# 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

**DESY/TEMF Meeting, Spring 2018**

TEMF, Darmstadt, 8.6.2018


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

**Beam Simulations:**
Martin Dohlus (DESY)


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

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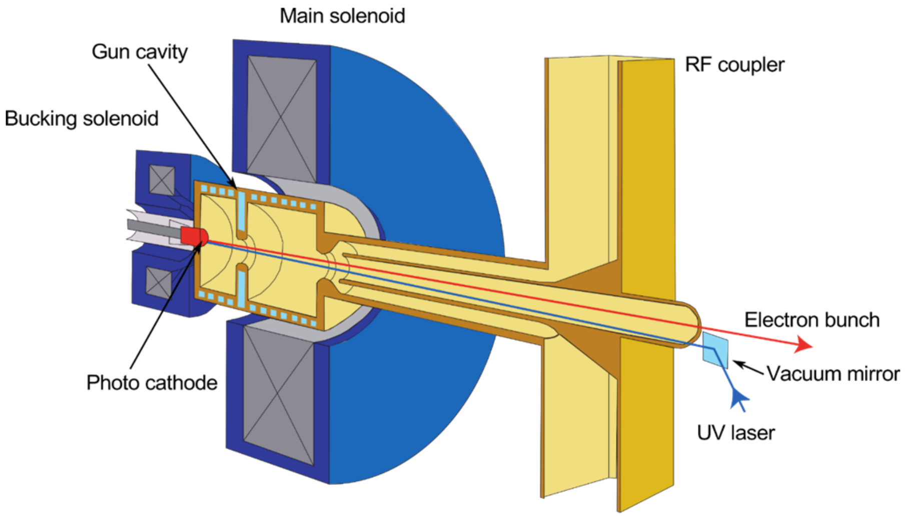
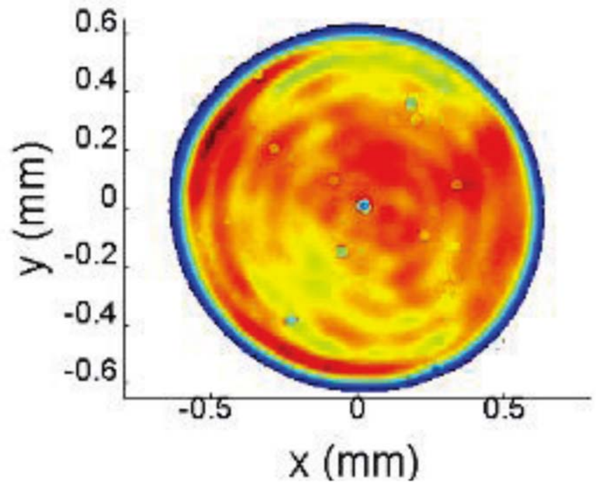
# Laser Beam of the XFEL-Photogun

## PITZ / XFEL-Photogun




(Image source: R. Martin, Master thesis, Institute of Physics, HU Berlin, 2013)

## Spatial Laser Spot Profile



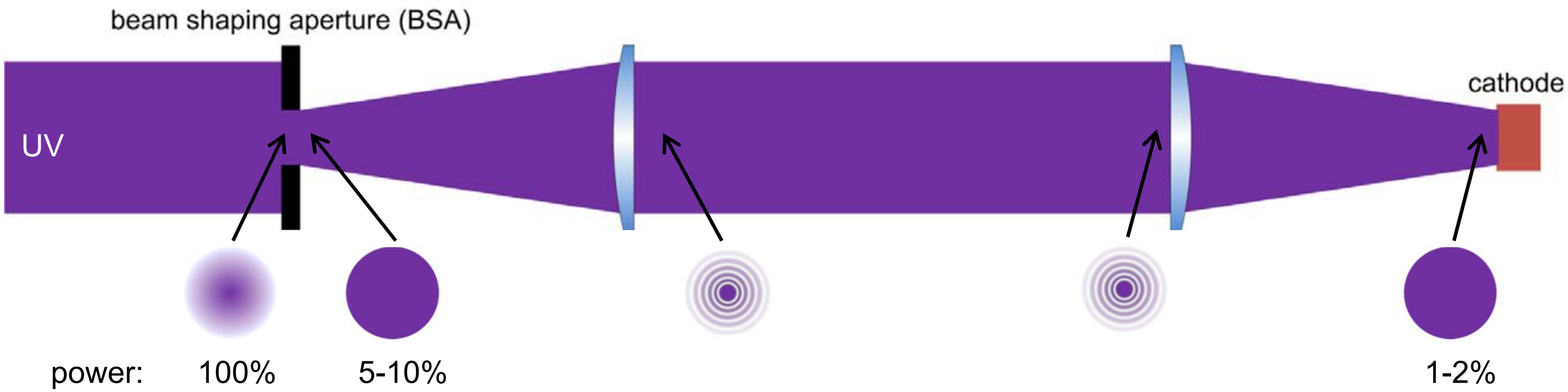

(Image source: M. Krasilnikov, et al., FEL2013, New York)

**⇒ 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)

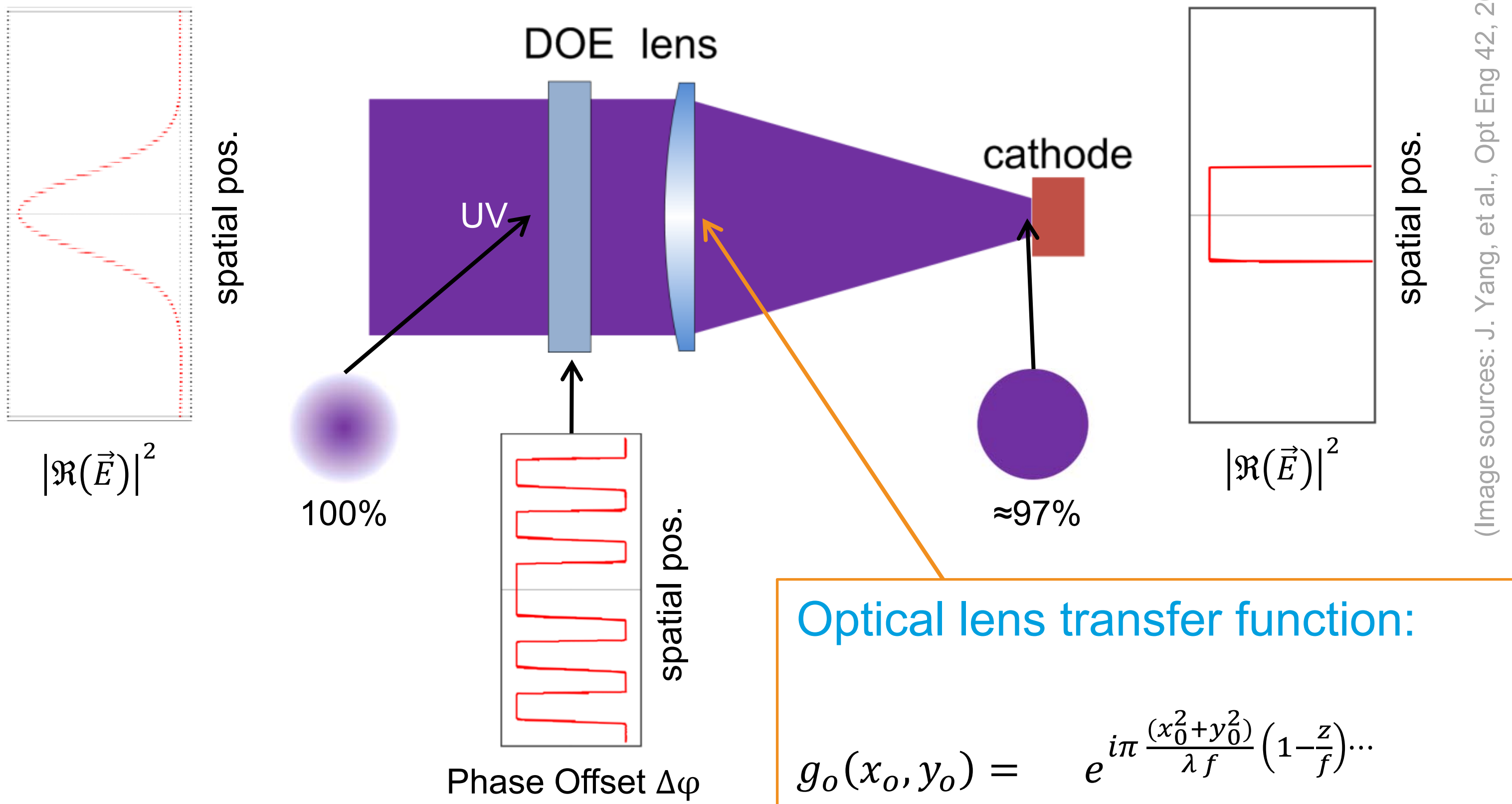



**+ Robust against deviations of input beam quality**

**- 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:**

$$g_o(x_o, y_o) = e^{i\pi \frac{(x_0^2+y_0^2)}{\lambda f}\left(1-\frac{z}{f}\right)} \cdots$$

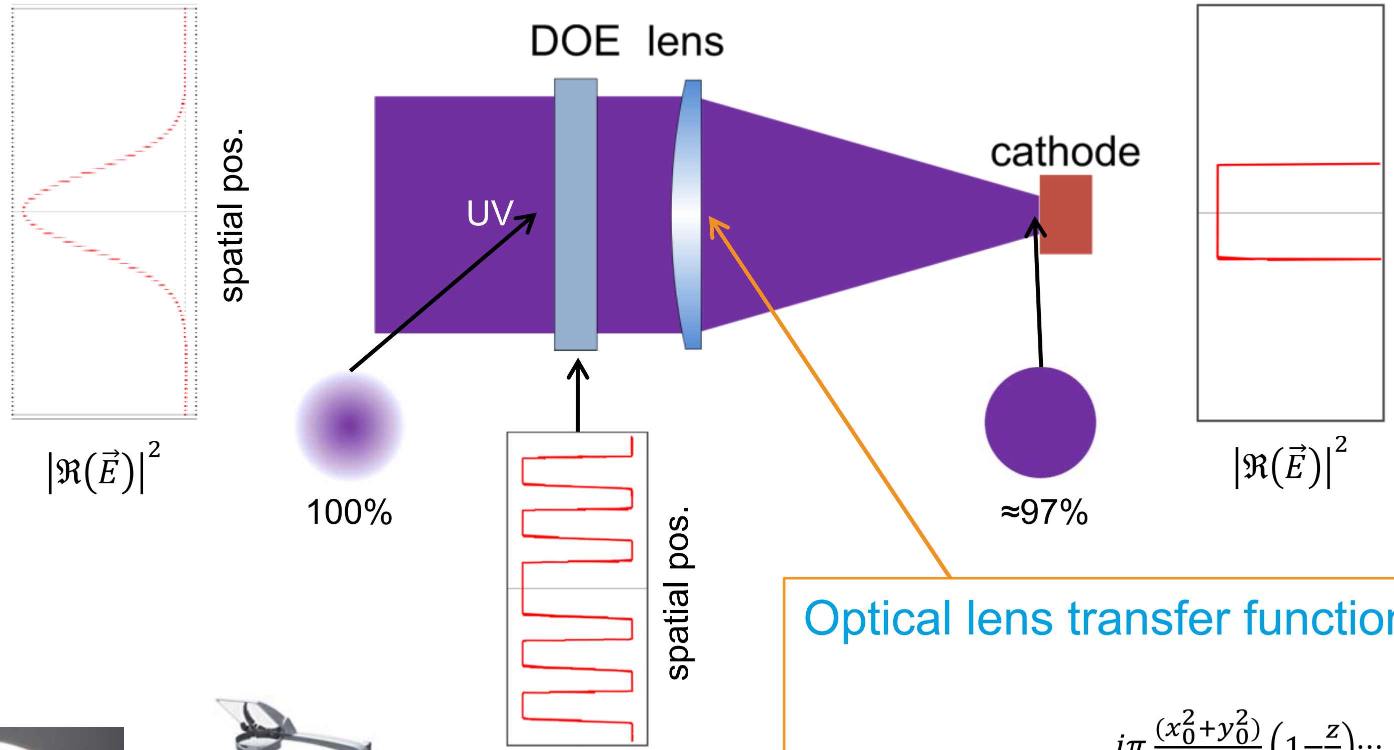
$$\cdots \iint g_i(x_i, y_i)\, e^{-\frac{2\pi i}{\lambda f}(x_o \cdot x_i + y_o \cdot y_i)}\, dx_i\, dy_i$$

⇒ Fourier Transformation

(Formula: MIT 2.71/2.710 04/08/09 wk9-b-18 )

# ”New Method“ - DOE

## (≡ Spatial Phase Modulation of Gaussian Laser Beam)




(Image sources: J. Yang, et al., Opt Eng 42, 2003)

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(lasercomponents.com)

(Apollo Model 1600)

# “New Method“ - DOE

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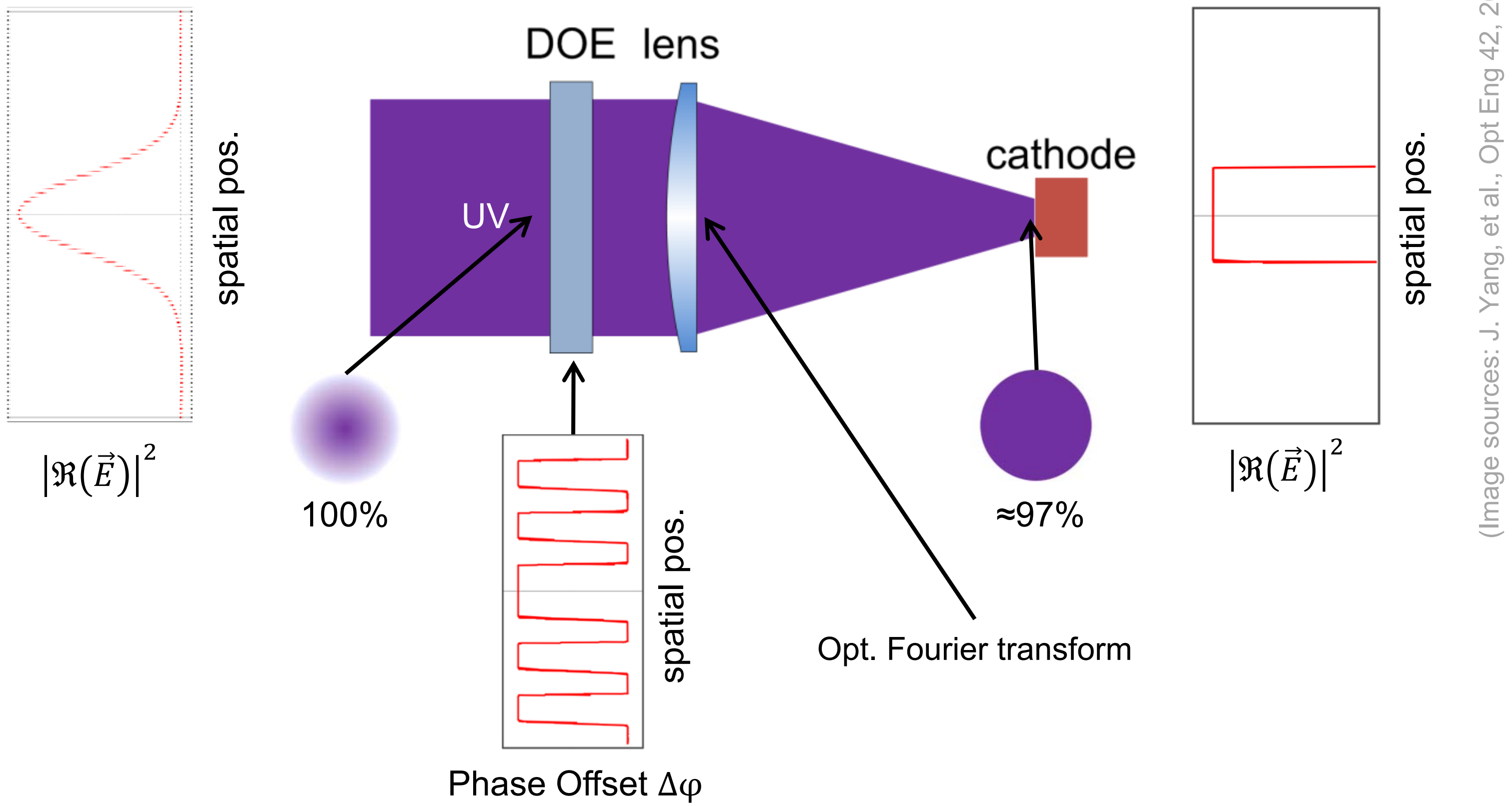
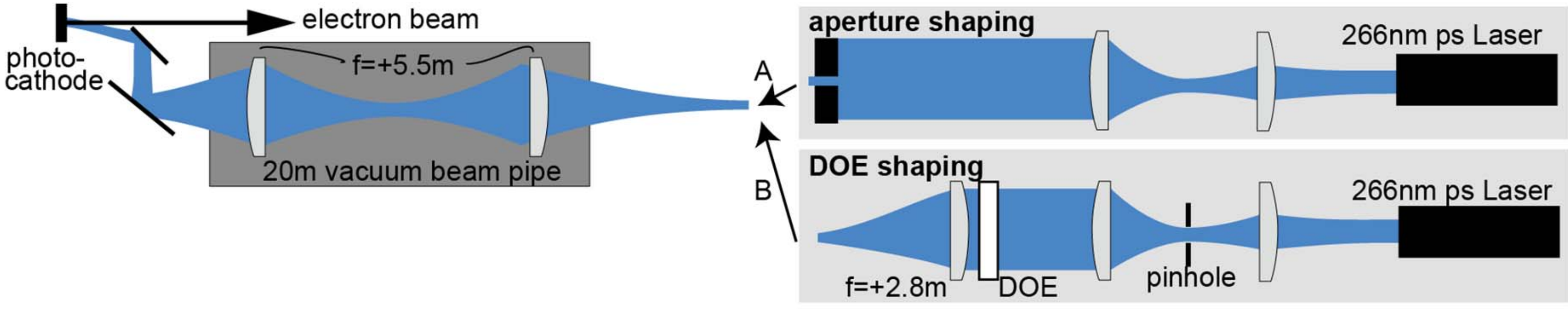



**+ “Simple” imaging system**
**+ Smaller spot sizes $(< 50\ \mu m)$ possible**
**+ Only $\sim 3\%$ of laser intensity gets lost ( increases setup stability )**

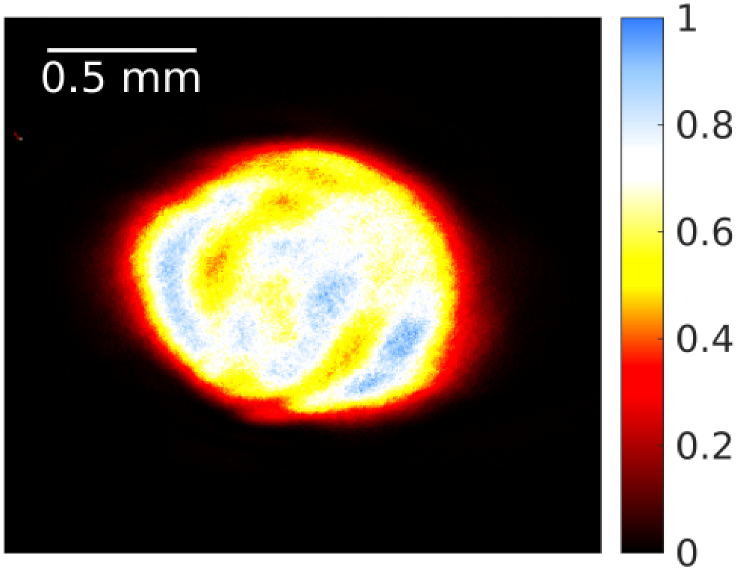
**- Sensitive on input beam quality**

# BSA and DOE spatial shaping at XFEL

Setup

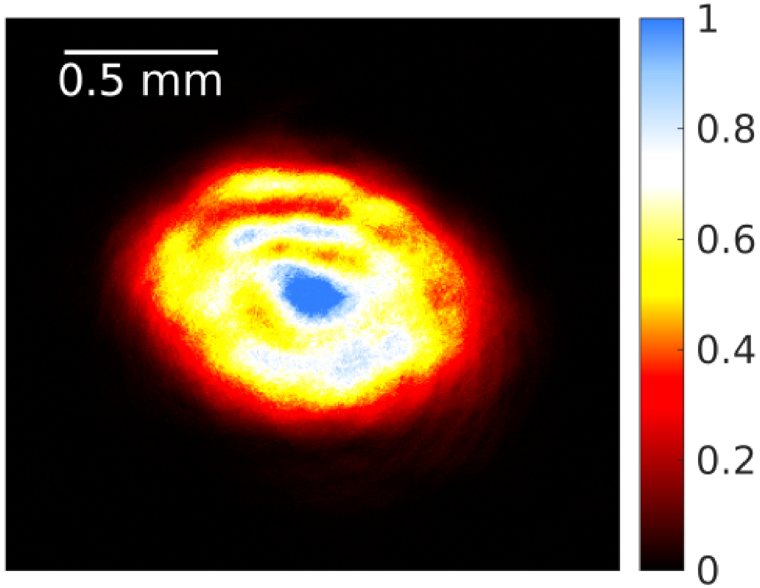



A: BSA




Efficiency: 10 %

B: DOE

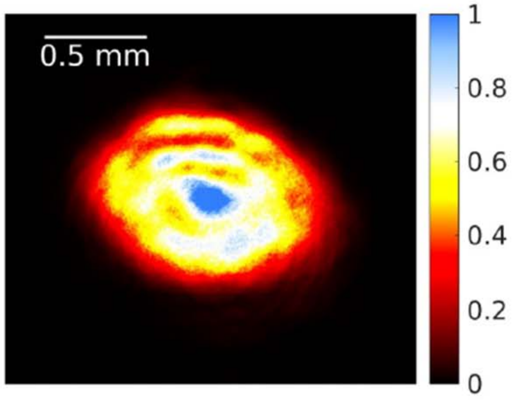



Efficiency: 94 %

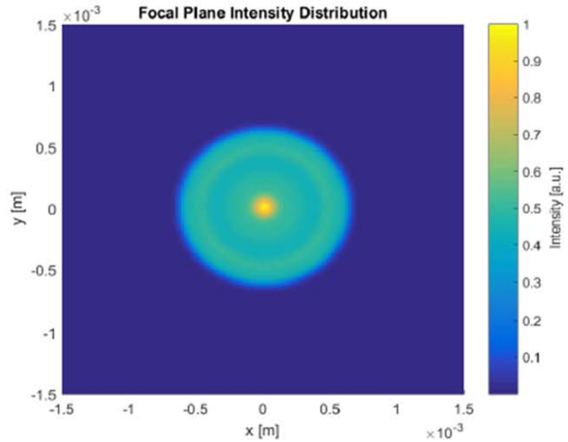
# Wavelength dependence of DOE

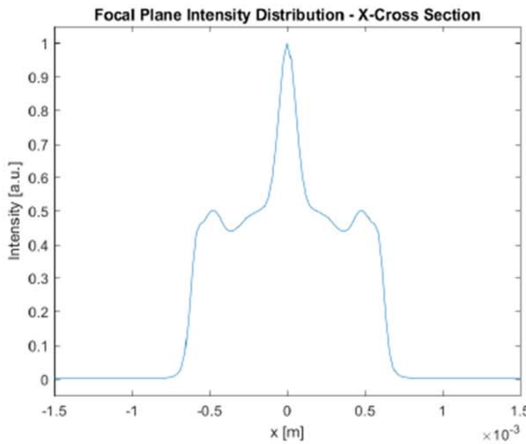
## XFEL Laser 1: 257 nm
## XFEL Laser 2: 266 nm

measured (266 nm)

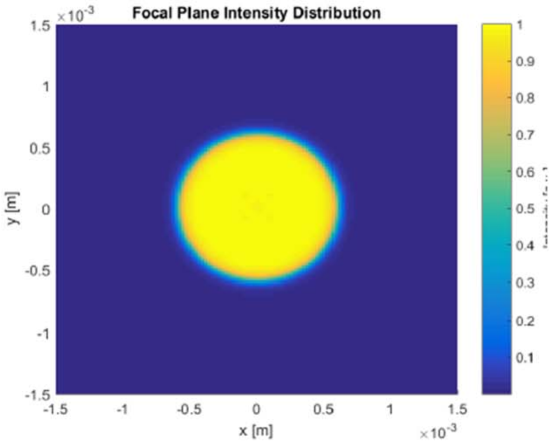


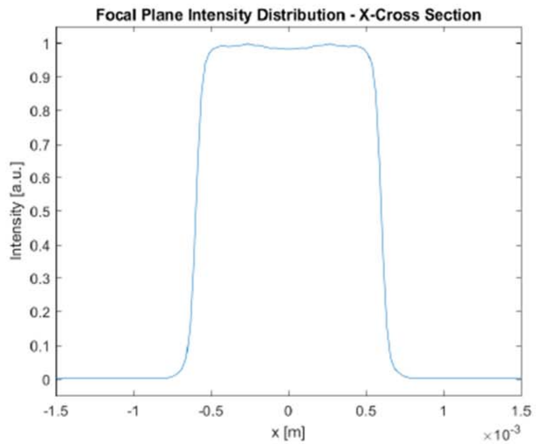

266 nm




257 nm

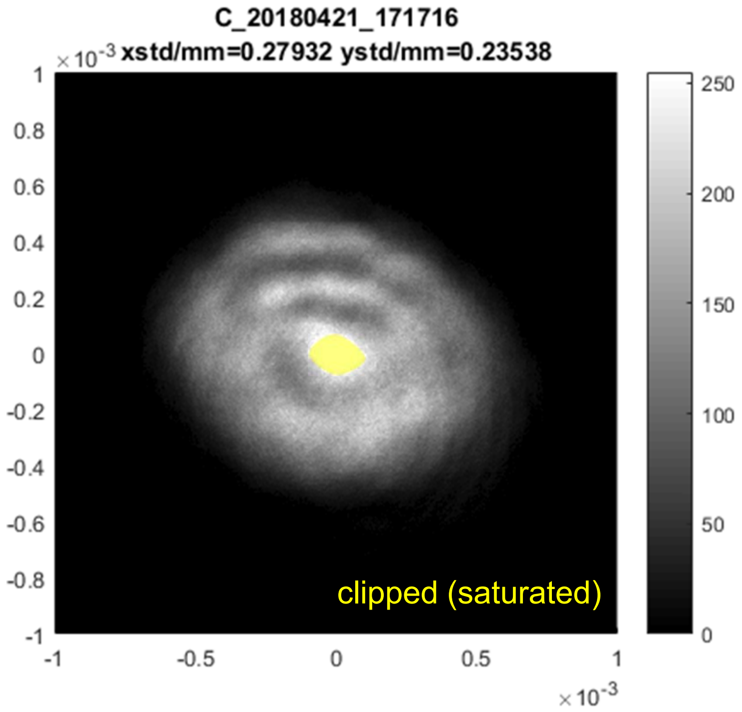



DOE designed for 257 nm

# Measured transverse Profiles und Ideal Pencil Profiles

DOE

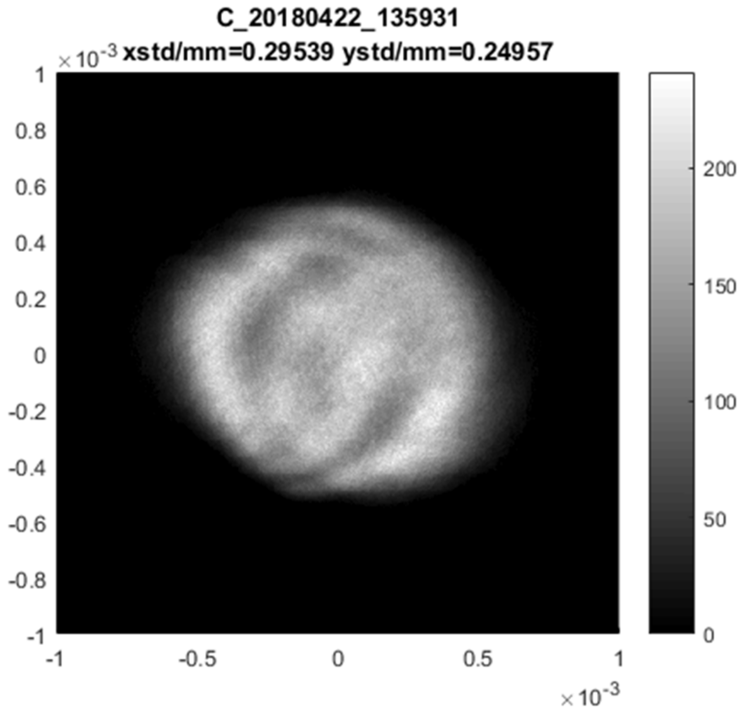



$$\frac{\sigma_x}{\sigma_z} = 1.19$$

$$\sqrt{\sigma_x \sigma_y} = 0.256 \text{ mm}$$

$\rightarrow$ pencil 1

BSA

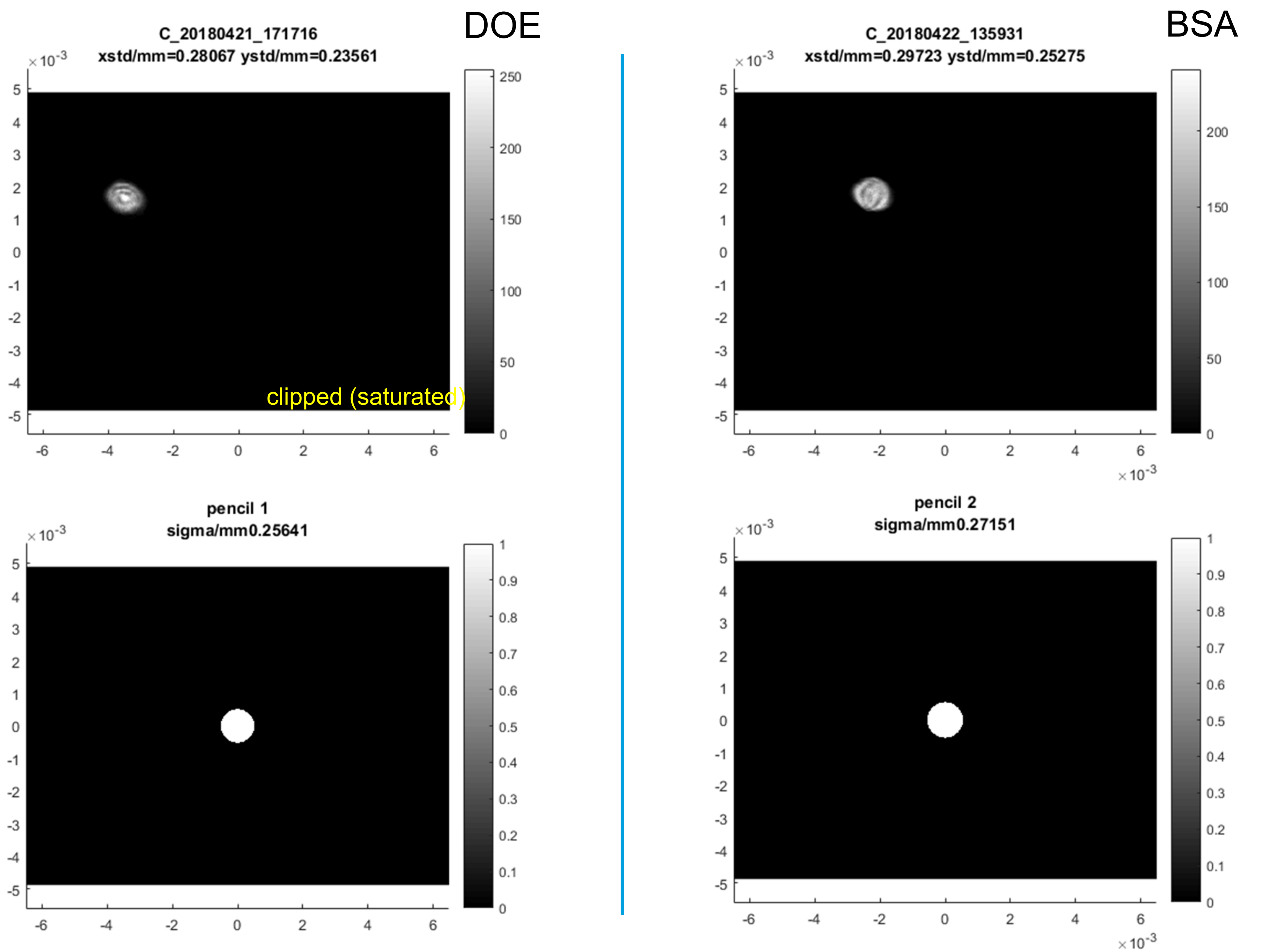



$$\frac{\sigma_x}{\sigma_z} = 1.18$$

$$\sqrt{\sigma_x \sigma_y} = 0.272 \text{ mm}$$

$\rightarrow$ pencil 2

# Measured transverse Profiles and Ideal Pencil Profiles



# 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 $0^{th}$ order peak in DOE spot intensity map

  ⇒ Repeat measurements with $\lambda_{laser} = 257\text{nm}$

- **BSA & DOE laser spots are both elliptical**

  ⇒ Effect of optics downstream of beam shaping setup

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# Beam Simulations

Martin Dohlus (DESY)

# 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)

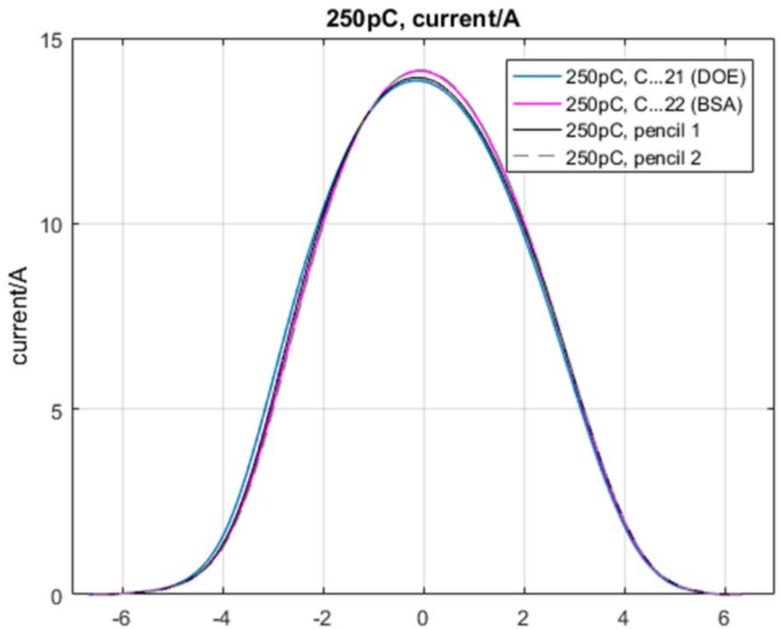
the start distribution is Gaussian in time (6.65 psec rms) and according to the measured profiles in the transverse dimension; simulations have been done with 250 pC, 400 pC and 500 pC with 1E6 particles

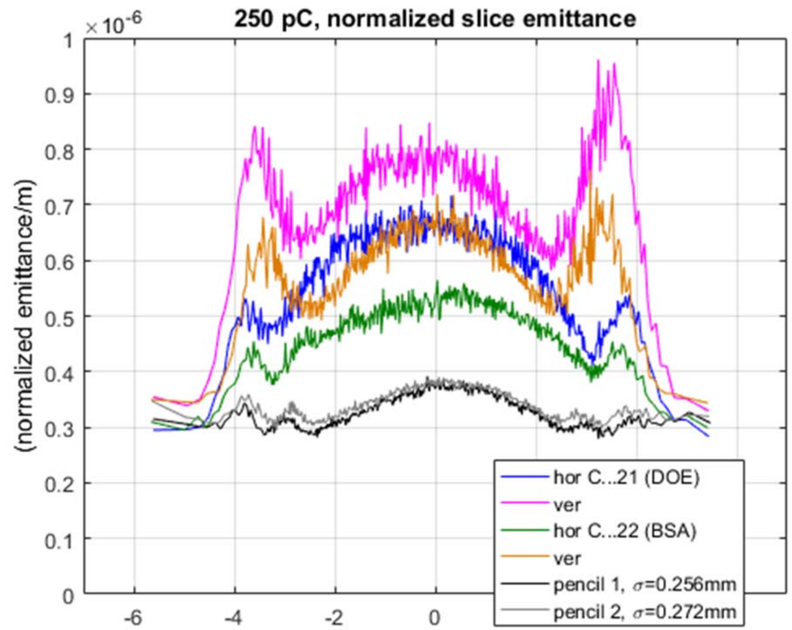
the transverse resolution is $0.07\sigma_t$; all external fields (gun, solenoid and 8 tesla cavities) have rz-symmetry; the distribution is tracked from the cathode to the exit of the last cavity of ACC1;

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




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

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

pencil 1 (sigma = 0.256 mm)
$B_{sol}$ = 0.2050 T $\varphi = \varphi_0 - 2.0$ deg
Q = 250 pC $I_{peak}$ = 13.93 A
$\alpha_x$ = –5.40 $\alpha_y$ = –5.61
$\beta_x$ = 53.1 m $\beta_y$ = 54.1 m
**$\varepsilon_{x,p}$ = 0.614 μm $\varepsilon_{y,p}$ = 0.612 μm**
**$\varepsilon_{x,s}$ = 0.375 μm $\varepsilon_{y,s}$ = 0.375 μm**

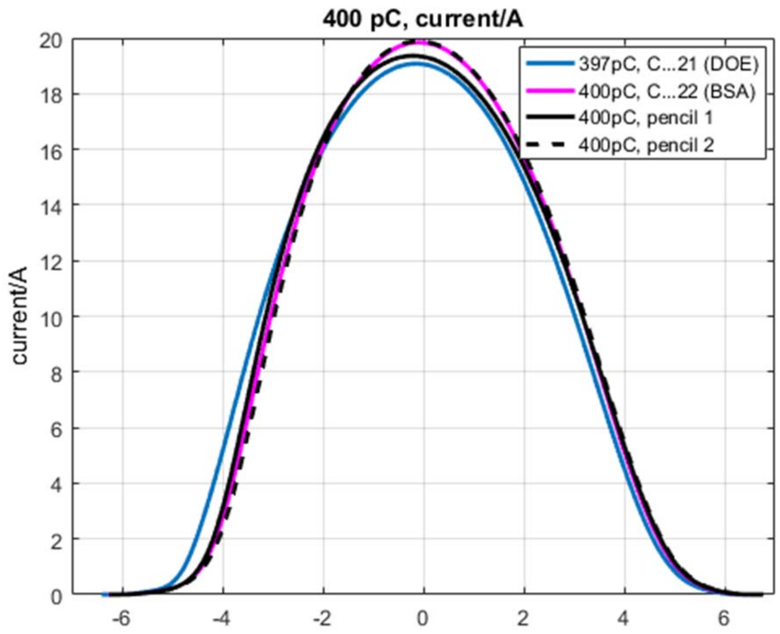
Measured (BSA):
$\varepsilon_{x,p} = 1.1223$ mm·mrad
$\varepsilon_{y,p} = 1.187$ mm·mrad

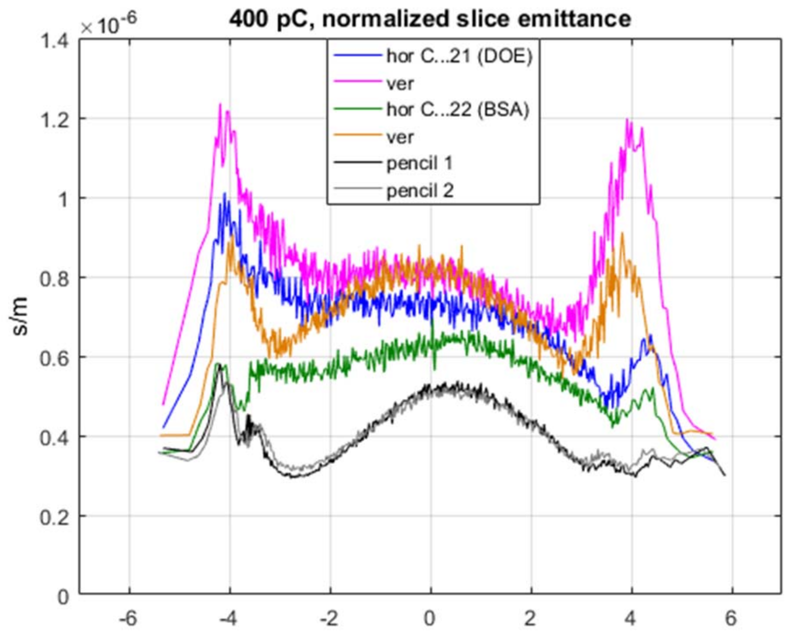
C_20180422 (BSA)
$B_{sol}$ = 0.2050 T $\varphi = \varphi_0 - 2.0$ deg
Q = 250 pC $I_{peak}$ = 14.11 A
$\alpha_x$ = –5.58 $\alpha_y$ = –2.45
$\beta_x$ = 50.5 m $\beta_y$ = 27.5 m
**$\varepsilon_{x,p}$ = 0.708 μm $\varepsilon_{y,p}$ = 0.925 μm**
**$\varepsilon_{x,s}$ = 0.53 μm $\varepsilon_{y,s}$ = 0.67 μm**

pencil 2 (sigma = 0.272 mm)
$B_{sol}$ = 0.2050 T $\varphi = \varphi_0 - 2.0$ deg
Q = 250 pC $I_{peak}$ = 14.14 A
$\alpha_x$ = –4.77 $\alpha_y$ = –4.69
$\beta_x$ = 43.0 m $\beta_y$ = 42.4 m
**$\varepsilon_{x,p}$ = 0.647 μm $\varepsilon_{y,p}$ = 0.647 μm**
**$\varepsilon_{x,s}$ = 0.38 μm $\varepsilon_{y,s}$ = 0.38 μm**

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

# Overview: Simulation of 400 pC from Cathode through ACC1 to Z=14.2 m




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

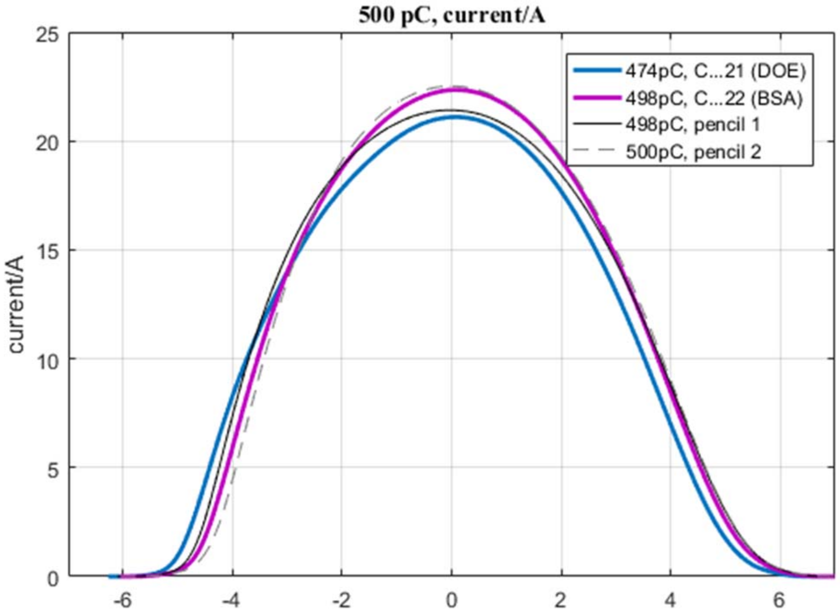
pencil 1 (sigma = 0.256 mm)
$B_{sol}$ = 0.2055 T $\varphi = \varphi_0 - 3.0$ deg
Q = 400 pC $I_{peak}$ = 19.36 A
$\alpha_x$ = –3.23 $\alpha_y$ = –3.31
$\beta_x$ = 36.4 m $\beta_y$ = 37.5 m
**$\varepsilon_{x,p}$ = 0.629 μm $\varepsilon_{y,p}$ = 0.632 μm**
**$\varepsilon_{x,s}$ = 0.51 μm $\varepsilon_{y,s}$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

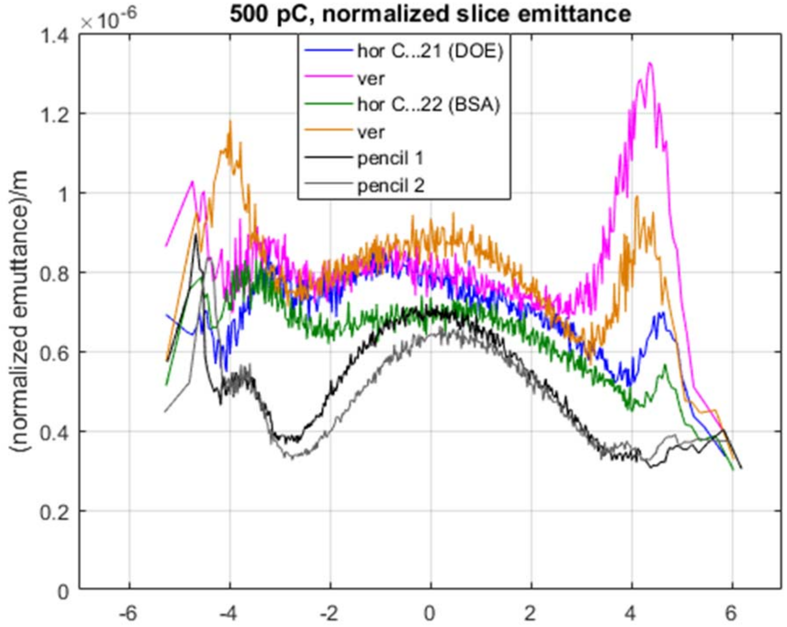
C_20180422 (BSA)
$B_{sol}$ = 0.2055 T $\varphi = \varphi_0 - 2.9$ deg
Q = 400 pC $I_{peak}$ = 19.84 A
$\alpha_x$ = –4.04 $\alpha_y$ = –2.45
$\beta_x$ = 38.9 m $\beta_y$ = 32.8 m
**$\varepsilon_{x,p}$ = 0.753 μm $\varepsilon_{y,p}$ = 1.02 μm**
**$\varepsilon_{x,s}$ = 0.62 μm $\varepsilon_{y,s}$ = 0.81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

pencil 2 (sigma = 0.272 mm)
$B_{sol}$ = 0.2057 T $\varphi = \varphi_0 - 2.5$ deg
Q = 400 pC $I_{peak}$ = 19.88 A
$\alpha_x$ = –2.62 $\alpha_y$ = –2.49
$\beta_x$ = 28.3 m $\beta_y$ = 27.0 m
**$\varepsilon_{x,p}$ = 0.653 μm $\varepsilon_{y,p}$ = 0.656 μm**
**$\varepsilon_{x,s}$ = 0.50 μm $\varepsilon_{y,s}$ = 0.50 μm**

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

# Overview: Simulation of 500 pC from Cathode through ACC1 to Z=14.2 m




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

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

C_20180422 (BSA)
$B_{sol}$ = 0.2055 T $\varphi = \varphi_0 - 3.5$ deg
Q = 498 pC $I_{peak}$ = 22.34 A
$\alpha_x$ = –3.53 $\alpha_y$ = –2.58
$\beta_x$ = 36.3 m $\beta_y$ = 36.7 m
**$\varepsilon_{x,p}$ = 0.817 µm $\varepsilon_{y,p}$ = 1.08 µm**
**$\varepsilon_{x,s}$ = 0.69 µm $\varepsilon_{y,s}$ = 0.87 µm**

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

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

# A Figure of Merit

power gain length
(assuming optimal beta function)

$$L_g = 1.18\sqrt{\frac{I_A}{I_{\text{peak}}}}\frac{(\varepsilon_n\lambda_w)^{5/6}}{\lambda_l^{2/3}}\frac{\left(1+\frac{K^2}{2}\right)^{1/3}}{KA_{JJ}}\left(1+\delta(\sigma_\gamma,\text{L})\right)$$

$$f = \frac{(\varepsilon_{x,s}\varepsilon_{y,s})^{5/12}}{\sqrt{I_{\text{peak}}}}\frac{\sqrt{\text{A}}}{(\mu\text{m})^{5/6}}$$

| | | | |
|---|---|---|---|
| 250 pC | C_20180421 (DOE) f = | 0.2038 | Z=14.2m |
| | C_20180422 (BSA) | 0.1729 | |
| | pencil_1 | 0.1183 | |
| | pencil_2 | 0.1181 | |
| 400 pC | C_20180421 (DOE) f = | 0.1830 | |
| | C_20180422 (BSA) | 0.1685 | |
| | pencil_1 | 0.1297 | |
| | pencil_2 | 0.1267 | |
| 500 pC | C_20180421 (DOE) f = | 0.1808 | |
| | C_20180422 (BSA) | 0.1711 | |
| | pencil_1 | 0.1606 | |
| | pencil_2 | 0.1508 | |

# 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