Start-to-end simulations for an X-ray FEL Oscillator at the LCLS-II and LCLS-II-HE

Weilun Qin

Peking University
SLAC National Accelerator Laboratory
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• What beam we want?
• How to make it?
X-ray FEL oscillator

High rep. beam

X-ray output

Focusing

Bragg Crystal

Proposed
R. Collela and A. Luccio (1984)

Cavity tuning

Harmonic
H. X. Deng et. al (2012)

Crystal response
~10 meV spectral acceptance
What kind of drive beam XFELo needs?

- High rep-rate, low energy spread, low emittance
- Narrow spectral acceptance → small correlated energy spread (flat chirp), relatively long bunch (~ps)

- KEK 3-GeV ERL: energy double to 6 GeV, radiation at 12.4 keV
- European XFEL 14.5 GeV, spent 4.9 kA beam, radiation at 12 keV
- LCLS-II 4 GeV beam, 5\textsuperscript{th} harmonic, radiation at 14.4 keV
- LCLS-II-HE 8 GeV beam, fundamental, radiation at 14.4 keV

Also proposed at Shanghai

R. Hajima et. al., FEL2012, Nara, Japan, WEPD30
J. Zemella et. al., FEL2012, Nara, Japan, WEPD29
T. Maxwell et. al., IPAC2015, Richmond, VA, USA
Talk by Haixiao
4 GeV LCLS-II SCRF linac driven 5\textsuperscript{th} harmonic XFELO

- 4 GeV beam direct to End Station A through Aline
  - 100 pC, \(~120\text{A}\)

- Simulation with 400fs, 50pC ideal Gaussian beam
  - 0.26 \(\mu\)J
  - \(10^8\) ph.
  - 5 meV

- However, wakefields induce large nonlinear chirp, only \(~150\) fs useful part

T. Maxwell et. al, IPAC2015 tupma028  
J. Zemella et. al, FEL2015 tup030
Elements contribute to final phase space shape

- **RF**
  - RF induces curvature in phase space
  - Determined by RF phase

- **Wakefield**
  - Cavities: weak
  - Long bypass: strong
  - Dechirper: strong

- **Bunch compression**
  - Determined by input phase space curvature and R56, T566, U5666

- **Structure Current**

\[ W(s) = L_{acc} \int_{-\infty}^{s} w(s - s') \lambda(s') ds' \]

- **RF phase, beam current, bunch compression and wakefields talk to each other.**
Wake induced loss: L3 + 2 km bypass + dechirper

\[ W(s) = L_{\text{acc}} \int_{-\infty}^{s} w(s - s') \lambda(s') ds' \]

- Assumed same FWHM of three current profile and same dechirper parameters
- Ramped current can largely linearize the overall wake induced loss

Shaping the current?
Assume ramp current at injector exit [Elegant]

Before L1

Before dechirper

After dechirper

Over 500fs flat chirp

LINAC parameters not changed
A more global scope: how to make a ramp (flat energy chirp)

Shaping the injector laser and/or Optimizing the LINAC

<table>
<thead>
<tr>
<th>Injector</th>
<th>Linac</th>
<th>XFELO</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTRA</td>
<td>LiTrack &amp;</td>
<td>Ginger</td>
</tr>
<tr>
<td></td>
<td>Elegant</td>
<td></td>
</tr>
</tbody>
</table>
**Two injector setups**

- APEX gun, w/o shaping
- SRF gun, w/ shaping

<table>
<thead>
<tr>
<th>Parameter</th>
<th>APEX gun</th>
<th>SRF gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$ (MHz)</td>
<td>186</td>
<td>200</td>
</tr>
<tr>
<td>$L_{gap}$ (cm)</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>$E_a$ (MV/m)</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>$E_{gun}$ (MeV)</td>
<td>0.75</td>
<td>4.1</td>
</tr>
<tr>
<td>$\varepsilon_{intri}$ (mrad)</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Q (pC)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$t_{laser}$ (ps)</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>$\varepsilon_n$, 100% (mm-mrad)</td>
<td>0.30</td>
<td>0.25</td>
</tr>
</tbody>
</table>

- Higher gun exit energy with SRF gun (~4.1 MeV), easier to control the emittance growth due to drive laser shaping.
- Lower emittance with higher gun gradient
Injector: SRF gun optimization

- SRF gun
- Buncher
- Sol1
- Sol2
- Cryomodule

Phase space at injector exit

Current evolution in the injector

Emittance and bunch length

Optimization with 10k macroparticles
Full simulation with 1M macro particles
Injector: APEX gun optimization

Emittance and bunch length
Optimization with 10k macroparticles
Full simulation with 1M macro particles
Fast LINAC optimizer

- LiTrack integrated with MOGA (MATLAB)
- Objectives
  - Flat length, length within 0.2 MeV energy spread
  - Average beam current within flat length
  - Fix L1, L2, L3 energy

**Graph:**
- Flat part with slice mean energy deviation and current.
- Flattening at 412.71 fs.
- Average current $I_{\text{avg}} = 83.99$ A.
- Energy deviation $\sigma_E = 110.07$ keV.
Linac optimization for APEX gun setup (4 GeV)

- **SRF gun, w/ shaping**
- **APEX gun, w/o shaping**

**APEX gun output @ undulator entrance**

- about 400 fs flat part, 120 A peak current
- Low slice emittance and slice energy spread
- Projected energy spread 0.07%
Linac optimization for SRF gun setup (8 GeV)

- **With shaping & SRF gun**
  - about twice useful charge in the flat part
  - better emittance
  - Higher energy spread (injector current lower than APEX)

- **SRF gun output @ undulator entrance**

  - Over 600 fs flat part, 120 A peak current
  - Low slice emittance and slice energy spread
  - Projected energy spread 0.02%
**XFELO performance at 14.4 keV [GINGER]**

- **8 GeV beam, SRF gun setup, fundamental XFELO**
  - Pulse energy: 28 $\mu$J
  - Number of passes: $1.2 \times 10^{10}$ ph.
  - FEL power: 693 fs
  - Energy spread: 3.4 meV

- **8 GeV beam, APEX gun setup, fundamental XFELO**
  - Pulse energy: 7 $\mu$J
  - Number of passes: $3.1 \times 10^9$ ph.
  - FEL power: 557 fs
  - Energy spread: 3.9 meV
### XFELO performance at 5 – 25 keV [GINGER]

**Table 1: XFELO simulation parameters and output pulse properties (the repetition rate is assumed to be 1 MHz).**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>4.9 keV</th>
<th>10 keV</th>
<th>14.4 keV</th>
<th>14.4 keV</th>
<th>14.4 keV</th>
<th>14.4 keV</th>
<th>20 keV</th>
<th>24.2 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron gun</td>
<td>SCRF</td>
<td>SCRF</td>
<td>NCRF</td>
<td>NCRF</td>
<td>SCRF</td>
<td>SCRF</td>
<td>SCRF</td>
<td>SCRF</td>
</tr>
<tr>
<td>FEL K</td>
<td>3.2128</td>
<td>2.0125</td>
<td>1.4304</td>
<td>1.4837</td>
<td>1.4837</td>
<td>1.0125</td>
<td>1.1539</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_n$ [(\mu\text{m})]</td>
<td>0.25</td>
<td>0.25</td>
<td>0.35</td>
<td>0.35</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>$\sigma_E$ [keV]</td>
<td>130</td>
<td>130</td>
<td>70</td>
<td>70</td>
<td>130</td>
<td>130</td>
<td>130</td>
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</tr>
<tr>
<td>$\lambda_u$ [cm]</td>
<td>2</td>
<td>2</td>
<td>2.6</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>$N_u$</td>
<td>1000</td>
<td>1000</td>
<td>1250</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>harmonic number</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$Z_R$ [m]</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Bragg crystal</td>
<td>C(220)</td>
<td>C(440)</td>
<td>C(733)</td>
<td>C(733)</td>
<td>C(733)</td>
<td>C(880)</td>
<td>C(888)</td>
<td></td>
</tr>
<tr>
<td>Output coupling</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Pulse energy [$\mu$J]</td>
<td>3.1</td>
<td>21</td>
<td>0.3</td>
<td>7</td>
<td>28</td>
<td>11</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>Spectral FWHM [meV]</td>
<td>10.9</td>
<td>5.4</td>
<td>5.8</td>
<td>3.9</td>
<td>3.4</td>
<td>2.7</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Temporal FWHM [fs]</td>
<td>138</td>
<td>530</td>
<td>400</td>
<td>557</td>
<td>693</td>
<td>905</td>
<td>1989</td>
<td></td>
</tr>
<tr>
<td>$\sigma_\tau \sigma_\omega$ (FWHM)</td>
<td>2.27</td>
<td>4.37</td>
<td>3.52</td>
<td>3.26</td>
<td>3.58</td>
<td>3.67</td>
<td>4.06</td>
<td></td>
</tr>
<tr>
<td># of Photons/pulse</td>
<td>$3.9 \times 10^9$</td>
<td>$1.3 \times 10^{10}$</td>
<td>$1.3 \times 10^8$</td>
<td>$3.1 \times 10^9$</td>
<td>$1.2 \times 10^{10}$</td>
<td>$3.4 \times 10^9$</td>
<td>$1.1 \times 10^9$</td>
<td></td>
</tr>
<tr>
<td>Spectral flux [ph/s/meV]</td>
<td>$3.6 \times 10^{14}$</td>
<td>$2.4 \times 10^{15}$</td>
<td>$2.2 \times 10^{13}$</td>
<td>$7.9 \times 10^{14}$</td>
<td>$3.6 \times 10^{15}$</td>
<td>$1.3 \times 10^{15}$</td>
<td>$8.5 \times 10^{14}$</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

- XFELO requires long flat chirp in the longitudinal phase space. Dechirper and bypass wakefields results in large nonlinear chirp in the longitudinal phase space, only ~150 fs useful part.

- We optimized the LINAC parameters to get over 400fs useful part for APEX gun setup. With SRF gun & injector laser shaping, we managed to get longer useful part and more useful charge.

- With this start-to-end beam, Ginger simulations show that $10^9 \sim 10^{10}$ photons/pulse can be obtained for 5-25 keV photons with ~meV bandwidth.
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