Photo Injector Test facility at DESY, Zeuthen site.

PITZ: facility overview

Mikhail Krasilnikov (DESY) for the PITZ Team
Mini-workshop on THz option at PITZ, Zeuthen, 22.09.2015
Photo Injector Test facility at DESY, Zeuthen site

The Photo Injector Test facility at DESY in Zeuthen (PITZ) focuses on the development, test and optimization of high brightness electron sources for superconducting 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 $\rightarrow$ small $\varepsilon_{it}$ (projected and slice)

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

+ Detailed comparison with simulations = benchmarking for the PI physics

Highest priority at PITZ currently:

Participate in the solution of the remaining problems of the RF gun for XFEL (RF windows, cathode RF contact spring, stability and long term reliability)
## High Brightness Photo Injector for XFEL

<table>
<thead>
<tr>
<th>parameter</th>
<th>XFEL injector, nominal</th>
<th>XFEL, commissioning</th>
<th>PITZ, 2015</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF gun gradient (peak power)</td>
<td>$E_{\text{cath}}=60\text{MV/m}$ (6.5MW)</td>
<td>$E_{\text{cath}}=50...53\text{MV/m}$ (4.5...5.0MW)</td>
<td>$E_{\text{cath}}=53\text{MV/m}$ (5MW)</td>
<td></td>
</tr>
<tr>
<td>RF pulse length</td>
<td>650us</td>
<td>650us</td>
<td>650us</td>
<td>Priority w.r.t. the peak power</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10Hz</td>
<td>10Hz</td>
<td>10Hz</td>
<td></td>
</tr>
<tr>
<td>RF gun phase stability (rms)</td>
<td>0.01deg</td>
<td></td>
<td>0.07deg</td>
<td></td>
</tr>
<tr>
<td>RF gun amplitude stability (rms)</td>
<td>0.01%</td>
<td></td>
<td>0.02%</td>
<td></td>
</tr>
<tr>
<td>Cathode laser (FWHM)</td>
<td>Flattop (2/20\2ps)</td>
<td>Gaussian (~13ps FWHM)</td>
<td>Gaussian (~11-12ps FWHM)</td>
<td>Pulse shaper issue</td>
</tr>
<tr>
<td>Bunch charge Beam emittance</td>
<td>0.02 – 1 nC 0.4 – 1 mm mrad</td>
<td>0.1 – 1 nC e.g. ≤ 1 mm mrad @500pC</td>
<td>0.1 – 1 nC 0.8 mm mrad</td>
<td>$E_{\text{cath}}=53\text{MV/m}$, Gaussian laser pulse</td>
</tr>
</tbody>
</table>

**Required electron beam quality demonstrated at PITZ in 2011 with ≤200us RF pulse length**
PITZ layout

- **GUN** → 7 MeV/c
- **CDS** → 22 MeV/c

- **Solenoids**
  - bucking
  - main

- **60°dipole**

- **TDS**

- **Acceleration:**
  - RF-gun
  - Booster

- **Magnets:**
  - Main and bucking solenoids
  - Dipoles
  - Steerers
  - Quadrupoles

- **Other components:**
  - Diagnostics
  - Plasma cell → PDWA
  - Auxiliary (e.g. BLM)
Current PITZ RF-Gun Setup

Now: **2 Thales RF window solution** is under test at PITZ:
- Peak RF power in gun ~6.5MW
- RF pulse length ~650 us
- Repetition rate 10Hz
- Goal: <1 gun IL(trip) / week

RF vacuum windows position:
- adapted to available RF components
- compatible with XFEL setup

- PMT - Photomultiplier tube
- e-det – Electron detector
- IGP – Ion getter pump (pressure reading)
- PG - Pressure gauge
RF gun

- L-band 1.6-cell copper cavity
- Cs$_2$Te photocathode (QE~5-10%)
- Dry ice cleaning → low dark current (<100uA@6MW)
- LLRF control for amplitude and phase stability
- Solenoid for emittance compensation

RFgun: L-band (1.3 GHz) nc (copper) standing wave 1½-cell cavity

Main solenoid, Bz_peak~0.2T

Cathode laser 262nm 20ps (FWHM)

Vacuum mirror

Electron bunch <1 pC – 5 nC, ~5-7MeV

Photo cathode (Cs$_2$Te) QE~0.5-5%
PITZ Photocathode laser (Max-Born-Institute, Berlin)

- **Yb:YAG oscillator**
- **Pulse selector**
  - $E_{\text{micro}} = 0.002 \, \mu\text{J}$
- **Pulse shaper**
- **Nonlinear fiber amplifier**
  - Optical Sampling System (OSS)
  - Resolution: $\tau < 0.5...1 \, \text{ps}$
  - Cross correlator (UV)
- **Yb:YAG regenerative amplifier**
  - $G \sim 10^6$
- **Pulse selector**
- **Two-stage Yb:YAG double-pass amplifier**
  - $G \sim 40$
- **Nonlinear amplifier (Yb:KGW)**
  - $E_{\text{micro}} \sim 2 \, \mu\text{J}$
- **LBO**
- **BBO**
  - $E_{\text{micro}} \sim 80 \, \mu\text{J}$
  - UV output pulses
  - $E_{\text{micro}} \sim 10 \, \mu\text{J}$

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Multicrystal birefringent pulse shaper containing 13 crystals

Gaussian:

Simulated pulse-stackker

Will, Klemz, Optics Express 16 (2008) 4922-14935
Variation of the pulse shape by using a single different Lyot filter (UV, measured with OSS)

- Edges of the flat-top pulses are slightly shorter than FWHM of the Gaussian pulse (measured without shaper)
- "Smoothening" of the Modulations in the flat-top region of the pulse

I. Will, G. Klemz „Increasing the flexibility in pulse shape of a Yb:YAG photocathode laser“ 20.06.2009
Photo cathode laser: transverse pulse shaping

Beam Shaping Aperture (BSA) plate is now replaced by an iris with remotely tunable opening.

Laser spot at “virtual cathode”

Laser beam steering

Imaging of the BSA onto the photo cathode
Photo cathode laser: transverse distributions

BSA=2.0mm (2nC)

BSA=1.2mm (1nC)

BSA=0.5mm (0.1nC)

BSA=0.1mm (0.02nC)
Trains with up to 600 (2700) laser pulses ➔ electron bunches of 1nC each

\[ \Delta t = 1 \mu s \quad (222\text{ns}) \]

Cathode laser pulse: temporal profile

FWHM = 25 ps

edge\(_{10\%}\) ~ 2.2 ps

edge\(_{90\%}\) ~ 2 ps

birefringent shaper: 13 crystals

27000 electron bunches per second
CDS booster (L-band, 14-cell copper Cut-Disc-Structure)

- **CDS = Cut-Disc-Structure**
- Improved water cooling system
- Higher peak gradients (final beam momentum ~25MeV/c)
- Long RF pulses (up to 700us)
- Longer acceleration (L~1.4m)
- Precise phase and amplitude control (RF probes)
- BUT: due to the dark current issue the peak power is currently restricted by 3MW (max)
## Beam diagnostics at PITZ

### GUN <7 MeV
- **Beam diagnostics**: Cathode laser, Solenoids, 60° dipole

### CDS <25 MeV
- **Beam diagnostics**: Beam position, Longitudinal momentum, Transverse distribution, Transverse phase space, Bunch current profile

<table>
<thead>
<tr>
<th>Component</th>
<th>Property</th>
<th>Diagnostics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cathode laser</strong></td>
<td>temporal profile</td>
<td>OSS, streak-camera</td>
</tr>
<tr>
<td></td>
<td>transverse distribution</td>
<td>Virtual cathodes, CCD cameras</td>
</tr>
<tr>
<td></td>
<td>pulse energy</td>
<td>Energy-meter, PMT</td>
</tr>
<tr>
<td></td>
<td>position stability</td>
<td>Quadrant-diode</td>
</tr>
<tr>
<td><strong>Electron beam</strong></td>
<td>bunch charge</td>
<td>Faraday cups (~1pC&lt;FC&lt;200pC), Integrating current transformers (100pC&lt;ICT&lt;5nC)</td>
</tr>
<tr>
<td></td>
<td>beam position</td>
<td>BPMs (Q&gt;200pC)</td>
</tr>
<tr>
<td></td>
<td><strong>longitudinal momentum</strong></td>
<td>Dipoles+ dispersive arms (LEDA, HEDA1,2)</td>
</tr>
<tr>
<td></td>
<td>transverse distribution</td>
<td>YAG and OTR screens with CCD cameras (LOW.Scr1,2,3; High1.Scr1-5; PST.Scr1-5; High2.Scr1,2)</td>
</tr>
<tr>
<td></td>
<td><strong>transverse phase space (emittance)</strong></td>
<td>Slit masks (EMSY1,2,3), quadrupoles, tomography module</td>
</tr>
<tr>
<td></td>
<td>Bunch current profile</td>
<td>Radiators (straight section) + streak read-out*, Transverse Deflecting System (TDS)</td>
</tr>
<tr>
<td></td>
<td><strong>longitudinal phase space</strong></td>
<td>Radiators (dispersive arms) + streak read-out*, TDS+HEDA2 (slice energy spread), LPS tomography using CDS phase scan</td>
</tr>
<tr>
<td></td>
<td>slice emittance</td>
<td>HEDA with booster off-crest, TDS+quad scan at PST-screens</td>
</tr>
</tbody>
</table>
Bunch charge measurements

Schottky scan → Q (rf gun phase)

Laser pulse energy scan → Q (LT)

Cathode #679.1 QE-map history
Slit Scan Technique for Emittance Measurements at PITZ

**Emittance Measurement SYstem**

**EMSY**: screens and slits $10$ (50) $\mu$m opening

**Beamlet collector screen**

**measured transverse phase space**

**E-beam at EMSY screen**

As conservative as possible!

**Correction factor** introduced to correct for low intensity losses from beamlet measurements

"we are measuring more and more of less and less…"

**"100%" rms emittance**
2011: Emittance versus Laser Spot Size for various charges

Measured (100%) rms normalized emittance vs. simulations

<table>
<thead>
<tr>
<th>Charge, nC</th>
<th>Measured, mm mrad</th>
<th>Simulated, mm mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.25±0.06</td>
<td>1.14</td>
</tr>
<tr>
<td>1</td>
<td>0.70±0.02</td>
<td>0.61</td>
</tr>
<tr>
<td>0.25</td>
<td>0.33±0.01</td>
<td>0.26</td>
</tr>
<tr>
<td>0.1</td>
<td>0.21±0.01</td>
<td>0.17</td>
</tr>
<tr>
<td>0.02</td>
<td>0.121±0.001</td>
<td>0.06</td>
</tr>
</tbody>
</table>

• Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
• Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
• Simulations of the emission needs to be improved
2011: Emittance and Brightness versus Bunch Charge

Cathode laser pulse duration was **fixed at 21.5 ps (FWHM)** for all bunch charges!

- **20pC measured**
  - [Graph showing X-Y projection]
  - [Graph showing X-Px projection]
  - [Graph showing Y-Py projection]

- **2nC measured**
  - [Graph showing X-Y projection]
  - [Graph showing X-Px projection]
  - [Graph showing Y-Py projection]

\[
B_{\text{injector}} = \frac{I_{\text{injector}}}{\varepsilon_x \varepsilon_y} = \frac{Q \cdot NoP \cdot RR}{\varepsilon_x \varepsilon_y}
\]

- **Bunch charge reduction at fixed cathode laser pulse duration → space charge (SC) modification**
  - ~linear SC
  - nonlinear SC
Emittance measurements in 2015:
Gun at 53 MV/m, Cathode laser $\rightarrow$ temporal Gaussian

100% RMS Measured Emittance, 500pC

**100% RMS emittance data**

- **2015:** $E_{\text{cath}} = 53\,\text{MV/m}$
  - Measurements
  - Simulations (C+H)

- **2011:** $E_{\text{cath}} = 60.6\,\text{MV/m}$
  - Measurements
  - Simulations (U)

**Cathode laser temporal profile**

- Flattop 2011 (meas.)
- Gaussian 2015 (estimated)

**xy-emittance, mm mrad**

- RMS laser spot size, mm

**Requirement for XFEL injector commissioning:** 1 mm mrad at 500pC $\rightarrow$ **fulfilled**!

**Laser transverse distribution**

**E-beam X-Y at EMSY1**

- $\varepsilon_{x,n} = 0.840 \, \text{mm mrad}$
- $\varepsilon_{y,n} = 0.798 \, \text{mm mrad}$

**X-Px**

**Y-Py**
Phase Space Tomography (e.g. at PITZ)

The most used technique is quadrupole(s) scan, but it yields only Twiss parameters and emittance, not the phase space. Therefore, phase space tomography includes:
- Back projection
- Filtered Back projection
- Algebraic reconstruction technique (ART)
- Maximum entropy (MENT)

Courtesy G. Asova (PITZ)
Transverse Deflecting System (TDS)

> Prototype for the XFEL injector
> Designed & manufactured by INR, Troitsk, Russia
> Travelling wave structure (based on LOLA)
> Design parameters:
  - 1.7 MV over 0.533 m
  - 14+2 cells (2π/3)
  - 2997.2 MHz
  - $Q = 11780$

> Expected power balance:
  - $Q \sim 88\%$ at 45°C, 44 m WG losses…
  - 2.1 MW @structure
  - 2.7 MW @klystron

> TDS commissioning started on 02.07.2015!
  - Structure conditioned up to ~600 kW (~25% of design value).
  - First measurements taken:
    - Calibration of couplers vs. e-beam deflection
    - Temperature dependencies
    - Bunch length vs. charge and booster phase
    - TDS+HEDA2= single-shot images of longitudinal phase space

Electron beam mean momentum (MeV/c)
Electron beam rms momentum spread (MeV/c)
Booster SP phase (deg)
**Longitudinal Phase Space Tomography with CDS**

**Measured at: HEDA1 F50 (whole screen)**

\[ \langle p \rangle_{\text{max}} = (21.480 \pm 0.005) \text{MeV/c at 49°} \]

\[ p_{\text{RMS}} = (38 \pm 9) \text{keV/c at 52°} \]

- Mean Momentum [MeV/c]
- RMS Momentum [MeV/c]

**Longitudinal phase space, 90% of total charge**

- \( p_z \) [keV/c], \( n = 292 \)
- \( z, [\text{mm}], n = 101 \)
- Current distribution

- Slice momentum spread, 50 slices
- \( \sigma_p [\text{keV/c}] \)

- Current, [A]
- Intensity, a.u.

- Booster: RF phase [deg]
- SP Phase Booster [deg]

\[ dpz = 4.257 \text{ [keV/c]} \]

\[ dz = 0.100 \text{ [mm]} \]

RMS bunch length = 1.91 [mm]

RMS momentum spread = 70.39 [keV/c]

Longitudinal Emittance = 90.01 [mm*keV/c]
New Developments at PITZ

- 3D ellipsoidal cathode laser pulses
- Particle driven wake field plasma acceleration experiment
- THz simulations
Various shapes of the photocathode laser pulse (Gaussian and Flattop temporal profiles vs. 3D-ellipsoid)

\[ z=15m \]
\[ E_{\text{beam}} \approx 150\text{MeV} \]
\[ \sigma_t \approx 7\text{ps} \]

**Beam Dynamics Simulations: XFEL Photo Injector (1nC)**

**PITZ gun**

**ACC1 = 8 x TESLA cavities**

**Projected emittance w.r.t. flat-top case (0.63 mm mrad)**

- Flat-top
- Gauss-2
- Ellipsoid-2

**Bunch current profiles and slice emittance at \( z=15m \)**

- Emittance (Gaussian)
- Emittance (Flattop)
- Emittance (3D-ellipsoid)
- Beam current (Gaussian)
- Beam current (Flattop)
- Beam current (3D-ellipsoid)

- **3D ellipsoidal cathode laser pulses** ➔ Major improvements on beam emittance
- Developments of the new laser system are on-going ➔ DESY (PITZ)+IAP+JINR collaboration
New photocathode laser system for 3D ellipsoidal pulses

> Installation finalized 12/2014

> Commissioning begun 2015

> First photoelectrons 04/2015

> Beamline finalized 04/15

Electron bunch with \((Q \sim 20 \text{ pC})\) measured with a Faraday cup (LOW.FC1).

Laser pulse on VC2 camera.

E-beam from 3D ella on LowScr1.

Cross-correlation measurement of pulse.

Installation finalized 12/2014

Commissioning begun 2015

First photoelectrons 04/2015

Beamline finalized 04/15

Electron bunch with \((Q \sim 20 \text{ pC})\) measured with a Faraday cup (LOW.FC1).

Laser pulse on VC2 camera.

E-beam from 3D ella on LowScr1.

Cross-correlation measurement of pulse.
Self-modulation Experiment with long Electron Beams

PITZ plasma cell:
- designed and fabricated
- commissioning mainly done (next step: Lithium vaporization, ionization)
- leaky plasma cell is being repaired

PITZ beamline was remodeled
Ionization laser is set up
Several preparatory experiments performed:
- <100μm focusing into plasma cell
- 8μm Kapton foil → for first experiments, 3μm → goal for the window thickness (from BD simulations and first experiments)

Simulation of experiment: Expected phase space
The Photo Injector Test facility at DESY in Zeuthen (PITZ) develops high brightness electron sources for SASE FELs:

- specs for the European XFEL have been demonstrated and surpassed (emittance <0.9 mm mrad at 1nC)
- beam emittance has also been optimized for a wide range of bunch charge (20pC…2nC)
- Now main focus → stability and reliability (high duty factor performance)

PITZ serves also as a benchmark for theoretical understanding of the photo injector physics (beam dynamics simulations vs. measurements)

- Emittance
- Photoemission
- Imperfections!

Outlook → new developments:

- slice diagnostics (RF deflector) → transverse emittance and longitudinal phase space (ongoing)
- 3D ellipsoidal cathode laser pulses → BMBF and HGF projects (collaboration DESY-IAP-JINR)
- PDPWA experiments
- THz option → simulations + brainstorming (this mini-WS = kick off meeting)
PITZ tunnel(s)

22,1 m
1,9 m
13,7 m
4,7 m
6,5 m
27,4 m
22,09.2015
## XFEL Photo Injector Performance Requirements → PITZ

<table>
<thead>
<tr>
<th>subsystem</th>
<th>parameter</th>
<th>value</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF gun cavity</td>
<td>frequency</td>
<td>1.3 GHz</td>
<td>L-band 10MW MBK</td>
</tr>
<tr>
<td></td>
<td>E-field at cathode</td>
<td>60 MV/m</td>
<td>dark current issue</td>
</tr>
<tr>
<td></td>
<td>RF pulse duration</td>
<td>650 us</td>
<td>max</td>
</tr>
<tr>
<td></td>
<td>Repetition rate</td>
<td>10 Hz</td>
<td>max</td>
</tr>
<tr>
<td>Cathode laser</td>
<td>Temporal → flat top → FWHM</td>
<td>~20 ps</td>
<td>challenge ~20ps</td>
</tr>
<tr>
<td></td>
<td>Temporal → flat top → rise/fall time</td>
<td>2 ps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transverse – rad.homogen.XYrms</td>
<td>0.3-0.4 mm</td>
<td>fine tuning -&gt; thermal emittance</td>
</tr>
<tr>
<td></td>
<td>Pulse train length</td>
<td>600 us</td>
<td>max</td>
</tr>
<tr>
<td></td>
<td>Bunch spacing</td>
<td>222 ns (4.5MHz)</td>
<td>1us (1MHz) at PITZ now</td>
</tr>
<tr>
<td></td>
<td>Repetition rate</td>
<td>10 Hz</td>
<td>max</td>
</tr>
<tr>
<td>Electron beam</td>
<td>Bunch charge</td>
<td>1 nC</td>
<td>0.02-1nC (Post-TDR)</td>
</tr>
<tr>
<td></td>
<td>Projected emittance at injector</td>
<td>0.9 mm mrad</td>
<td>⇒ for 1 nC</td>
</tr>
<tr>
<td></td>
<td>Bunch peak current</td>
<td>5 kA</td>
<td>after bunch compression (not at PITZ)</td>
</tr>
<tr>
<td></td>
<td>Emittance (slice) at undulator</td>
<td>1.4 mm mrad</td>
<td>0.4-1.0 mm mrad (Post-TDR)</td>
</tr>
</tbody>
</table>