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

Prach Boonpornprasert

Mini-Workshop on THz Option at PITZ
DESY, Zeuthen
22.09.2015
Proposal for IR/THz source at PITZ

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

**Considering**

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 $\lambda_{\text{rad}} \leq 100 \mu\text{m}$ ($f \geq 3 \text{ THz}$)
- Coherent Transition Radiation (CTR) for $\lambda_{\text{rad}} \geq 100 \mu\text{m}$ ($f \leq 3 \text{ THz}$)

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

(Reference: E.A. Schneidmiller et al., WEPD55, FEL2012 conf.)
Simulations of the IR/THz source at PITZ (SASE FEL and CTR)

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Mini-Workshop on THz Option at PITZ, DESY, Zeuthen, 22.09.2015
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 ($B_{max}$):

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

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 ($K$)

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

Radiation Wavelength ($\lambda_{rad}$)

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

where $\gamma$ is Lorentz factor.

Sketch of APPLE-II Undulator*

Reference:
SASE FEL: Consideration of undulator parameters

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

Selections:
- $\lambda_u$ of 40 mm
- 22 MeV/c for 20 \(\mu\text{m}\)
- 15 MeV/c for 100 \(\mu\text{m}\)

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.
### SASE FEL: Beam Dynamics Simulations (for $\lambda_{\text{rad}} = 100 \, \mu\text{m}$)

#### Simulation Tool: ASTRA code

#### Goals of the beam transport:

- $<P_z> \sim 15 \, \text{MeV/c}$ 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>$Z_{\text{start}}$ to $Z_{\text{end}}$</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 $&lt;P_z&gt; \sim 15 , \text{MeV/c}$)</td>
</tr>
<tr>
<td>Gun phase</td>
<td>Optimized for: High peak current, Low energy spread</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

![Evolutions of transverse beam sizes and emittances](image)

#### The longitudinal profiles at undulator entrance

- **Slice emittances**
- **Current profile**
  - $\sim 200 \, \text{A}$
  - $\sim 6 \, \text{mm FWHM}$
- **Momentum spread**
- **Long. phase space**

Simulations of the IR/THz source at PITZ (SASE FEL and CTR) at Mini-Workshop on THz Option at PITZ, DESY, Zeuthen, 22.09.2015
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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](image)

![Temporal profile of radiation pulse at the saturation](image)

![Spectral profile of radiation pulse at the saturation](image)

Energy in the radiation pulse as a function of Undulator length: ~1 mJ

Temporal profile of radiation pulse at the saturation: ~200 MW
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

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

\[ \text{Expected acceptance angle: } \theta_{\text{max}} = \frac{6}{\gamma} \]

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

\[ \text{Transm. coef. Vs } \lambda \text{ for 0.5 mm thick window}^* \]

* 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 $\sim 15 \text{ MeV/c}$

<table>
<thead>
<tr>
<th>Input Parameters for ASTRA</th>
<th></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

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

Long. phase spaces at the CTR station

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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

$$\frac{d^2U_{\text{bunch}}}{d\omega d\Omega} = \frac{e^2}{4\pi^3\varepsilon_0c} \frac{\beta^2 \sin^2 \theta}{(1 - \beta^2 \cos^2 \theta)^2} \cdot N^2 |F_{\text{long}}(\omega)|^2 \cdot \left[ \frac{2c}{\omega r_b \sin \theta} J_0 \left( \frac{\omega r_b \sin \theta}{c} \right) - \frac{2c\beta \gamma}{\omega r_b} I_0 \left( \frac{\omega r_b}{c\beta \gamma} \right) T(\gamma, \omega a, \theta) \right]^2$$

**Longitudinal Form factor**

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

$$T(\gamma, \omega a, \theta) = \frac{\omega a}{c\beta \gamma} J_0 \left( \frac{\omega a \sin \theta}{c} \right) K_1 \left( \frac{\omega a}{c\beta \gamma} \right) + \frac{\omega a \sin \theta}{c\beta^2 \gamma^2 \sin \theta} J_1 \left( \frac{\omega a \sin \theta}{c} \right) K_0 \left( \frac{\omega a}{c\beta \gamma} \right)$$
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

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

2 µJ@1 nC
4 nJ@20 pC

20 pC
1 nC
Summary
► FWHM bunch length reaches only ~0.5 mm (1.6 ps) when compressed by velocity bunching using the booster.
► The radiation has low energy (nJ - µJ) and low frequency (0.01-0.5 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)

- **PITZ SASE FEL** (10^3 µJ)
- **PITZ CTR (1 nC)**
- **PITZ CTR (20 pC)**

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

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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>
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<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>

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P. Boonpornprasert et al., MOP055. FEL2013
SASE FEL: Parameter Optimizations

The optimized parameters are:

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

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