Photo injector optimization at PITZ, status 2011: measurements vs. simulations

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  • core emittance
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Beam Dynamics Simulations (ASTRA) for PITZ-1.8 Setup

Cathode laser pulse profiles

Measured

Transverse distribution (VC2)

Ideal temporal profile: 2ps/21.5ps/2ps

Used in beam dynamics simulations

Transverse distribution radial homogeneous
BD simulations (ASTRA) for various charges

<table>
<thead>
<tr>
<th>parameter</th>
<th>unit</th>
<th>20pC</th>
<th>100pC</th>
<th>250pC</th>
<th>1nC</th>
<th>2nC</th>
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</thead>
<tbody>
<tr>
<td>temporal profile</td>
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<td>Flat-top</td>
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<td>XYrms</td>
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<td>0.102</td>
<td>0.230</td>
<td>0.401</td>
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<td>0.1</td>
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<td>2</td>
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<td>50%</td>
<td>74%</td>
<td>56%</td>
<td>44%</td>
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<td>&lt;sl. emit.</td>
<td>mm mrad</td>
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<td>0.121</td>
<td>0.219</td>
<td>0.538</td>
<td>0.978</td>
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</table>

E-beam at EMSY1 (z=5.74m)

- Emit (2nC)
- Emit (1nC)
- Emit (0.25nC)
- Emit (0.1nC)
- Emit (0.02nC)
- Current (2nC)
- Current (1nC)
- Current (0.25nC)
- Current (0.1nC)
- Current (0.02nC)

Slice emittance, mm mrad

Emittance, mm mrad vs z from cathode, m

Slice emittance, mm mrad vs z<z>, mm
Emittance at PITZ-1.8: Measurements vs. Simulations
# Measured Phase Spaces for various bunch charges

<table>
<thead>
<tr>
<th>Qbunch</th>
<th>Beam at EMSY1</th>
<th>Horizontal phase space</th>
<th>Vertical phase space</th>
<th>$\phi_{\text{gun}}$</th>
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<tbody>
<tr>
<td></td>
<td>XY-Image</td>
<td>$\sigma_x/\sigma_y$</td>
<td>$\varepsilon_x$</td>
<td>$\varepsilon_y$</td>
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<tr>
<td>2 nC</td>
<td><img src="image" alt="2 nC image" /></td>
<td>0.323mm / 0.347mm</td>
<td>1.209 mm mrad</td>
<td>1.296 mm mrad</td>
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<tr>
<td>1 nC</td>
<td><img src="image" alt="1 nC image" /></td>
<td>0.399mm / 0.328mm</td>
<td>0.766 mm mrad</td>
<td>0.653 mm mrad</td>
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<tr>
<td>0.25 nC</td>
<td><img src="image" alt="0.25 nC image" /></td>
<td>0.201mm / 0.129mm</td>
<td>0.350 mm mrad</td>
<td>0.291 mm mrad</td>
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<tr>
<td>0.1 nC</td>
<td><img src="image" alt="0.1 nC image" /></td>
<td>0.197mm / 0.090mm</td>
<td>0.282 mm mrad</td>
<td>0.157 mm mrad</td>
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<tr>
<td>0.02 nC</td>
<td><img src="image" alt="0.02 nC image" /></td>
<td>0.066mm / 0.083mm</td>
<td>0.111 mm mrad</td>
<td>0.129 mm mrad</td>
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<tr>
<td>0.08 mm</td>
<td><img src="image" alt="0.08 mm image" /></td>
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</tbody>
</table>

*Note: Zoomed in images for Qbunch 0.02 nC.*
Optimized Emittance vs. Bunch Charge

Rather good agreement on emittance values, but …
Emittance (Q, rms laser size): simulations vs. measurements

- 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)
- A radial homogeneous laser pulse distribution is used in simulations whereas the experimental transverse distribution is not perfect
- Artificial increase of the thermal kinetic energy at the cathode (from 0.55eV to 4eV) did not improve the understanding
Core Emittance for various bunch charges

?phase space collimator?
“0.25nC core from 1nC beam”
$\varepsilon(25\%\text{of}1\text{nC}) \sim \varepsilon(100\%\text{of}250\text{pC})/3$
$\varepsilon(25\%\text{of}1\text{nC}) \sim \varepsilon(100\%\text{of}20\text{pC})$

?to be simulated?
Collimator $\rightarrow$ FODO $\rightarrow$ collimator
Emittance vs. I\text{main} for various bunch charges

- Measured emittance vs. solenoid current

- Graph showing emittance vs. solenoid current for various bunch charges:
  - 2 nC (rms laser 0.5 mm, gun 0 deg)
  - 2 nC (rms laser 0.38 mm, gun 6 deg)
  - 1 nC (rms laser 0.3 mm, gun 0 deg)
  - 1 nC (rms laser 0.3 mm, gun 6 deg)
  - 0.25 nC (rms laser 0.182 mm, gun 0 deg)
  - 0.1 nC (rms laser 0.123 mm, gun 0 deg)
  - 0.02 nC (rms laser 0.058 mm, gun 0 deg)

- Additional graphs showing:
  - Bunch charge vs. gun phase
  - Measured charge vs. gun phase
  - Measured momentum vs. gun phase

- Legend with different markers and colors for each charge level.
Emittance vs. \((I_{\text{main}}/I^* - 1)\) for various bunch charges: \(M\leftrightarrow S\)

- **2 nC (rms laser 0.5 mm, gun 0 deg)**
- **2 nC (rms laser 0.38 mm, gun 6 deg)**
- **2 nC, simulated (0.6 mm / -2.6 deg)**

- **0.25 nC (rms laser 0.182 mm, gun 0 deg)**
- **0.25 nC, simulated (0.225 mm / 1.3 deg)**

- **0.1 nC (rms laser 0.123 mm, gun 0 deg)**
- **0.1 nC, simulated (0.102 mm / 1.2 deg)**
- **0.1 nC, simulated (0.123 mm / -1.5 deg)**

- **0.02 nC (rms laser 0.058 mm, gun 0 deg)**
- **0.02 nC, simulated (0.037 mm / 1.4 deg)**

- **2 nC (rms laser 0.5 mm, gun 0 deg)**
- **2 nC (rms laser 0.38 mm, gun 6 deg)**
- **2 nC, simulated (0.6 mm / -2.6 deg)**
Measured and Simulated Emittance: 0.1nC

Rather good agreement in both beam rms size and emittance!
Measured and Simulated Phase Space at EMSY1: 0.1nC

**Measured**

- **X-Y**
  - Strong X-Y asymmetry!

**Simulated**

- **X-Y**
- **X-X’**
- **Y-Y’**

0.1nC
Measured and Simulated Emittance: 2nC

- Good agreement only on the minimum emittance value
- Strong disagreement in the optimum laser spot size (no 2nC simulated at 0.5 mm, but measured)
- Simulated electron beam size is much larger than the measured one
Measured and Simulated Phase Space at EMSY1: 2nC

Measured

Simulated

Sign of the X-X' (Y-Y') correlation?
Measured and Simulated Emittance: \(1 \text{nC}\)

**Electron beam size at EMSY1**

- Measured XY\(\text{rms}\) (05.05.2011, 03 mm / 6 deg)
- Measured XY\(\text{rms}\) (07.05.2011, 03 mm / 6 deg)
- Simulated XY\(\text{rms}\) (0.4 mm / 1.4 deg)

**Electron beam emittance at EMSY1**

- Measured XY-emit (05.05.2011, 03 mm / 6 deg)
- Measured XY-emit (07.05.2011, 03 mm / 6 deg)
- Simulated XY-emittance (0.4 mm / 1.4 deg)

- Optimum laser rms spot sizes:
  - **Experimental** XY\(\text{rms}\)=0.30 mm (BSA=1.2 mm)
  - XY\(\text{rms}\)=0.4 mm → from **simulations**
- Simulated electron beam size at EMSY1 is still larger than the measured one
- Applying 0.3 mm laser spot to the simulation – it is impossible to produce \(1 \text{nC}\)!
Measured and Simulated Phase Space at EMSY1: 1nC

Measured

Simulated

Tails (~horizontal) in the beam distribution!
Reasone of discrepancy for high Q? → Emission from the cathode?

- Direct plug-un machine settings into ASTRA does not produce 1nC at the gun operation phase (+6deg), whereas 1nC and even higher charge (~1.2nC) are experimentally detected
- Simulated (ASTRA) phase scans w/o Schottky effects (solid thick lines) have different shapes than the experimentally measured (thin lines with markers)

**Possible reasons:**
- Field enhancement of the photo emission (Schottky-like effect) should be taken into account
- Laser imperfections (transverse halo and temporal tails) could contribute at high charge densities
Simulated (ASTRA) bunch charge for XYrms=0.32 mm

Using XYrms=0.30mm it was not possible to produce measured charges for any combination \((Q_0; S_{RT\_Q\_Schottky}; Q\_Schottky)\) \(\Rightarrow\) light increase of laser spot size? (e.g. from 0.30 mm to 0.32 mm rms)

\[
\begin{align*}
\text{ASTRA simulations:} & \\
\quad & \text{Ecath}=60.58\text{MV/m} \\
\quad & \text{Meas. Phase } \rightarrow +8\text{ deg (not } +6\text{deg!)} \\
\quad & \text{Laser XYrms}=0.32\text{mm (not 0.3mm!)} \\
\quad & \text{Qbunch(62%)=0.595nC; } Q\_\text{Schottky}=0.01\text{nC/(MV/m); } S_{RT\_Q\_Schottky}=0.05\text{nC/(MV/m)}^{1/2}
\end{align*}
\]
Corresponding beam emittance simulations

- **Opti (no Schottky)**
  - \( XY_{\text{rms}} = 0.40 \text{mm} \)
  - \( Q_{\text{bunch}} = 1 \text{nC} \)
  - \( Q_{\text{Schottky}} = 0.0 \text{nC} \)
  - \( \text{SRT}_{Q_{\text{Schottky}}} = 0.0 \text{nC} \)
  - 1nC e-beam, optimized simul.

- **No Schottky**
  - \( XY_{\text{rms}} = 0.32 \text{mm} \)
  - \( Q_{\text{bunch}} = 1 \text{nC} \)
  - \( Q_{\text{Schottky}} = 0.0 \text{nC} \)
  - \( \text{SRT}_{Q_{\text{Schottky}}} = 0.0 \text{nC} \)
  - 0.995nC e-beam

- **Schottky**
  - \( XY_{\text{rms}} = 0.32 \text{mm} \)
  - \( Q_{\text{bunch}}(62\%) = 0.595 \text{nC} \)
  - \( Q_{\text{Schottky}} = 0.01 \text{nC} \)
  - \( \text{SRT}_{Q_{\text{Schottky}}} = 0.05 \text{nC} \)
  - 1nC e-beam

\[ \text{Imain}^* \to \min(\varepsilon_{xy}) \]
Measured and Simulated Phase Space at EMSY1: 1nC bunches

measured
laserXYrms=0.3mm

simulated, no Schottky
laserXYrms=0.32mm

simulated+Schottky
laserXYrms=0.4mm
Problems

- Simulated optimum machine parameters (laser spot size and RF gun phase) ≠ to those obtained experimentally
- Photo emission (bunch charge) needs more detailed modeling in simulations
- Tails (~horizontal) in the beam distribution:
  - X-Y asymmetry
  - Large scaling factor (beamlets from tails are not detectable)

??Reasons:
- Remaining magnetizable components
- Vacuum mirror
- Solenoid imperfection
- Stray fields from IGPs
- …
Measurements vs. Simulations at PITZ-1.8: Summary

- PITZ serves also as a **benchmark** for theoretical understanding of the photo injector physics (beam dynamics simulations vs. measurements)
- BD simulations → to establish **experimental optimization procedure**
- Rather good agreement on **emittance values** between measurements and simulations
- Optimum machine parameters: **simulations ≠ experiment**
- Simulated and measured phase space:
  - Rather good agreement for **0.1 nC**
  - Large deviation for **higher charges**
  - Correlations have different signs for higher charges
- **Emission** (charge production) from experiment is not easy reproducible by nominal simulations:
  - Schottky-like effect?
  - Imperfection in the laser distributions (t- and r-tails)
  - More detailed studies (benchmarking + other codes) are needed
- **Tails** in X-Y distributions especially for high space charge dominated beams – ?reasons:
  - Remaining magnetizable components
  - Vacuum mirror
  - Solenoid imperfection
  - Stray fields from IGPs
  - …
## Simulation request for PITZ

<table>
<thead>
<tr>
<th>Observation / problem / idea</th>
<th>? to be simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core emittance</td>
<td>“Phase space collimator (beam scraper)” ?influence of image charges + wakes</td>
</tr>
<tr>
<td>Measured e-beam shape (asymmetry, tails), transverse phase space (emittance) depend on trajectory</td>
<td>• Magnetic components (active, passive), e.g. solenoid imperfections?</td>
</tr>
<tr>
<td></td>
<td>• Wake field (like) effects (VM, DDC,...)</td>
</tr>
<tr>
<td>Charge production, influence of real laser transverse and temporal profiles (imperfections)</td>
<td>Beam dynamics simulations, especially in the cathode vicinity (emission), slice emittance formation</td>
</tr>
<tr>
<td>E-beam matching into the tomography section</td>
<td>Using V-code with space charge to find quad strength</td>
</tr>
<tr>
<td>Particle driven plasma wake field acceleration</td>
<td>Self modulation of the driver, etc</td>
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</table>