Simulation Study of PAL XFEL

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Outline

• History
• FEL parameters
• Layout
• Simulations
  Injector – photocathode
  Linac – C-band
  Undulator – out-vacuum
• Design issues
• Summary
History

• 2004 : PAL proposed a 0.3 nm SASE-FEL.
  - 3.0 GeV, 3 mm in-vacuum undulator
  - 0.1 nm radiation obtained by a third harmonic
    But, potential users strongly demanded 0.1 nm.

• 2008 : A 0.1 nm SASE-FEL was proposed.
  \( E_e = 10.053 \text{ GeV}, L \sim 900 \text{ m} \) (Linac: \sim 550 m, BTL: \sim 50 m,
  In-vacuum Undulator: \sim 100 m, PTL+Exp: \sim 200 m)

• 2009 : Detailed study was performed.
  \( \text{(Tracking simulation with wakefield & error)} \)

• 2010 : Parameters are modified, new subjects are under study.
  \( \text{(0.06 nm SASE-FEL, Tunability, laser seeding)} \)
  Government Preliminary Evaluation completed.
  20 M$ for 2011 budget approval in progress.
One hard X-ray FEL undulator (HXFEL1) and one soft X-ray FEL undulator (SXFEL1)

**APPLE II undulator** provides the capability of **full polarization control**

<table>
<thead>
<tr>
<th><strong>XFEL</strong></th>
<th><strong>HXFEL1</strong></th>
<th><strong>SXFEL1</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Wavelength [nm]</td>
<td>0.7 ~ 0.06</td>
<td>10 ~ 1</td>
</tr>
<tr>
<td>Wavelength tuning</td>
<td>Beam energy</td>
<td>Undulator gap</td>
</tr>
<tr>
<td>Undulator type</td>
<td>Planar</td>
<td>Planar (or APPLE)</td>
</tr>
<tr>
<td>Undulator period [cm]</td>
<td>2.14</td>
<td>5.0</td>
</tr>
<tr>
<td>Undulator gap [mm]</td>
<td>6.8</td>
<td>8.3 ~ 25.5</td>
</tr>
</tbody>
</table>
## FEL parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0.06nm 0.2 nC</th>
<th>0.1nm 0.2 nC</th>
<th>1nm 0.2 nC</th>
<th>10nm 0.2 nC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>0.2 nC</td>
<td>0.2 nC</td>
<td>0.2 nC</td>
<td>0.2 nC</td>
</tr>
<tr>
<td>E (GeV)</td>
<td>10.004</td>
<td>7.749</td>
<td>3.997</td>
<td>3.997</td>
</tr>
<tr>
<td>FWHM bunch length (ps)</td>
<td>0.063</td>
<td>0.063</td>
<td>0.063</td>
<td>0.063</td>
</tr>
<tr>
<td>Peak current, $I_p$ (kA)</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Normalized emittance ($\mu$m)</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Average $\beta$ function in undulator (m)</td>
<td>20</td>
<td>20</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Rms energy spread in terms of rest energy</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Relative rms energy spread</td>
<td>1.0E-04</td>
<td>1.3E-04</td>
<td>2.6E-04</td>
<td>2.6E-04</td>
</tr>
<tr>
<td>Period (cm)</td>
<td>2.14</td>
<td>2.14</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Magnet full gap (mm)</td>
<td>6.81</td>
<td>6.81</td>
<td>25.55</td>
<td>8.30</td>
</tr>
<tr>
<td>$B_u$ (T)</td>
<td>0.7585</td>
<td>0.7585</td>
<td>0.3644</td>
<td>1.4672</td>
</tr>
<tr>
<td>$K_u$</td>
<td>1.5160</td>
<td>1.5160</td>
<td>1.7016</td>
<td>6.8517</td>
</tr>
<tr>
<td>Photon Energy (keV)</td>
<td>20.67</td>
<td>12.40</td>
<td>1.24</td>
<td>0.12</td>
</tr>
<tr>
<td>Total slipage length ($\mu$m)</td>
<td>0.2104</td>
<td>0.2622</td>
<td>0.8855</td>
<td>3.8563</td>
</tr>
<tr>
<td>Pierce parameter ($\rho$)</td>
<td>3.809E-04</td>
<td>4.516E-04</td>
<td>1.561E-03</td>
<td>3.435E-3</td>
</tr>
<tr>
<td>Power gain length $L_g$ (m)</td>
<td>4.22</td>
<td>3.04</td>
<td>2.30</td>
<td>0.92</td>
</tr>
<tr>
<td>Cooperation length $L_c$ ($\mu$m)</td>
<td>0.01183</td>
<td>0.01422</td>
<td>0.04592</td>
<td>0.18413</td>
</tr>
<tr>
<td>Cooperation time (fs)</td>
<td>0.03945</td>
<td>0.04742</td>
<td>0.15317</td>
<td>0.61418</td>
</tr>
<tr>
<td>$2\pi L_c$ ($\mu$m)</td>
<td>0.07</td>
<td>0.09</td>
<td>0.29</td>
<td>1.16</td>
</tr>
<tr>
<td>$P_{sat}$ (GW)</td>
<td>6.9</td>
<td>8.6</td>
<td>12.3</td>
<td>31.4</td>
</tr>
<tr>
<td>$L_{sat}$ (m)</td>
<td>75.0</td>
<td>56.1</td>
<td>44.3</td>
<td>19.3</td>
</tr>
</tbody>
</table>
Layout of Start-to-end Simulation

Injector (PARMELA) → LINAC (ELEGANT) → Undulator (GENESIS)

Tracking with Np 200,000

**Injector**
- 135MeV
- 27MV/m
- -19.8deg
- 4 cavities

**S-band**
- 27.5MV/m
- -188.4deg
- 1 cavity

**X-band**
- 413MeV
- 9m
- R56=-30mm

**Bunch Compressor**
- 35MV/m
- -14.0deg
- 32 cavities

**C-band**
- 2.8GeV
- 22.6m
- R56=-10mm

**Match**
- 0.2nC
- 413MeV
- 96um
- 0.41umrad
- 3.7

**Transport Line**
- 0.2nC
- 10GeV
- 4.9um
- 0.42umrad
- 1.5

**Undulator**
- 0.2nC
- 10GeV
- 4.9um
- 0.42umrad
- 1.6

**Legend**
- Q 0.2nC
- E 135MeV
- σz 0.5mm
- ε slice 0.41umrad
- Δγ 3.5
Injector

Photo-cathode gun
S-band
2 accelerating column
Matching & diagnostic section

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>0.2 nC</td>
</tr>
<tr>
<td>Laser transverse profile</td>
<td>hard-edge</td>
</tr>
<tr>
<td>Laser radius</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Laser temporal shape</td>
<td>flat-top</td>
</tr>
<tr>
<td>Laser rise-time</td>
<td>0.36 ps</td>
</tr>
<tr>
<td>Laser phase</td>
<td>32.2°</td>
</tr>
<tr>
<td>Maximum RF gun field strength</td>
<td>120 MV/m</td>
</tr>
<tr>
<td>Main solenoid peak strength</td>
<td>2.752 kG</td>
</tr>
<tr>
<td>1st cavity-phase</td>
<td>161.3°</td>
</tr>
<tr>
<td>1st cavity-amplitude</td>
<td>19.8 MV/m</td>
</tr>
<tr>
<td>1st cavity-length</td>
<td>3 m</td>
</tr>
<tr>
<td>2nd cavity-phase</td>
<td>76.5°</td>
</tr>
<tr>
<td>2nd cavity-amplitude</td>
<td>24.0 MV/m</td>
</tr>
<tr>
<td>2nd cavity-length</td>
<td>3 m</td>
</tr>
<tr>
<td>Total length</td>
<td>14.3733 m</td>
</tr>
</tbody>
</table>
Injector – emittance, twiss

Laser spot size – emittance
(with solenoid tuning)

- 0.2 nC
- 0.6 mm radius
- 5 ps FWHM length
- Flat-top shape

Emittance
- 0.5 umrad

Graphs showing:
- Variation of emittance with S1 peak field (kG)
- Variation of emittance with beam radius (mm)
- Normalized emittance over z (m)
- Twiss α over z (m)
### Injector - sensitivities

Charge, Solenoid, laser timing, cavity phase – emittance, energy spread, length, twiss

<table>
<thead>
<tr>
<th>Parameter</th>
<th>design value</th>
<th>Emittance</th>
<th>ΔE/E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>0.2 nC</td>
<td>+8%</td>
<td>+18%</td>
</tr>
<tr>
<td>Solenoid peak strength</td>
<td>2.752 kG</td>
<td>+3.2%</td>
<td></td>
</tr>
<tr>
<td>Laser phase</td>
<td>32.2°</td>
<td>± 5°</td>
<td>± 0.5°</td>
</tr>
<tr>
<td>1st cavity phase</td>
<td>161.34°</td>
<td></td>
<td>± 1°</td>
</tr>
<tr>
<td>2nd cavity phase</td>
<td>76.5°</td>
<td></td>
<td>± 0.7°</td>
</tr>
<tr>
<td>Laser radius</td>
<td>0.6 mm</td>
<td>+20%</td>
<td>-17%</td>
</tr>
<tr>
<td>Laser rise-time</td>
<td>0.36 ps</td>
<td>0.8 ps</td>
<td></td>
</tr>
</tbody>
</table>
Linac – wake, twiss

Geometrical wake from cavity’s iris
Linac – BC 1

Bunch compressor 1 in & out
Linac – BC 2

Bunch compressor 2 in & out
Linac - exit

At entrance of undulator

Current >3kA
Emittance >0.5umrad
Energy deviation ($\Delta \gamma$) > 1.5
Linac – tuning process

Cavity phases \((S,C,X)\), angle & length of \(BC\) – length, emittance, linearity

Slice properties

Emittance growth by CSR

Moments with 2 variables

Linear fitting in 2D space
Undulator – 0.06nm

Undulator – 10GeV, 2.35cm, 8.56mm – 0.06nm
Undulator – 0.1, 0.24 nm

Gap change

10 GeV
period 2.35 cm
gap 6.11 mm

6.5 GeV
period 2.35 cm
gap 6.05 mm

Rad. Power (Arb. unit)

Wave length (nm)

Gap & Energy change

10 GeV
period 2.35 cm
gap 6.11 mm

6.5 GeV
period 2.35 cm
gap 6.05 mm

Rad. Power (Arb. unit)

Wave length (nm)
Design issues

- Optimization and full error study for tolerance
- Laser heater
- Repetition rate
- Tunability and switching method
Design issues

• Atto-second XFEL Generation
ESASE (Enhanced Self-Amplified Spontaneous Emission)
Increasing the peak current and keeping the emittance by lowering the charge can make it possible to reduce $L_g$. Peak current after the Laser-modulated bunching: $> 8$ kA $\rightarrow$ saturation length is decreased by 30%

• Jitter-free Pump-probe Experiment
jitter induced by amplitude noise of Linac RF systems is known to be $> 50$ fs
Optical laser synchronized to ESASE XFEL is used for pump signal $\rightarrow$ jitter is reduced to below 10 fs
Summary

✓ 0.06nm SASE FEL in progress.

✓ 3 parts studied by tracking codes.
✓ Injector: Photo-cathode + S-band
✓ Linac: S-band, X-band, main C-band
✓ Undulator: out vacuum
✓ Target performances are obtained by start-to-end simulations.

✓ Detailed & advanced subjects are under study.

Thank you for attention!