Non-uniform transverse laser shaping for slice emittance improvement in photoinjector

‘Uniform’ Gaussian truncation vs ‘1-σ’ Gaussian truncation

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27.09.2018
Outline

- Motivation
- Beam dynamics simulation
- Transverse laser shaping modification at PITZ
- Slice emittance measurement for space charge beam
- Summary
‘Uniform’ Gaussian truncation vs ‘1-σ’ Gaussian truncation

LCLS-I injector example

- 2012, LCLS experience: (prst ab 15, 090701)
  - 150 pC, ~1.3 ps (rms) laser
  - Uniform → 1.1-σ Gaussian truncation

Experiment: projected emittance

Simulated slice emittance

Fixed BSA
Vary laser rms size

Pancake emission regime
z/x=0.1

Comparison of transverse space charge linearization
‘Uniform’ Gaussian truncation vs ‘1-σ’ Gaussian truncation

PITZ/FLASH experience

- 2010, Marc Hänel, PHD thesis (PITZ), 1 nC, 20 ps laser
- 2013, Tim Plath, Master thesis (FLASH), 20 pC, 1 ps laser
‘Uniform’ Gaussian truncation vs ‘1-σ’ Gaussian truncation

Beyond ‘pancake’ photoemission

- Three photoemission regimes
  - LCLS-I: ~3 GHz, ~115 MV/m
  - PITZ: ~1.3 GHz, ~60 MV/m
  - LCLS-II: ~0.187 GHz, ~20 MV/m

- Space charge force linearization

Transverse axis: x

Longitudinal axis: z

LCLS-I: z/x << 1
  - ‘pancake’ z/x~0.1

PITZ: z/x~1

LCLS-II: z/x >> 1
  - ‘cigar’ z/x~10
Why ‘1-\(\sigma\)’ Gaussian truncation

**Analytical prediction**

- A special parabolic radial distribution can linearize transverse space charge to the 3rd order
  - 2013, T. Rao and D. Dowell, *An engineering guide to photo injectors*

Truncation at 0.8 sigma  
Truncation at 0.9 sigma  
Truncation at 1.0 sigma

\[
\sigma(\rho) = \sigma_0 \left( 1 - \frac{\rho^2}{3R^2} \right)
\]

\( \sigma_0 \)  
\( R \)

\( z/x \approx 1 \)

![Graphs showing truncation at different sigma values]
‘Uniform’ Gaussian truncation vs ‘1-σ’ Gaussian truncation

PITZ injector full simulation

Temporal Gaussian laser (19 ps)

Temporal flattop laser (22 ps)

Slice emittance

<table>
<thead>
<tr>
<th>0.5 nC</th>
<th>Gaussian</th>
<th>Flattop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>0.38</td>
<td>0.36</td>
</tr>
<tr>
<td>Truncated Gaussian</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>Reduction</td>
<td>-0.24</td>
<td>-0.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1.0 nC</th>
<th>Gaussian</th>
<th>Flattop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>0.6</td>
<td>0.59</td>
</tr>
<tr>
<td>Truncated Gaussian</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Reduction</td>
<td>-0.32</td>
<td>-0.32</td>
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</tbody>
</table>

Proj. emittance

<table>
<thead>
<tr>
<th>0.5 nC</th>
<th>Gaussian</th>
<th>Flattop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Truncated Gaussian</td>
<td>0.58</td>
<td>0.31</td>
</tr>
<tr>
<td>Reduction</td>
<td>-0.17</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1.0 nC</th>
<th>Gaussian</th>
<th>Flattop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>1.1</td>
<td>0.65</td>
</tr>
<tr>
<td>Truncated Gaussian</td>
<td>0.87</td>
<td>0.46</td>
</tr>
<tr>
<td>Reduction</td>
<td>-0.21</td>
<td>-0.29</td>
</tr>
</tbody>
</table>

Need experimental proof!
Imaging from Laser to BSA (Current Setup: Telescope with $M = 10$)

### Baseline

- For varying bunch charge and further optimization → need variable laser spot size on cathode (current PITZ setup is fixed to FWHM ≈ 3 mm on BSA)

- Simulation results:
  - Image quality: RMS spot radius of on-axis and off-axis beams
  - Magnification (ratio of image size to object size $|IMA/OBJ|$ for off-axis beam)

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ZEMAX simulation results (ray tracing)

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20.09.2018
Total Axial Length: 13914.04000 mm
Vertical scale stretched by 200,000 x

Matthias Groß
DESY Zeuthen
Platanenallee 6
shift beam line CVT lenses optimized.zmx
Configuration 1 of 1
Requirement: Zoom Range of Telescope (Magnification M)

Specifications for truncated Gaussian and THz experiments

- Looking for charge range of 20 pC to 2 nC (emittance characterization at PITZ)
  - minimal BSA size (=2\(\sigma\) of laser distribution): is 0.8 mm \(\rightarrow\) \(M = 3.3 \rightarrow M_{\text{min}} = 2.5\) (with safety margin)
  - maximal BSA size used: 3mm \(\rightarrow\) \(M = 10\), but:
  - For THz experiments: telescope magnification of \(M_{\text{max}} = 20\) would be helpful
    - Then the laser FWHM size is about 6 mm and the photocathode is fully illuminated

- Additional conditions:
  - For later experiments with “green photocathodes”: Check performance for 515 nm laser wavelength
  - Fits to existing laser beamline (lenses)
Simulation Results
Add Galileian zoom telescope with 3 lenses (f: 500 mm - 25 mm 500 mm)

- Image quality for second harmonic (515 nm) almost identical to 257 nm case

<table>
<thead>
<tr>
<th>Telescope config</th>
<th>Magnification</th>
<th>RMS radius on-axis</th>
<th>RMS radius off-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current setup</td>
<td>9.8</td>
<td>&lt;1 µm</td>
<td>&lt;1 µm</td>
</tr>
<tr>
<td>Telescope config 1</td>
<td>20.0</td>
<td>&lt;1 µm</td>
<td>&lt;1 µm</td>
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<tr>
<td>Telescope config 2</td>
<td>10.0</td>
<td>&lt;1 µm</td>
<td>&lt;1 µm</td>
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<tr>
<td>Telescope config 3</td>
<td>5.0</td>
<td>&lt;1 µm</td>
<td>2.0 µm</td>
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<tr>
<td>Telescope config 4</td>
<td>2.5</td>
<td>2.0 µm</td>
<td>7.5 µm</td>
</tr>
</tbody>
</table>

07.06.2018
Total Axial Length: 11914,30000 nm
Vertical scale stretched by 200,000 X
Moving Range of Lenses in Telescope

Requirement for moving stages

• \( L_1 \) is fixed

\[
\begin{align*}
\text{L}_3 & : 48 \text{ mm} \\
\text{L}_3(\text{green}) & : 52 \text{ mm} \\
\text{L}_3(\text{total}^*) & : 168 \text{ mm} \\
\text{L}_2(\text{UV}) & : 82 \text{ mm} \\
\text{L}_2(\text{green}) & : 89 \text{ mm} \\
\text{L}_2(\text{total}^*) & : 156 \text{ mm} \\
\end{align*}
\]

• Result: telescope works for the requested range

*one setup for both wavelengths
Telescope Setup

Design is ready; parts are ordered; setup this fall
Slice emittance measurement for space charge beam

1st test at PITZ looks promising

- New slice emittance measurement technique is under commissioning at PITZ
Summary

• Simulations
  • ‘1-σ’ Gaussian truncation VS ‘uniform’ Gaussian truncation
  • PITZ slice emittance (0.5 – 1 nC) improves by 24-32%
• PITZ laser shaping redesign
  • Variable laser beam sizes at cathode with ‘1-σ’ Gaussian truncation
  • For both UV and green laser
  • Setup to be done this fall
• Experiment planning
  • Slice emittance for space charge dominated beam is under commissioning.
  • Measurement will start next year to test the ‘1-σ’ Gaussian truncation
• If verified in experiment, both beam emittance and UV efficiency can be improved for PITZ/FLASH/XFEL.