DOE laser beam shaping at XFEL
On the Generation of Spatial Flat-Top Laser Spots
and the Influence of Optical Errors on the Beam Dynamics

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Optical Setup:
Steffen Schmid (TEMF), Sebastian Pumpe (DESY)

Beam Simulations:
Martin Dohlus (DESY)
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Laser Beam of the XFEL-Photogun

**PITZ / XFEL-Photogun**

Spatial Laser Spot Profile

⇒ Spatial flat-top profile of laser spot on cathode needed

**Two Possibilities:**

“Old“: Beam Shaping Aperture (BSA)
“New“: Diffractive Optical Elements (DOE)
"Old Method“ - BSA
(≡ Optical Imaging of an Aperture)

+ Robust against deviations of input beam quality

- Sophisticated imaging system needed
- Smaller spot sizes require larger optics
- 98% of laser intensity gets lost (leads to further problems)
"New Method" - DOE
(≡ Spatial Phase Modulation of Gaussian Laser Beam)

Optical lens transfer function:

\[ g_o(x_o, y_o) = e^{i\pi \frac{(x_o^2 + y_o^2)}{\lambda f}} (1 - \frac{z}{f}) \ldots \]

\[ \ldots \int \int g_i(x_i, y_i) e^{-\frac{2\pi i}{\lambda f}(x_o \cdot x_i + y_o \cdot y_i)} \, dx_i \, dy_i \]

⇒ Fourier Transformation

(Formula: MIT 2.71/2.710 04/08/09 wk9-b-18)
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“New Method“ - DOE
(≡ Spatial Phase Modulation of Gaussian Laser Beam)

+ “Simple” imaging system
+ Smaller spot sizes (< 50 μm) possible
+ Only ~3% of laser intensity gets lost (increases setup stability)

- Sensitive on input beam quality

DESY. Original slide by Sebastian Pumpe, edited by Steffen Schmid
BSA and DOE spatial shaping at XFEL

Setup

A: BSA

 Efficiency: 10%

B: DOE

 Efficiency: 94%
Wavelength dependence of DOE

XFEL Laser 1: 257 nm
XFEL Laser 2: 266 nm

measured (266 nm)

DOE designed for 257 nm
Measured transverse Profiles und Ideal Pencil Profiles

\[ \frac{\sigma_x}{\sigma_z} = 1.19 \]
\[ \sqrt{\sigma_x \sigma_y} = 0.256 \text{ mm} \]
\[ \rightarrow \text{pencil 1} \]

\[ \frac{\sigma_x}{\sigma_z} = 1.18 \]
\[ \sqrt{\sigma_x \sigma_y} = 0.272 \text{ mm} \]
\[ \rightarrow \text{pencil 2} \]
Measured transverse Profiles and Ideal Pencil Profiles

clipped (saturated)
Summary: Optical Setup

- Laser output to cathode transmission efficiency $T$ increased
  - Beam Shaping Aperture (BSA): $T = 10\%$
  - Diffractive Optical Element (DOE): $T = 94\%$
  - Investigate long-term stability of DOE system

- Laser used for measurements (266nm) $\neq$ DOE design (257nm)
  - Clipped 0th order peak in DOE spot intensity map
  - Repeat measurements with $\lambda_{laser} = 257$nm

- BSA & DOE laser spots are both elliptical
  - Effect of optics downstream of beam shaping setup
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Gun Simulation with Krack

Krack is an implementation of a Poisson solver (approach 2 or EB-method); it uses binning of the charge to an equidistant grid and the convolution with a kernel function (charged cuboids).

The start distribution is Gaussian in time (6.65 psec rms) and according to the measured profiles in the transverse dimension; simulations have been done with 250 pC, 400 pC and 500 pC with 1E6 particles.

The transverse resolution is $0.07 \sigma_t$; all external fields (gun, solenoid and 8 tesla cavities) have rz-symmetry; the distribution is tracked from the cathode to the exit of the last cavity of ACC1;

The injection is calculated with 500 time steps and a longitudinal resolution better than 10 $\mu$m by a 2$^{nd}$ order RK-integrator; the rest is calculated with a longitudinal resolution of $0.05 \sigma_z$ by a 5$^{th}$ order RK-integrator;

The gun-phase and solenoid strength are optimized for minimal projected emittance after ACC1; criterion $\varepsilon_{x,n} \varepsilon_{x,n} = \min$
Overview: Simulation of 250 pC from Cathode through ACC1 to Z=14.2 m

C_20180421 (DOE)
\(B_{\text{sol}} = 0.2050 \ T\)
\(\varphi = \varphi_0 - 2.0 \ \text{deg}\)
\(Q = 250 \ \text{pC}\)
\(I_{\text{peak}} = 13.85 \ \text{A}\)
\(\alpha_x = -4.79\)
\(\alpha_y = -2.49\)
\(\beta_x = 47.5 \ \text{m}\)
\(\beta_y = 29.6 \ \text{m}\)
\(\varepsilon_{x,p} = 0.776 \ \mu\text{m}\)
\(\varepsilon_{y,p} = 0.975 \ \mu\text{m}\)
\(\varepsilon_{x,s} = 0.66 \ \mu\text{m}\)
\(\varepsilon_{y,s} = 0.78 \ \mu\text{m}\)

C_20180422 (BSA)
\(B_{\text{sol}} = 0.2050 \ T\)
\(\varphi = \varphi_0 - 2.0 \ \text{deg}\)
\(Q = 250 \ \text{pC}\)
\(I_{\text{peak}} = 13.93 \ \text{A}\)
\(\alpha_x = -5.40\)
\(\alpha_y = -5.61\)
\(\beta_x = 53.1 \ \text{m}\)
\(\beta_y = 54.1 \ \text{m}\)
\(\varepsilon_{x,p} = 0.614 \ \mu\text{m}\)
\(\varepsilon_{y,p} = 0.612 \ \mu\text{m}\)
\(\varepsilon_{x,s} = 0.375 \ \mu\text{m}\)
\(\varepsilon_{y,s} = 0.375 \ \mu\text{m}\)

Measured (DOE):
\(\varepsilon_{x,p} = 0.858 \ \text{mm} \cdot \text{mrad}\)
\(\varepsilon_{y,p} = 0.802 \ \text{mm} \cdot \text{mrad}\)

projected/slice emittance
slice properties at z\(I_{\text{peak}}\)

pencil 1 (sigma = 0.256 mm)
\(B_{\text{sol}} = 0.2050 \ T\)
\(\varphi = \varphi_0 - 2.0 \ \text{deg}\)
\(Q = 250 \ \text{pC}\)
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\(\varepsilon_{x,s} = 0.375 \ \mu\text{m}\)
\(\varepsilon_{y,s} = 0.375 \ \mu\text{m}\)

pencil 2 (sigma = 0.272 mm)
\(B_{\text{sol}} = 0.2050 \ T\)
\(\varphi = \varphi_0 - 2.0 \ \text{deg}\)
\(Q = 250 \ \text{pC}\)
\(I_{\text{peak}} = 14.14 \ \text{A}\)
\(\alpha_x = -4.77\)
\(\alpha_y = -4.69\)
\(\beta_x = 43.0 \ \text{m}\)
\(\beta_y = 42.4 \ \text{m}\)
\(\varepsilon_{x,p} = 0.647 \ \mu\text{m}\)
\(\varepsilon_{y,p} = 0.647 \ \mu\text{m}\)
\(\varepsilon_{x,s} = 0.38 \ \mu\text{m}\)
\(\varepsilon_{y,s} = 0.38 \ \mu\text{m}\)
Overview: Simulation of 400 pC from Cathode through ACC1 to Z=14.2 m

C_20180421 (DOE)
B_{sol} = 0.2055 T \varphi = \varphi_0 - 2.7 \text{ deg}
Q = 397 pC \ I_{\text{peak}} = 19.08 A
\alpha_x = -3.13 \quad \alpha_y = -2.14
\beta_x = 32.5 m \quad \beta_y = 31.2 m
\epsilon_{x,p} = 0.835 \mu m \quad \epsilon_{y,p} = 1.04 \mu m
\epsilon_{x,s} = 0.73 \mu m \quad \epsilon_{y,s} = 0.80 \mu m

C_20180422 (BSA)
B_{sol} = 0.2055 T \varphi = \varphi_0 - 2.9 \text{ deg}
Q = 400 pC \ I_{\text{peak}} = 19.84 A
\alpha_x = -4.04 \quad \alpha_y = -2.45
\beta_x = 38.9 m \quad \beta_y = 32.8 m
\epsilon_{x,p} = 0.753 \mu m \quad \epsilon_{y,p} = 1.02 \mu m
\epsilon_{x,s} = 0.62 \mu m \quad \epsilon_{y,s} = 0.81 \mu m

pencil 1 (sigma = 0.256 mm)
B_{sol} = 0.2055 T \varphi = \varphi_0 - 3.0 \text{ deg}
Q = 400 pC \ I_{\text{peak}} = 19.36 A
\alpha_x = -3.23 \quad \alpha_y = -3.31
\beta_x = 36.4 m \quad \beta_y = 37.5 m
\epsilon_{x,p} = 0.629 \mu m \quad \epsilon_{y,p} = 0.632 \mu m
\epsilon_{x,s} = 0.51 \mu m \quad \epsilon_{y,s} = 0.51 \mu m

pencil 2 (sigma = 0.272 mm)
B_{sol} = 0.2055 T \varphi = \varphi_0 - 2.5 \text{ deg}
Q = 400 pC \ I_{\text{peak}} = 19.88 A
\alpha_x = -2.62 \quad \alpha_y = -2.49
\beta_x = 28.3 m \quad \beta_y = 27.0 m
\epsilon_{x,p} = 0.653 \mu m \quad \epsilon_{y,p} = 0.656 \mu m
\epsilon_{x,s} = 0.50 \mu m \quad \epsilon_{y,s} = 0.50 \mu m
Overview: Simulation of 500 pC from Cathode through ACC1 to Z=14.2 m

**C_20180421 (DOE)**
- $B_{sol} = 0.2055 \, T$
- $\varphi = \varphi_0 - 4.0 \, \text{deg}$
- $Q = 474 \, \text{pC}$
- $I_{peak} = 21.10 \, \text{A}$
- $\alpha_x = -2.77$
- $\alpha_y = -2.18$
- $\beta_x = 30.0 \, \text{m}$
- $\beta_y = 33.6 \, \text{m}$
- $\varepsilon_{x,p} = 0.866 \, \mu\text{m}$
- $\varepsilon_{y,p} = 1.03 \, \mu\text{m}$
- $\varepsilon_{x,s} = 0.80 \, \mu\text{m}$
- $\varepsilon_{y,s} = 0.80 \, \mu\text{m}$

**C_20180422 (BSA)**
- $B_{sol} = 0.2055 \, T$
- $\varphi = \varphi_0 - 3.5 \, \text{deg}$
- $Q = 498 \, \text{pC}$
- $I_{peak} = 21.41 \, \text{A}$
- $\alpha_x = -3.53$
- $\alpha_y = -2.58$
- $\beta_x = 36.3 \, \text{m}$
- $\beta_y = 36.7 \, \text{m}$
- $\varepsilon_{x,p} = 0.817 \, \mu\text{m}$
- $\varepsilon_{y,p} = 1.08 \, \mu\text{m}$
- $\varepsilon_{x,s} = 0.69 \, \mu\text{m}$
- $\varepsilon_{y,s} = 0.87 \, \mu\text{m}$

**pencil 1 (sigma = 0.256 mm)**
- $B_{sol} = 0.2055 \, T$
- $\varphi = \varphi_0 - 3.2 \, \text{deg}$
- $Q = 498 \, \text{pC}$
- $I_{peak} = 21.41 \, \text{A}$
- $\alpha_x = -3.45$
- $\alpha_y = -3.40$
- $\beta_x = 43.9 \, \text{m}$
- $\beta_y = 43.1 \, \text{m}$
- $\varepsilon_{x,p} = 0.749 \, \mu\text{m}$
- $\varepsilon_{y,p} = 0.749 \, \mu\text{m}$
- $\varepsilon_{x,s} = 0.70 \, \mu\text{m}$
- $\varepsilon_{y,s} = 0.70 \, \mu\text{m}$

**pencil 2 (sigma = 0.272 mm)**
- $B_{sol} = 0.2057 \, T$
- $\varphi = \varphi_0 - 2.8 \, \text{deg}$
- $Q = 500 \, \text{pC}$
- $I_{peak} = 22.52 \, \text{A}$
- $\alpha_x = -2.75$
- $\alpha_y = -2.68$
- $\beta_x = 33.4 \, \text{m}$
- $\beta_y = 32.9 \, \text{m}$
- $\varepsilon_{x,p} = 0.719 \, \mu\text{m}$
- $\varepsilon_{y,p} = 0.724 \, \mu\text{m}$
- $\varepsilon_{x,s} = 0.64 \, \mu\text{m}$
- $\varepsilon_{y,s} = 0.64 \, \mu\text{m}$

**Projected/slice emittance**
- Slice properties at $z(I_{peak})$

**DESY.**
A Figure of Merit

\[
L_g = 1.18 \sqrt{\frac{I_A}{I_{\text{peak}}}} \left( \frac{\varepsilon_r \lambda_w}{\lambda_i^{2/3}} \right)^{5/6} \left( 1 + \frac{K^2}{2} \right)^{1/3} \frac{K \Gamma_{JJ}}{A} \left( 1 + \delta \left( \sigma_r, L \right) \right)
\]

\[
f = \frac{\left( \varepsilon_{\lambda,s} \varepsilon_{\lambda,s} \right)^{5/12}}{\sqrt{I_{\text{peak}}}} \frac{\sqrt{A}}{(\mu\text{m})^{5/6}}
\]

<table>
<thead>
<tr>
<th>Voltage (pC)</th>
<th>File Name</th>
<th>f Value</th>
<th>Z Value (m)</th>
</tr>
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<tbody>
<tr>
<td>250</td>
<td>C_20180421 (DOE)</td>
<td>0.2038</td>
<td>14.2</td>
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<tr>
<td></td>
<td>C_20180422 (BSA)</td>
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<tr>
<td></td>
<td>pencil_1</td>
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</tr>
<tr>
<td></td>
<td>pencil_2</td>
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<td>C_20180421 (DOE)</td>
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<tr>
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<td>pencil_2</td>
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<tr>
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<td>C_20180421 (DOE)</td>
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</tr>
<tr>
<td></td>
<td>pencil_2</td>
<td>0.1508</td>
<td></td>
</tr>
</tbody>
</table>
Summary/Conclusion: Gun Simulations

**simulation for 250pC:** pencil emittances < BSA emittances < DOE emittances; this is more pronounced for slice emittances → there is a lot to gain by a flat profile

**simulation for 500pC:** saturation effects, differences in emittance are less significant

figure of merit based on gain length prefers flat beams with lower charge
Summary/Conclusion

DOE measurements have been done with laser 2 (266 nm); the measured profile is not flat; better results are expected for laser 1 (257 nm);

measured DOE profile is clipped

BSA & DOE beams are not round → it is not possible to optimize both foci simultaneously

simulation for 250pC: pencil emittances < BSA emittances < DOE emittances;
this is more pronounced for slice emittances → there is a lot to gain by a flat profile
simulation for 500pC: saturation effects, differences in emittance are less significant

figure of merit based on gain length prefers flat beams with lower charge

DOE measurements with laser 1 are planned