Advanced photo cathode laser pulse shaping for ultimate XFEL photo injector performance

(Activity at PITZ in the frame of ARD-ST3 “ps – fs Electron and Photon Beams”)

Mikhail Krasilnikov (DESY) for the PITZ Team
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High Brightness Photo Injector Developments at PITZ

- 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 SASE FELs:
  - Gun-3.1 from PITZ → FLASH
  - Gun-4.3 → European XFEL, spare XFEL gun-4.4 → currently at PITZ for conditioning and characterization
- Fundamental research in photo injector physics
- Test bed for critical photo injector components (cavity, laser, cathode, etc.)
- Developments of electron and laser beam diagnostics
- Other R&D developments (PWA, THz, …)
**Photo Injector Test Facility at DESY in Zeuthen (PITZ)**

**Cathode laser** $\lambda = 257 \text{nm}$

Trains with up to **800 pulses** *(1MHz)* at **10Hz** repetition rate

**Temporal (micro) pulse shaping**

*Flattop* (nominal)

FWMH $= 25 \text{ ps}$

$\theta_{10\%} = 2.2 \text{ ps}$

$\theta_{90\%} = 2 \text{ ps}$

*Birefringent shaper, 13 crystals*

**Electron bunches:**

- 1nC nominal charge
- $\sim 7 \text{MeV/c}$ max. mean momentum
- Pulse trains

**RF-gun:**

- L-band *(1.3 GHz)* normal conducting (copper) standing wave $\frac{1}{2}$-cell cavity
- Peak rf power: $\sim 7 \text{MW}$ (Ez@cathode: $> 60 \text{MV/m}$)
- 850 $\mu$s RF pulse length with a repetition rate of **10 Hz**, duty cycle $\sim 1\%$
- Dry ice cleaning
  - Dark current < 50 $\mu$A at 7.75 MW

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- $\sim 7 \text{MeV/c}$ max. mean momentum
- Pulse trains

**Legend:**

- **Gaussian:**
  - FWHM $= 2 \text{ ps}$
  - FWHM $= 7 \text{ ps}$
  - FWHM $= 11 \text{ ps}$
  - FWHM $= 17 \text{ ps}$

**Photo cathode** *(Cs$_2$Te)*

- QE $\sim 0.5$-$10\%$

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PITZ:

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

Bunch charge reduction at fixed cathode laser pulse duration $\rightarrow$ space charge (SC) modification.

M. Krasilnikov, F. Stephan et al., PRST-AB 15, 1000701 (2012).
**Motivation:** Further improvement of the electron beam quality by reduction of the transverse projected beam emittance.

**Main idea:** Optimization of the cathode laser pulse shape in order to minimize the impact of the space charge on the transverse emittance.

\[
\epsilon = \sqrt{\epsilon_{cath}^2 + \epsilon_{RF}^2 + \epsilon_{SpCh}^2}
\]

cathode laser shape: \(\epsilon_{SpCh} \rightarrow \text{min}\)

- Minimum SC influence on beam emittance
- Better longitudinal compression
- Reduced beam halo
- Less sensitivity to the machine settings

German-Russian collaboration:
- IAP (Nishny Novgord) will build laser
- Installation at PITZ starts autumn 2014
Beam Dynamics Simulations: XFEL Photo Injector (1nC)

Various shapes of the photocathode laser pulse (Gaussian and Flattop temporal profiles vs. 3D-ellipsoid)

Bunch current profiles and slice emittance at z=15m

3D ellipsoidal cathode laser pulses ➔ improvements on transverse projected and slice emittance
Various shapes of the photocathode laser pulse (Gaussian and Flattop temporal profiles vs. 3D-ellipsoid)

Bunch slice brightness at z=15m

\[ B_s(z) = \frac{I(z)}{\varepsilon_x(z)\varepsilon_y(z)} \]

3D ellipsoidal cathode laser pulses ➔ significant increase of the beam brightness
Beam Dynamics Simulations: **PITZ (1nC)**

Transverse phase spaces at z=5.74m

- **Gaussian**
  - ~no beam halo → better signal/noise, reduced radiation damage
- **Flat-top**
  - ~pure sinusoidal longitudinal phase space +3\(^{rd}\) harm. → simplify/allow required compression
- **3D Ellipsoid**
  - less sensitive to machine settings → higher stability

Longitudinal phase space (Z-Pz) at z=5.74m

- Gaussian: 106.7 mm keV
- Flat-top: 98.2 mm keV
- 3D Ellipsoid: 88 mm keV
Short bunch generation: PITZ+BC (1pC preliminary simulations)

Setup:

- PITZ Gun
- CDS Booster
- chicane

Vary parameters and try different cathode laser shapes

<table>
<thead>
<tr>
<th>Q=1pC</th>
<th>σ_t=1.2ps</th>
<th>FWHM=9.4ps</th>
<th>σ_t=4ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ_t</td>
<td>9.1 fs</td>
<td>9.6…8 fs</td>
<td>10.3 fs</td>
</tr>
<tr>
<td>I_peak</td>
<td>~60A</td>
<td>65…90A</td>
<td>~200A</td>
</tr>
<tr>
<td>σ_x</td>
<td>8.5 μm</td>
<td>5.4…13.4 μm</td>
<td>7.7 μm</td>
</tr>
<tr>
<td>σ_y</td>
<td>8.8 μm</td>
<td>9.9…4.7 μm</td>
<td>10.4 μm</td>
</tr>
</tbody>
</table>

Longitudinal phase space

for LPA with external injection or other applications (e.g. THz)
Practical realization:

> Collaboration: **DESY – JINR** (Dubna, Russia) – **IAP** (Nizhny Novgorod, Russia)

> Goal – develop a photo cathode laser system with following parameters:

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
<th>remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavelength</td>
<td>258</td>
<td>nm</td>
<td>1030 nm fundamental $\lambda$</td>
</tr>
<tr>
<td>micropulse energy</td>
<td>15</td>
<td>$\mu$J</td>
<td>for 1 nC bunch production from Cs$_2$Te photo cathodes</td>
</tr>
<tr>
<td>pulse train frequency</td>
<td>1</td>
<td>MHz</td>
<td>In the future 4.5 MHz will be a goal</td>
</tr>
<tr>
<td>pulse train length</td>
<td>0.3</td>
<td>ms</td>
<td>In the future 0.6 ms will be a goal</td>
</tr>
<tr>
<td>pulse train rep.rate</td>
<td>10</td>
<td>Hz</td>
<td>1,2,5 Hz as an option</td>
</tr>
<tr>
<td>micropulse rms duration</td>
<td>$6 \pm 2$</td>
<td>ps</td>
<td>3D quasi ellipsoidal distribution</td>
</tr>
<tr>
<td>transverse rms size</td>
<td>$0.5 \pm 0.25$</td>
<td>mm</td>
<td></td>
</tr>
</tbody>
</table>

**BMBF** project “**Development and experimental test of a laser system for producing quasi 3D ellipsoidal laser pulses**”:

→ **Laser system development at IAP**

→ **Installation at PITZ for tests with e-beam**
The current status

- All necessary equipment is installed and functioning
- The energy of fundamental pulses close to the calculated (70μJ instead 100μJ)
- The first experiments demonstrates the possibility of UV generation with energy 1.7μJ (required 10÷12μJ) in micro pulse.
- Shaper is ready for managing spatial-temporal parameters
3D-Ellipsoid laser system: developments at IAP

Image at nonlinear crystal of cross-correlator

1ω

2ω

Pulse Shaper Tests at IAP

Reflected signal flickering

Hamamatsu SLMs

HOLOEYE Photonics AG, Germany (www.holoeye.com)
PLUTO-NIR: High-Resolution LCOS Phase Only Spatial Light Modulators

Hamamatsu SLMs

Pulse profile measurements
comparison of scanning methods
Border sharpness modeling for beam simulations

Transverse distribution of the 3D ellipsoidal laser at different time cross sections (t = 0; 1; 2; 2.5; 3; 3.3 ps).

Modification of initial photon distribution by applying laser shape imperfections

\[ \rho = \rho_0 \left\{ \frac{1}{2} \left( \frac{1}{2} \sin \left[ \pi \left( \frac{\vartheta - 1}{2} \delta(r,t) + \frac{1}{2} \right) \right] \right) + 1 - \delta(r,t) \right\}, \quad 1 - \delta(r,t) \leq \vartheta \leq 1 \]

\[ \rho = \rho_0 \left\{ \frac{1}{2} \left( \frac{1}{2} \sin \left[ \pi \left( \frac{\vartheta - 1}{2} \delta(r,t) + \frac{1}{2} \right) \right] \right) \right\}, \quad 1 - \delta(r,t) \leq \vartheta \leq 1 \]

\[ \rho_0 = \sqrt{\left( \frac{r}{R} \right)^2 + \left( \frac{t}{T} \right)^2}, \quad 0 \leq r \leq R, \quad 0 \leq t \leq T \]

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\[ \delta_r \rightarrow \text{Border radial sharpness parameter} \]

\[ \delta_t \rightarrow \text{Border temporal sharpness parameter} \]

Perfect 3D shape

20% distortions over pulse

20% distortion temporally

20% distortion spatially

Laser beam radial vs. temporal distribution at the cathode:

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Emittance growth due to non perfect border width

- Modified intensity distribution for each border width (temporal and radial) has been put into ASTRA simulations for electron beam tracking up to EMSY1
- Parameters responsible for bunch rms emission time ($T_{\text{rms}}$ or initial bunch length) and laser beam transverse projection onto the z axis ($XY_{\text{rms}}$) were kept unchanged during the studies

**Transverse emittance growth (in %) vs. temporal ($\delta_t$) and radial ($\delta_r$) border sharpness parameters.**

**Stronger effect on transverse emittance due to imperfections in radial direction!**
First tests with 3D pulse shaper

- only amplitude mask applied to SLM
- measured using the cross-correlator
- strong modulation (SLM noise) observed

Main requirements to the cross-correlator scanning system:

- \( t_d \ll t_m \)
- Minimized time jitter of the diagnostic pulse w.r.t. the working pulse
- Scanning speed \( V = ct_w/T \), where \( T = 0.3\, ms \) is a pulse train length
- \( V \approx 1500\, cm/s \approx \text{const} \) within the scanning time \( t_w \)
- Angular synchronism \( \theta = \theta_s \pm 2.5\, mrad \)
Conclusions and Outlook

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)
- tests key and critical components for high brightness electron sources
- cathode laser pulse properties → one of major tools for the photo injector optimization

3D ellipsoidal cathode laser pulses → next step in photo injector optimization.

Beam dynamics simulations → benefits from 3D ellipsoidal laser pulses for linac driven light sources:

- 30-50% lower average slice emittance → higher brilliance
- ~no beam halo → better signal/noise, reduced radiation damage
- “more sinusoidal” longitudinal phase space +3rd harm. → simplify/allow required compression
- less sensitive to machine settings → higher stability

3D ellipsoidal cathode laser pulses, practical realization → BMBF and HGF projects (collaboration DESY-IAP-JINR):

- Laser system developments at IAP RAS, Nizhny Novgorod (Russia), SLM based pulse shaper
- Delivery and installation at PITZ for tests with e-beam → from September 2014

R&D on IR/THz sources at PITZ are ongoing (tunable + pulse train structure)
R&D on THz sources at PITZ

- The combination of THz and X-ray pulses in **pump and probe** experiments at the European XFEL facility finds application for a wide range of experiments.

- Also → produced radiation = additional e-bunch diagnostic.

> Single cycle radiation, electric field ~ few MV/m
- Transition radiation (TR) or Synchrotron Radiation (SR) obtained using a compressed electron beam

> Narrow band
- SASE FEL obtained using an uncompressed e-beam accelerated on crest:
  - e.g. 4nC bunches at PITZ + APPLE-II undulator ($\lambda_u=4\text{cm}, L=5\text{m}$)
  - $\lambda_{\text{rad}} \sim 10\mu\text{m} \rightarrow 1\text{mm} (30 \rightarrow 0.3\text{THz})$
  - Radiation pulse energy: some $100\mu\text{J}$ (up to $1\text{mJ}$!)
  - Peak power 10 – 100MW
  - Spectrum bandwidth 2-3%

- Modulated beam → TR or SR obtained using a comb beam

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**Hadrontron radiation from 4nC bunch**

IR/THz simulations (ASTRA, GENESIS,…): B. Marchetti, P. Boonpornprasert

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**TR from a single compressed bunch (200 pC) for different booster phases**

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PITZ pulse train structure 800 pulses (1MHz) x 10Hz (RR)!