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

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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.

\[ \lambda_{\text{rad}} \approx 100 \mu m \rightarrow <Pz> = 16.7 \text{MeV/c} \]
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

ASTRA

Gun + Solenoids + CDS-booster

**Fields**

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

- **Booster**: 
  - $E_{\text{max}}<20\text{MV/m}$
  - Phase=$\phi_2^*$

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

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:
\[ \text{MaxE}(2) = 12.6 \text{MV/m} \]
\[ \phi(2) = -24^\circ \]

Photocath. laser:
\[ \text{XYrms} = 1.25 \text{mm} \]

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

\[ GF(Q_1, \ldots, Q_9) \propto \sqrt{ \frac{1}{L} \int_{z_{wall}}^{z_{wall}+d} X_{rms} \cdot Y_{rms} \, dz } \]
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:

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

where

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

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

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

Field integrals of the undulator:

\[
I_{1y} = \int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x = 0, y = 0, z) dz, \quad \Rightarrow \quad I_{1y} = a_0 L, \quad \Rightarrow \quad a_0 = 0
\]

\[
I_{2y} = \int_{-\frac{L}{2}}^{\frac{L}{2}} dz \int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x = 0, y = 0, z_1) dz_1. \quad \Rightarrow \quad I_{2y} = \frac{L^2}{2} \left\{ a_0 + \sum_{n=1}^{\infty} \frac{(-1)^n}{\pi n} b_n \right\}, \quad \Rightarrow \quad \sum_{n=1}^{\infty} \frac{(-1)^n}{\pi n} b_n = 0
\]
LCLS-I Undulator field

3D field map generation

Vertical and longitudinal components of undulator magnetic field:

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

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

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

$$\tilde{b}_n = \frac{2}{N_U \lambda_U} \int_{N_U \lambda_U}^{2 N_U \lambda_U} B_{y,2}(x = 0, y = 0, z_1) \sin\left(\frac{2\pi n z_1}{N_U \lambda_U}\right) dz,$$

$N_h = 17; N_U = 120$

Used as external field map for ASTRA (static magnetic cavity) and for CST Trk/PIC solver.
### 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><strong>On-axis</strong></td>
<td><img src="image1.png" alt="Graph 1" /></td>
<td><img src="image2.png" alt="Graph 2" /></td>
</tr>
<tr>
<td><strong>Off-axis</strong></td>
<td><img src="image3.png" alt="Graph 3" /></td>
<td><img src="image4.png" alt="Graph 4" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(0), mm</td>
<td>0.7</td>
</tr>
<tr>
<td>X'(0), mrad</td>
<td>-0.35</td>
</tr>
<tr>
<td>Y(0), mm</td>
<td>0.21</td>
</tr>
<tr>
<td>Y'(0), mrad</td>
<td>-1.19</td>
</tr>
</tbody>
</table>
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” \( z=25.587 \text{m} \)

![Graph showing beam distributions and matching parameters](image)

<table>
<thead>
<tr>
<th>Quad</th>
<th>Z from wall (m)</th>
<th>Z from cathode (m)</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>

\[
GFX(x_{\text{rms},0}, y_{\text{rms},0}, x'_{\text{rms},0}, y'_{\text{rms},0}) \propto \frac{1}{L} \int_0^L x_{\text{rms},i} \, dz
\]

\[
GFY(x_{\text{rms},0}, y_{\text{rms},0}, x'_{\text{rms},0}, y'_{\text{rms},0}) \propto \frac{1}{L} \int_0^L \text{std}(Y_{\text{rms}}) \, dz
\]

\[
GF = w_x \cdot GFX + w_x \cdot GFY
\]

Using SC-Optimizer

Using ASTRA
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" alt="X-Y plot" /></td>
<td><img src="image2" alt="X-X' plot" /></td>
<td><img src="image3" alt="Y-Y' plot" /></td>
<td><img src="image4" alt="X-T plot" /></td>
<td><img src="image5" alt="Z-Pz plot" /></td>
</tr>
</tbody>
</table>
GENESIS 1.3 Simulations

ASTRA at 27.15m + tuning (scaling) → GENESIS 1.3 Simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal beam</th>
<th>Tuned beam 0.25(β_y, α_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(λ_u=3cm) 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:** ∅ 5mm, 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_{xy}(EMSY1)~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}~100μm

- Refine (improve) preliminary optimum solution:
  - Realistic PC laser parameters ∅3-4mm, 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)
  - ...

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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 $\lambda_{rad} \approx 100\mu$m

### E-beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{rad}$</td>
<td>105 µm</td>
</tr>
<tr>
<td>Q</td>
<td>0.43</td>
</tr>
<tr>
<td>$A_{JJ}$</td>
<td>0.74</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>0.11</td>
</tr>
<tr>
<td>$\gamma_i$</td>
<td>12.0</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>5.4 m⁻¹</td>
</tr>
<tr>
<td>$I_{peak}$</td>
<td>190 A</td>
</tr>
<tr>
<td>$\epsilon_{n,x,y}$</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

\[
Q = \frac{K^2}{4 + 2K^2} \quad A_{JJ} = J_0(Q) - J_1(Q) \quad \theta_i = K/\gamma \quad \frac{1}{\gamma_i^2} = \frac{1}{\gamma^2} + \frac{\theta_i^2}{2} \\
\Gamma = \sqrt{\frac{I_{peak}A_{JJ}^2\omega^2\theta_i^2}{2I_c^2c^2\gamma_i^2\gamma}}
\]

### 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>

### 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>

### Vacuum chamber

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>W / H / R$_{eff}$</td>
<td>11 / 5 / 4.2 mm</td>
</tr>
</tbody>
</table>