Simulations of the IR/THz source at PITZ (SASE FEL and CTR)

Outline
- Introduction
- Simulations of SASE FEL
- Simulations of CTR
- Summary
- Issues for Discussion
Proposal for IR/THz source at PITZ

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

Development of “Intense and wide wavelength range” IR/THz source at PITZ

Motivations & Goals

Photon diagnostics
Radiation based e-bunch diagnostics
Service for light users

Case studies of radiation generation produced by the PITZ electron beam
• SASE FEL for $\lambda_{rad} \leq 100 \, \mu m$ ($f \geq 3 \, \text{THz}$)
• Coherent Transition Radiation (CTR) for $\lambda_{rad} \geq 100 \, \mu m$ ($f \leq 3 \, \text{THz}$)

PITZ is an ideal machine for development of the prototype IR/THz source

(Reference: E.A. Schneidmiller et al., WEPD55, FEL2012 conf.)
Photocathode RF Gun
Cut Disk Structure (CDS) Booster
UV photocathode laser
  - Cylindrical pulse shape (Gaussian, flat-top)
  - 3D-ellipsoidal pulse shape
Electron beam diagnostics stations
Radiation stations for simulations studies
  - CTR station
  - Extension for SASE FEL

Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser temporal length</td>
<td>2 - 20 ps FWHM</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>few pC ... 4 nC</td>
</tr>
<tr>
<td>Maximum mean momentum ( &lt;P_z &gt; )</td>
<td>(~22) MeV/c</td>
</tr>
</tbody>
</table>
Simulations of SASE FEL

- Consideration of undulator parameters
- Overview of FEL parameter space
- Beam dynamics simulations
- Radiation calculations
- Summary and outlook
**SASE FEL: Consideration of undulator parameters**

**Important Equations**

The Peak magnetic field \( (B_{\text{max}}) \):

\[
B_{\text{max}}[T] = a_1 \cdot \exp \left[ a_2 \frac{g}{\lambda_u} + a_3 \left( \frac{g}{\lambda_u} \right)^2 \right],
\]

where \( a_1, a_2, \) and \( a_3 \) are coefficients and \( 0.1 < \frac{g}{\lambda_u} < 1 \).

For APPLE-II in helical mode*:

\( a_1 = 0.39, a_2 = 0.42, \) and \( a_3 = 0.001 \)

**Undulator Parameter (K)**

\[
K = 0.934 \cdot B_{\text{max}}[T] \cdot \lambda_u [cm]
\]

**Radiation Wavelength (\( \lambda_{\text{rad}} \))**

\[
\lambda_{\text{rad}} = \frac{\lambda_u}{2\gamma^2} \left( 1 + K_{\text{rms}}^2 \right)
\]

where \( \gamma \) is Lorentz factor.

---

**Sketch of APPLE-II Undulator**

Reference:

SASE FEL: Consideration of undulator parameters

**Conditions:**
- $\lambda_{\text{rad}}$ of 20 – 100 µm
- $P_z$ of 15 – 22 MeV/c
- $g \geq 10$ mm

**Selections:**
- $\lambda_u$ of 40 mm
- 22 MeV/c for 20 µm
- 15 MeV/c for 100 µm

**Plot of $P_z(g, \lambda_{\text{rad}}, \lambda_u)$**
The calculations have been performed with code FAST (Calculated by M.Yurkov & E. Schneidmiller).

Generate SASE FEL radiation wavelength of **100 µm** using:

- Helical undulator with period length of **40 mm**
- Electron beam with **15 MeV/c** momentum, **4 nC** bunch charge, ~**2 mm** rms bunch length

- Transverse normalized emittance ($\varepsilon_n$) has almost no impact on saturation power.
- Higher $\varepsilon_n$ $\Rightarrow$ lower saturation length.
**Simulation Tool:** ASTRA code

**Goals of the beam transport:**
- $<P_z> \sim 15$ MeV/c at the undulator entrance
- Symmetric transverse beam sizes and emittances at the undulator entrance

## Input for ASTRA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser pulse shape</td>
<td>Flattop</td>
</tr>
<tr>
<td>Laser temporal length</td>
<td>20 ps FWHM</td>
</tr>
<tr>
<td>Rms laser spot size</td>
<td>1.25 mm</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>4 nC</td>
</tr>
<tr>
<td>$Z_{start}$ to $Z_{end}$</td>
<td>0 (cathode) to 22.500 m</td>
</tr>
<tr>
<td>Gun peak E-field</td>
<td>60 MV/m</td>
</tr>
<tr>
<td>Booster peak E-field</td>
<td>10 MV/m (for $&lt;P_z&gt; \sim 15$ MeV/c)</td>
</tr>
<tr>
<td>Gun phase</td>
<td>Optimized for: <code>High peak current</code></td>
</tr>
<tr>
<td></td>
<td><code>Low energy spread</code></td>
</tr>
<tr>
<td>Booster phase</td>
<td></td>
</tr>
<tr>
<td>Solenoid fields</td>
<td></td>
</tr>
</tbody>
</table>

---

**Evolutions of transverse beam sizes and emittances**

**The longitudinal profiles at undulator entrance**

- Slice emittances
- Current profile
- Long. phase space
- Momentum spread
- ~200 A
- ~6 mm FWHM
GENESIS 1.3 code (Version 2) was used for numerical calculations of SASE FEL.

**Input for GENESIS:**
- Time-dependent mode, space-charge calculation included.
- Helical undulator with period length of 40 mm
- SASE FEL, Radiation wavelength of 100 μm (3 THz)

**Energy in the radiation pulse as a function of Undulator length**

```
Radiation pulse energy [μJ]
```

```
Position along the undulator [m]
```

- ~1 mJ

**Temporal profile of radiation pulse at the saturation**

```
Power [MW] vs. Current [A]
```

- ~200 MW

**Spectral profile of radiation pulse at the saturation**

```
P(λ) [a.u.]
```

- Wavelength [μm]
Summary

- The saturation length is ~3 m (75 periods)
- The radiation has high energy (~1 mJ) and long temporal length (~20 ps).

Outlook for Simulation Studies

- Studies for radiation wavelength of 20 µm.
- Use hybrid undulator instead of APPLE-II (PPM) ?
- Boundary conditions in the GENESIS1.3 code
- Radiation profiles & transport
Simulations of CTR

- Parameters of CTR station
- Beam dynamics simulations
- Radiation calculations
- Summary & outlook
CTR: Preliminary Design of CTR station

- Deflecting Cavity
- CTR Station
- APPLEII Undulator

Proposal extension for SASE FEL

CTR Station

\[ \theta_{\text{max}} = \tan \left(\frac{10 \text{ mm}}{40 \text{ mm}}\right) \approx 0.25 \]

- Expected acceptance angle: \( \theta_{\text{max}} = \frac{6}{\gamma} \)

\[ \gamma = \frac{6}{0.25} = 24 \rightarrow P_z \approx 12 \rightarrow 15 \text{ MeV/c} \]

Transm. coef. Vs \( \lambda \) for 0.5 mm thick window*

* Casalbuoni et al., TESLA 2006-04
CTR: Beam Dynamics Simulations

- **Simulation Tool: ASTRA code**
- **The bunch compressed by velocity bunching in the booster.**
- **Minimum $<P_z>$ is limited to \(~15~\text{MeV}/c\)**

### Input Parameters for ASTRA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser pulse shape</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Laser temporal time</td>
<td>2.43 ps (FWHM)</td>
</tr>
<tr>
<td>Rms laser spot size</td>
<td>1 mm</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>20 pC to 1 nC</td>
</tr>
<tr>
<td>$Z_{start}$ to $Z_{end}$</td>
<td>0 (cathode) to 16.30 m</td>
</tr>
<tr>
<td>Gun peak field</td>
<td>60 MV/m</td>
</tr>
<tr>
<td>Booster peak field</td>
<td>18 MV/m</td>
</tr>
<tr>
<td>Gun phase*</td>
<td>0°</td>
</tr>
<tr>
<td>Booster phase*</td>
<td>-60°</td>
</tr>
</tbody>
</table>

*with respect to maximum momentum gain phase

### Evolutions of simulated rms bunch length

![Graph showing evolutions of simulated rms bunch length](image)

### Rms momentum spread and peak current VS bunch charges at the CTR station

![Graph showing rms momentum spread and peak current](image)

### Long. phase spaces at the CTR station

![Graph showing long. phase spaces](image)
CTR: Radiation Calculations

- CTR calculations were performed by using **Generalized Ginzburg-Frank Formula** [Casalbuoni et al., TESLA 2005-15].

- Assume:
  - The radiation screen is a finite circular metallic screen with the radius $a$.  
  - Electron beam with transverse radius of $r_b$ impinges normally on the screen.

- The spectral and spatial radiation energy in the far-field regime for backward CTR are given by

\[
\frac{d^2 U_{\text{bunch}}}{d\omega d\Omega} = \frac{e^2}{4\pi^3\varepsilon_0 c} \frac{\beta^2 \sin^2 \theta}{(1 - \beta^2 \cos^2 \theta)^2} \cdot N^2 |F_{\text{long}}(\omega)|^2 \cdot \left[ \frac{2c}{\omega r_b \sin \theta} J_0 \left( \frac{\omega r_b \sin \theta}{c} \right) - \frac{2c\beta Y}{\omega r_b} J_0 \left( \frac{\omega r_b}{c\beta Y} \right) T(Y, \omega a, \theta) \right]^2
\]

**Longitudinal Form factor of the e-beam**

\[
F_{\text{long}}(\omega) = \int_{-\infty}^{+\infty} \rho_{\text{long}}(t)e^{-i\omega t} dt
\]

\[
T(Y, \omega a, \theta) = \frac{\omega a}{c\beta Y} J_0 \left( \frac{\omega a \sin \theta}{c} \right) K_1 \left( \frac{\omega a}{c\beta Y} \right) + \frac{\omega a \sin \theta}{c\beta Y^2 \sin \theta} J_1 \left( \frac{\omega a \sin \theta}{c} \right) K_0 \left( \frac{\omega a}{c\beta Y} \right)
\]
**CTR: Radiation Calculations**

- CTR calculations were performed by using Generalized Ginzburg-Frank Formula [Casalbuoni et al., TESLA 2005-15].

- **Assumptions and input:**
  - Perfect conductor and circular screen with radius of 15 mm.
  - Backward radiation, far-field regime calculation
  - E-beam with radius of 0.5 mm is normal incident to the screen.

**Form factors of the compressed bunch at the CTR station**

**Total radiation energy VS bunch charge**

- 2 µJ@1 nC
- 4 nJ@20 pC

**Normalized radiation energy VS frequency (f) and the emission angle (θ)**

- 20 pC
- 1 nC
CTR: Summary & Outlook

Summary

- FWHM bunch length reaches only \( \sim 0.5 \text{ mm (1.6 ps)} \) when compressed by velocity bunching using the booster.
- The radiation has low energy (\( nJ - \mu J \)) and low frequency (\( 0.01-0.5 \text{ THz} \)).

Outlook

- Bunch compressor is needed.
  - New bunch compressor ?
  - Try to use HEDA2 section

- Simulations:
  - an oblique screen, Near-field regime
  - Radiation profiles & transport
- The first CTR experiment is foreseen to take place in 2016.
Preliminary S2E simulations for the SASE FEL and the CTR using the PITZ accelerator were studied.

Comparison to the other IR/THz sources
(the radiation from the PITZ sources are just estimation)

Pulse energy VS FWHM of the generating bunch for the various sources

Spectral peak power density VS frequency

Comments from DESY Beschleuniger Ideenmarkt September 2015

Kommentar und Empfehlung

Combining a PITZ-like accelerator with the XFEL as has been suggested by Schneidmiller et al. could be promising for THz pump-XFEL probe experiments. Following this suggestion the options to generate intense THz-radiation with a PITZ-like accelerator have been simulated which is certainly a good idea. So far the simulations show very intense THz pulses for a 75-period undulator as a radiation source albeit at the expense of generating very long pulses. For single cycle pulses from CTR the calculations show fairly low pulse energies. It should be investigated whether such a source would actually serve the user demands for THz pump-XFEL probe experiments.

Interesting and remarkable experiments those can be done at PITZ within time frame of 1 year from now.

- CTR
- SASE FEL
- Etc.,

In this starting step, research activities at PITZ concerning this proposal should be focused on:

- Optimization of e-beam parameters
- Quality of generated radiations
- Radiation based e-bunch diagnostics
Acknowledgement

PITZ Team

M. Yurkov, Y. Schneidmiller, B. Marchetti  
DESY, Hamburg

C. Thongbai, S. Rimjaem  
CMU, Thailand

Thank you for your attention!
BACKUP SLIDES
APPLE-II Type Undulator

\[ B_{\text{max}}[T] = a_1 \times \exp \left[ a_2 \frac{g}{\lambda_u} + a_3 \left( \frac{g}{\lambda_u} \right)^2 \right], \]

<table>
<thead>
<tr>
<th>Polarization</th>
<th>(a_1)</th>
<th>(a_2)</th>
<th>(a_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>1.76</td>
<td>-2.77</td>
<td>-0.37</td>
</tr>
<tr>
<td>Circular</td>
<td>1.54</td>
<td>-4.46</td>
<td>0.43</td>
</tr>
<tr>
<td>Vertical</td>
<td>2.22</td>
<td>-5.19</td>
<td>0.88</td>
</tr>
</tbody>
</table>

*Reference: Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007

Example of APPLE-II Parameters

<table>
<thead>
<tr>
<th></th>
<th>UE40**</th>
</tr>
</thead>
<tbody>
<tr>
<td>gap (magnetic)</td>
<td>6.5 – 25 mm</td>
</tr>
<tr>
<td>gap (vacuum)</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>period length</td>
<td>40 mm</td>
</tr>
<tr>
<td>undulator length</td>
<td>4 m</td>
</tr>
</tbody>
</table>

**T.Schmidt, Undulators for SwissFEL, FEL2009, Liverpool
### SASE FEL: Sensitivities to the electron beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed</th>
<th>Varied</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Initial</td>
</tr>
<tr>
<td>$\alpha_x, \alpha_y$</td>
<td>0</td>
<td>-10</td>
</tr>
<tr>
<td>$\sigma_x, \sigma_y$ [mm]</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>$\epsilon_x, \epsilon_y$ [um]</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$I_{\text{peak}}$ [A]</td>
<td>160</td>
<td>200</td>
</tr>
<tr>
<td>$P_{z,\text{rms}} / P_{z,\text{avg}}$ [%]</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Diagram:**

- Peak Power [a.u.]
- # step [a.u.]

- **100 µm**
SASE FEL using a model beamline*

* P. Boonpornprasert et al., MOP055. FEL2013

Simulations of the IR/THz source at PITZ (SASE FEL and CTR)

Prach Boonpornprasert
SASE FEL: Parameter Optimizations

The optimized parameters are:

- Gun phase = -20°
- Booster phase = -10°
- Main solenoid current = 356 A

Simulations of the IR/THz source at PITZ (SASE FEL and CTR)
Mini-Workshop on THz Option at PITZ, DESY, Zeuthen, 22.09.2015
Prach Boonpornprasert
CTR: Other approach for RF compression

Simulations of the IR/THz source at PITZ (SASE FEL and CTR)