Results from PITZ

Developing the electron source for the European XFEL

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Outline

The European XFEL project
- History and motivation: from TESLA to XFEL
- XFEL: work principle and applications
- Motivation for injector R&D

Development and characterization of electron sources at PITZ
- History of PITZ
- Machine improvements over the last 10 years
- Measurement and optimization of beam parameters
- Achievements in electron beam quality

Problems and Perspectives
- Comparison of experimental results to simulation
- Possible explanations to solve discrepancies
- Summary
The TESLA project

- TESLA = TeV Electron Superconducting Linear Accelerator
- Combination of a new particle physics accelerator for high energy precision measurements with a next generation light source for applied research

**Applied Sciences:**
- biomolecular systems with atomic resolution
- individual macromolecules
- matter under extreme conditions
- ultra fast dynamics (movies)
- ...
  → now European XFEL

**Particle Physics:**
- solve fundamental questions like
  - origin of mass
  - Higgs particle
  - antimatter enigm
  - ...
  → now ILC
FEL radiation is similar to synchrotron radiation, but
> wavelength tunable down to 1 Å → atomic scale resolution
> ultra short pulses (fs scale) → molecular movies
> transverse spatial coherence → single nanoscale objects
> extremely high peak brilliance → matter under extreme conditions
FEL Peak Brilliance

- **ESRF (Grenoble, F) 1994**
- **SLS (Villigen, CH) 2000**
- **SPEAR (SLAC, USA) 1974**
- **BESSY (Berlin, D) 1982**
- **European XFEL 2016**

X-ray tube with rotating anode

Photonen/s/mm²/mrad²/0.1% Bb

10⁶ 10¹² 10¹⁸ 10²⁴ 10³⁰ 10³⁶

1900 1950 2000

1. Generation
2. Generation
3. Generation

Synchrotron

Courtesy R. Bakker
The SASE principle

\( \text{SASE} = \text{Self Amplified Spontaneous Emission} \)

> electrons emit spontaneous radiation in the undulator

> emitted photons interact with the electrons:
  \( \rightarrow \) energy modulation of the electrons
  \( \rightarrow \) density modulation (micro-bunching)

> electrons in a slice radiate \textit{coherently}

> exponential growth of radiation until saturation is reached (full micro-bunching)

\textbf{Typical frequency spectrum:} many lines due to start-up from noise

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

\[ \lambda_{\text{min}}[\text{nm}] \approx \frac{4\pi}{10} \frac{\varepsilon_n[\text{mm mrad}]}{\sqrt{I_p[\text{kA}] \cdot L_u[\text{m}]}} \]

\[ \text{Example: TTF1 at 70 nm NIM A429 (1999) 424-428} \]
Operating SASE FELs

- **TTF1** has demonstrated SASE in 2000 at 108.3 nm
- **FLASH** runs as user facility since 2005, reaching ~4 nm
- **LCLS** at SLAC provides wavelength down to 1.5 Å since 2009
- **SCSS** at SPRing8 started commissioning down from 55 nm to 1 Å in 2011
- many further (X-ray) FELs are planned world wide
Status of the XFEL project

- The 3.3 km long X-ray Free Electron Laser facility was approved by the BMBF in 2003
- The project is being realized in European collaboration
- Current status:
  - Tunnel construction completed, infrastructure installations started
  - Injector installation (with gun from PITZ) will start in summer 2013
  - Commissioning of the accelerator in 2014
  - First X-rays (SASE) expected end of 2015

View of the experimental hall

Tunnel, Oct. 2012
FEL performance

- performance of an FEL depends strongly on the electron beam quality delivered by the injector, since beam quality degrades in the accelerator.
- electron source must provide very small emittance electron beam.

\[ \lambda_{\text{min}}[\text{nm}] \approx \frac{4\pi}{10} \frac{\varepsilon_n[\text{mm mrad}]}{I_p[\text{kA}] \cdot L_u[\text{m}]} \]

Goal emittance for the XFEL:
0.9 mm mrad @ injector, corresponding to 1.4 mm mrad @ undulator entrance.
The PITZ project

Injector R&D became important to reach XFEL emittance requirements

→ construction of a Photo Injector Test facility in Zeuthen with the goals:

> develop an electron source for the XFEL:
  → very small transverse emittance (≤ 1 mm mrad @ 1 nC)
  → stable production of short bunches with small energy spread

> extensive R&D on photo injectors independent of serving special user requests

> detailed comparison of experimental results with simulations:
  → benchmark theoretical understanding of photo injectors

> prepare rf guns for subsequent operation at FLASH / XFEL

> test new developments (laser, cathodes, beam diagnostics)

> long term plans: e.g. flat beams, polarized electrons for ILC
Short PITZ history

- **1999**: decision to build PITZ
- **2000**: civil construction
- **2001**: infrastructure and first setup (PITZ1)
- **13.1.2002**: first photo electrons are produced
- **Nov. 2003**: first optimized gun is sent to FLASH
- **2005**: continuous upgrade of the facility starts
- **2007**: first demonstration of XFEL requirements
- **2009 - 2011**: best emittance measurements (world record)
PITZ collaboration

- **BESSY Berlin**: ICTs, magnets, PS, vacuum expert
- **CCLRC Daresbury**: phase space tomography module
- **DESY Hamburg**: new cavities (guns, booster)
- **INRNE Sofia**: emittance measurement system (EMSY)
- **INR Moscow**: TDS (deflecting cavity)
- **INR Troitsk**: CDS booster cavity
- **LAL Orsay**: high energy spectrometers
- **LASA Milano**: cathode system
- **MBI Berlin**: laser system
- **TU Darmstadt**: beam dynamics simulations
- **Uni Hamburg**: bunch length measurement
- **YERPHI Yerevan**: accelerator controls

**Funding through DESY (BMBF), HGF, EC (IA-SFS, EUROFEL)**
Continuous upgrade of subsystems

- **Laser system:**
  transverse and longitudinal distributions close to optimum case from simulations

- **Water cooling system:**
  improved cooling water temperature stability increases phase stability of the accelerating cavities

- **RF system:**
  improved RF regulation and phase stability due to the installation of an in-vacuum directional coupler at the gun, and setup of feedback algorithms

- **Gun cavities:**
  reduced dark current due to dry-ice cleaning (important for user operation);
  improved cooling channel design for higher average power

- **Booster cavities (TESLA type / CDS type):**
  increased beam energy allows for lower emittance

- **Diagnostics:**
  extension of the capabilities for detailed electron beam characterization
PITZ laser system: architecture

Yb:YAG laser with integrated optical sampling system made by MBI

Highly-stable Yb:YAG oscillator

Pulse selector

E\textsubscript{micro} = 2 nJ

Yb:YAG power regenerator

G \sim 10^6

Pulse selector

E\textsubscript{micro} \sim 2 \mu J

Two-stage Yb:YAG double-pass amplifier

G \sim 40

Nonlinear fiber amplifier

(Yb:KGW)

scanning amplifier

UV output pulses

E\textsubscript{micro} \sim 10 \mu J

\tau \sim 1.7 \text{ ps}

Resolution: \tau < 0.5...1 \text{ ps}
Laser profiles at the cathode plane

- **transverse profile:** ~ flat-top
  Examples:

  - BSA=1.2mm (1nC)
    \[ \sigma_x = 0.30 \text{ mm} \]
    \[ \sigma_y = 0.29 \text{ mm} \]
  - BSA=0.5mm (0.1nC)
    \[ \sigma_x = 0.13 \text{ mm} \]
    \[ \sigma_y = 0.12 \text{ mm} \]

- **longitudinal profile:** ~ 21 ps flat-top, 2-3 ps rise / fall times

(RMS sizes; no Gaussian fit!)
PITZ laser system: time structure

> using s.c. linac technology for FLASH / XFEL → long pulse trains needed

Pulse train structure:

Micro pulse structure:

Birefringent pulse shaper of 13 temperature controlled crystals
I.Will, G.Klemz, Optics Express 16 (2008) , 4922-14935
RF system and distribution

- 2 multi-beam klystrons, 2 arms, 5 MW each → 10 MW in total
- Delivery system via long waveguide line (~40 m) → losses: < 8 MW arrive at gun / booster
- T-combiner combines power from both arms in front of the gun (booster has two power feeds)
- RF regulation acts on signals before the T-combiner (2x forward power, 2x reflected power) → exact power in the gun is unknown
- Since 2010/11: 10 MW in-vacuum directional coupler used for RF regulation → improved regulation
- In addition: feedback algorithm improves phase stability significantly
RF phase stability

**2009** (no FB)
Reconstructed FPGA-Phase based on the signals of two 5 MW directional couplers

Phase change ~5 deg / 40 μs

Phase jitter:
10-15 deg (peak-peak)
2-4 deg (rms)

**2010/11** (FB on)
Measured FPGA-Phase from the 10 MW directional coupler

Phase stays flat over the full electron bunch train

Phase jitter:
1-1.5 deg (peak-peak)
0.2-0.3 deg (rms)
The PITZ gun cavities

1.3 GHz 1.5 cell photo cathode RF gun

- capable of high average power $\Rightarrow$ long electron bunch trains (s.c. linac)
- delivers very low normalized transverse emittance

View through the full cell onto iris and backplane (with cathode)
Gun development

Gun4 design: improved cooling for higher average power

Cut through the iris:

Courtesy J. Meißner
The PITZ diagnostics beamline (PITZ1.8 setup)

Status summer 2011
Electron beam characterization with PITZ2

Scheme of the PITZ2 setup:

- bunch charge: Faraday Cups, ICTs
- beam size: YAG screens
- momentum and momentum spread: spectrometer
- bunch length: aerogel / quartz + streak camera, later also RF deflector (TDS)
- emittance (thermal, projected, slice) with EMSYs, quads, tomographic section (PST)
- …
Emittance measurements at PITZ

Longitudinal emittance:
> bunch length measurements
> bunch energy spread measurements

Transverse Projected Emittance:
> slit scan method (main method at PITZ)
> quad(s) scan
> transverse phase space tomography

Transverse slice emittance:
> booster off-crest + spectrometer
> upcoming: RF deflector
Emittance concept

- $\varepsilon = 6D$ phase space volume occupied by a given number of particles
- Longitudinal emittance: $\varepsilon_z \sim (\text{bunch length}) \cdot (\text{bunch energy spread})$
- Transverse emittance: $\varepsilon_{x,y} \sim (\text{beam size}) \cdot (\text{beam angular divergence})$

- Effect of acceleration on emittance: adiabatic damping (reduction of angular divergence)

- Normalized emittance $\varepsilon^n$ is conserved in general:

$$\varepsilon^n_x = \beta \cdot \gamma \cdot \sqrt{\sigma_x^2 \cdot \sigma_{x'}^2} - \text{cov}^2(x, x')$$

$$\beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}}, \quad x' = \frac{dx}{ds}$$
Emittance measurement procedure: principle

> **Emittance Measurement System** consisting of horizontal / vertical actuators with YAG / OTR screens and slits (50 μm / 10 μm)
> single slit scan technique is applied
> measurement procedure is under permanent improvement
> as conservative as possible: 100% rms emittance

Procedure:

- beam size $\sqrt{\sigma_x^2}$ is measured @ slit position using screen
- beam local divergence $\sqrt{\sigma_x^2}$ is estimated from beamlet sizes @ observation screen (12 bit camera)

N.B.: measured emittance numbers are permanently reducing as a result of machine upgrades and extensive optimization:

"We are measuring more and more of less and less…"
Emittance measurement procedure: scaling

measured beam at EMSY screen

measured transverse phase space

$\sigma_x \leftarrow$ x-projection

$\epsilon_{\text{unscaled}}^n = \beta \gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$

$\sqrt{\langle x^2 \rangle}$

$\epsilon_{\text{scaled}}^n = \frac{\beta \gamma}{\sigma_x} \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$

scale factor (>1) corrects for underestimation of the beamlet size due to low intensity losses

Statistics over all pixels in all beamlets using full dynamic range of the 12-bit camera
### Emittance measurements: examples

<table>
<thead>
<tr>
<th>Qbunch</th>
<th>Beam at EMSY1</th>
<th>Horizontal phase space</th>
<th>Vertical phase space</th>
<th>$\phi_{\text{gun}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XY-Image</td>
<td>$\sigma_x / \sigma_y$</td>
<td>$\varepsilon_x$</td>
<td>$\varepsilon_y$</td>
</tr>
<tr>
<td>2 nC</td>
<td>0.323mm 0.347mm</td>
<td>1.209 mm mrad</td>
<td>1.296 mm mrad</td>
<td>+6deg</td>
</tr>
<tr>
<td>1 nC</td>
<td>0.399mm 0.328mm</td>
<td>0.766 mm mrad</td>
<td>0.653 mm mrad</td>
<td>+6deg</td>
</tr>
<tr>
<td>0.25 nC</td>
<td>0.201mm 0.129mm</td>
<td>0.350 mm mrad</td>
<td>0.291 mm mrad</td>
<td>0deg</td>
</tr>
<tr>
<td>0.1 nC</td>
<td>0.197mm 0.090mm</td>
<td>0.282 mm mrad</td>
<td>0.157 mm mrad</td>
<td>0deg</td>
</tr>
<tr>
<td>0.02 nC</td>
<td>0.066mm 0.083mm</td>
<td>0.111 mm mrad</td>
<td>0.129 mm mrad</td>
<td>0deg</td>
</tr>
</tbody>
</table>

**Qbunch** (Las.XYrms)

- 2 nC: 0.38 mm
- 1 nC: 0.30 mm
- 0.25 nC: 0.18 mm
- 0.1 nC: 0.12 mm
- 0.02 nC: 0.08 mm

**XY-Image** and **Horizontal phase space** are shown for each Qbunch level.

**Vertical phase space** for each Qbunch level is shown.

**$\phi_{\text{gun}}$**

- +6deg
- 0deg

**Courtesy M.Krasilnikov**
Reaching XFEL beam quality (TESLA booster, bad phase stability)

These results + experience from LCLS (only small degradation of slice emittance from gun towards undulator)

XFEL can be operated with 14 GeV beam energy (possibility to save ~33M€)
Improvements due to

- higher beam energy (CDS booster: 25 MeV)
- better laser profile
- significantly improved phase stability
- reducing magnetic fields

<table>
<thead>
<tr>
<th>Q (nC)</th>
<th>$\varepsilon$(2011) (mm mrad)</th>
<th>$\delta\varepsilon$ (2011→2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.70</td>
<td>-20%</td>
</tr>
<tr>
<td>0.25</td>
<td>0.33</td>
<td>-30%</td>
</tr>
<tr>
<td>0.1</td>
<td>0.21</td>
<td>-35%</td>
</tr>
</tbody>
</table>

→ higher emittance improvement for lower bunch charges due to long pulse train operation and using full dynamic range of 12-bit camera for beamlet detection

Courtesy F.Stephan

LCLS data:
J. Frisch, "Operation and Upgrades of the LCLS", LINAC2010, Tsukuba, Japan.
Emittance optimization

- for each bunch charge, the photo injector has been optimized in experiment and in simulations while keeping the temporal laser profile fixed (21.5ps FWHM, 2ps rise/fall time)

- simulated optimum machine parameters do not agree with the experimentally obtained ones (e.g. gun phase, laser spot size)

- differences are smaller for small charges (e.g. for 100 pC good agreement in all distributions for simulation and experiment)

- differences could explained by modeling problems of the photo emission process
Simulation of the photo emission process

- direct plug-in machine settings into ASTRA does not produce 1nC at the gun operation phase (+6deg), whereas 1nC and even higher charge (~1.2nC) are experimentally detected
- simulated (ASTRA) phase scans w/o Schottky effects (solid thick lines) have different shapes than the experimentally measured (thin lines with markers)

→ Photo emission (bunch charge) needs more detailed modeling in simulations.

- laser intensity (LT) scan for the MMMG phase (red curve with markers) shows higher saturation level, whereas the simulated charge even goes slightly down while the laser intensity (bunch charge) increases

Courtesy M.Krasilnikov

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Further discrepancies

- **Tails in the beam distribution:**
  - obviously X-Y asymmetry in the beam (~horizontal)
  - Mainly for space charge dominated beams (high bunch charge)
  - large emittance scaling factor (beamlets from tails are not detectable)

![Graphs showing beam distribution for 0.1 nC, 1 nC, and 2 nC charge](image)

- **Possible reason: magnetic fields along the beamline**
  - remaining magnetizable components, mainly in the low energy section
  - solenoid imperfections
  - stray fields from vacuum pumps (IGP)
  - …
Summary

- Development of high brightness electron sources at PITZ
  - specs for the European XFEL have been demonstrated and even surpassed (normalized emittance <0.9 mm mrad at 1nC)
  - PITZ serves also as a benchmark for theoretical understanding of the photo injector physics (beam dynamics simulations vs. measurements)

- Emittance measurements procedure
  - nominal method: single slit scan for detailed phase space reconstruction
  - as conservative as possible; scaling procedure → 100% rms emittance
  - continuous improvement of the procedure

- Emittance measurements at PITZ:
  - Beam emittance has been optimized for a wide range of bunch charges (20pC; 100pC; 250pC; 1nC; 2nC)
  - emittance ~ linearly on the bunch charge
  - rather good agreement between measured and simulated emittance values

- Open problems:
  - optimum machine parameters: simulations ≠ experiment
  - emission (charge production) from experiment is not straightforward reproduced by simulations
  - tails in X-Y distributions especially for highly space charge dominated beams
  - gun temperature stability is still to be improved (to reach the HH level of 0.006deg)
  - …