Space charge dominated photoemission at PITZ

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Photo Injector Test facility at DESY, Zeuthen site (PITZ)

PITZ ➔ development, test and optimization of high brightness electron sources for sc linac driven FELs:
 ➔ test-bed for FEL injectors: FLASH, the European XFEL (gun cavities and subsystems, e.g. photocathode laser)
 ➔ High brightness ➔ small $\varepsilon_{x,y}$ (projected and slice)
 ➔ further studies ➔ e.g. photocathodes (PC): dark current, photoemission, QE, thermal emittance, …

+ detailed comparison with simulations = benchmarking for the PI physics

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E-beam: 7MeV/c
~20ps, ~1nC
<1 mm mrad

PC UV laser pulse
~20ps, ~1mm

NC L-band
1.6cell
$E_{\text{cath}}$~60MV/m

Cs$_2$Te PC
QE~5-10%

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PITZ: Simulations versus Measurements

Asymmetry $\Rightarrow$ kick?

Charge production

Photocathode laser

Charge vs. laser pulse energy

Experimental emittance minimization: optimum PC laser spot size (space charge density) $\Rightarrow$ transition: linear (QE-limited) to saturated (SC limited) regime

M. Krasilnikov et al., PRSTAB 15, 100701, 2012.
Photoemission: impact of RF gradient and laser pulse temporal profile

Experiment ➔ Emission curves: bunch charge $Q(E_{cath}, \varphi_0^{MMG}, E_{laser}, \text{Laser temporal profile})$

From the parallel plate capacitor (sheet beam) model:

$$Q_{SC-\lim} = \pi \varepsilon_0 R^2 E_0 \sin \varphi_0 = \pi \varepsilon_0 R^2 E_{cath}$$

E.g. for $E_{cath} = 50 \text{ MV/m}$; $R = 0.6 \text{ mm}$;

$$Q_{QE-\lim,PPCM} \approx 500 \text{ pC} << \text{observed!!!}$$

Photoemission depends on:
- $E_{cath} \rightarrow \text{Schottky}(like)\text{ effect}$
- Laser pulse duration $\rightarrow$ space charge effect
- Emission curves $Q(E_{laser})$ saturate weaker
Photoemission: laser transverse halo modeling

Laser transverse distribution: Core + Halo model (C+H)

\[ F_l(r) = \frac{E_l}{\pi R_c^2 + 2\pi \xi \sigma_r^2} \begin{cases} \frac{1}{\xi e^{\frac{2\sigma_r^2}{p_c^2 - r^2}}} \text{, if } r \leq R_c \\ \frac{1}{\xi e^{\frac{2\sigma_r^2}{p_c^2 - r^2}}} \text{, if } r > R_c \end{cases} \]

\[ Q = Q_{\text{core}} + Q_{\text{halo}} \]

\[ Q_{\text{core}} = \frac{1}{1 + \xi \cdot \eta} \begin{cases} Q_{\text{exp}} \text{, if } Q_{\text{exp}} \leq Q_{\text{max}} \\ Q_{\text{max}} \text{, if } Q_{\text{exp}} > Q_{\text{max}} \end{cases} \]

\[ Q_{\text{halo}} = \frac{\eta}{1 + \xi \cdot \eta} \begin{cases} \xi \cdot Q_{\text{exp}} \text{, if } \xi \cdot Q_{\text{exp}} \leq Q_{\text{max}} \\ Q_{\text{max}} \cdot \left(1 + \ln \frac{\xi \cdot Q_{\text{exp}}}{Q_{\text{max}}} \right) \text{, if } \xi \cdot Q_{\text{exp}} > Q_{\text{max}} \end{cases} \]

\[ Q_{\text{max}} = \rho_{\text{scl}} \cdot \left(\pi R_c^2 + 2\pi \xi \sigma_r^2\right) \]

\[ \frac{\rho_{\text{scl}}(\text{flat-top})}{\rho_{\text{scl}}(\text{Gaussian})} \approx 1.51 \]

C+H \rightarrow \text{charge exceed}
If a uniform distribution is used instead, the charge saturates.

Extracted charge with core + halo for 0.8 mm beam diameter with 1.5 ps rms Gaussian temporal at maximum cathode field ($\phi_0=90^\circ$)

- $E_0 = 58 MV/m$
- $E_0 = 44 MV/m$
- $E_0 = 29 MV/m$

C. Hernandez-Garcia et al., NIM A 871 (2017) 97–104
ASTRA simulations for 2011 case using Core+Halo

> BUT for flattop photocathode laser pulses

Parameters "plugged" from measurements:

- $\phi_{\text{gun}}=\text{MMMG}+6^\circ$
- $Q=1\text{nC}^*$
- $\epsilon_x=0.72\text{ mm mrad}$
- $\epsilon_y=0.60\text{ mm mrad}$

Simulated

X-Y: $\phi_{\text{gun}}=\text{MMMG}+6^\circ$

Q=0.97nC

$\epsilon_{x}=2.5\text{ mm mrad}$
### Electron beam X-Y asymmetry studies at PITZ

**Possible sources of the beam asymmetry:**
- Vacuum mirror
- Stray magnetic fields
- Related to the laser polarization
- Particular cathode
- ...
- RF coupler field asymmetry
- Solenoid imperfections (anomalous quadrupole fields)

**Larmor angle experiment**

<table>
<thead>
<tr>
<th>Main solenoid ( \text{max}[B_z], \text{max} \left(I_{\text{main}}\right) \text{for meas.} )</th>
<th>Laser X-Y distribution at cathode</th>
<th>Electron beam X-Y distribution at ( z=0.18 ) m</th>
<th>E-beam X-Y distribution at ( z=5.277 ) m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured at VC2</td>
<td>Used in simulations</td>
<td>Simulated</td>
<td>Measured at EMSY1</td>
</tr>
<tr>
<td>-0.2087T ((-360A)) (\text{opposite polarity})</td>
<td>Core + Halo</td>
<td><img src="image1" alt="Simulated distribution" /></td>
<td><img src="image2" alt="Measured distribution" /></td>
</tr>
<tr>
<td><img src="image1" alt="Image1" /></td>
<td><img src="image2" alt="Image2" /></td>
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<td>+0.2087T ((+360A)) (\text{normal polarity})</td>
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</table>

?45° Kick at \( z \approx 0.2 \) m → skew quadrupole?
Electron beam X-Y asymmetry compensation with gun quads

(0.5nC, Gaussian photocathode laser pulse)

Electron beam measurements without gun quadrupoles

Electron beam measurements with gun quadrupoles

\( I_{\text{Gun.Quad}1} = -0.6 \text{A}; \ I_{\text{Gun.Quad}2} = -0.5 \text{A} \)

\[ \begin{array}{c|cc}
\text{No gun quads} & \text{With gun quads} \\
\hline
I_{\text{main}} (\text{A}) & 386 & 384 \\
I_{\text{gun.quad}1} (\text{A}) & 0 & -0.5 \\
I_{\text{gun.quad}2} (\text{A}) & 0 & -0.6 \\
\sigma_x @ \text{EMSY1 (mm)} & 0.50 & 0.28 \\
\sigma_y @ \text{EMSY1 (mm)} & 0.35 & 0.32 \\
\varepsilon_{x,n} (\text{mm mrad}) & 1.13 & 0.82 \\
\varepsilon_{y,n} (\text{mm mrad}) & 0.73 & 0.84 \\
\sqrt{\varepsilon_{x,n} \varepsilon_{y,n}} (\text{mm mrad}) & 0.91 & 0.83 \\
\beta_x (\text{m}) & 6.53 & 3.18 \\
\beta_y (\text{m}) & 6.49 & 3.24 \\
g_x (\text{mrad}) & 0.56 & 0.32 \\
g_y (\text{mrad}) & 0.16 & 0.31 \\
\end{array} \]

M. Krasilnikov et al., FEL2017 proceedings, WEP007
ASTRA simulations for **Gaussian pulses using Core+Halo**

> BUT for flattop photocathode laser pulses

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**Measured**

- \( X - Y \)
- \( X - X' \)
- \( Y - Y' \)

\( \Phi_{\text{gun}} = \text{MMG} \)

- \( Q = 0.5 \text{nC} \)
- \( \varepsilon_x = 0.82 \text{ mm mrad} \)
- \( \varepsilon_x = 0.84 \text{ mm mrad} \)

**Used in simulations**

- Parameters "plugged" from measurements:
  - \( \Phi_{\text{gun}} = \text{MMG} \)
  - \( Q = 0.5 \text{nC} \)
  - \( \varepsilon_x = 1.05 \text{ mm mrad} \)

**Charge vs. laser pulse energy**

- **measured**
- **simulated (homogeneous)**
- **simulated (Core+Halo)**
Photoemission from Cs2Te photocathode

Three step model of photoemission:

1. **Absorption** of laser photons in bulk material and excitation (isotropically distributed) of photo-e⁻ → factors:
   - reflectivity \( R(\omega) \)
   - penetration depth \( \delta(\omega) \)
   - complex dielectric constant \( \varepsilon(\omega) \)

2. **Transport** of excited photoelectrons to surface with inelastic and isotropic scattering → factors:
   - electron energy \( E \)
   - scattering rates (relaxation times) \( \tau(E) \), mainly e-p
   - mean free path \( l_{MFP}(E) = \frac{\hbar k(E)}{m^* \tau(E)} \rightarrow \frac{\delta(\omega)}{l_{MFP}(E)} \)
   - scattering factor \( f_\Lambda(\cos \theta, E) \)
   - “fatal” approximation is less applicable…

3. **Emission** → probability of transport over barrier \( V_0 \)
   - barrier height \( E_a \) (measured from conduction band minimum), band gap \( E_g \)
   - escape cone \( \theta_{max} \)
   - normal energy \( E \cos^2 \theta \) of photo-e⁻: \( P(E > V_0) \)- Heaviside step function of emission probability → Airy function
   - Band bending

\[ J_{FD*} \propto (\hbar \omega - E_a - E_g)^\gamma \]


FIG. 3. Schematic energy-level diagram of a semiconductor photoemitter where \( E_g \gg E_A \). The minimum threshold energies for electron-electron scattering (2\( E_g \)) and for secondary electron emission (\( E_g + E_F \)) are indicated.
Photoemission: slice emittance formation

Very short non-relativistic bunch at the cathode $\rightarrow$ nonlinear Lorentz force

$$E_r(\rho) = \frac{\sigma_0}{4\epsilon_0} \left[ \frac{\rho}{r_b} + \frac{3}{8} \left( \frac{\rho}{r_b} \right)^3 \right]$$

NB: for infinitely long cylinder

$$E_r(\rho) = \frac{Q/V}{2\epsilon_0 \rho}$$

$$F_r(\rho) = \frac{eI\rho}{2\pi\epsilon_0\gamma^2\beta c r_b^2}$$

Space charge term in the envelope equation

Emission in SC tracking or PIC codes:

- Macroparticle distribution $f(x, y, z=0, t_{\text{start}}, p_x, p_y, p_z)$
- Space charge calculation (incl. cath. mirror charge)
- Macroparticles reflected back to the cathode ($z<0$) $\rightarrow$ lost…
Photoemission modeling and simulation using a Lienard-Wiechert (LW) approach

**Motivation**
- Dynamic generation of emitted particle distribution at cathode
- Flexibilities to incorporate emission models
- Taking into account full electromagnetic fields (RF + space-charge) during emission
- Improving the agreement between measurement and simulation

\[ E = \frac{q}{4\pi\varepsilon_0} \left[ \frac{(\mathbf{n} - \mathbf{\beta})(1 - |\mathbf{\beta}|^2)}{(1 - \mathbf{\beta} \cdot \mathbf{n})^3 R^2} + \frac{\mathbf{n} \times (\mathbf{n} - \mathbf{\beta}) \times \dot{\mathbf{\beta}}}{(1 - \mathbf{\beta} \cdot \mathbf{n})^3 R} \right] \bigg|_{t=t_r} \]
\[ n = \frac{R}{|R|}, \quad (x-x_r)^2 + (y-y_r)^2 + (z-z_r)^2 = c^2(t-t_r)^2 \]

Given N particles’ full history to find the EM fields produced by the particles at the observation time

**LW Approach with 3D emission process**
- LW solution for the electromagnetic field of a charged particle in arbitrary motion
- Full particle trajectory stored and used for field computation
- Accuracy depends only on time step and number of particles
- Parallelized PP code

**Status of Application**
- QE limited regime $\rightarrow$ OK
- In space charge dominated regime, remaining deviations w.r.t. simulations probably due to:
  - Ideal beam distributions initially plugged in the simulations
  - Or/and time dependent work function variation resulting from quantum mechanical effects

\[ \Delta \Phi_f (r_\perp, t) = \sqrt{\frac{q^3}{4\pi\varepsilon_0}} \left[ E_{rf} (r_\perp, t) + E_{sc} (r_\perp, t) \right] \]

\[ dQ (r_\perp, t) = \Delta t \int_S q \frac{P_t (r_\perp, t)}{\hbar \nu} QE (r_\perp, t) dS \]

\[ QE_J = \frac{(1 - R_w)\sqrt{1 + \frac{\hbar \nu - \Phi_w}{E_a}}}{2(p_0 + 1) \left(1 + \frac{E_a}{\hbar \nu - \Phi_w}\right)^2} \]

Courtesy Ye Chen

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Some experimental observations might be related to photoemission issues
Gun-4.6 (PITZ): mean momentum and MMMG phase

\[ \alpha = \frac{eE_{cat}}{2mc^2k} \approx 0.047 \frac{E_{cat}\text{[MV/m]}}{f\text{[GHz]}} \]

**Measurements vs. Simulations**

**MMMG = Maximum Mean Momentum Gain**

- **gun-4.6, simulated \(<P_z>\)**
- **measured \(p_z\) max**
- **meas. \(P_z\) max, 650us**
- **gun-4.6, simul. MMMG phase**
- **measured \(\Phi\)(MMMG)**
- **meas. \(\Phi\)(MMMG), 650us**

**Parameters**

- \(E_{cat} = 60.6\text{MV/m}\)
- \(\alpha \approx 0.047\frac{E_{cat}\text{[MV/m]}}{f\text{[GHz]}}\)
Zero-crossing phase determination

Still not understood: Zero-crossing phase $\leftrightarrow$ MMMG phase $\Rightarrow$ 2-3 deg phase shift between measurements and simulations

Gun phase = 33.8$^\circ$ - SPPhase
Measured MMMG = 46.8$^\circ$
Simulated MMMG = 43.3$^\circ$

$\sim$3deg

Phase shift widening
Another emission related topic at PITZ: slice energy spread

Main idea $\rightarrow$ $\delta E$ measurements using TDS + HEDA2 dipole for various photo injector parameters (photocathode laser pulse temporal profiles, SC effect, etc.)

$$\delta_{E,\text{measured}} \approx \sqrt{(\delta_{E,\text{real}})^2 + (\delta_{\beta})^2 + (\delta_{E,\text{TDS}})^2}$$

Still resolution on the slice energy spread seems to be a limiting factor:

- Beam transverse size in the HEDA2 dipole (beta function)
- TDS induced energy spread (estimated $\frac{d(\delta E)}{d\delta P(TDS)} \sim 3 \text{ eV/MV}$)

$\delta E \approx 6.8 \text{ keV}$ for TDS SP=0

Similar measurements for short Gaussian (2 ps FWHM) PC pulses:

$\delta E \approx 8.2 \text{ keV}$ for TDS SP=0

Longitudinal Phase Space (LPS) measurements: TDS SP scan in HEDA2 (Long Gaussian PC laser pulse, 11.5ps FWHM)
Slice energy spread: measurements vs. ASTRA simulations

ASTRA simulations:
- $Q=100\,\text{pC}$
- Gun+Booster $\rightarrow$ =measurements
- PC laser pulse parameters
  - Temporal: Gaussian (11.5 ps FWHM)
  - Transverse: Core+Halo, XYrms=0.186mm

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Measured Long. Phase Space

SP(TDS)=0.1

0.3 keV rms

SP(TDS)=0.25

11 keV rms
**P_z-modulation from the Gaussian PC laser pulses?**

E-beam momentum modulations observed in:
- LEDA (P_z~6.4MeV/c) and HEDA1 (P_z~22.1MeV/c)

<table>
<thead>
<tr>
<th>Temporal profile</th>
<th>FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Gaussian</td>
<td>~11-11.5ps</td>
</tr>
</tbody>
</table>

**Temporal profile**

**BSA=2.8mm**

**BSA=2.0mm**

**6.4MeV/c**

**22MeV/c**

Equation:

\[ \text{Emitted charge} \rightarrow \text{fields on surface that affects subsequent emissions} \rightarrow \text{“oscillations induced by a sudden influx of charge can persist”}. \]

Demonstration for Cu and Cs_3Sb using PIC code MICHELLE

Might be related to the PC laser temporal profile \( \rightarrow \)
investigations are ongoing
Conclusions and Outlook

- The Photo Injector Test facility at DESY in Zeuthen (PITZ) \( \rightarrow \) high brightness electron sources for SASE FELs:
  - Low transverse emittance has been experimentally achieved
  - Still discrepancies between measured and simulated machine parameters

- Possible reasons of these discrepancies:
  - Imperfections (beam asymmetry) \( \rightarrow \) compensation with gun quads
  - Photoemission

Photoemission studies:

- Best experimental emittance \( \rightarrow \) space charge dominated photoemission
- Generally: \( Q_{\text{measured}} > Q_{\text{simulated}} \) (ideal case)
- Transverse **Core+Halo** model helps better for Gaussian than for flattop temporal PC laser profiles
- Could charge exceed be explained by secondary emission?
- Still discrepancy measured-simulated phase spaces
- “Phase offset” (1-3°) measured-to-simulated zero-crossing RF phase is not well understood
- Slice energy spread: \( \delta E_{\text{measured}} >> \delta E_{\text{simulated}} \)
- Observed \( P_z \)-modulations for Gaussian temporal laser pulses might be related to the photocathode laser

- Outlook \( \rightarrow \) new developments:
  - 3D ellipsoidal cathode laser pulses \( \rightarrow \) experiments with electron beams