THz Activities at PITZ

PITZ studies towards an accelerator driven high power, tunable THz source for pump-probe experiments at European XFEL

Prach Boonpornprasert for the PITZ team

1st ARD Alliance Meeting
DESY Hamburg, 5.9.2018
Outline of the Talk

- Photo Injector Test facility at DESY, Zeuthen site (PITZ)
- A proposal for Accelerator based THz source for P&P at E-XFEL
- IR/THz Options at PITZ:
  - High-gain SASE FEL
  - Coherent Transition Radiation (CTR) and Coherent Diffraction Radiation (CDR)

  Topic of my PhD thesis

- SASE FEL based on PITZ accelerator and LCLS-I undulators
- LUSIA proposal (Attosecond SIngle-cycle Undulator Light ➔ Horizon2020 FETOPEN call)
Photo Injector Test facility at DESY, Zeuthen site (PITZ)

Development, test and optimization of high brightness e-sources for SC linac driven FELs + applications:

- test-bed for FEL injectors: FLASH, the **European XFEL** (conditioning, characterization and optimization of gun cavities and photo injector subsystems, e.g. photocathode laser)
- **high brightness → small transverse emittance** *(projected and slice)*
- further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, … → applications like THz, plasma acceleration, UED, …

<7 MeV

<25 MeV

Total length of ~22 m but can be reduced significantly if some diagnostics parts are removed.
PITZ “engine”: RF-Gun and Photocathode Laser

Highlights of the facility

RF gun
• L-band (1.3 GHz) 1.6-cell copper cavity
• Ecath>~60MV/m $\rightarrow$ 7MeV/c e-beams
• 650us x 10Hz $\rightarrow$ up to 45 kW av. RF power
• Cs$_2$Te PC (QE~5-10%) $\rightarrow$ up to 5nC/bunch
• LLRF control for amp&phase stability
• Solenoids for emittance compensation

Pulse Train Time Structure:
PITZ and EXFEL trains with up to 600 (2700) laser pulses

Photocathode laser(s) (UV)

Different lasers
$\Rightarrow$ Possible to use simultaneously
$\Rightarrow$ various THz options

Institute of Applied Physics of the Russian Academy of Sciences

New laser system

3D ellipsoidal
Pulse shapers:
• Spatial Light Modulator (SLM) based
• Upgrade with Volume Bragg Grating (VBG)

Oscillator upgrade – Pharos-20W-1MHz frontend
Pulse length 0.25-10ps+

DESY. THz Activities at PITZ | Prach Boonpornprasert | 1st ARD Alliance Meeting | DESY Hamburg | 5.9.2018
Accelerator based tunable IR/THz source for P&P at E-XFEL

PITZ can be used as a prototype!

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


→ PITZ can be used for proof of principle and optimization!
IR/THz Options at PITZ: High-gain SASE FEL

Case studies of generating THz radiation by PITZ electron beam

PITZ beamline layout

extension for simulation studies

PITZ Highlights:

- Pulse train structure
- High charge feasibility (4 nC)
- Advanced photocathode laser shaping
- E-beam diagnostics
- Available tunnel annex
- …

Current PITZ “boundary conditions”:

- 22-25 MeV/c max
- No bunch compressor
- No undulator (yet…)
- …

SASE FEL for $\lambda_{\text{rad}} \leq 100 \, \mu$m ($f \geq 3$ THz)
THz SASE FEL at PIZZ

Undulator and beam parameter space

Example: APPLE- II Undulator*

Radiation wavelength

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

\[ K_{rms} = 0.66 \cdot B_0[T] \cdot \lambda_u[cm] \]

\[ B_0 = 1.54e^{-4.46 \frac{g}{\lambda_u} + 0.43 \left( \frac{g}{\lambda_u} \right)^2} \]

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

Conditions:

- \( \lambda_{rad} \) of 20 – 100 µm
- Max \( P_z \) ~ 22 MeV/c
- gap \( g \geq 10 \) mm

Selections:

- \( \lambda_u \) of 40 mm
- 22 MeV/c for 20 µm
- 15 MeV/c for 100 µm

FEL Parameter Space with FAST code (\( \lambda_{rad} = 100 \) µm)

SASE FEL simulations assuming:

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

Preliminary conclusions:

- Transverse normalized emittance \( \varepsilon_n \) has almost no impact on saturation power
- Higher \( \varepsilon_n \) \( \Rightarrow \) lower saturation length
- Beam peak current (charge) \( \Rightarrow \) most impact

Courtesy M. Yurkov
THz SASE FEL: Beam Dynamics Simulations and Experiments

\( \lambda_{\text{rad}} = 100 \, \mu\text{m} \) (3 THz)

**Setup:**

\[ 4nC \rightarrow I_{\text{peak}} \approx 200A, \sim 15\text{MeV/c}, \]
\( \lambda_u = 40 \, \text{mm}, \, K=1.8, \, L_u=5\text{m} \)

- **Start-to-end:** Astra\( \rightarrow \)Genesis1.3
  - Photocathode laser: \( \varnothing 5\text{mm}, \) flattop 2/20/2ps
  - Gun and booster phases and main solenoid optimized for high \( I_{\text{peak}} \) and small \( \delta E \)

<table>
<thead>
<tr>
<th>FEL pulse energy</th>
<th>FEL radiation pulse at undulator exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(average and rms fluct.)</td>
<td>temporal profiles</td>
</tr>
</tbody>
</table>

![Graphs showing temporal and spectral profiles](image)

**E-beam from experiment\( \rightarrow \) Genesis1.3**

- Photocathode laser: \( \varnothing 3.7\text{mm}, \) Gaussian 11ps FHWM
- Phase spaces \( \rightarrow \) from measurements

![Phase space plots](image)

\( X-X' \) 7.13 mm mrad

\( Y-Y' \) 11.05 mm mrad

\( t-P_z \)
THz SASE FEL: Comparison with laser-based THz sources

PITZ-like accelerator can produce ~mJ THz pulses ($\lambda_{rad}$=20-100µm) matching time structure to XFEL X-ray pulses.

But still SASE (starting from the shot noise) ...

?How to improve stability (CEP= carrier envelope phase)?

Laser based THz pulse energy is limited at high repetition rate


Options to improve THz radiation stability

Pre-bunching → "Seeding"

- Photocathode laser pulse temporal modulation
- Using IR laser, modulator and BC for E or δE modulations
- Using CDR from short seeding bunch
- Using corrugated structures
- Using Dielectric Lined Waveguides - DLW (first experiments)

Measured e-beam current profile without (blue trace) with DLW (red trace), λ = 1.03 mm; The peaks are consistent with the wavelength of the structure 3.3 ps.

Future topics for PhD research at PITZ

In collaboration with CFEL (F. Lemery) and APC FNAL (P. Piot)
F. Lemery et al., Experimental demonstration of ballistic bunching with dielectric-lined waveguides at PITZ, IPAC 2017, WEPAB122
First THz Radiation Generated at PITZ

CTR/CDR for THz generation

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

PITZ Highlights:
• Pulse train structure
• High charge feasibility (4 nC)
• Advanced photocathode laser shaping
• E-beam diagnostics
• Available tunnel annex
• …

Current PITZ “boundary conditions”:
• 22-25 MeV/c max
• No bunch compressor
• …

THz Michelson interferometer measurements of CTR

Measured electron beam temporal profiles

PST.Scr2 is modified to be a CTR/CDR station
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

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<th>Details</th>
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<tr>
<td>Type</td>
<td>planar hybrid (NdFeB)</td>
</tr>
<tr>
<td>K-value</td>
<td>3.49</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>
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</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.
Single Cycle THz Pulse Generation from Undulator Participation in the LUSIA proposals (Attosecond SIngle-cycle Undulator Light on the horizon)

Manipulated undulator radiation: coherent emission from a chirped microbunched beam passing through strongly tapered undulator

Develop a new technology to generate isolated attosecond single-cycle μJ-level X-ray pulses

proof-of-principle in the terahertz (THz) regime at PITZ.

THz pulse calculated after the radiator undulator

Seed 1

Energy (1st method): 73.4 nJ
Energy (2nd method): 113.4 nJ

Undulator radiation from microbunch seeded by short IR laser pulse

Simulations: Pécs University group (Hungary)

Install LCLS-I Undulators and LUSIA in PITZ Tunnel + Annex

Will be used for proof-of-principle experiments at PITZ

Currently improving radiation shielding and preparing for operation permission for tunnel annex
Summary & Outlook

Studies on the tunable accelerator-based THz source (for P&P at EU-XFEL) are ongoing at PITZ

⇒ SASE FEL (~mJ@100μm), CTR&CDR

- **Short-term (1-2 years)**
  - Continue CTR/CDR experimental studies
  - Detailed simulations for THz SASE FEL with LCLS-I undulators

- **Mid-term (1-5 years)**
  - Installation and commissioning of 2 LCLS-I undulators in the PITZ tunnel annex, electron beamline
  - THz SASE FEL experiments with LCLS-I undulators
  - Studies on seeding options to improve CEP stability
  - Single cycle undulator THz radiation (LUSIA proof-of-principle experiments 1 and 2)

- **If funded by EU-XFEL: Long-term (3-7+X years)**
  - APPLE-II undulator or other modern undulators
  - Realization of the seeding option
  - THz facility optimization (BC, layout, etc.)
  - Delivery knowhow/hardware for acc.-based THz source for the pump-probe experiments
Outlook: Possible “PITHz” Layout

“all options” included
reduction in size and costs possible

Hardware costs:
VERY rough estimations

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<td>Dump&amp;THzdiag</td>
<td>2</td>
<td>25</td>
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</table>

~14M€, full option, can be reduced according to needs
CDR as seeding

Electron beam direction

CDR radiator

Bunch for CDR Main bunch for FEL

CDR for FEL seeded

Undulator

+chicane?
Use of LCLS I undulators for THz studies at PITZ

THz SASE FEL at PITZ as proof-of-principle for accelerator based THz source for pump-probe experiments at XFEL

- Contact with Heinz-Dieter Nuhn (HDN, SLAC) about current LCLS I undulators
- During visit at SLAC beginning of May 2018 HDN showed undulator components:
  - 3.4 m long modules, Ø = 30 cm (titanium), weight ~1 ton
  - Vacuum chamber
  - Support structure

- Norbert Holtkamp (SLAC) was asked if PITZ could have a long term loan of 2 undulator segments:
  → very positive reply
  → request should be content of a letter from H. Dosch
  → should be agreed at next DESY/SLAC directorate meeting in autumn 2018

- Components that are NOT re-used at LCLS II (and might be on loan)
  - undulators
  - the girder beneath the undulator
  - the motors for sliding the undulator in and out of the beam path
  - the vacuum chamber (outside: 6mm, inside: racetrack shape with 5mm height)
  - cavity BPM and electronics for the BPM
Motivation for accelerator based tunable IR/THz source for pump probe experiments at the European XFEL

General:
- Time structure of IR/THz source \(\rightarrow\) time structure of x-ray pulses
- IR/THz source should have wide tunability range
- IR/THz source \(\rightarrow\) wide possibilities for generation of different temporal and spectral patterns, polarization. (i.e. strong single-cycle pulses, narrow band radiation)
- Many applications require high peak power (field strength) or high pulse energy.
- Time jitter of pump and probe pulses should be small enough for resolving time-dependent phenomena

Specific for the European XFEL:
- EXFEL \(\rightarrow\) burst mode: 10Hz x 0.6 ms x 4.5 MHz = \(\approx\)27000 pulses per sec
- Current range of interest:

<table>
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<tr>
<th>(\lambda, \mu m)</th>
<th>from</th>
<th>to</th>
</tr>
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<tbody>
<tr>
<td>(f,\ THz)</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>(h\nu, meV)</td>
<td>207</td>
<td>1.24</td>
</tr>
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</table>

- Pulse energy spans a lot: \(\mu J \rightarrow\) hundreds of \(\mu J\) \(\rightarrow\) mJ
- Time jitter: 2 types of experiments:
  I. field driven dynamics where temporal resolution \(~\)few fs \(\rightarrow\) CEP stability
  II. "intensity" driven dynamics where temporal resolution \(~\)longest pulse duration (e.g. if THz pulse is 3 ps than the timing only need to be 3 ps).

Attractive features are:
- clean in-vacuum radiation production
- tunability of radiation with e.g. electron beam manipulation
- potential to provide high power (high field)
- polarization control

Methods of generation:
- radiation in a bend magnet
- undulator radiation
- transition radiation (i.e., crossing metallic foil)
- diffraction radiation (i.e. passing through an aperture)
- ...
THz SASE FEL: Beam Dynamics Simulations and Experiments

\( \lambda_{rad} = 100 \ \mu m \ (3 \ THz) \)

Simulation Tools:

- **ASTRA code** → goals of the beam transport (0→22.5m):
  - \(<P_z> \sim 15 \ MeV/c \) at the undulator entrance
  - Symmetric transverse beam sizes and emittances at the undulator entrance
  - Bunch charge 4 nC
  - PC laser: Ø5mm, flattop 2/20\ps
  - Gun and booster phases and main solenoid optimized for high \( I_{peak} \) and small \( \delta E \)

- **GENESIS 1.3 code (Version 2)** for SASE FEL:
  - Time-dependent mode, space-charge calculation included.
  - Helical undulator with \( \lambda_u=40 \ mm \)
  - SASE FEL, \( \lambda_{rad}\sim100 \ \mu m \ (3 \ THz) \)

- \( I_{peak} \sim200A \)
- \( E_{pulse} \sim3mJ \)
- \( L_{und} \sim5m \)
- \( BW\sim5-10\% \)

**Experimental data**
- 4nC electron beam
- \(<P_z>\sim15MeV/c \)
- 7.13 mm mrad
- 11.05 mm mrad
- \( t-P_z \)

**P. Boonpornprasert**
THz-related PITZ publications and talks

2012-2018

Papers and conference proceedings

Talks and posters
3. P. Boonpornprasert et al., "Start-to-End Simulations for a 100 μm SASE FEL at PITZ", talk at DPG-Frühjahrstagung, Wuppertal, Germany, March 9–13, 2015
4. P. Boonpornprasert, M. Krasilnikov, B. Marchetti, F. Stephan, "Simulations of the IR/THz Options at PITZ (High-gain FEL and CTR)", talk and poster at 3rd ARD ST3 Workshop, Karlsruhe, Germany: July 15–17, 2015
5. P. Boonpornprasert "Simulations of the IR/THz Options at PITZ (High-gain FEL and CTR)", talk at DESY Beschleuniger Ideenmarkt, Hamburg: September, 2015
7. P. Boonpornprasert et al., 'First Characterizations of a 4 nc Electron Beam for Thz Options at PITZ', talk at DPG-Frühjahrstagung (Spring Meeting), Darmstadt: 14 - 18 March 2016
10. M. Krasilnikov, "Tunable IR/THz source based on PITZ (like) accelerator for pump probe experiments at the European XFEL", Teraheertz Science at European XFEL, 1-2 June 2017, Schenefeld
12. M. Krasilnikov, "Update on THz studies at PITZ", LUSIA project meeting, 27.11.2017, Szentgyoth research Centre, Pécs, Hungary