
• Coupling iris rounded
## Dual-feed Input Coupler Design Comparison

![Graph showing quad head-tail Δ(γβ⊥)/m: 10 Degree bunch comparison](image)

### Input coupler: comparison of quad head-tail Δ(γβ⊥)/m: 10 Degree bunch

<table>
<thead>
<tr>
<th>Coupler Type</th>
<th>Δ(γβ⊥)/m</th>
<th>Head-tail angle Δθ (rad/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC Single feed</td>
<td>0.78</td>
<td>0.078</td>
</tr>
<tr>
<td>Symmetric dual</td>
<td>0.63</td>
<td>0.063</td>
</tr>
<tr>
<td><strong>Race-track dual</strong></td>
<td><strong>0.04</strong></td>
<td><strong>0.004</strong></td>
</tr>
<tr>
<td>Cross Dual</td>
<td>0.20</td>
<td>0.020</td>
</tr>
</tbody>
</table>
Design Choice For L01/L02 Couplers

- Dual-feed with racetrack cell profile

<table>
<thead>
<tr>
<th></th>
<th>$\Delta (\gamma \beta_{\perp})/m$</th>
<th>Head-tail angle $\Delta \theta$ (rad/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC Single feed</td>
<td>0.78</td>
<td>0.078</td>
</tr>
<tr>
<td><strong>Race-track dual</strong></td>
<td><strong>0.04</strong></td>
<td><strong>0.004</strong></td>
</tr>
</tbody>
</table>

Dipole field is zero by symmetry
Rounding of Iris Radius

- 18 MV/m gradient with average $T_f = 830$ ns

- Iris rounding of 1 mm - $\Delta T \sim 7^0C$
Dual-feed Input Coupler Dimensions

\[ b = 35.8583 \]
\[ w = 25.0200 \]
\[ d = 13.000 \]
\[ W_g = 61.0810 \]
\[ R = 3.0861 \]
\[ r = 1.000 \]
\[ h_g = 29.1338 \]
\[ t = 5.84200 \]
\[ t_f = 0.78740 \]
## Dual-Feed Input Coupler Dimensions Table

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dimension at 45°C</th>
<th>Dimension at 20°C (0.99958)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe diameter</td>
<td>19.0932</td>
<td>19.0852</td>
</tr>
<tr>
<td>Beam pipe cutoff hole rounding $R$</td>
<td>3.0861</td>
<td>3.0861*</td>
</tr>
<tr>
<td>Racetrack arc radius $b$</td>
<td>35.8583+0.0004</td>
<td>35.8437</td>
</tr>
<tr>
<td>Racetrack arc separation $d$</td>
<td>13.0000</td>
<td>12.9945</td>
</tr>
<tr>
<td>Cell iris radius $a$</td>
<td>13.1102</td>
<td>13.1047</td>
</tr>
<tr>
<td>Disk thickness $t$</td>
<td>5.8420</td>
<td>5.8420*</td>
</tr>
<tr>
<td>Disk rounding radius $R$</td>
<td>3.0861</td>
<td>3.0861*</td>
</tr>
<tr>
<td>Disk flat part $tf$</td>
<td>0.7874</td>
<td>0.7874*</td>
</tr>
<tr>
<td>Coupling iris opening $w$</td>
<td>25.0200</td>
<td>25.0095</td>
</tr>
<tr>
<td>Coupling iris rounding $r$</td>
<td>1.0000</td>
<td>0.99958</td>
</tr>
<tr>
<td>Waveguide width $Wg$</td>
<td>61.0810</td>
<td>61.0553</td>
</tr>
<tr>
<td>Waveguide height $hg$</td>
<td>29.1338</td>
<td>29.0216</td>
</tr>
</tbody>
</table>

Note: *) numbers from the old SLC drawing, not scaled
Tolerances On Input Coupler Matching

-0.05
0
0.05

S11_real

0
0.05

S11_imag

-0.05
0
0.05

-0.05

design

cell radius off -0.02mm

arc center off -0.02mm

iris width off -0.02mm

wg location off -0.02mm
Summary

- Performed 3D multipole field analysis of the SLC coupler
- Dipole and quadrupole fields in existing design were found too large to meet the LCLS beam emittance requirements.
- Dual-feed input coupler with racetrack cell profile has been designed for the L01 & L02 structures to eliminate the dipole fields and minimize the quadrupole fields.
- Coupler dimensions were generated for mechanical design
- Single-feed output coupler needs further evaluation and dual-feed design will proceed as needed