Emittance Optimization at PITZ for FLASH and for the European XFEL

Mikhail Krasilnikov (DESY) for the PITZ Team

ICFA Workshop on Future Light Sources, March 5-9, 2012
Thomas Jefferson National Accelerator Facility, Newport News, VA

Content:

• Photo Injector Test facility at DESY in Zeuthen (PITZ)
  • motivation, specs and PITZ-1.8 setup
  • main components (gun, booster, cathode laser)
• Emittance experimental optimization at PITZ
  • 13.01.2012 → 10 years of photo electrons at PITZ
  • measurement procedure
  • emittance 2009-2011 improvements
  • emittance for bunch charge from 20pC to 2nC
• Summary and outlook
Photo Injector Test facility at DESY in Zeuthen

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
⇒ small transverse emittance (<1 mm mrad @ 1 nC)
⇒ stable production of short bunches with small energy spread
⇒ further studies: dark current, QE, thermal emittance, …

+ detailed comparison with simulations = benchmarking for the PI physics
extensive R&D on photo injectors in parallel to FLASH operation
test and optimize rf guns for subsequent operation at the FLASH and XFEL
test new developments (laser, cathodes, beam diagnostics)
PITZ-1.8 setup

Symbols:
- BPM
- SW
- Collimator
- Kicker
- OTR / YAG-screen
- ICT
- Cherenkov radiator
- Steering dipole
- Sweeper
- Rest gas detector
- Quadrupole
- FC / Beam dump
- Stray readout
- Wire scanner
**XFEL Photo Injector Key Parameters to be tested at 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></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>700 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 -&gt; flat top -&gt; FWHM</td>
<td>20 ps</td>
<td>challenge</td>
</tr>
<tr>
<td></td>
<td>Temporal -&gt; flat top -&gt; rise/fal 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>other charges under consideration</td>
</tr>
<tr>
<td></td>
<td>Projected emittance at injector</td>
<td>0.9 mm mrad</td>
<td></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></td>
</tr>
</tbody>
</table>

**Main efforts at PITZ towards XFEL photoinjector**
RFgun: L-band (1.3 GHz) nc (copper)
standing wave 1½-cell cavity

Main solenoid, Bz_peak~0.2T

Cathode laser 257nm ~20ps (FWHM)

Vacuum mirror

electron bunch
1nC, ~5-7MeV

Coaxial RF coupler

Photo cathode
(Cs₂Te)
QE~0.5-5%

UHV

Bucking solenoid
RF Gun Feed System

10-MW MB KLYSTRON

- Vacuum windows
- Phase shifter
- T-combiner
- 5MW couplers
- 10MW in-vacuum directional coupler
- SF₆ - Gas
- UHV

Mikhail Krasilnikov | Emittance Optimization at PITZ for FLASH and for the European XFEL | FLS 2012, 6.03.2012 | Page 6
Improvement of the RF gun phase stability

2009 (no FB)

- FPGA phase, reconstructed from virtual ADC probes based on 2x5MW directional couplers
- Phase slope within the RF pulse ~5deg/40us

Phase fluctuations:
- 10..15 deg (p-p)
- 2..4 deg (rms)

2011 (FB is ON!)

- FPGA phase, measured by 10MW in-vacuum directional coupler
- Zero phase slope within the electron pulse train

Phase fluctuations:
- 1..1.5 deg (p-p)
- 0.2..0.3 deg (rms)

10-MW in-vacuum directional coupler installed since 2010

Manufacturer: Mega Industries, USA
Booster upgrade at PITZ: TESLA → CDS

Old TESLA-booster was in 2010 replaced with a specially designed for PITZ CDS-booster

- restricted peak gradient (final beam momentum ~13MeV/c)
- short RF pulses only (50-100us)

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)
- Symmetrical couplers

Booster schematic cavity layout.
1 - regular cells,
2 - rf coupler, 3 - rf flanges,
5, 5a - photo multipliers,
6, 6a - vacuum gauges,
7 - pumping ports,
8 - ion pumps,
9 - internal cooling circuit,
10 - outer cooling circuit,
11 - support and adjustment.

Graph:
- <Pz>, MeV/c vs. RF peak power, MW
- gun4.2, gun4.2+TESLA booster, gun4.1, gun4.1+CDS booster
Yb:YAG laser at PITZ with integrated optical sampling system

- Highly-stable Yb:YAG oscillator
  - \( E_{\text{micro}} = 0.002 \ \mu\text{J} \)

- Two-stage Yb:YAG double-pass amplifier
  - \( G \sim 40 \)

- Pulse selector

- Pulse shaper
  - \( \tau \sim 1.7 \ \text{ps} \)
  - \( E_{\text{micro}} = 0.002 \ \mu\text{J} \)

- Yb:YAG power regen
  - \( G \sim 10^6 \)
  - \( E_{\text{micro}} \sim 2 \ \mu\text{J} \)

- Optical Sampling System (OSS)
  - Resolution: \( \tau < 0.5...1 \ \text{ps} \)

- Nonlinear fiber amplifier
  - Scanning amplifier (Yb:KGW)
  - \( E_{\text{micro}} \sim \text{10} \ \mu\text{J} \)

- UV output pulses

- LBO and BBO
  - \( E_{\text{micro}} \sim 80 \ \mu\text{J} \)

Photo cathode laser (Max-Born-Institute, Berlin)
Multicrystal birefringent pulse shaper containing 13 crystals

Will, Klemz, Optics Express, 16 (2008), 4922-14935

Shaped output pulses

Motorized rotation stage

Temperature controlled birefringent crystal

Gaussian input pulses

Gaussian:

FWHM ~ 2 ps

FWHM ~ 7 ps

FWHM ~ 11 ps

FWHM ~ 17 ps

FWHM ~ 20 ps

Simulated pulse-stackker

FWHM ~ 24 ps

FWHM ~ 24 ps

Birefringent shaper, 13 crystals

FWHM = 25 ps

Edge 10-90 ~ 2 ps

OSS signal (UV)
Trains with up to 600 (2700) laser pulses ➔ electron bunches of 1nC each

Time structure: PITZ (European XFEL)

FWHM = 25 ps

edge_{10-90} ~ 2.2 ps

edge_{10-90} ~ 2 ps

birefringent shaper, 13 crystals
## PITZ evolution 2000-2011

<table>
<thead>
<tr>
<th>Year---&gt;</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>cavity</td>
<td>gun-2</td>
<td>gun-1</td>
<td>gun-3.1</td>
<td>gun-3.2</td>
<td>gun-4.2</td>
<td>gun-4.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ez</td>
<td>35MV/m</td>
<td>37MV/m</td>
<td>42MV/m---&gt;60MV/m</td>
<td>43MV/m</td>
<td>60MV/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>beam energy</td>
<td>~4MeV</td>
<td>4.3MeV---&gt;6MeV</td>
<td>4.5MeV</td>
<td>~6MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>booster</td>
<td>cavity</td>
<td>no</td>
<td>TESLA at 2.5m</td>
<td>TESLA at 3.1m</td>
<td>CDS at 3m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>beam energy</td>
<td>~13MeV</td>
<td>~25MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>laser</td>
<td>temporal</td>
<td>10ps</td>
<td>6/24\6ps</td>
<td>6/24\6ps</td>
<td>2/22\2ps</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMSY1 at</td>
<td>z=1.618m</td>
<td>z=4.3m</td>
<td>z=5.74m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ldrift</td>
<td>1.01m</td>
<td>2.334m</td>
<td>2.64m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>emittance</td>
<td>methodics</td>
<td>center BL</td>
<td>3xBLs</td>
<td>e-meter</td>
<td>11xBLs</td>
<td>detailed scan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>min $\varepsilon_{xy}$ (1nC) mm mrad</td>
<td>3</td>
<td>1.5-1.7</td>
<td>1.37</td>
<td>1.26</td>
<td>0.9</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Graph
- **emittance (100% rms)**
- **beam energy after gun**
- **final beam energy**

### X-axis: Year
- **2000**
- **2001**
- **2002**
- **2003**
- **2004**
- **2005**
- **2006**
- **2007**
- **2008**
- **2009**
- **2010**
- **2011**

### Y-axis: beam energy, MeV
- **0**
- **5**
- **10**
- **15**
- **20**
- **25**

### Y-axis: min emittance, mm mrad
- **0**
- **0.5**
- **1**
- **1.5**
- **2**
- **2.5**
- **3**

**XFEL photo injector specs**
Slit scan technique at PITZ: how it works now

**EMSY: screens and slits 10 (50) μm opening**

**Beamlet collector screen**

**measured transverse phase space**

\[ \sigma_x = \sqrt{\langle x^2 \rangle} \]

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

**The emittance measurement procedure at PITZ:**
- under permanent improvement in terms of resolution and sensitivity
- as conservative as possible (100% rms emittance)!

**NB:** 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...”**

**As conservative as possible!**

**Statistics over all pixels in all beamlets**

12-bit camera is important!
Quality criteria: max bit ≥ 3000 (at least from 4095=2¹²-1 max)
Emittance Improvement 2009 → 2011

Improvements:
- Gun phase stability (10MW coupler+FB)
- Laser stability + beam transport
- Magnetizable components removing

Better emittance improvement for lower bunch charges → due to the long pulse train operation (→ “3000-creteria” = f[gain, NoP] )
Emittance vs. Laser Spot size for various charges

Minimum emittance measured in 2011 at PITZ

<table>
<thead>
<tr>
<th>Charge, nC</th>
<th>100% rms xy-emittance, mm mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.25±0.080</td>
</tr>
<tr>
<td>1</td>
<td>0.70±0.026</td>
</tr>
<tr>
<td>0.25</td>
<td>0.33±0.003</td>
</tr>
<tr>
<td>0.1</td>
<td>0.21±0.001</td>
</tr>
<tr>
<td>0.02</td>
<td>0.12±0.0005</td>
</tr>
</tbody>
</table>

Measurements vs. simulations: rather good agreement in emittance values, but optimum machine parameters…
# Measured Phase Space for various bunch charges

<table>
<thead>
<tr>
<th>Qbunch (nC)</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><strong>2 nC</strong></td>
<td><img src="image1" alt="XY-Image" /></td>
<td><img src="image2" alt="horizontal phase" /></td>
<td><img src="image3" alt="vertical phase" /></td>
<td>+6deg</td>
</tr>
<tr>
<td>0.38 mm</td>
<td>0.323mm, 0.347mm</td>
<td>1.209 mm mrad</td>
<td>1.296 mm mrad</td>
<td></td>
</tr>
<tr>
<td><strong>1 nC</strong></td>
<td><img src="image4" alt="XY-Image" /></td>
<td><img src="image5" alt="horizontal phase" /></td>
<td><img src="image6" alt="vertical phase" /></td>
<td>+6deg</td>
</tr>
<tr>
<td>0.30 mm</td>
<td>0.399mm, 0.328mm</td>
<td>0.766 mm mrad</td>
<td>0.653 mm mrad</td>
<td></td>
</tr>
<tr>
<td><strong>0.25 nC</strong></td>
<td><img src="image7" alt="XY-Image" /></td>
<td><img src="image8" alt="horizontal phase" /></td>
<td><img src="image9" alt="vertical phase" /></td>
<td>0deg</td>
</tr>
<tr>
<td>0.18 mm</td>
<td>0.201mm, 0.129mm</td>
<td>0.350 mm mrad</td>
<td>0.291 mm mrad</td>
<td></td>
</tr>
<tr>
<td><strong>0.1 nC</strong></td>
<td><img src="image10" alt="XY-Image" /></td>
<td><img src="image11" alt="horizontal phase" /></td>
<td><img src="image12" alt="vertical phase" /></td>
<td>0deg</td>
</tr>
<tr>
<td>0.12 mm</td>
<td>0.197mm, 0.090mm</td>
<td>0.282 mm mrad</td>
<td>0.157 mm mrad</td>
<td></td>
</tr>
<tr>
<td><strong>0.02 nC</strong></td>
<td><img src="image13" alt="XY-Image" /></td>
<td><img src="image14" alt="horizontal phase" /></td>
<td><img src="image15" alt="vertical phase" /></td>
<td>0deg</td>
</tr>
<tr>
<td>0.08 mm</td>
<td>0.066mm, 0.083mm</td>
<td>0.111 mm mrad</td>
<td>0.129 mm mrad</td>
<td></td>
</tr>
</tbody>
</table>
Core Emittance for various bunch charges

![Graph showing emittance for various bunch charges](image)

<table>
<thead>
<tr>
<th>Charge, nC</th>
<th>PITZ, 100%, mm mrad</th>
<th>LCLS, 95%, mm mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.70</td>
<td>1.10</td>
</tr>
<tr>
<td>0.7</td>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td>0.25</td>
<td>0.33</td>
<td>0.35</td>
</tr>
<tr>
<td>0.1</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>0.12</td>
<td>0.19</td>
</tr>
</tbody>
</table>

LCLS data:
- P. Emma, "Beam Brightness Measurements in the LCLS Injector"
- J. Frisch, "Operation and Upgrades of the LCLS", LINAC2010
> PITZ has set a new benchmark for high brightness electron sources:
   - 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)

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

> Emittance measurements at PITZ:
   - 2009-2011 upgrade (gun phase stability) resulted in ~ 30% emittance value reduction
   - Optimized measured emittance (100% rms $\varepsilon_{xy}$):
     $\varepsilon(20pC)$=0.12mm mrad; $\varepsilon(100pC)$=0.21mm mrad; $\varepsilon(250pC)$=0.182mm mrad; $\varepsilon(1nC)$=0.70mm mrad; $\varepsilon(2nC)$=1.25 mm mrad
   - For chosen measurement conditions: emittance ~ linearly on the bunch charge

> PITZ serves also as a benchmark for theoretical understanding of the photo injector physics (beam dynamics simulations vs. measurements)
   - Rather good agreement on emittance values between measurements and simulations
   - Optimum machine parameters: simulations ≠ experiment (talk on Thursday)

> Outlook:
   - New klystron for the gun
   - New diagnostics for slice emittance and slice energy spread
   - XFEL gun conditioning and characterization
Outlook: PITZ upgrade ongoing this year

Transverse Deflecting Structure (TDS)

→ time resolved measurements

HEDA2
→ together with TDS: measure slice momentum spread down to 1 keV/c