S2E simulations for proof-of-principle experiment on THz SASE FEL at PITZ

M. Krasilnikov for PITHz team
DESY-TEMF-Meeting, 15th of November 2018, DESY Hamburg,

Photo Injector Test facility at DESY, Zeuthen site (PITZ)

L-band NC gun for EXFEL
- 60MV/m
- Flattop PC laser
- 0-5nC
IR/THz SASE source for pump-probe experiments @E-XFEL

PITZ-like accelerator can enable high power, tunable, synchronized IR/THz radiation

• Accelerator based IR/THz source meets requirements for pump-probe experiments (e.g. the same pulse train structure !)
• Construction of radiation shielded area for installing reduced copy of PITZ is possible close to user experiments at E-XFEL
• Prototype of accelerator already exists → PITZ facility at DESY in Zeuthen

Simulation of THz SASE FEL @PITZ

~mJ THz pulse @ MHz train (SASE simulation with PITZ beam, ~4 nC, I_peak ~200A)

Required beam (~4nC, I_peak ~200A) already demonstrated at PITZ → PITZ can be used for proof of principle and optimization!
SASE FEL based on PITZ accelerator and LCLS-I undulators

LCLS-I undulators (available on loan from SLAC) → under study and negotiations

Some Properties of the LCLS-I undulator

<table>
<thead>
<tr>
<th>Properties</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>planar hybrid (NdFeB)</td>
</tr>
<tr>
<td>K-value</td>
<td>3.49 (3.585)</td>
</tr>
<tr>
<td>Support diameter / length</td>
<td>30 cm / 3.4 m</td>
</tr>
<tr>
<td>Vacuum chamber size</td>
<td>11 mm x 5 mm</td>
</tr>
<tr>
<td>Period length</td>
<td>30 mm</td>
</tr>
<tr>
<td>Periods / a module</td>
<td>113 periods</td>
</tr>
</tbody>
</table>


Preliminary conclusions on LCLS-I undulators at PITZ:

- Not such extremely high performance as for the APPLE-II, but is clearly proper for the proof-of-principle experiment!
- 4 nC electron beam transport through the vacuum chamber needs efforts, but seems to be feasible.

\[ \lambda_{\text{rad}} \sim 100 \mu m \rightarrow \langle P_z \rangle = 16.7 \text{MeV/c} \]
Start-to-end simulations for proof-of-principle experiment at PITZ

PITZ main tunnel and tunnel annex for the LCLS-I undulator installation

S2E simulations: from photocathode → undulator → THz SASE FEL

Main challenges:
• 4 nC (200A) x 16.7 MeV/c → SC dominated beam
• ~30 m transport (incl. 1.5 m wall) → LCLS-I undulator in the tunnel annex
• 3D field of the undulator field
• Matching into the undulator (narrow vacuum chamber issue)

Tools:
• ASTRA
• SC-Optimizer
• GENESIS 1.3
Beam Dynamics Simulation Setup

**Gun + Solenoids + CDS-booster**

**Fields**

- **Gun:**
  - $E_{\text{cath}}=60\text{MV/m}$ (fixed)
  - MMMG

- **Booster:**
  - $E_{\text{max}}<20\text{MV/m}$
  - Phase=phi2*

$$\Rightarrow \langle P_z \rangle = 16.7\text{MeV/c} + \min \delta E_{\text{undulator?}}$$

**Photocathode laser:**
- FT 21.5ps FWHM
- $\varnothing \leq 5\text{mm}$
- 4nC

**NB:**
- Core + Halo model for real laser!
- Imperfections (photoemission + asymmetry)
Gun, solenoid, booster parameters

Extremely small emittance is not a goal

\[ \phi_{2}^{*} = \text{booster phase for } \langle P_z \rangle = 16.7 \text{MeV/c} \]

Minimizing correlated energy spread close to the undulator

Booster: Max\( E(2) = 12.6 \text{MV/m} \)
\[ \Phi(2) = -24 \text{ deg} \]

Photocath. laser:
\[ \text{XY}_{\text{rms}} = 1.25 \text{mm} \]

Gun solenoid:
\[ \text{MaxB(1)} = -0.21285 \text{T} \]
Beam at EMSY1 – “ready” for transport

Z=5.277m from the cathode
PITZ Beam from the cathode → tunnel wall

ASTRA input → SC-Optimizer → check with ASTRA

\[ GF(Q_1, \ldots, Q_9) \propto \frac{1}{L} \int_{z_{wall}}^{z_{wall}+d} X_{rms} \cdot Y_{rms} \, dz \]
LCLS-I Undulator field

By(0,0,z) field profile measurements done on 02.10.2013 at SLAC for the undulator L143-112000-07 after the final tuning

Measurements provided by Heinz-Dieter Nuhn, SLAC
LCLS-I Undulator field

Fourier Analysis

Performing Fourier transformation for $-\frac{L}{2} \leq z \leq \frac{L}{2}$, where $L = N_U \lambda_U$ is the undulator length:

$$B_y(x = 0, y = 0, z) = \sum_{n=0}^{\infty} \left\{ a_n \cos \left( \frac{2\pi nz}{N_U \lambda_U} \right) + b_n \sin \left( \frac{2\pi nz}{N_U \lambda_U} \right) \right\},$$

where

$$a_n = \frac{2}{L} \int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x = 0, y = 0, z) \cos \left( \frac{2\pi nz}{N_U \lambda_U} \right) \, dz,$$

$$a_0 = \frac{1}{L} \int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x = 0, y = 0, z) \, dz,$$

$$b_n = \frac{2}{L} \int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x = 0, y = 0, z) \sin \left( \frac{2\pi nz}{N_U \lambda_U} \right) \, dz.$$

Field integrals of the undulator:

$$I_{1y} = \int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x = 0, y = 0, z) \, dz,$$

$$I_{2y} = \int_{-\frac{L}{2}}^{\frac{L}{2}} dz \int_{z_1}^{z} B_y(x = 0, y = 0, z_1) \, dz_1.$$

$$I_{1y} = a_0 L, \quad a_0 = 0$$

$$I_{2y} = \frac{L^2}{2} \left\{ a_0 + \sum_{n=1}^{\infty} \frac{(-1)^n}{\pi n} b_n \right\}, \quad \sum_{n=1}^{\infty} \frac{(-1)^n}{\pi n} b_n = 0$$
LCLS-I Undulator field

3D field map generation

Vertical and longitudinal components of undulator magnetic field:

\[ B_y(x, y, z) = \sum_{n=1}^{N_h \cdot N_U} \left[ \tilde{a}_n \cos(k_n z) + \tilde{b}_n \sin(k_n z) \right] \cdot \cosh(k_n y), \]
\[ B_z(x, y, z) = \sum_{n=1}^{N_h \cdot N_U} \left[ -\tilde{a}_n \sin(k_n z) + \tilde{b}_n \cos(k_n z) \right] \cdot \sinh(k_n y), \]

where \( k_n = \frac{2\pi n}{N_U \lambda_U} \) is the wavenumber of the \( n \)-th Fourier harmonic.

\[ \tilde{b}_n = 2 \cdot \frac{N_U \lambda_U}{N_U \lambda_U} \int_{-\frac{N_U \lambda_U}{2}}^{\frac{N_U \lambda_U}{2}} B_{y,2}(x = 0, y = 0, z) \sin \left( \frac{2\pi n z}{N_U \lambda_U} \right) \, dz, \]

\[ N_h = 17; \quad N_U = 120 \]
On-axis particle trajectory in the undulator

**Reference particle:** ASTRA and CST tracking

<table>
<thead>
<tr>
<th>Reference particle</th>
<th>ASTRA with 3D field map</th>
<th>CST Particle Studio Trk</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-axis</td>
<td><img src="https://via.placeholder.com/150" alt="Graph" /></td>
<td><img src="https://via.placeholder.com/150" alt="Graph" /></td>
</tr>
</tbody>
</table>

**Off-axis**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X(0), mm</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>X'(0), mrad</td>
<td>-0.35</td>
<td></td>
</tr>
<tr>
<td>Y(0), mm</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Y'(0), mrad</td>
<td>-1.19</td>
<td></td>
</tr>
</tbody>
</table>

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DESY. | Mikhail Krasilnikov, S2E simulations for proof-of-principle experiment on THz SASE FEL at PITZ | DESY-TEMF-Meeting, 15.11.2018, DESY, Hamburg
Beam matching into the undulator

ASTRA simulations with space charge and 3D undulator field map

- “Ideal” (Gaussian-FT) beam

Asymmetric (X-Px-Y-Py) beam for proper matching into the undulator!
New transport / matching
Further “through the wall” + prepare for asymmetric matching into the undulator
Fine matching into the undulator

Starting with “beam at wall of the new tunnel” z = 25.587 m

Using SC-Optimizer

Using ASTRA

<table>
<thead>
<tr>
<th>Quad</th>
<th>Z from wall</th>
<th>Z from cathode</th>
<th>Matching M1</th>
<th>Matching M2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>T/m</td>
<td>A</td>
</tr>
<tr>
<td>Q(25)</td>
<td>0.3663</td>
<td>25.9533</td>
<td>1.107</td>
<td>~1.6</td>
</tr>
<tr>
<td>Q(26)</td>
<td>0.7663</td>
<td>26.3533</td>
<td>-3.277</td>
<td>~4.8</td>
</tr>
<tr>
<td>Q(27)</td>
<td>1.1663</td>
<td>26.7533</td>
<td>2.564</td>
<td>~3.8</td>
</tr>
</tbody>
</table>

\[
GFX(X_{rms,0}, Y_{rms,0}, X'_{rms,0}, Y'_{rms,0}) \propto \frac{1}{L} \int_0^L X_{rms} \, dz \\
GFY(X_{rms,0}, Y_{rms,0}, X'_{rms,0}, Y'_{rms,0}) \propto \frac{1}{L} \int_0^L \text{std}(Y_{rms}) \, dz
\]

\[
GF = w_x \cdot GFX + w_x \cdot GFY
\]
Electron beam transport for LCLS-I undulator option at PITZ

Matching into the undulator → beam size

NB1: Space charge model is not fully correct for the undulator (dipole field)
Beam at undulator entrance
ASTRA monitors at z=27.15m ➔ input for GENESIS 1.3 simulations

<table>
<thead>
<tr>
<th>X-Y</th>
<th>X-X'</th>
<th>Y-Y'</th>
<th>X-T</th>
<th>Z-Pz</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**Diagram:**
- x (mm)
- y (mm)
- P (MeV)

**Graph:**
- Slice X-emit. (nm mrad)
- Slice Y-emit. (nm mrad)
- Slice energy spread (keV)
- Beam current (A)

**Equation:**
- x (mm)
- y (mm)
- z (mm)
GENESIS 1.3 Simulations

ASTRA at 27.15m + tuning (scaling) → GENESIS1.3 Simulations

Nominal beam S2E → \((\beta_y, \alpha_y)\)

Tuned beam → \((\beta_y, \alpha_y)\) + 0.25

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal beam ((\beta_y, \alpha_y))</th>
<th>Tuned beam ((\beta_y, \alpha_y))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy (mJ)</td>
<td>0.44±0.11</td>
<td>0.60±0.13</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>43.0±10.2</td>
<td>58.5±14.3</td>
</tr>
<tr>
<td>Pulse duration (ps)</td>
<td>5.6±0.7</td>
<td>5.7±0.7</td>
</tr>
<tr>
<td>Arrival rms time jitter (ps)</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Centre wavelength (μm)</td>
<td>106.5</td>
<td>106.8</td>
</tr>
<tr>
<td>Spectrum FWHM width (μm)</td>
<td>4.5</td>
<td>4.8</td>
</tr>
</tbody>
</table>

GENESIS model:
- Only fundamental mode\((\lambda_u=3\text{cm})\) of one undulator
- No waveguide effect (vacuum chamber) included
Conclusions and outlook

Star-to-End simulations for the proof-of-principle experiment for SASE THz FEL at PITZ using LCLS-I undulator

- PITZ Setup for THz SASE FEL:
  - Gun: 60MV/m, 0deg
  - Photocathode laser: Ø5mm, 21.5ps FWHM, 4nC
  - CDS booster setup: 12.6MV/m, -24deg → 16.7MeV/c + min dE@-undulator
  - Main solenoid: MaxB(1)=0.21285T (~365A) → ε_y(EMS1)~4 mm mrad
  - Transport: 3 quad. triplets → transport through the tunnel wall (1.5m)
  - Transport: +1 quad triplet to match into undulator

- Undulator field:
  - Based on measured profile B_y(z,0,0)
  - Treated (improved) profile to minimize field integrals
  - 3D field map reconstructed → CST and ASTRA

- Tracking beam through the undulator:
  - On-axis reference particle: CST Trk ↔ ASTRA with 3D field map
  - Off-axis reference particle in ASTRA to find initial guess for matching
  - 4nC beam by ASTRA (with space charge*) → matching found

- GENESIS simulations with s2e electron beam → ~440uJ (up to 600uJ by β_y-α_y-tuning) at λ_rad~100um

- Refine (improve) preliminary optimum solution:
  - Realistic PC laser parameters Ø3-4mm, other temporal profiles, core+halo (using experimental data)
  - Other imperfections (photoemission, asymmetry)
  - Flat beam option?
  - Transport with less quads?
  - Collimator?
  - Scale / re-optimize setup for λ_rad=50-60μm

- Undulator error, tolerances
  - Implement horizontal gradient
  - ...

- "Full physics" FEL code?
  - Waveguide effects
  - Space charge effects
  - Wakefields?
  - Tolerances on the input beam (imperfections)
  - ...

- Mikhail Krasilnikov, S2E simulations for proof-of-principle experiment on THz SASE FEL at PITZ | DESY-TEMF-Meeting, 15.11.2018, DESY, Hamburg
Planned installation of LCLS-I undulators in PITZ tunnel annex

To use for proof-of-principle experiments at PITZ
“PITHz collaboration”:

P. Boonpornprasert, X.-K. Li, H. Shaker, F. Stephan, DESY, Zeuthen, Germany
E.A. Schneidmiller, M.V. Yurkov, DESY, Hamburg, Germany
H.-D. Nuhn, SLAC, Menlo Park, California, USA

Special thanks:

V. Balandin, N. Golubeva, DESY, Hamburg, Germany
SASE FEL with LCLS-I Undulator at PITZ

Estimations of parameters (theory) for $\lambda_{\text{rad}} \approx 100 \mu$m

### e-beam

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, $E_0$</td>
<td>16.65 MeV</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>32.6</td>
</tr>
<tr>
<td>$\sigma_E$</td>
<td>70 keV</td>
</tr>
<tr>
<td>$&lt;\sigma_x&gt;$</td>
<td>1..0.5..1 mm</td>
</tr>
<tr>
<td>$&lt;\sigma_y&gt;$</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>charge</td>
<td>4 nC</td>
</tr>
<tr>
<td>$I_{\text{peak}}$</td>
<td>190 A</td>
</tr>
<tr>
<td>$\varepsilon_{n,x,y}$</td>
<td>4 mm mrad</td>
</tr>
<tr>
<td>$\beta_x$</td>
<td>8 m</td>
</tr>
<tr>
<td>$\beta_y$</td>
<td>0.3 m</td>
</tr>
</tbody>
</table>

### FEL radiation

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{\text{rad}}$</td>
<td>105 $\mu$m</td>
</tr>
<tr>
<td>$Q$</td>
<td>0.43</td>
</tr>
<tr>
<td>$A_{JJ}$</td>
<td>0.74</td>
</tr>
<tr>
<td>$\theta_l$</td>
<td>0.11</td>
</tr>
<tr>
<td>$\gamma_l$</td>
<td>12.0</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>5.4 $m^1$</td>
</tr>
<tr>
<td>$\Gamma_1$</td>
<td>0.19 $m$</td>
</tr>
</tbody>
</table>

$Q = \frac{K^2}{4 + 2K^2}$

$A_{JJ} = J_0(Q) - J_1(Q)$

$\theta_l = K/\gamma$

$\frac{1}{\gamma_l^2} = \frac{1}{\gamma^2} + \frac{\theta_l^2}{2}$

$\Gamma = \sqrt{\frac{I_{\text{peak}}A_{JJ}^2\omega^2\theta_l^2}{2I_Ac^2\gamma_l^2\gamma}}$

### Undulator

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_u$</td>
<td>30 mm</td>
</tr>
<tr>
<td>$K$</td>
<td>3.585</td>
</tr>
</tbody>
</table>

### FEL dimensionless

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>0.052</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>5.7</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.013</td>
</tr>
<tr>
<td>$\tilde{\Lambda}_p^2$</td>
<td>0.41</td>
</tr>
<tr>
<td>$\tilde{\Lambda}_T^2$</td>
<td>0.11</td>
</tr>
</tbody>
</table>