LCLS RF Gun Design Studies

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LCLS RF Gun Review
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Outline

• Zero-mode issues
• SW cavity model for zero-mode field calculation
• Zero-mode in present Gun design
  – Amplitude & phase
  – Phase optimization with shaped pulse
• Zero-Pi mode separation
Zero-mode Issues

Present Gun design operates at Pi-mode
- $\Delta F = -3.4$ MHz separation from zero-mode
- $Q_0 = 12500$
- $Q_{ext,\pi} = 6250$
- $Q_{ext,0} = 11000$

- Zero-mode will be excited when driven at Pi mode resonant frequency due to overlap of its resonance width with drive pulse bandwidth
- Zero-mode amplitude and phase impact on beam emittance
- How to modulate/control zero-mode?
SW Model For Simulating Zero-Mode Excitation
Calculation Of Zero-mode Fields

Pi-mode driven at resonance while zero-mode driven at -3.4 MHz from resonance with square or shaped pulse

Simulation provides:
- Frequency
- $Q_{\text{ext}}$
- $Q_0$, Ratio of $V_0^2/U_0$ where
  - $U_0$ – normalized stored energy in cavity
  - $V_0$ - cathode voltage when $U_0$ energy is stored in cavity

For known emitted power $P_e$
- Total stored energy in cavity $U=Q_{\text{ext}}P_e/\omega$
- Cathode voltage: $V=V_0*(U/U_0)^{1/2}$

Need to calculate $P_e$ for given $P_{\text{in}}$ and pulse shape
SW Cavity Model - Farkas-Wilson SLED

Differential Equation:
\[
\frac{dE_e}{dt} + qE_e = \frac{\alpha E_i}{T_L}, \quad q = \frac{1 - j \tan(\psi)}{T_L}
\]
\[
\tan(\psi) = 2Q_L \frac{\Delta f}{f}, \quad \alpha = 2 \beta/(1 + \beta)
\]

Input Field
\[
E_i = a_0 e^{j\phi_0} e^{bt} + a_1 t e^{j\phi_0} e^{bt}
\]
\[
a_1 = \frac{a_f - a_0}{RT}, \quad b = \frac{\phi_f - \phi_0}{RT}
\]

Emitted Field
\[
E_e = C_{be} e^{bt} + C_q e^{-qt} + C_{tbe} t e^{bt}
\]

Let \( z_a = \frac{\alpha e^{j\phi_0}}{T_L (q + b)} \),
\[
C_{be} = z_a [a_0 - \frac{a_1}{q + b}], \quad C_q = E_e(0) - C_{be}, \quad C_{tbe} = z_a a_1
\]
Zero-Mode In The Present Gun Design

- Square Pulse Excitation
- Shaped Pulse Excitation
- Phase Modulation
Square Pulse Excitation (20ns rise time)

- Input:
  - $v_{\text{pi},e} = 1.3134$
  - $v_{0,e} = 0.076$

- Pin = 10 MW
- $P_e = v_e^2 \times Pin$
- $V_{\text{cathode}_{\text{pi}}} = 120 \text{ MV/m}$
- $V_{\text{cathode}_{0}} = 11.8 \text{ MV/m}$

- 3-μs input pulse
  - Steady state
  - Relative zero-mode amplitude & phase fixed
  - Zero-mode is 90 degrees ahead of Pi-mode in half cell
Shaped Pulse Excitation (20ns rise time)

\[
V_{\text{pi}, e} = 0.9585 \\
V_{0, e} = 0.04678
\]

\[
\text{Pin} = 19 \text{ MW} \\
\text{Pe} = v_e^2 \ast \text{Pin}
\]

\[
V_{\text{cathode}_{\text{pi}}} = 120 \text{ MV/m} \\
V_{\text{cathode}_{0}} = 9.99 \text{ MV/m}
\]

0.82-\(\mu\)s shaped input pulse
- Transient
- Amplitude and phase adjustable
Emitance Impact Of Zero Mode

- Zero-mode field is too large when driven by either excitation pulses
- Emittance dilution too large (at arbitrary phase)
- Square pulse excitation reaches steady state, with phase locked at 90 degrees relative to Pi-mode
- With shaped pulse zero-mode still in transient phase
- Phase optimization possible with shaped pulse excitation
Zero-mode Phase Adjustment

- Only possible with shaped/transient pulse

Zero Mode

- Phase can be adjusted by modulating the klystron phase
- Phase in half cell adjustable to 90±25 degrees relative to pi-mode
- Impact on present design minimal at about 90 degrees RF phase

Zero-mode Phase Adjustment

- Zero-mode Phase Adjustment

Zero Mode

- Only possible with shaped/transient pulse

Zero Mode

- Phase can be adjusted by modulating the klystron phase
- Phase in half cell adjustable to 90±25 degrees relative to pi-mode
- Impact on present design minimal at about 90 degrees RF phase
Zero-Pi mode Separation
Reducing Zero-mode

- Increase zero-pi mode separation by reducing zero-mode field using
  - larger iris size
  - thicker disk

- 3 cases studied for zero-mode emittance impact

<table>
<thead>
<tr>
<th>Iris a (MM)</th>
<th>$R_{\text{beam pipe}}$ (mm)</th>
<th>Disk T (mm)</th>
<th>$\Delta F$ (MHz)</th>
<th>$E_s/E_a$</th>
<th>$R$ (MΩ/m)</th>
</tr>
</thead>
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<tr>
<td>12.4968</td>
<td>12.4968</td>
<td>22.047</td>
<td>3.4</td>
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<td>19.050</td>
<td>15.0</td>
<td>1.96</td>
<td>48.70</td>
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</tbody>
</table>

- Omega3P field maps used in PARMELA simulation

- More geometry optimization needed when $\Delta F$ is chosen
Reducing Zero-mode with Larger $\Delta F$

$\Delta F = -15$ MHz

$P_{in} = 19$ MW
$P_{e} = v_e^2 \times P_{in}$

$V_{cathode_{pi}} = 120$ MV/m
$V_{cathode_0} = 2.86$ MV/m
Advantages with Larger $\Delta F$

- Broader emittance minimum in zero-mode phase
- Less dependent on driving pulse profile
- Field balance less sensitive to geometry error:
  - 10-micron error in half-cell cell radius results in field imbalance of 20% for $\Delta F=3.5$MHz and 6% for $\Delta F=15$MHz
- Less sensitive to thermal expansion
- Easier to measure field flatness in real operation
Summary

• **Existing Gun design**
  – Zero-mode field significant
  – Using shaped pulse can optimize zero-mode phase to minimize emittance dilution

• **Ongoing design improvement and optimization**
  – Increase mode separation to reduce zero-mode fields and relaxe geometry tolerance
  – Re-design and optimize coupler and multipole fields
  – Calculate accurate field maps for beam dynamics simulations