Tunable IR/THz source based on PITZ (-like) accelerator for pump probe experiments at the European XFEL

Mikhail Krasilnikov (DESY) for the PITZ Team
Terahertz Science at European XFEL,
1-2 June 2017, European XFEL, Schenefeld

Outline:
• PITZ Introduction
• PITZ based THz source for p&p experiments
  • CTR/CDR
  • SASE FEL
  • Other options (seeding, single cycle)
• Conclusions and outlook
PITZ focuses on the development, test and optimization of high brightness e-sources for SC linac driven FELs:

⇒ test-bed for FEL injectors: FLASH, the **European XFEL** (conditioning and characterization of gun cavities and photo injector subsystems, e.g. photocathode laser)

⇒ high brightness ⇒ small $\varepsilon_{tr}$ (projected and slice)

⇒ further studies ⇒ e.g. cathodes: dark current, photoemission, QE, thermal emittance, …

⇒ currently highest priority at PITZ ⇒ participate in the solution of the remaining problems of the RF gun for EXFEL (long term reliability and stability, RF windows, cathode RF contact spring)
PITZ “engine”: RF-Gun and Photocathode (PC) Laser

**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
- Solenoid for emittance compensation

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

**Photocathode laser(s) (UV)**

**Default PC laser system**
(Max-Born-Institute, Berlin)

- Gaussian:
  - FWHM ~ 2 ps
  - FWHM ~ 7 ps
  - FWHM ~ 11 ps
  - FWHM ~ 17 ps

**Simulated pulse-stacker**

**Multicrystal birefringent pulse shaper containing 13 crystals**

**Flattop**

**Cathode laser pulse: temporal profile**

Delta t = 1μs (222ns)

Different lasers
- various THz options
- possibility of simultaneous usage

New PC laser ELLA
- 3D (ellipsoidal) pulse shaper:
  - SLM based
  - Upgrade with VBG
- Oscillator upgrade – Pharos-20W-1MHz frontend
  - Pulse length 0.25-10ps+

Institute of Applied Physics of the Russian Academy of Sciences
### PITZ evolution 2000-2017

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>cavity</td>
<td>gun-2</td>
<td>gun-1</td>
<td>gun-3.1</td>
<td>g-3.2</td>
<td>gun-4.2</td>
<td>g-4.1</td>
<td>g-3.1</td>
<td>4.3</td>
<td>g-4.1</td>
<td>4.3</td>
<td>g-4.1</td>
<td>4.3</td>
<td>g-4.1</td>
<td>4.3</td>
<td>g-4.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Ez, MV/m</td>
<td>35</td>
<td>37</td>
<td>42 $\rightarrow$ 60</td>
<td>43</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Ebeam</td>
<td>$\sim$4 MeV</td>
<td>4.3 MeV $\rightarrow$ 6 MeV</td>
<td>4.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
<td>$\sim$6.5 MeV</td>
</tr>
<tr>
<td>beam energy, MeV</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>min $\varepsilon_{xy}$ (mm mrad)</td>
<td>3 (1nC)</td>
<td>1.5-1.7 (1nC)</td>
<td>1.37 (1nC)</td>
<td>1.26 (1nC)</td>
<td>0.9 (1nC)</td>
<td>0.7 (1nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
<td>0.8 (0.5nC)</td>
</tr>
</tbody>
</table>

**PITZ goals**
- Small emittance (nominal EXFEL)
- +reliability at full performance
- +emittance (EXFEL startup)
- +THz
- +plasma

**Highlights:**
- Increasing the brightness (decreasing the emittance)
- Improving gun stability and reliability
- Extending beam diagnostics
- Use high brightness beam capability
### Motivation for accelerator based tunable IR/THz source for pump probe experiments at the European XFEL

#### Requirements to the pump source

**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: 
  \[
  10 \text{Hz} \times 0.6 \text{ ms} \times 4.5 \text{ MHz} = 27000 \text{ pulses per sec}
  \]
- Current **range** of interest:
<table>
<thead>
<tr>
<th>$\lambda, \mu m$</th>
<th>from</th>
<th>to</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f, \text{THz}$</td>
<td>50 - 15</td>
<td>3 - 0.3</td>
</tr>
<tr>
<td>$h\nu, \text{meV}$</td>
<td>207 - 62</td>
<td>12.4 - 1.24</td>
</tr>
</tbody>
</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 $\sim$few fs $\rightarrow$ **CEP stability**
  II."**intensity"** driven dynamics where temporal resolution $\sim$longest pulse duration (e.g. if THz pulse is 3 ps than the timing only need to be 3 ps).

#### Generation of IR/THz radiation by relativistic electron beams

**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)
- ...
Accelerator based tunable IR/THz source: PITZ as a prototype?

- Accelerator based IR/THz source **meets all requirements** for pump-probe experiments
- Construction of a radiation shielded **annex** (like present PITZ facility) is possible close to user experiments at the European XFEL
- **Prototype** of the accelerator already exists – it is **PITZ** facility at DESY in Zeuthen
- Can be excellent investment of efforts of accelerator consortium after finishing construction and commissioning phases of the European XFEL

=> **PITZ** can serve as prototype for such a development
IR/THz Options at PITZ (High-gain FEL and CTR)

Case studies of THz radiation generation produced by the PITZ electron beam

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

PITZ beamline layout including extension for simulation studies

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

Current PITZ “boundary conditions”:
• 22-25 MeV/c max
• No bunch compressor
• …
Experimental tests with electron beams for CTR option at PIZT

\[ \frac{d^2 U_{\text{bunch}}}{d\omega d\Omega} \propto N^2 |F_{\text{long}}(\omega)|^2; \quad F_{\text{long}}(\omega) = \int_{-\infty}^{\infty} \rho_{\text{long}}(t)e^{-i\omega t} dt \rightarrow T_{\text{bunch}} \ll 1/f \rightarrow \text{short bunches for CTR!} \]

CTR Calculations from simulated Velocity Bunching at PIZT

ASTRA simulations with short Gaussian photocathode laser and CDS booster -60deg off-crest

Form factors of the compressed bunch at the CTR station (z=16m)

Experiments on velocity bunching with short Gaussian PC laser pulses

Measured electron bunch length

MEASURED bunch current profiles

Calculated form-factors

P. Boonpornprasert

Mikhail Krasilnikov | Tunable IR/THz source based on PIZT (-like) accelerator… | 02.06.2017 | Page 8
Experimental tests with electron beams for CTR option at PITZ

**Experimental Optimization of Comb-beams**

Examples of measured comb-beam profiles with various bunch charges and booster phases

\[
\text{measured beam current (A)}
\]

<table>
<thead>
<tr>
<th>Bunch Charge (pC)</th>
<th>Angle (deg)</th>
<th>Beam Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>MMMG-20</td>
<td>45</td>
</tr>
<tr>
<td>250</td>
<td>MMMG-30</td>
<td>40</td>
</tr>
<tr>
<td>500</td>
<td>MMMG-30</td>
<td>35</td>
</tr>
</tbody>
</table>

Corresponding form factors

\[
\text{frequency (THz)}
\]

<table>
<thead>
<tr>
<th>Bunch Charge (pC)</th>
<th>Form Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.E+06</td>
</tr>
<tr>
<td>250</td>
<td>1.E+04</td>
</tr>
<tr>
<td>500</td>
<td>1.E+02</td>
</tr>
</tbody>
</table>

**Preliminary Design of CTR/CDR Station**

- PST.Scr2 → CTR station
- THz radiation diagnostics system → tunnel
- The system will be used to measure THz radiation:
  - energy/power
  - spatial profile
  - polarization
  - spectrum (Michaelson interferometer)
- The detectors are pyroelectric detector and THz camera with minimum response speed of 10 Hz
- 1st experiments → Autumn 2017

*P. Boonpornprasert*
IR/THz Options at PITZ (High-gain FEL and CTR)

Case studies of THz radiation generation produced by the PITZ electron beam

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

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

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

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

APPLEII Undulator Proposal extension for SASE FEL

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

PITZ beamline layout including extension for simulation studies

Photocathode RF Gun
Booster (Linac)
Deflecting Cavity
Quadrupole magnet
Dipole magnet
Screen
HEDA2
APPLEII Undulator

Proposal extension for SASE FEL

22.500 m
THz SASE FEL at PITZ: Undulator and beam parameter space

APPLE- II Undulator*

\[ \lambda_{\text{rad}} = \frac{\lambda_u}{2y^2} \left( 1 + \frac{K^2}{2} \right) \]

\[ K = 0.934 \cdot B_0 [T] \cdot \lambda_u [cm] \]

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

Conditions:
- \( \lambda_{\text{rad}} \) of 20 – 100 µm
- Max \( P_z \sim 22 \) 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 (\( \lambda = 100 \) µm)

Saturation power [W]

Saturation length [cm]

SASE FEL simulations assuming:
- Helical undulator with period length of 40 mm
- Electron beam with 15 MeV/c momentum,
  4 nC bunch charge, \( \sim 2 \) 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


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

Mikhail Krasilnikov | Tunable IR/THz source based on PITZ (like) accelerator… | 02.06.2017 | Page 11
Simulation Tools:

- **ASTRA code** → goals of the beam transport (0→22.5m):
  - \( <P_z> \sim 15 \text{ MeV/c} \) at the undulator entrance
  - Symmetric transverse beam sizes and emittances at the undulator entrance
  - Bunch charge 4 nC
  - PC laser: \( \phi 5 \text{mm, flattop 2/20\,\text{ps}} \)
  - Gun and booster phases and main solenoid optimized for high \( I_{\text{peak}} \) and small \( \delta E \)

- **GENESIS 1.3 code (Version 2)** for SASE FEL:
  - Time-dependent mode, space-charge calculation included.
  - Helical undulator with \( \lambda_u = 40 \text{ mm} \)
  - SASE FEL, \( \lambda_{\text{rad}} \sim 100 \mu \text{m} \) (3 THz)

- **Power and energy in the radiation pulse as a function of undulator length**

  - \( I_{\text{peak}} \sim 200 \text{A} \)
  - \( E_{\text{pulse}} \sim 3 \text{mJ} \)
  - \( L_{\text{und}} \sim 5 \text{m} \)
  - \( \text{BW} \sim 5\text{-}10\% \)

**Temporal profile of radiation pulse**

**Spectral profile of radiation pulse**
**Experimental Characterization of 4 nC Beams for THz SASE FEL Option**

**Calculation of SASE FEL for measured profiles**

<table>
<thead>
<tr>
<th>Procedure</th>
<th>THz pulse energy (z=5m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-to-End (S2E) simulations (ASTRA→GENESIS)</td>
<td>2.6 mJ</td>
</tr>
<tr>
<td>ASTRA→GENESIS</td>
<td>0.9 mJ</td>
</tr>
<tr>
<td>Measured (not optimized) electron beam → GENESIS</td>
<td>0.5 mJ</td>
</tr>
</tbody>
</table>
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
- Exchange transverse to longitudinal modulation
- Using CDR from short seeding bunch?
- Using corrugated structures
- Using Dielectric Lined Waveguides - DLW (first experiments)
- ...

<table>
<thead>
<tr>
<th>Pipe radius ( a ), mm</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe length ( l ), m</td>
<td>0.5-3</td>
</tr>
<tr>
<td>Corrugation depth ( h ), mm</td>
<td>0.05</td>
</tr>
<tr>
<td>Corrugation period ( p ), mm</td>
<td>0.04</td>
</tr>
<tr>
<td>Corrugation gap ( g ), mm</td>
<td>0.02</td>
</tr>
<tr>
<td>Gaussian bunch rms ( \sigma ), mm</td>
<td>0.1-0.3(*6)</td>
</tr>
</tbody>
</table>

\( E_0 = 8 \text{ MeV} \)
\( f \approx 0.33 \text{ THz} \)

\( E_0 = 20 \text{ MeV} \)
\( f \approx 0.3 \text{ THz} \)

\( \Delta E [\text{mJ}] \)
First Experiments with DLW 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

Measured Longitudinal Phase Space

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.

Longitudinal Phase Space

Beams without DLW (blue trace) with DLW (red trace), λ=1.03 mm; The peaks are consistent with the wavelength of the structure 3.3 ps.
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
- Exchange transverse to longitudinal modulation
- Using CDR from short seeding bunch?
- Using corrugated structures
- Using Dielectric Lined Waveguides - DLW (first experiments)

> Single cycle schemes (discussions with Uppsala and KEK ongoing)

- Manipulated undulator radiation (idea of Takashi Tanaka)


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

- With short IR laser
  → Pécs University group (Hungary) simulations
Single cycle schemes by seed (preliminary simulations from University of Pécs)

Assumed parameters of the two Seeds and Modulator

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Seed 1</th>
<th>Seed 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_1$</td>
<td>1000 um</td>
<td></td>
</tr>
<tr>
<td>$f_i$</td>
<td>0.3 THz</td>
<td></td>
</tr>
<tr>
<td>Waist ($w_0$)</td>
<td>2000 um</td>
<td></td>
</tr>
<tr>
<td>Rayleigh length</td>
<td>1.26 cm</td>
<td></td>
</tr>
<tr>
<td>Electric field</td>
<td>1 MV/cm</td>
<td>0.4 MV/cm</td>
</tr>
<tr>
<td>Power</td>
<td>83 MW</td>
<td>13.3 MW</td>
</tr>
<tr>
<td>($c_0\varepsilon_0 E^2 \pi w_0^2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse duration</td>
<td>~3.3 ps</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>~0.3 mJ</td>
<td>~0.04 mJ</td>
</tr>
<tr>
<td>$K$</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>$\lambda_u$</td>
<td>8.65 cm</td>
<td></td>
</tr>
<tr>
<td>$L/\lambda_u$</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Assumed parameters of the Radiator

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength</td>
<td>100 um (3 THz)</td>
</tr>
<tr>
<td>Undulator parameter ($K$)</td>
<td>0.5</td>
</tr>
<tr>
<td>Radiator period length</td>
<td>39.27 cm</td>
</tr>
</tbody>
</table>

Results (calculated 8 m after the radiator undulator)

<table>
<thead>
<tr>
<th>Seed 1</th>
<th>Seed 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (1st method):</td>
<td>Energy (1st method):</td>
</tr>
<tr>
<td>73.4 nJ</td>
<td>22.6 nJ</td>
</tr>
<tr>
<td>Energy (2nd method):</td>
<td>Energy (2nd method):</td>
</tr>
<tr>
<td>113.4 nJ</td>
<td>47.3 nJ</td>
</tr>
</tbody>
</table>

Courtesy Zoltan Tibai, University of Pécs, Hungary
Idea: Accelerator based THz (1) & electron diffraction source (2) for XFEL users

Basic PITZ parameters:
- bunch length: sub ps to 22 ps
- bunch charge: sub pC to > 5 nC
- max Pz ~ 24 MeV/c
- pulse train structure similar to XFEL

(1) Linac based THz source
Attractive features:
- provides high power (high field)

(2) Femtosecond e⁻ diffraction
v.s. X-ray:
- sub-pm wavelength, good spatial resolution
- ~10⁶ higher scattering cross section, good for thin or low density sample

v.s. other MeV electron diffraction source:
- higher rep. rate & higher flux;
- trade flux for higher transverse coherence;

new methodology:
- XFEL pump, electron probe;

Complementary tool for XFEL user to get a full picture of the ultrafast atomic world!

H. Qian

- tunability of radiation
- polarization control
- clean production of the radiation in vacuum

Possible options:
- Undulator → SASE THz FEL
- Other, e.g. transition, diffraction, synchrotron, edge radiation

Challenges:
- Phase locking (CEP stability) for field driven dynamics
- Short bunches (bunch compression) for single-cycle radiation

Current status:
- First electron beam measurements for SASE THz FEL option were done
- CTR experiment station is under realization
- Seeding options under study
Conclusions

- The Photo Injector Test facility at DESY in Zeuthen (PITZ) develops high brightness electron sources for SASE FELs:
  - specs for the European XFEL (nominal and startup) have been demonstrated and surpassed
  - beam emittance has also been optimized for a wide range of bunch charge (pC→nC)
  - now main focus → stability and reliability (high duty factor performance)

- PITZ highlights:
  - Pulse train structure → EXFEL
  - Advanced PC laser systems
  - High bunch charge (several nC) attainable
  - High stability achieved
  - Extensive beam diagnostics

- THz activities at PITZ (since 2012) → Tunable linac based IR/THz source
  - CTR/CDR with short/pre-bunched using velocity bunching (short Gaussian PC laser pulses + comb-like):
    - Estimations – E-beam measurements – calculations
    - CTR station under construction
  - THz SASE FEL with 4nC bunches:
    - Estimations → s2e simulations (3mJ@100um) → E-beam measurements → simulations
  - Other options:
    - Seeding (PC laser modulation, DLW- first tests, corrugated pipe, etc) → under studies
    - Single cycle THz production → under discussion in collaboration with Uppsala, KEK, Pécs University group
    - Femtosecond e- diffraction

- Outlook
Outlook: Possible “PITHz” Layout

• “all options” included
• reduction in size and costs possible

Supplementary Systems and Infrastructure

General: Radiation protection and personal IL

Control system and DAQ

Water Cooling System

Electronics: e-beam diagnostics

Electronics: THz diagnostics

Quadrupole magnet

Screen

Laser(s)

UED

CTR

Chicane BC

CTR

Undulator

Laser(s)

UEΔ

CTR

Chicane BC

CTR

Undulator

Vacuum components supplies

10MW MBK

10MW MBK

Water Cooling System

Electronics: e-beam diagnostics

Electronics: THz diagnostics

Quadrupole magnet

Screen

Laser(s)

UEΔ

CTR

Chicane BC

CTR

Undulator

Vacuum components supplies

10MW MBK

10MW MBK

Hardware costs: VERY rough estimations

Section | length | startZ | endZ |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PC system</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>gun</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>LE</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>CDS-1</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>matching</td>
<td>1</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>modulator</td>
<td>2</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>matching</td>
<td>1</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>CDS-2</td>
<td>2</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>matching</td>
<td>1</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>BC</td>
<td>14</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>matching</td>
<td>16</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>TDS</td>
<td>1</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>matching</td>
<td>1</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>undulator</td>
<td>19</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Dump&amp;THzdiag</td>
<td>25</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

∑~15M€

Mikhail Krasilnikov | Tunable IR/THz source based on PITHZ (-like) accelerator... | 02.06.2017 | Page 20
Outlook: PITZ tunnel(s)
PITZ focuses on the development, test and optimization of high brightness e-sources for SC linac driven FELs:

⇒ test-bed for FEL injectors: FLASH, the European XFEL (conditioning and characterization of gun cavities and photo injector subsystems, e.g. photocathode laser)

⇒ High brightness → small $\varepsilon_{ir}$ (projected and slice)

⇒ further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, …

⇒ Currently highest priority at PITZ → Participate in the solution of the remaining problems of the RF gun for EXFEL (RF windows, cathode RF contact spring, stability and long term reliability)

<table>
<thead>
<tr>
<th>parameter</th>
<th>XFEL injector, nominal</th>
<th>XFEL, commissioning</th>
<th>PITZ, 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF gun gradient</td>
<td>$E_{cath}=60\text{MV/m}$ (6.5MW)</td>
<td>$E_{cath}=50...53\text{MV/m}$ (4.5...5.0MW)</td>
<td>$E_{cath}=53\text{MV/m}$ (5MW)</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>650us</td>
<td>650us</td>
<td>650us</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10Hz</td>
<td>10Hz</td>
<td>10Hz</td>
</tr>
<tr>
<td>RF gun rms stability</td>
<td>$\phi=0.01\text{deg}$</td>
<td>$\phi=0.07\text{deg}$</td>
<td>$\phi=0.02%$</td>
</tr>
<tr>
<td></td>
<td>$A=0.01%$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cathode laser (FWHM)</td>
<td>Flattop (2/20/2ps)</td>
<td>Gaussian (~13ps FWHM)</td>
<td>Gaussian (~11.5ps FWHM)</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.02 – 1 nC</td>
<td>0.1 – 1 nC</td>
<td>0.1 – 1 – 5 nC</td>
</tr>
<tr>
<td>Beam emittance</td>
<td>0.4 – 1 mm mrad</td>
<td>e.g. $\leq 1\text{ mm mrad}$</td>
<td>0.8 mm mrad @500pC</td>
</tr>
</tbody>
</table>

Required electron beam quality demonstrated at PITZ in 2011 with $\leq 200\text{us}$ RF pulse length
Experimental Characterization of 4 nC Beams for THz SASE FEL Option

<table>
<thead>
<tr>
<th>X-X'</th>
<th>~22 MeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.26 mm mrad</td>
<td>horizontal slice emittance</td>
</tr>
<tr>
<td></td>
<td>horizontal slice momentum spread</td>
</tr>
<tr>
<td>Y-Y'</td>
<td>6.86 mm mrad</td>
</tr>
<tr>
<td>t-P_z</td>
<td></td>
</tr>
<tr>
<td>E-beam Current Profiles</td>
<td></td>
</tr>
</tbody>
</table>

Calculation of SASE FEL for measured profiles

\[\lambda_{rad} = 20 \mu m\]

<table>
<thead>
<tr>
<th>#</th>
<th>Photocathode laser pulse</th>
<th>Procedure</th>
<th>THz pulse energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td>ASTRA→GENESIS</td>
<td>0.6 mJ</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Measured electron beam → GENESIS</td>
<td>0.5 mJ</td>
</tr>
</tbody>
</table>