The Photo Injector Test Facility at DESY in Zeuthen
Anne Oppelt for the PITZ collaboration
19.12.2006
Overview

• Motivation: FLASH and XFEL → photo injector R&D for DESY’s FELs
• The photo injector at Zeuthen → a brief history of PITZ
• The PITZ1 research program → presentation of the PITZ1 results
• Facility upgrade: towards PITZ2 → current status and future plans
• Summary
**FELs at DESY**

- **TTF1** has reached SASE in 2000

- **FLASH** is running as user facility since August 2005
• performance of the planned **XFEL** (>2012) depends strongly on the electron beam quality of the **injector**
• beam quality can only **deteriorate** in the accelerator
• electron source must provide **very small emittance beam**
• photo injector development is **urgent**
The PITZ project

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 concrete FEL / user requests
- compare detailed 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
The PITZ project

Construction of the photo injector test facility (summer 2000)
The PITZ project

Commissioning of the photo injector (2001)
The PITZ project

First photoelectrons (January 2002)
The PITZ electron gun

- normal conducting 1.5 cell copper cavity
- frequency: 1.3 GHz ($\pi$-mode)
- coaxial RF input coupler
- 3 similar prototypes exist
The PITZ1 setup

Schematics:

- PITZ1 phase (2001–2004) included the full characterization of the installed gun cavity
- Full parameter optimization for emittance minimization has been done
- Very good emittances have been obtained ($\varepsilon \sim 1.6 \text{ mm mrad}$)
Emittance at PITZ1

- FLASH startup request clearly fulfilled in 2003
  → gun is transferred to Hamburg and installed in FLASH
- PITZ continues with a replacement gun
- meanwhile a spare gun for FLASH was prepared

24.8.2004

PITZ1 result = 1.6
World record = 1.2

2004

Startup (30 nm)
FLASH = 3.0

Request (6 nm)
FLASH = 2.0

Requirement for XFEL = 0.9
PITZ-gun → FLASH

Nov. 2003
PITZ1 research program

- Conditioning of the Gun cavity and dark current studies
- The laser system / measurement of laser parameters
- Characterization of the electron beam
  - charge
  - momentum and momentum spread
  - bunch length
  - beam size and transverse emittance
  - thermal emittance
PITZ1 results
- Gun conditioning -

1st Problem: max. acceleration gradient only reachable when full RF power in the cavity

→ condition Gun for all possible RF settings (power level, pulse length, repetition rate) and solenoid magnet currents

→ mainly improve cavity surface

→ field emission (multipacting, sparks) may cause damage of cavity, cathode, coupler, RF window

→ vacuum survey during the conditioning process (interlocks)
PITZ1 results
- Gun conditioning -

<table>
<thead>
<tr>
<th></th>
<th>10 Hz</th>
<th>5 Hz</th>
<th>10 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>repetition rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rf pulse length</td>
<td>0.5 ms</td>
<td>1.3 ms</td>
<td>1.0 ms</td>
</tr>
<tr>
<td>peak power at gun</td>
<td>4 MW</td>
<td>4 MW</td>
<td>3 MW</td>
</tr>
<tr>
<td>average power</td>
<td>20 kW</td>
<td>26 kW</td>
<td>30 kW</td>
</tr>
<tr>
<td>duty cycle</td>
<td>0.5 %</td>
<td>0.65 %</td>
<td>1.0 %</td>
</tr>
</tbody>
</table>

limited by 5 MW klystron and water cooling system

necessary upgrades:
- 10 MW klystron
- new cooling system

Requirements of FLASH fulfilled

Goal parameters for the XFEL (60 MV/m):
~ 7 MW, ≤ 0.65 ms, 10 Hz
PITZ1 results
- Gun conditioning -

1st Problem: max. acceleration gradient only reachable when full RF power in the cavity

→ condition Gun for all possible RF settings (power level, pulse length, repetition rate) and solenoid magnet currents
→ mainly improve cavity surface
→ field emission (multipacting, sparks) may cause damage of cavity, cathode, coupler, RF window
→ vacuum survey during the conditioning process (interlocks)

2nd Problem: dark current is emitted (mainly from cathode) during the full RF pulse duration

→ large amount at high power levels / long pulses
→ may destroy cathode and diagnostics (e.g. screens)
→ can be transported until the undulator and damage it
We experienced damages on screens and cathodes.

PITZ1 results
- Damages due to dark current ? -
PITZ1 results
- Dark current measurements -

Dark current measurements in dependence on
• accelerating gradient at the cathode
• cathode material (Mo / Cs₂Te)
• solenoid current
and its time development

19.12.2006, PSI Villigen
A. Oppelt: The PITZ project
PITZ1 results
- Dark current studies -

Possible dark current sources:
- \(\text{Cs}_2\text{Te} \) film
- edge of \(\text{Cs}_2\text{Te} \) film
- Mo plug
- edge of Mo plug

→ field emission model for the cathode

Discrepancy between simulation and measurement
→ additional emission mechanisms could contribute
PITZ1 results
- Dark current studies -

Screen1 (z = 0.87m)

Screen3 (z = 2.63m)

19.12.2006, PSI Villigen

A. Oppelt: The PITZ project
The PITZ laser system

using sc linac technology for FLASH / XFEL → long pulse trains

Pulse trains

Micro pulses

19.12.2006, PSI Villigen

A. Oppelt: The PITZ project
The PITZ laser system

19.12.2006, PSI Villigen

A. Oppelt: The PITZ project
Longitudinal laser pulse shape can be changed between **gaussian** and **flat-top**

- **gaussian**
  - e.g. before 23.6.03
  - FWHM = 7 ± 1 ps
- **flat-top**
  - e.g. after 23.6.03
  - FWHM ≈ 19-23 ps
  - rise / fall time 5-7 ps

**Minimum measured emittance:**

- ≥ 3 mm mrad
- 1.6 mm mrad
Laser parameters

Transverse laser profile
(pictures from the ‘virtual cathode’)

\[ \sigma_x = (0.57 \pm 0.02) \text{ mm} \]
\[ \sigma_y = (0.58 \pm 0.02) \text{ mm} \]
PITZ1 results
- Bunch charge -

- charge measurement with FC or ICT
- measured charge depends on
  - position of measurement device
  - phase of the RF field
  - solenoid current

Nominal charge: 1 nC

• charge measurement with FC or ICT
• measured charge depends on
  - position of measurement device
  - phase of the RF field
  - solenoid current

Nominal charge: 1 nC

Beam Charge / nC

charge / nC

RF phase / deg

l=300A, measured
- I=300A, simulated

charge / nC

RF phase / deg
Application:
**Determination of the reference phase**
(phase of maximum energy gain)
→ measure the electron beam size
as function of the launch phase

- measured with YAG screen
- study dependence on
  - screen position
  - RF phase
  - solenoid current

PITZ1 results
- Beam size measurements

[Graph showing measured and simulated beam sizes and energies vs. RF phase.]

19.12.2006, PSI Villigen
A. Oppelt: The PITZ project
PITZ1 results
- Momentum measurements -

Principle of momentum measurement

**The Lorentz-Force:** Motion of electrons with velocity \( \vec{v} \) and momentum \( p \) in magnetic field \( \vec{B} \)

\[
F_L = e(\vec{E} + \vec{v} \times \vec{B})
\]

**Magnetic Rigidity:**

\[
F_L = evB = \frac{mv^2}{\rho}
\]

\( \rho \) : Radius of curvature of the path

\[
B\rho = \frac{mv}{e} = \frac{p}{e}
\]
PITZ1 results
- Momentum and momentum spread -

Measurement as function of the RF phase:

max. mean momentum: 5.20 MeV/c
min. rms momentum spread: 16 keV/c
phase difference between $p_{\text{mean}}^{\text{max}}$ and $p_{\text{RMS}}^{\text{min}}$ only ~5 degrees

Q = 1 nC
PITZ1 results
- Bunch length measurements -

**Principle:**
- electron bunch hits radiator (aerogel / quartz) and radiates photons
- analysis of time development with streak camera

**Minimum length (FWHM):**
(21.04 ± 0.45stat ± 4.14syst) ps
(6.31 ± 0.14stat ± 1.24syst) mm
PITZ1 results
- Emittance measurements -

transverse normalized emittance
\[ \varepsilon_n^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle x \cdot x' \rangle^2 \]

\~ beam size \cdot angular divergence

phase space reconstruction = approximation of real phase space
Problems with multi-slit measurements:

- overlapping beamlets (large divergence)
- only few beamlets (small beam size)

→ not used at PITZ
Single-slit scan technique

The size of the beamlet is measured for three slit positions:

\[ y_n = \langle Y \rangle + n \cdot 0.7 \sigma_y \]

\( n \in \{-1, 0, 1\} \)
**Simulated emittance for optimum parameters**

- **Charge**: 1 nC
- **Max. gradient**: 42 MV/m
- **Longitudinal laser profile**:
  - flat top
  - 20 ps FWHM
  - 5 ps rise/fall time
- **Transverse laser profile**:
  - homogeneous
  - $\sigma_{x,y} = 0.6$ mm

---

19.12.2006, PSI Villigen
A. Oppelt: The PITZ project
PITZ1 results
- Measured emittance -

e.g. measured transverse emittance as function of the current in the compensating magnet

![Graph showing measured transverse emittance as function of the current in the compensating magnet.]

- Measured emittance -

<table>
<thead>
<tr>
<th>$\varepsilon_x$</th>
<th>$\varepsilon_y$</th>
<th>$\sqrt{\varepsilon_x \varepsilon_y}$</th>
<th>ASTRA sim.</th>
<th>$\varepsilon_{xy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>1.2</td>
<td>1.5</td>
<td>1.8</td>
<td>2.1</td>
</tr>
</tbody>
</table>

$Q = 1 \text{ nC}$
$\Phi = \Phi_0 - 5^\circ$
$Imain = 305A$
PITZ1 results - Thermal emittance -

\[ \varepsilon_{th} = \sigma \sqrt{\frac{2E_k}{3m_0c^2}} \]

- average kinetic energy of the emitted photo electrons
- laser spot size

- thermal emittance adds in quadrature to the other emittance contributions:

\[ \varepsilon_n \approx (\varepsilon_{th}^2 + \varepsilon_{rf}^2 + \varepsilon_{sc}^2)^{1/2} \]

→ thermal emittance sets the lower emittance limit of an electron source

- define operation conditions such that \( \varepsilon_{rf} \ll \varepsilon_{th} \) and \( \varepsilon_{sc} \ll \varepsilon_{th} \):
  - Q~2-3 pC, \( \sigma_t = 3 \) ps, \( E_0 < 34 \) MV/m, laser spot size: 0.48 - 0.55 mm
PITZ1 results
- Thermal emittance -

Kinetic energy of the emitted electrons:

Cathode #60:
(QE ~ 1%)
\[ E_k = (1.1 \pm 0.2) \text{ eV} \]

Cathode #61:
(QE ~ 1.5%)
\[ E_k = (0.9 \pm 0.2) \text{ eV} \]

- thermal emittance is individual for each photocathode
- depends on gun operation history and cathode surface chemistry: \( \varepsilon_{\text{th}} = \varepsilon_{\text{th}} (t) \)
- more cathode studies are needed (INFN-LASA)
PITZ1 results
- Thermal emittance -

Impact of the electric rf field

Assuming emittance growth due to Schottky effect:

\[ \varepsilon_{th} = \sqrt{A + B \sqrt{E_{\text{field}}}} \]

Cathode #43:
(Nov.2004, QE ~ 3%)
\[ \varepsilon_{43} = \sqrt{0.08 + 0.11 \sqrt{E}} \]

Cathode #61:
(Apr.2004, QE ~ 1%)
\[ \varepsilon_{61} = \sqrt{0.01 + 0.05 \sqrt{E}} \]

Extrapolation for the XFEL case:
(emittance budget: 0.9 mm mrad)
\[ \varepsilon = \frac{\sigma_x}{\sigma_y} \sqrt{A + B \sqrt{E_{\text{field}}}} \approx 0.7 \text{ mm mrad} \]
The PITZ1 setup

Tunnel view at the end of the PITZ1 phase (November 2004)
• small emittance beams have been produced at PITZ1
• but: emittance growth due to space charge
• install booster cavity to further accelerate the beam
• apply emittance conservation principle to conserve small emittance
PITZ2 – a large extension of the facility and its research program

- **study the emittance conservation principle:**
  install booster and new diagnostics beamline

- **benchmark theoretical understanding of photoinjectors:**
  improved simulation tools, detailed comparison simulation vs. measurement

- **reach XFEL requirements (0.9 mm mrad @ 1 nC):**
  increase RF field at the cathode, improve laser system and photocathodes

- **study XFEL parameter space:**
  low charge, short bunches, higher repetition rates

- **test new developments:**
  RF system, gun cavities, diagnostics, cathodes, laser
Collaboration partners

- **BESSY Berlin**: ICTs, magnets, PS, vacuum expert
- **CCLRC Daresbury**: phase space tomography module
- **DESY Hamburg**: new cavities (Gun3, Gun4, CDS booster)
- **INRNE Sofia**: emittance measurement system (EMSY)
- **INR Troitsk**: CDS booster cavity
- **LAL Orsay**: high energy spectrometers
- **LASA Milano**: cathode system
- **LNF Frascati**: RF deflecting cavity
- **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)**
The PITZ2 project
- The emittance conservation principle-

Solenoid strength, drift length, and accelerating gradient are defined with the „invariant envelope“ technique:

→ place entrance of booster at local emittance maximum and beam size minimum
→ define accelerating gradient by:

\[ \gamma_{\text{boost}} = \frac{2}{\sigma_w \sqrt{3 I_0 \gamma}} \]

- \( \gamma_{\text{boost}} \) = energy gain booster
- \( \sigma_w \) = rms beam size
- \( \hat{I} \) = peak current
- \( \gamma \) = mean beam energy
- \( I_0 \) = Alfvén current

(17 kA for electrons)
The PITZ2 project
- Simulation of emittance conservation -

Simulation parameters:
40MV/m
20ps FWHM
2ps rise/fall time

→ check that the principle works and optimize it!

19.12.2006, PSI Villigen
A. Oppelt: The PITZ project
Towards PITZ2
- The booster cavities -

- use a n.c. TESLA prototype cavity as preliminary booster
- the final booster cavity specially designed for PITZ is in production and will be available in 2008

19.12.2006, PSI Villigen
A. Oppelt: The PITZ project
The PITZ2 project
- The facility upgrade -

For the realization of PITZ2
• upgrade power and cooling systems
• take into operation a 2\textsuperscript{nd} RF system for the booster
• install booster, beam dump, new diagnostics

→ start with a minimum version of PITZ2

19.12.2006, PSI Villigen A. Oppelt: The PITZ project 45
Towards PITZ2
- The PITZ1.5 setup -

after the gun: 4.6 MeV

after the booster: 13.4 MeV

19.12.2006, PSI Villigen
A. Oppelt: The PITZ project
Towards PITZ2
- The PITZ1.5 setup -

View of the extended PITZ facility (Summer 2005)
Towards PITZ2
- First results from PITZ1.5 -

- commissioning of new diagnostics
- studies of energy gain in gun and booster
- comparison of emittance measurements with EMSY (PITZ) and e-meter (LNF)

![Graph showing emittance measurements with and without booster.]

- Vertical emittance without booster
- Vertical emittance with booster on

Q = 1 nC
p = 12.8 MeV/c

Courtesy of D. Filippetto (INFN-LNF)
Towards PITZ2
- The 10 MW MBK klystron -

- 10 MW klystron necessary to reach gradients above 42 MV/m in the gun
- use multi beam klystron from Thales
- RF output via two 5 MW arms → power combiner needed
Towards PITZ2
- High power tests of a gun cavity-

- Gun1 with 10 MW klystron tested up to ~57 MV/m in 2005
- Goal for XFEL: reach 60 MV/m → tests in 2007 with different guns

**Problem:**
thermal load of the gun → new gun with improved cooling

![Graph showing the relationship between gun peak power and maximum mean momentum. The graph includes the target of 60 MV/m.](image)
Towards PITZ2
- High power tests of a gun cavity-

Calculations of thermal load:

• 27 kW of average RF power: ⇒ 80°C
  (40MV/m, 900µs, 10 Hz) ✓ done
  (PITZ1)

• 130 kW of average RF power: ⇒ 170°C !!!
  (60MV/m, 650µs, 30 Hz)

  • vacuum
  • dark current
  • new cathodes !!!
  • new gun geometry ?

Courtesy of Frank Marhauser (BESSY)
Gun history at PITZ

**Gun2**: prepared at PITZ in 2001-2003
→ used at FLASH since 2004

**Gun1**: used at PITZ in 2004/2005
→ high power tests up to 7 MW (57 MV/m)

**Gun3.1**: prepared in 2006 as spare gun for FLASH
→ conditioning up to the full FLASH specifications:
  - 10 Hz repetition rate
  - 900 us pulse length
  - 3.5 MW peak power
  - 31.5 kW average power (maximum ever reached)

**Gun3.2**: installation at PITZ in preparation
→ run with gradients up to 60 MV/m

**Gun4.1 / Gun4.2**: with improved cooling
→ under production at DESY
• sophisticated e\(^-\) sources are needed for the operation of FELs
  → RF photo cathode guns
• **PITZ** is a dedicated test facility at DESY in Zeuthen
• **PITZ1** has been successfully finished, and a completely characterized gun has been installed at FLASH
• the facility upgrade is ongoing, a preliminary booster and first **PITZ2** diagnostics have been taken into operation
• next steps are: study *emittance conservation principle* and approach the XFEL emittance requirements
• in parallel: do gun power tests and prepare new guns