PhotonMEADOW 2023

INSTITUT FÜR NANOPHOTONIK

# Wavefront metrology and beam propagation in the EUV/X-ray spectral range


Đông Du Mai

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*DESY, Hamburg, Germany*

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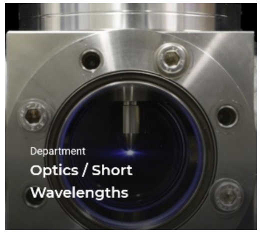
# Intermediary between Science and Industry




# Optics / Short Wavelengths

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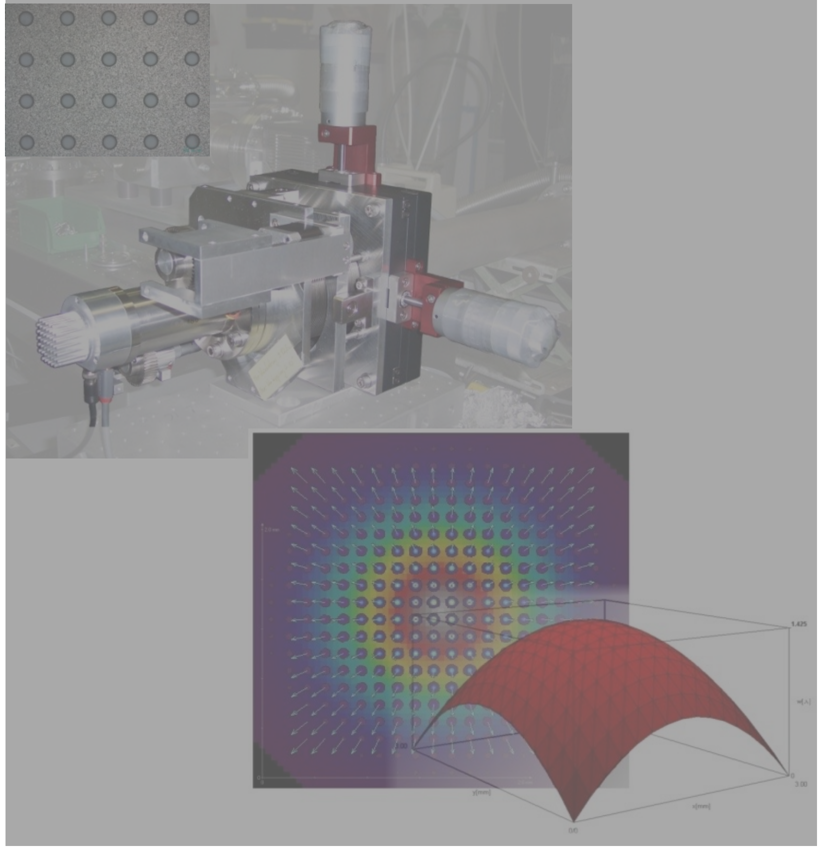
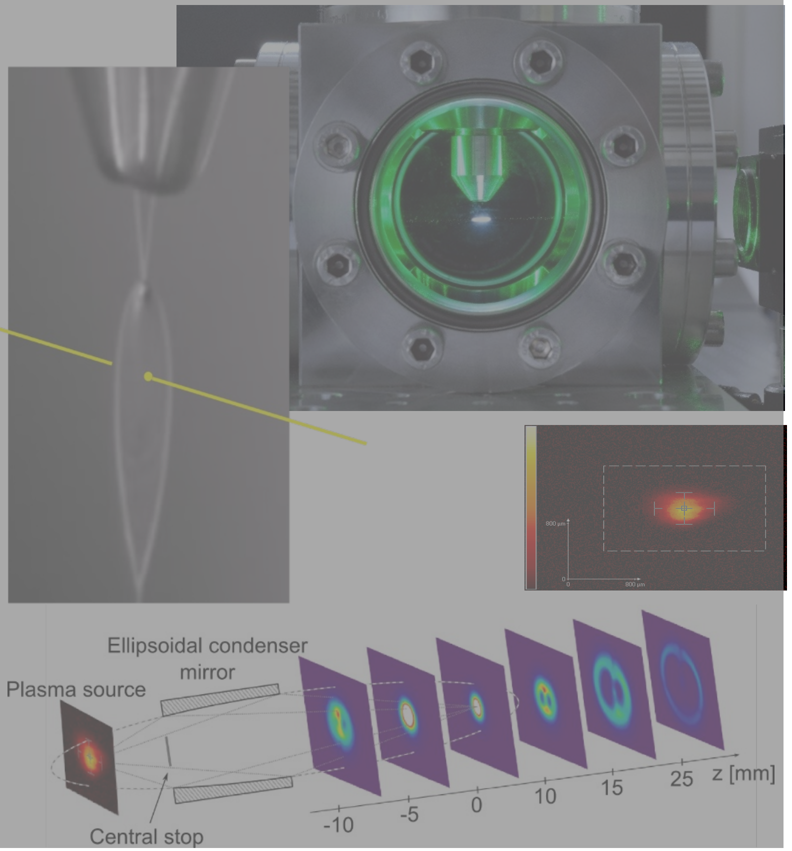
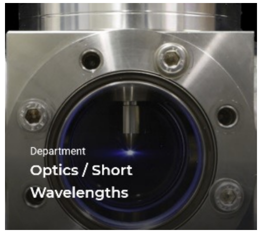
## Beam Profile Analysis



## Optics Characterization

## EUV/X-ray Generation & Spectroscopy






# Optics Characterization

## Semiconductor Lithography: Beam and Sensor Qualification (DUV)

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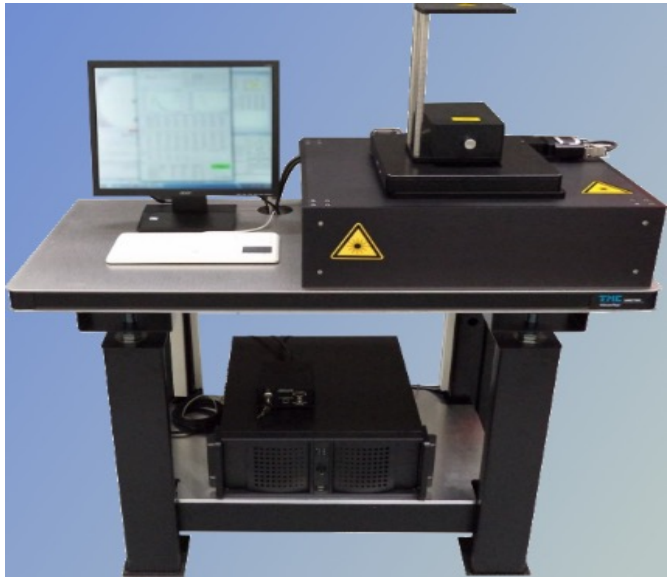
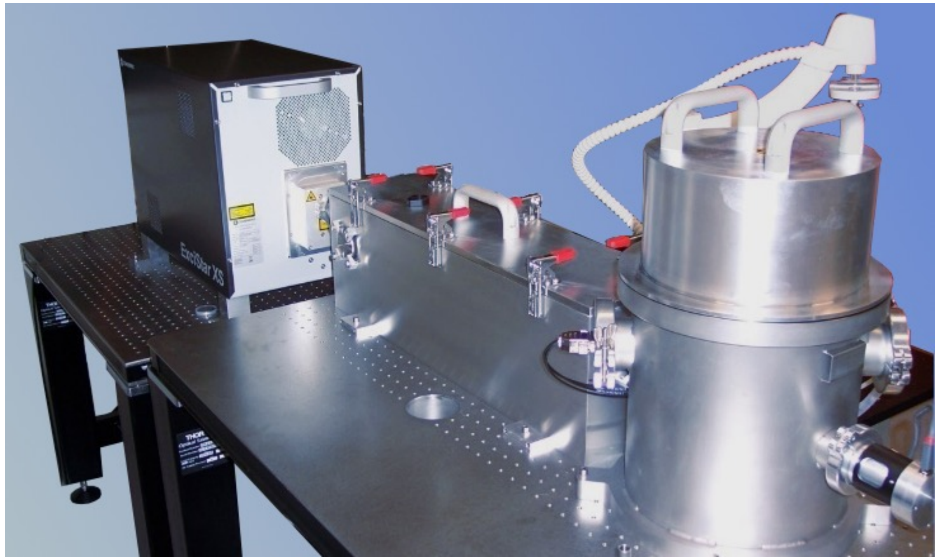
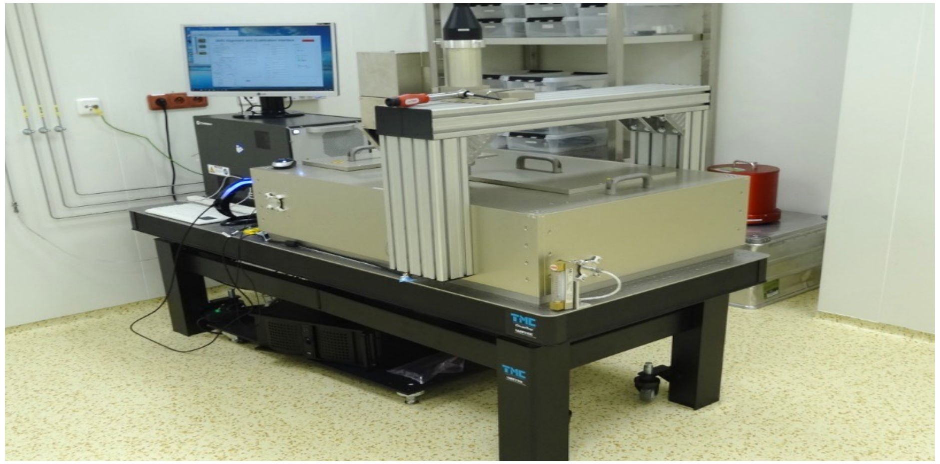
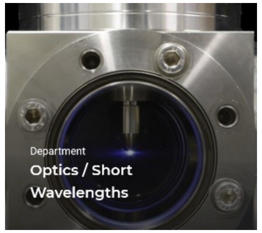
- Qualification systems for dose control sensors
  - 193nm
  - 248nm
  - 365nm








ASML




# Optics / Short Wavelengths

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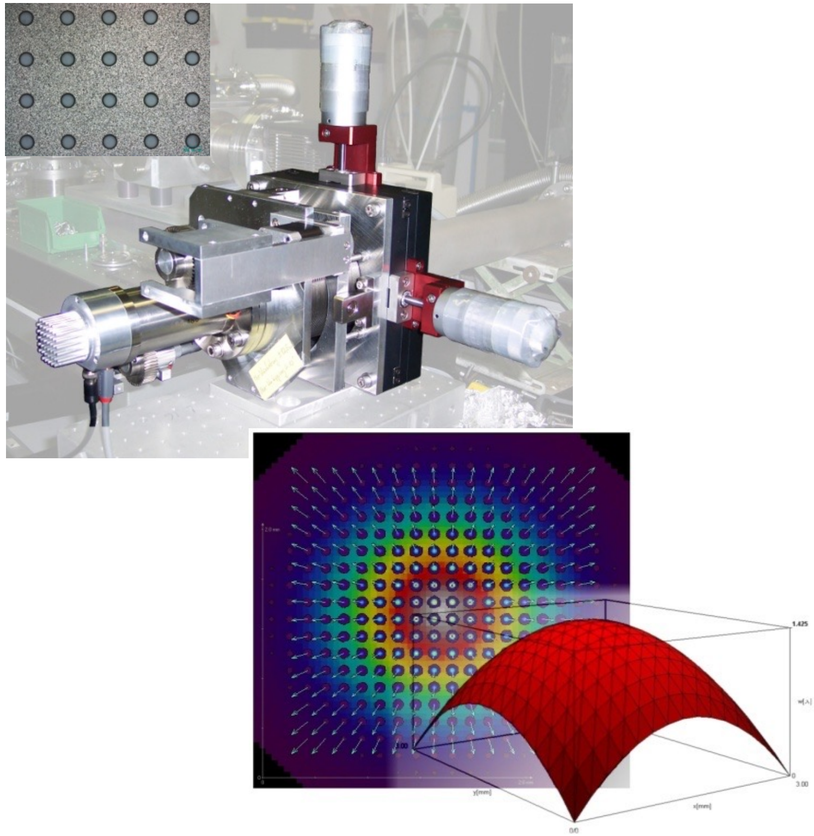
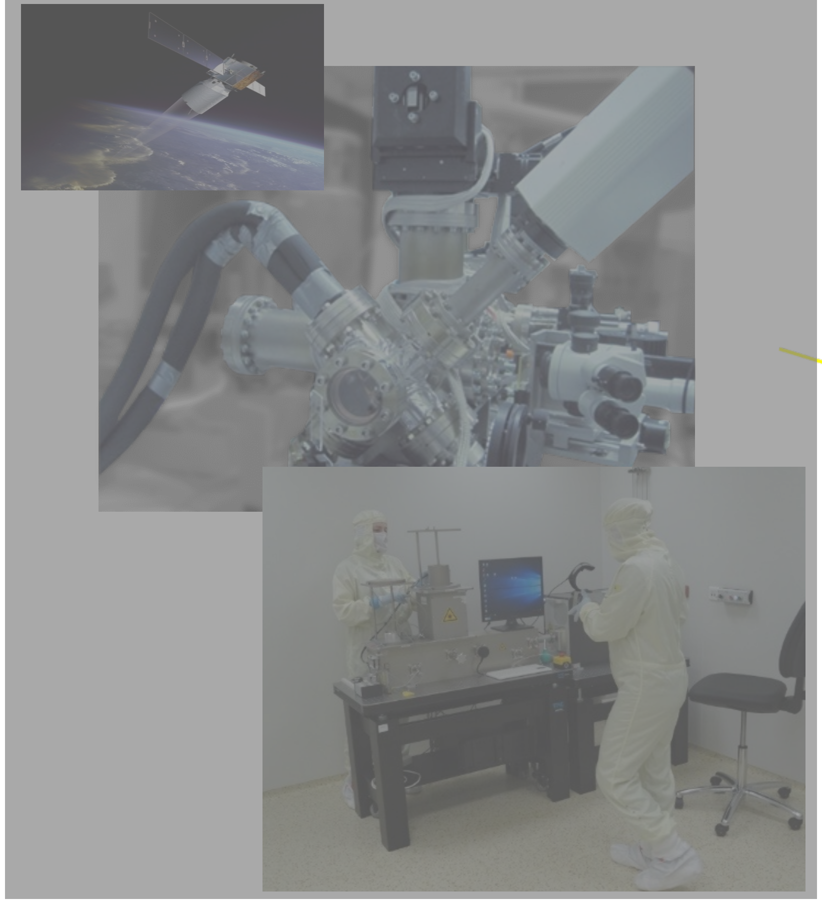
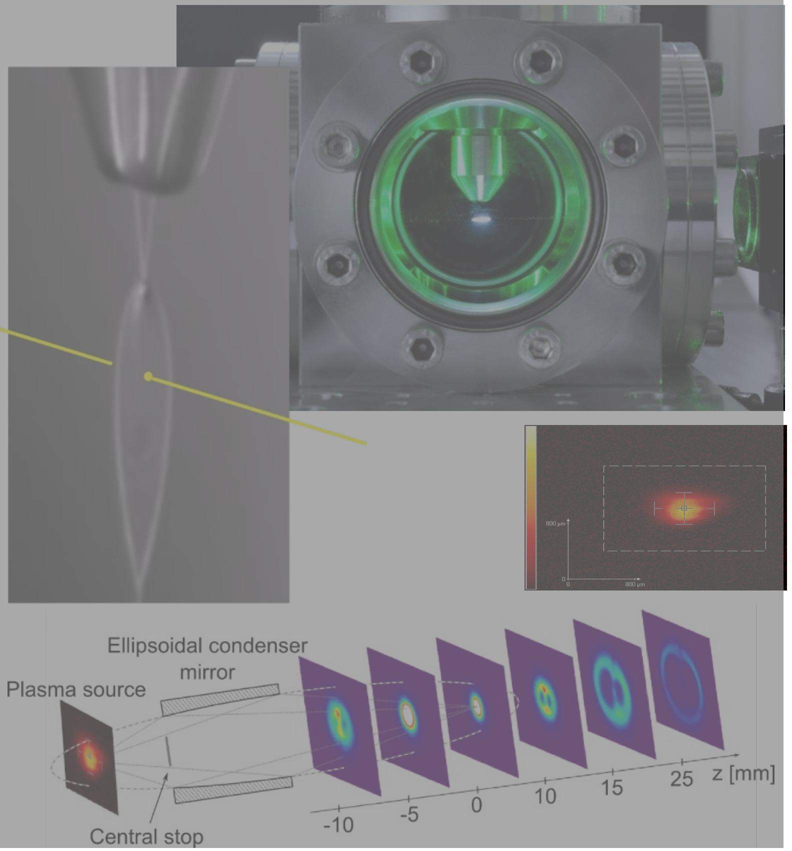
## Beam Profile Analysis

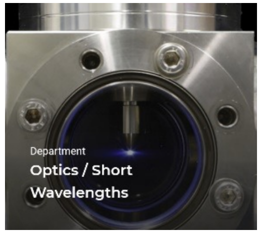


## Optics Characterization



## EUV/X-ray Generation & Spectroscopy





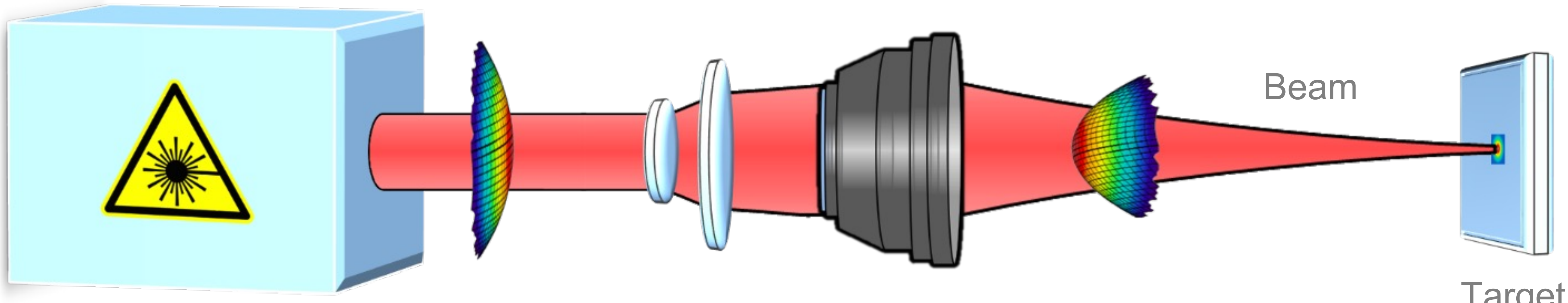

# Beam Profile Analysis

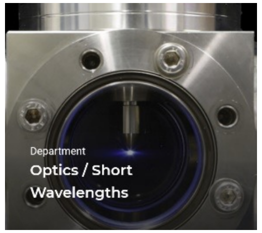
## VIS Beam Propagation



- Objective
  - Exact beam characterization
  - Focus monitoring: spot size, irradiance
  - Stability of optical elements (degradation, thermal lensing)

⇔ Wavefront metrology






# Beam Profile Analysis

## Wave Front Metrology

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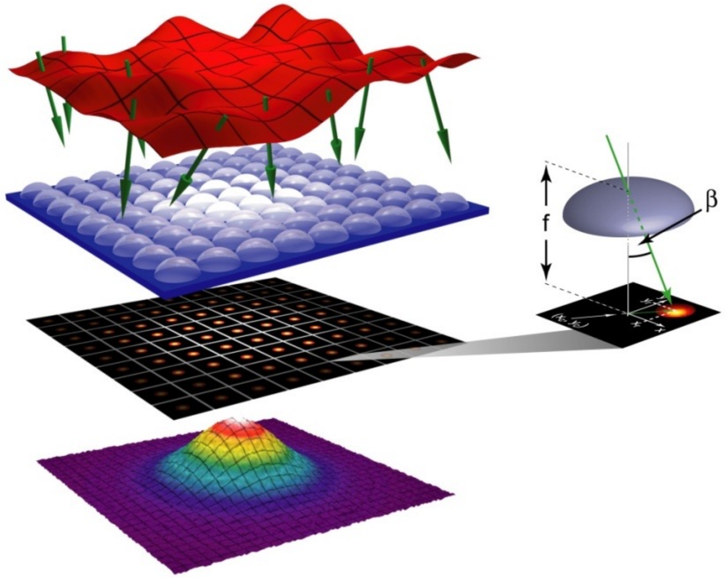
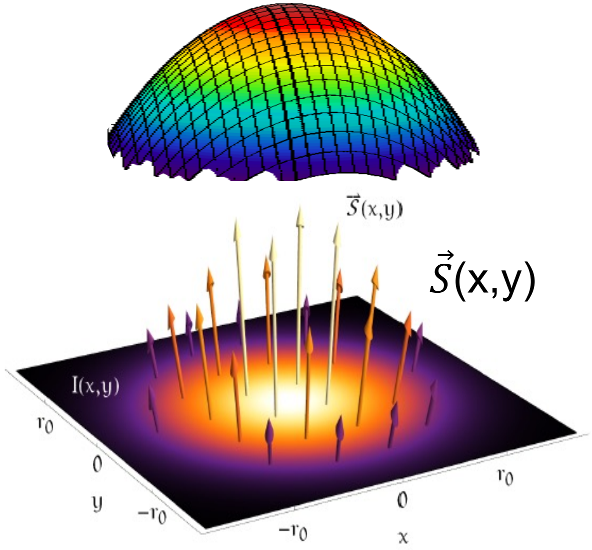
- Wavefront (ISO 15367) $\boxed{WF(x,y) \coloneqq surface \perp Poynting\ Vector\ \vec{S}(x,y)}$

Hartmann-Shack:

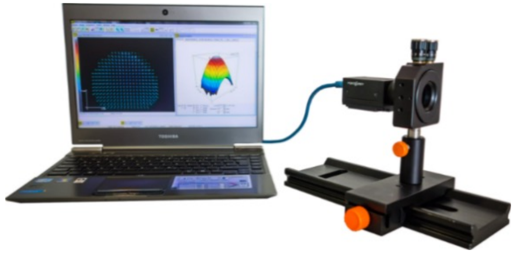
**VIS:**
**micro-lens array**




Wavefront WF(x,y)

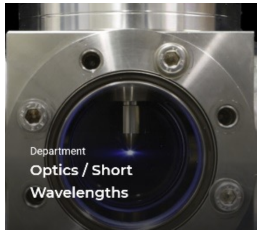



Irradiance I(x,y)



ProOpto

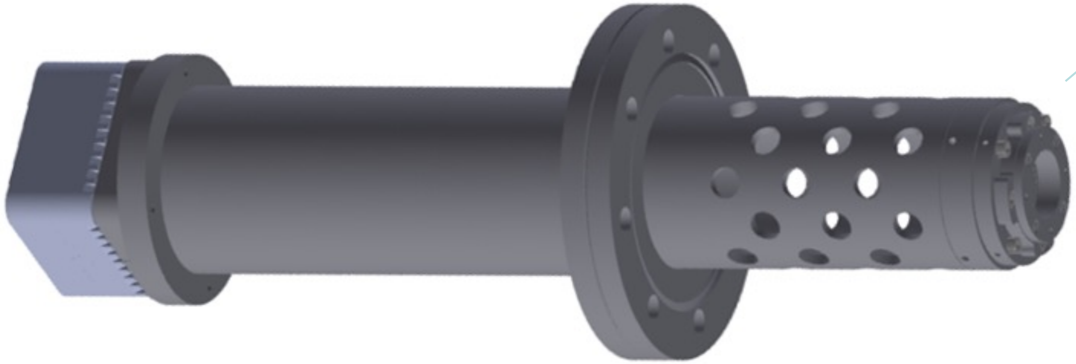
- Advantages
  - Compact, robust
  - High dynamics & sensitivity
  - Low requirements for coherence and spectral purity

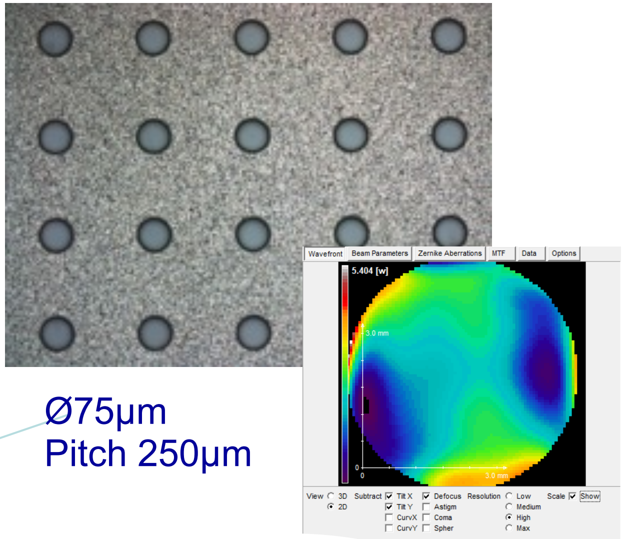



# Beam Profile Analysis

## DUV-> EUV/X-rays: Hartmann Wavefront Sensor

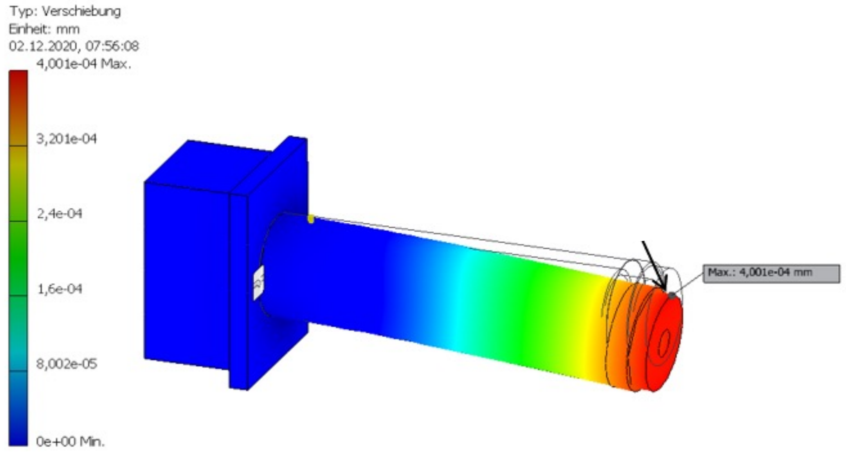
- Objective
  - Microlens array -> pinhole plate
  - high sensitivity (λ/10)
    - larger distance plate – sensor (cantilever)
  - improved mechanical stability: FEM simulations
  - Cooperation with FLASH/DESY since 2006 (Barbara Keitel, Elke Plönjes)



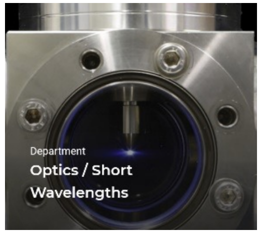


**Hartmann Plate**

Ø75µm
Pitch 250µm




EUV / X-ray camera
- back-illuminated CCD
- P43-coated CCD
- Wavelength range: λ < 1..60nm




# Beam Profile Analysis

## Wave Front Metrology

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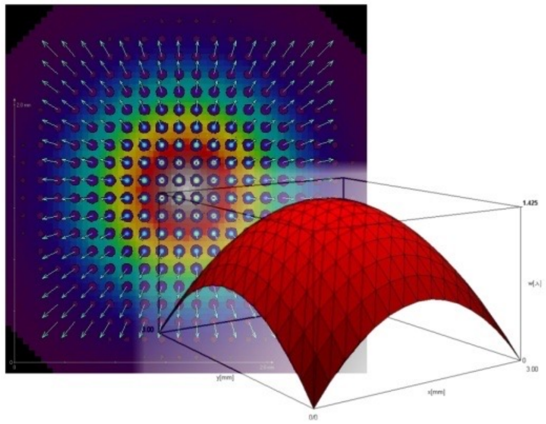
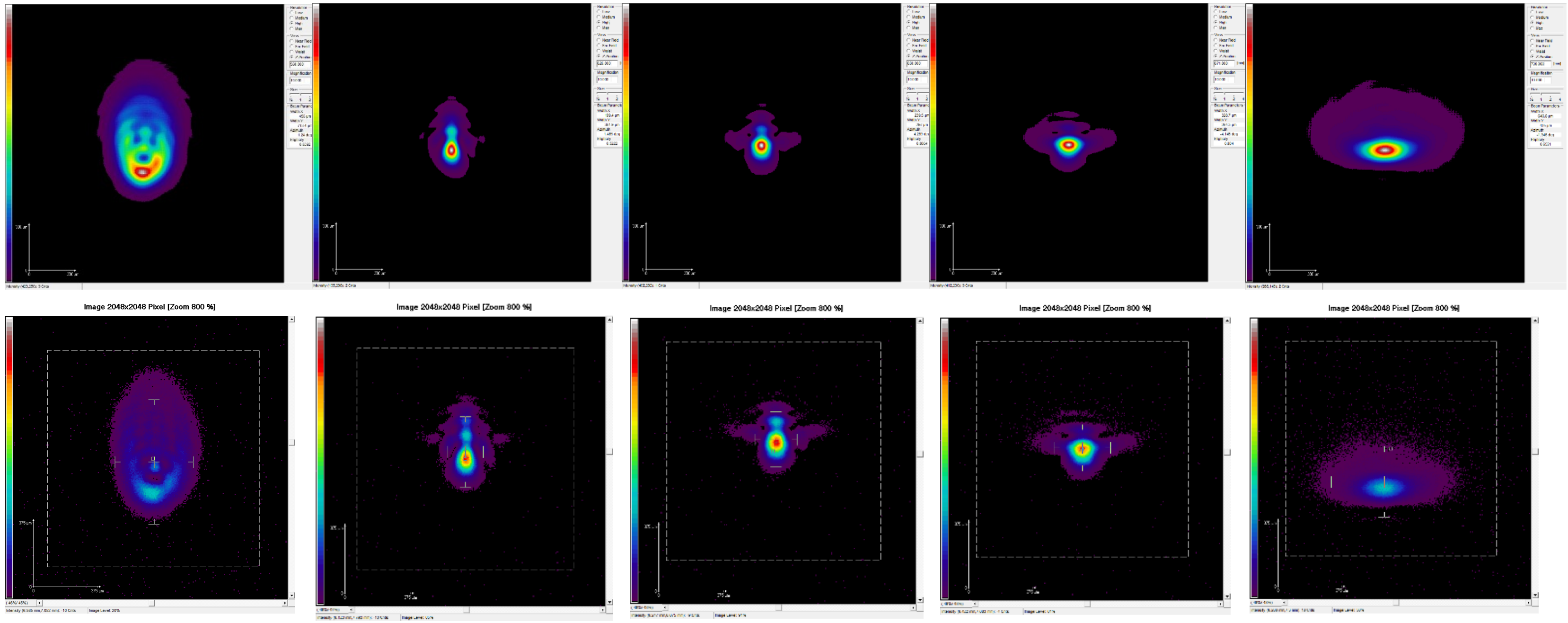
**Single Hartmann-Shack measurement at z=0** → **Wavefront WF(x,y)** **Irradiance I(x,y)** →

$$I(x,y,z)=\left|\frac{ik}{2\pi z}\iint_{\infty}\sqrt{I}e^{ikw}\cdot e^{\frac{ik\left[(x-x')^2+(y-y')^2\right]}{2z}}dx'dy'\right|^2$$

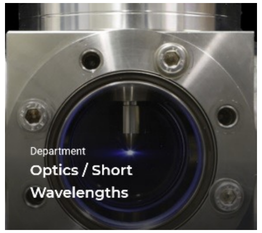
Fresnel-Kirchhoff integral





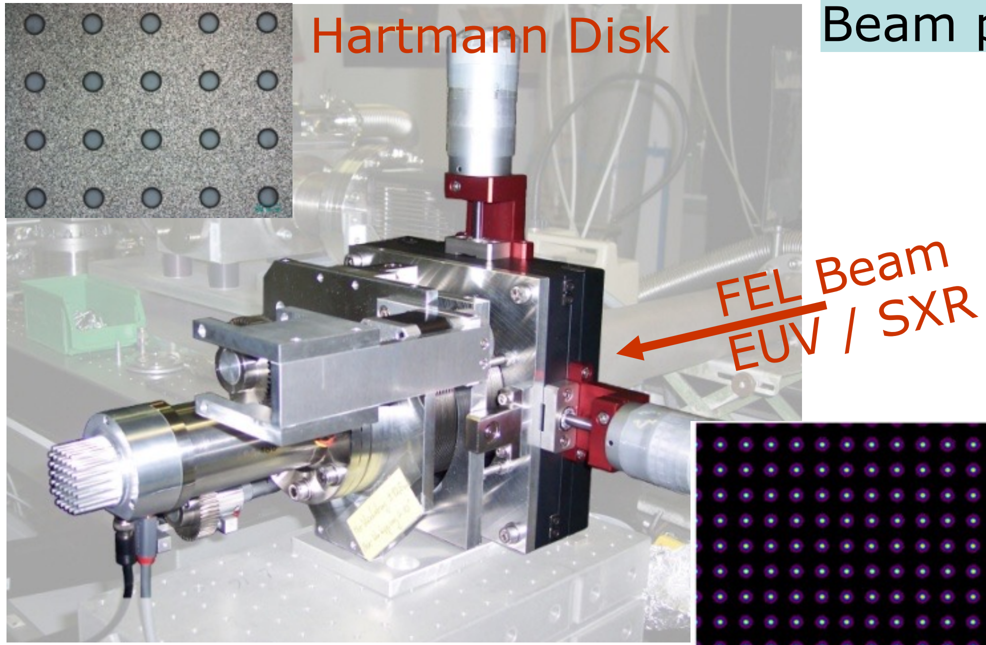

z=0

Works only for spatially coherent beams!

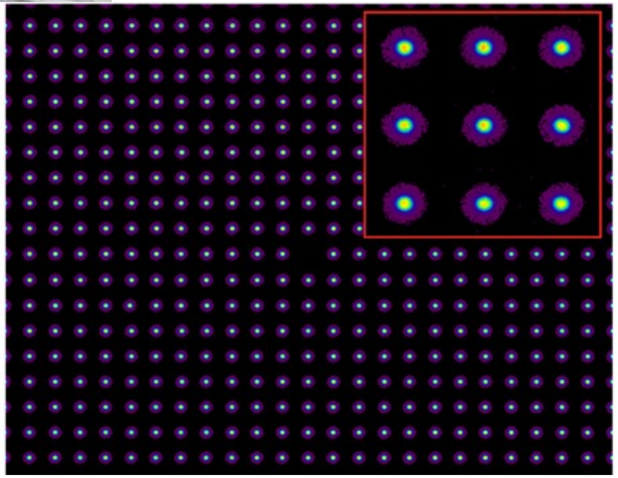


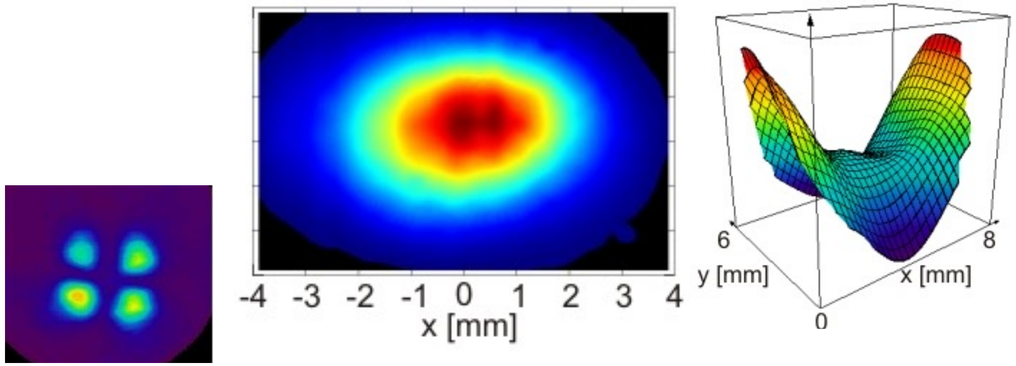

# Beam Profile Analysis

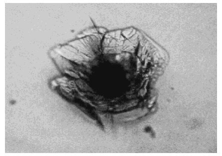
## EUV Wavefront Sensor



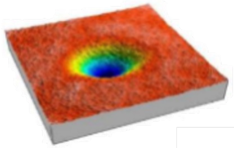

### Beam profile analysis



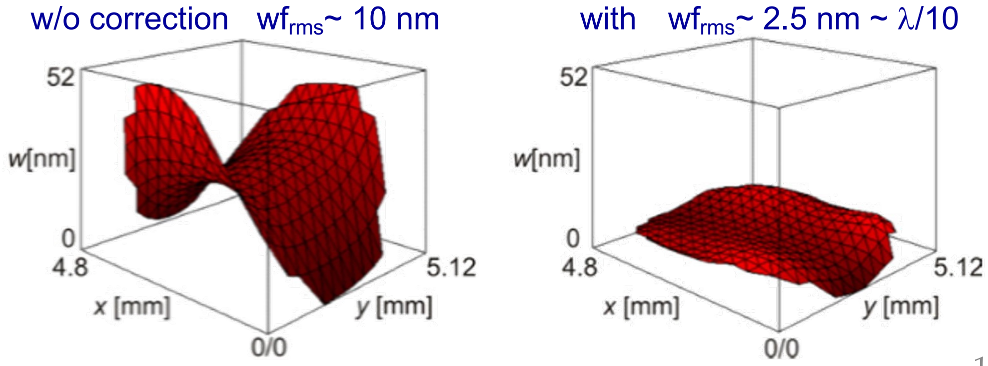


- Beam dimensions
- Waist diameter
- Beam quality factor $M^2$

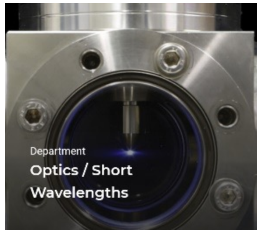


### Beam profile correction: FLASH @ 25 nm




- FLASH / DESY, Hamburg
- Fermi / Elettra, Triest
- PTB BESSY II, Berlin
- European XFEL

B. Floeter, B. Keitel, K. Mann, E. Plönjes, B. Schäfer, K. Tiedtke et al.: New J. Phys. 12 083015 (2010)
B. Keitel, E. Plönjes, T. Mey, B. Schäfer, K. Mann et al., J. Synchrotron Rad. 23 (2016)




# Beam Profile Analysis

## Wave Front Metrology

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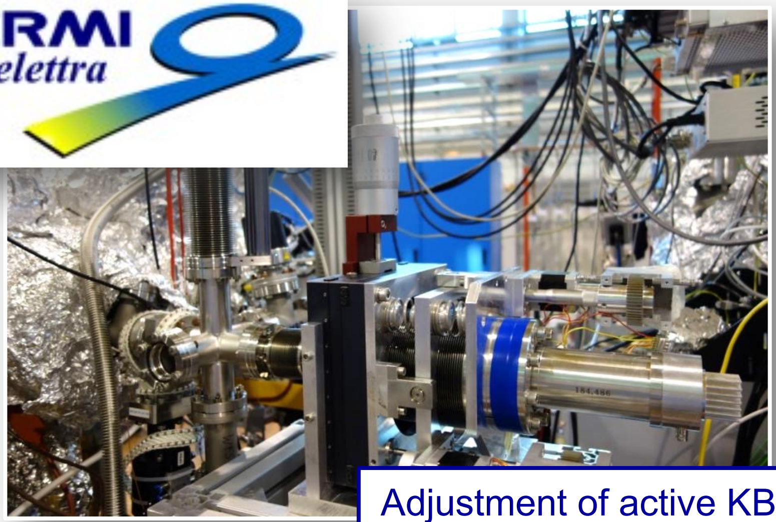
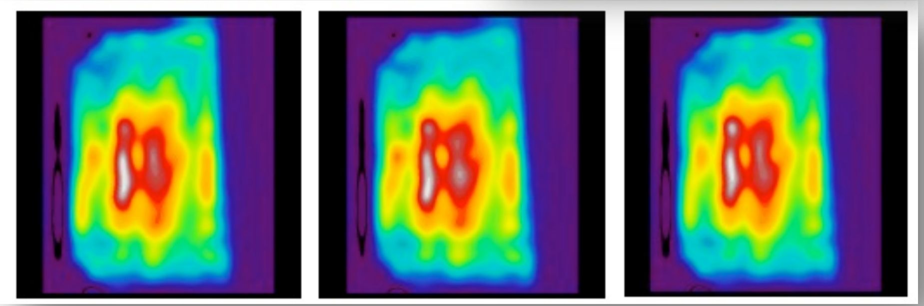
FERMI @elettra



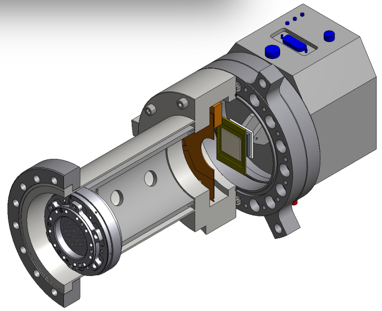
Adjustment of active KB-system
→ 10µm x 10µm focal size

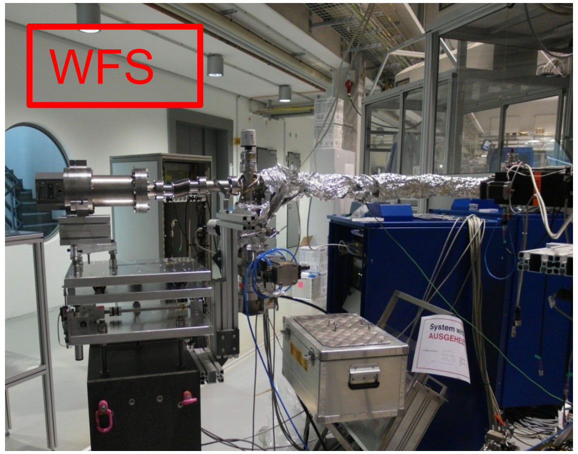
LCLS

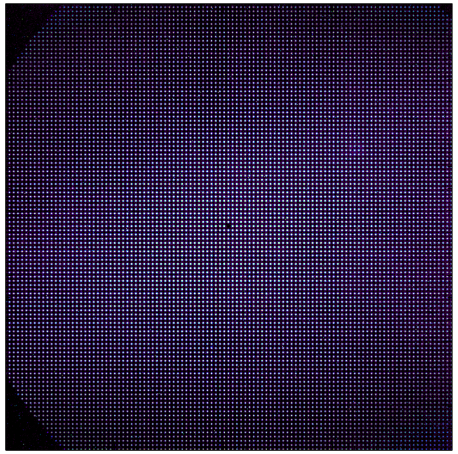


High pulse-to-pulse stability!

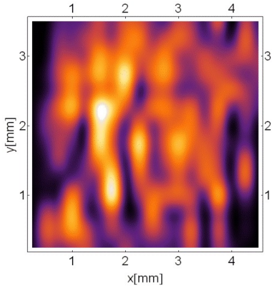
PTB Physikalisch Technische Bundesanstalt



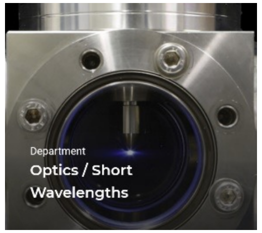


Online optics alignment
at MLS synchrotron
@ 13.5 nm




Frank Scholze
et al.




# Beam Profile Analysis

## European XFEL SQS Instrument

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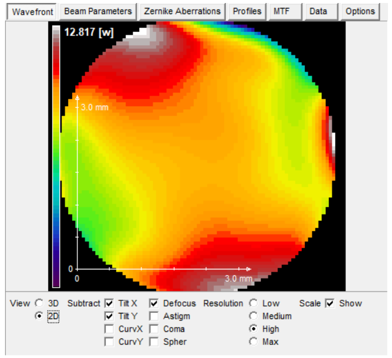
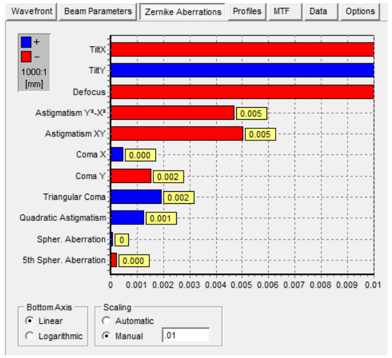
**before:**

Wavefront

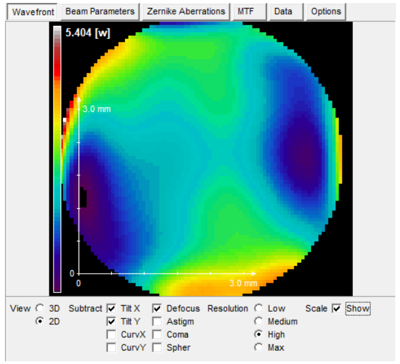



Zernike

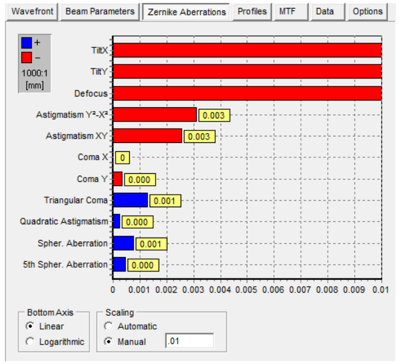



**after:**

Wavefront

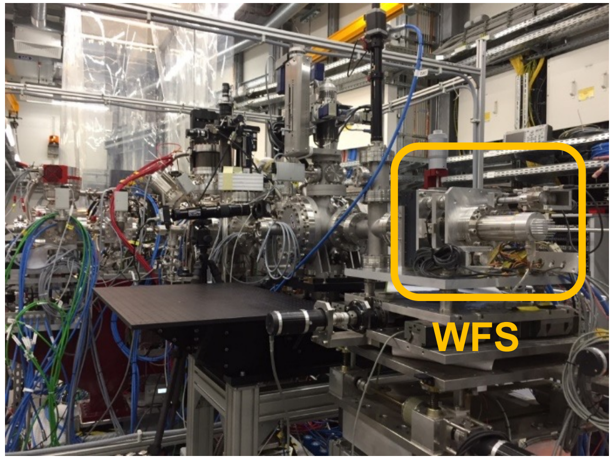



Zernike

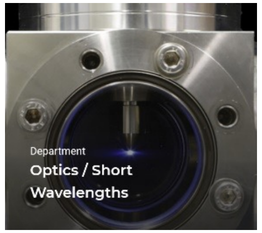



European XFEL

Michael Meyer




- Irradiance and Wavefront -> Focus monitoring
  - Beam parameters / M²
  - Waist position / diameter




# Beam Profile Analysis

## European XFEL SQS Instrument

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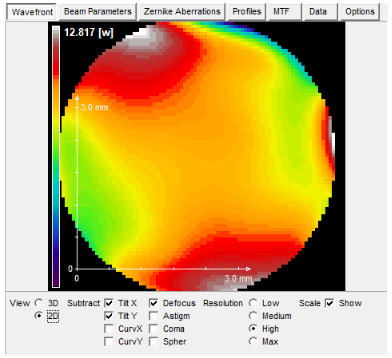
European XFEL

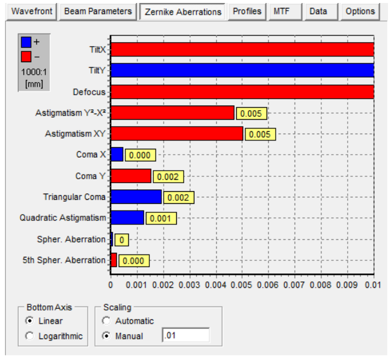
Michael Meyer

**before:**

Wavefront

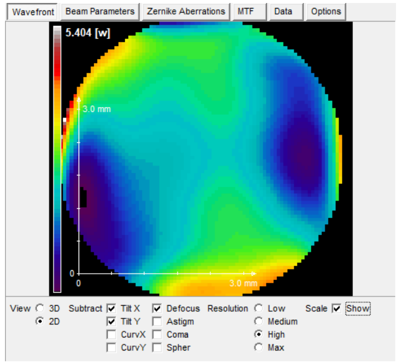



Zernike

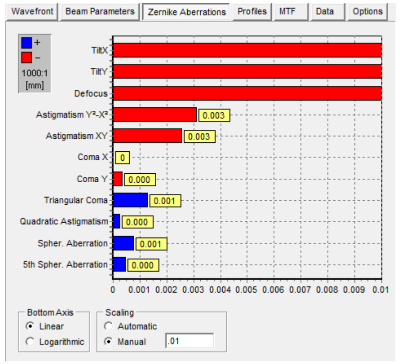



**after:**

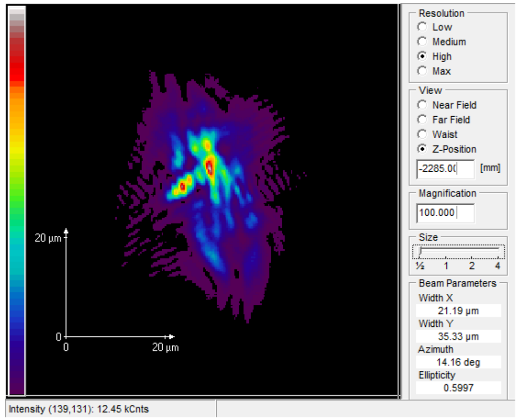
Wavefront

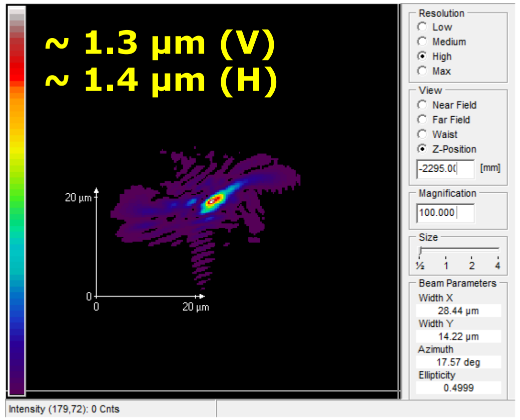



Zernike




Fresnel-Kirchhoff propagation to focus

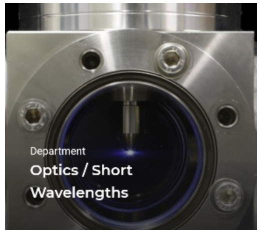



- Optimum or local minimum?
- Spatial coherence?



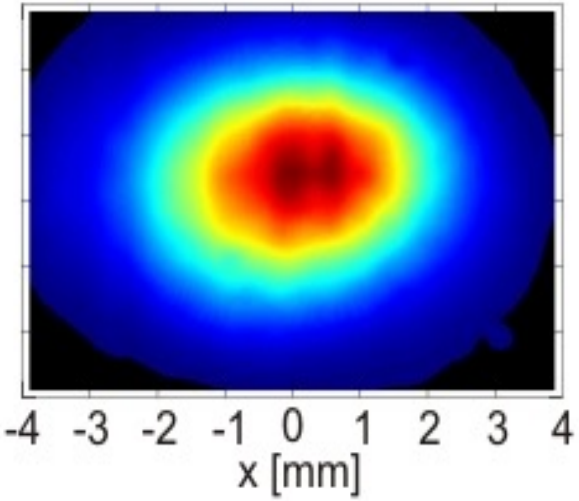
M. Meyer et al. (XFEL), E. Plönjes, B. Keitel (DESY), K. Mann, S. Lange, B. Schäfer (LLG)



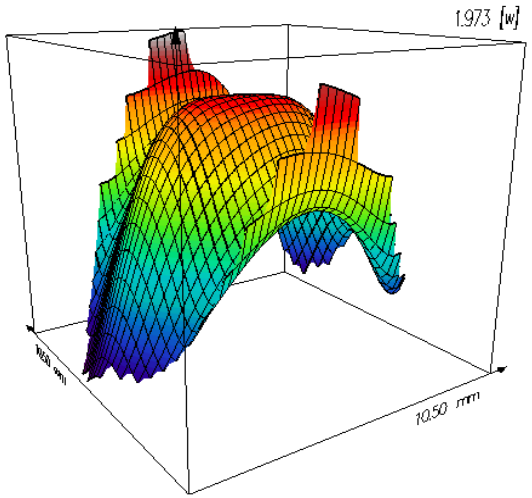

# Beam Profile Analysis

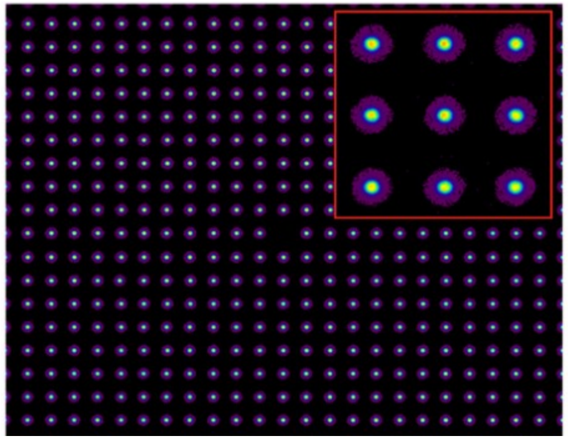
## FLASH @ λ=13.5 nm (behind KB-Optics)

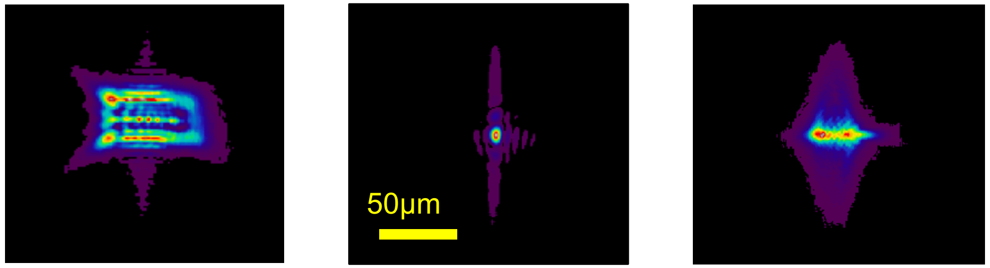
- Irradiance



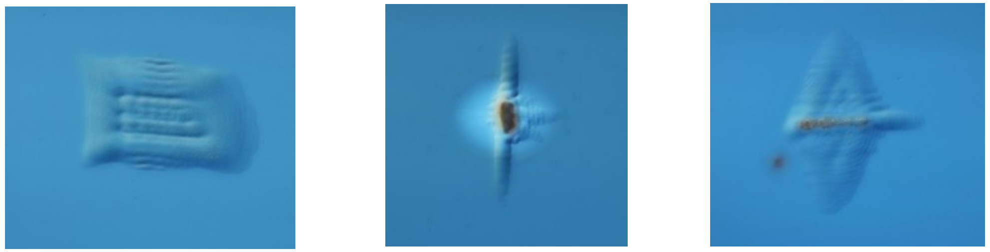

Wavefront



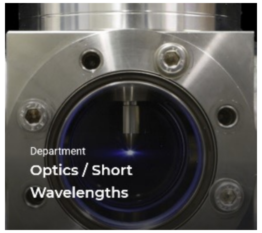



- Fresnel-Kirchhoff propagation (coherent)
- PMMA imprints



21 mm upstream | focus position | 18 mm downstream

J. Chalubski, L. Juha et al. / CZ




# Beam Profile Analysis

## Propagation of partially coherent radiation from wavefront data

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Quasi-Homogeneus Beam

FT center coordinate x

**Mutual Intensity**

$$J(x,s) = J_{coh}(x,s) \cdot g(s)$$

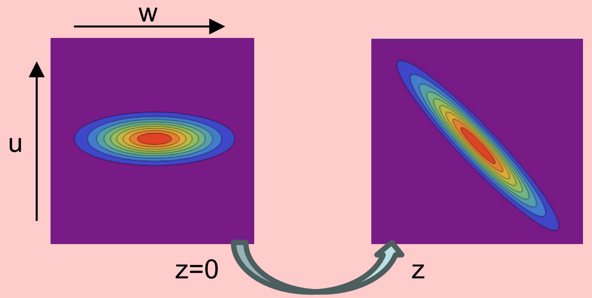
**Ambiguity function**

$$Z(w,u) = Z_{coh}(w,u) \cdot g(u = k \cdot s_x)$$

Simple Shear in reciprocal space

**Propagation:** $Z(w,u;z) = Z(w,u + z \cdot w\,; z = 0)$

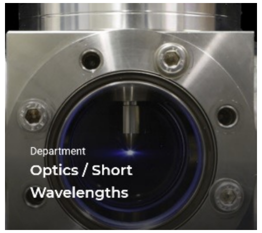
→ $Z(w,0;z)$ : FT $\tilde{I}(w)$ of Intensity Distribution @ z
$g(w{\cdot}z/k)$: degree of coherence @ z




**Consideration of partial coherence requires simply multiplication of FT't coherent Intensity by a rescaled coherence**

### Algorithm for Propagation of quasi-homogeneous partially coherent Radiation

1. 2D Fresnel-Propagation of coherent Amplitude to Target Position z (using Data from Wavefront Analysis) $\rightarrow \mathrm{I}_{coh}(\mathbf{x}; \mathrm{z})$
2. 2D Fourier-Transformation of coherent Intensity Distribution $\rightarrow \tilde{\mathrm{I}}_{coh}(\mathbf{w}; \mathrm{z})$
3. Product of $\tilde{\mathrm{I}}_{coh}(\mathbf{w}; \mathrm{z})$ and ***scaled*** Coherence Function $\mathrm{g}\left(\frac{\mathbf{w}\mathrm{z}}{\mathrm{k}}; \mathrm{z} = 0\right)$ $\rightarrow \tilde{\mathrm{I}}_{part.\,coh}(\mathbf{w}; \mathrm{z})$
4. 2D Inverse Fourier-Transformation $\rightarrow \mathrm{I}_{part.\,coh}(\mathbf{x}\,; \mathrm{z})$

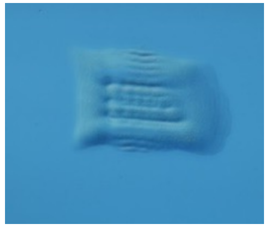


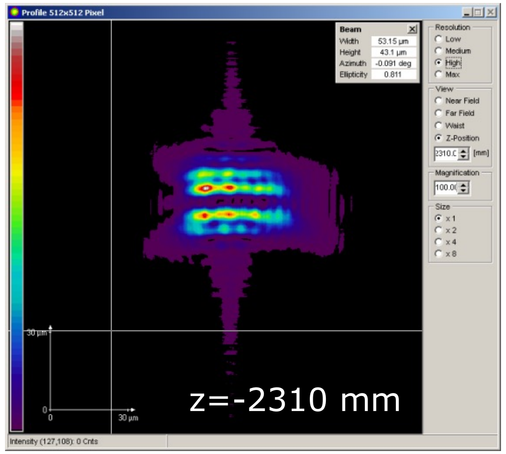

# Beam Profile Analysis

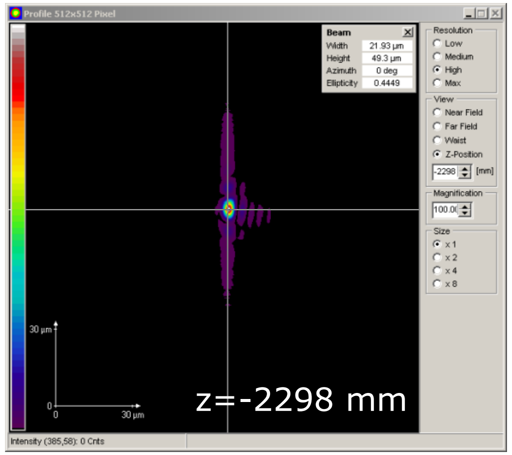
## FLASH @ λ=13.5 nm (behind KB-Optics)

- Fully coherent propagation:

**K = 1**





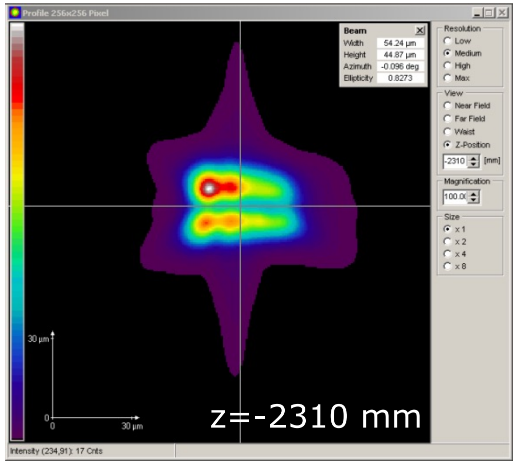

Focus size:

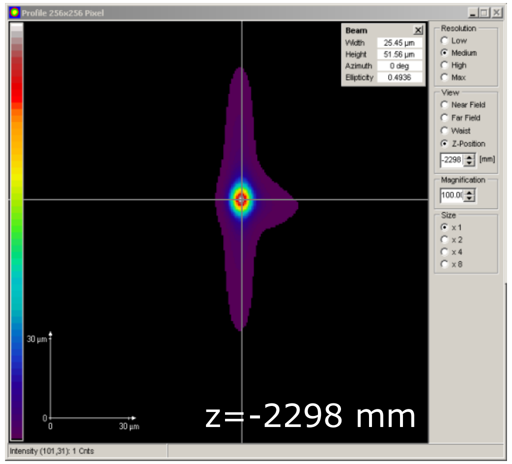
FWHM: 5 µm / 8 µm

diffraction limited: 3µm!

- Influence of partial coherence:

**K = 0.1**

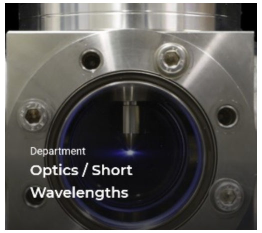



FWHM: 12.5 µm / 16.7 µm

Fit of propagated profiles to experimental data (e.g. PMMA imprints)

Coherence information




# Beam Profile Analysis

## Coherence Determination by Wigner Distribution

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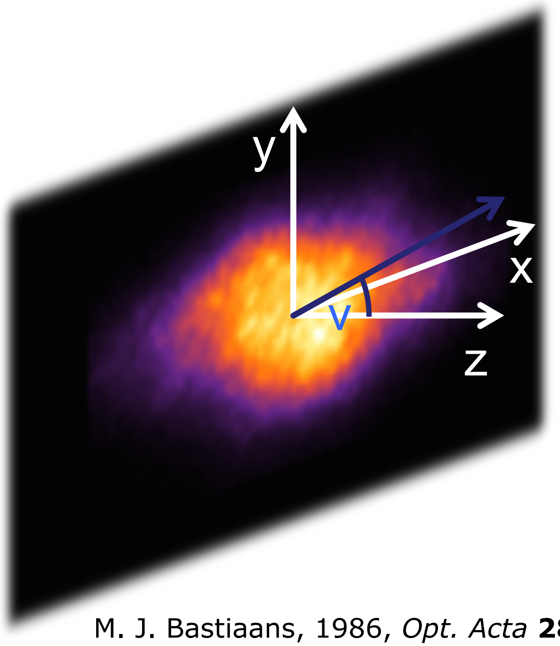



M. J. Bastiaans, 1986, *Opt. Acta* **28** 1215-24

h = Fourier transform of Mutual Coherence Function

Wigner distribution

mutual coherence function

$$\boxed{h(\vec{x},\vec{u}) = \left(\frac{1}{2\pi}\right)^2 \cdot \iint \Gamma(\vec{x},\vec{s}) \cdot e^{-i\vec{u}\cdot\vec{s}} d^2 s}$$

spatial coordinate $\vec{x} = \binom{x}{y}$

angular coordinate $\vec{u} = \binom{u}{v}$

Interpretation: radiance at position $\vec{x}$ in direction of $\vec{u}$

$$[h] = \mathrm{W}/_{\mathrm{m}^2 \cdot \mathrm{sr}}$$

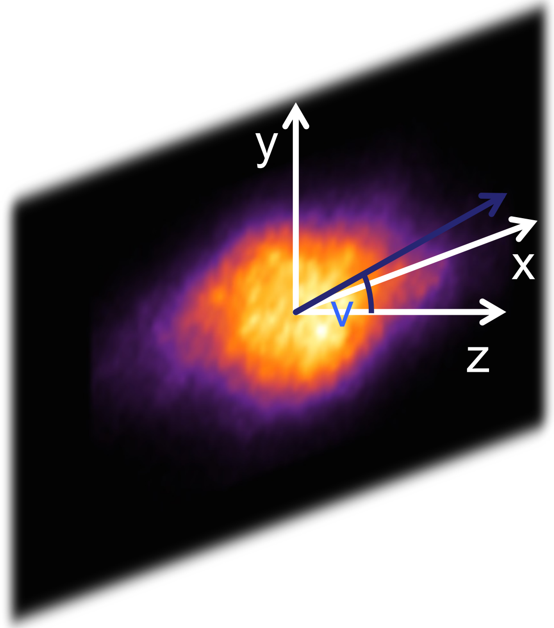
**Eugene Paul Wigner**
**Nobel price 1963**

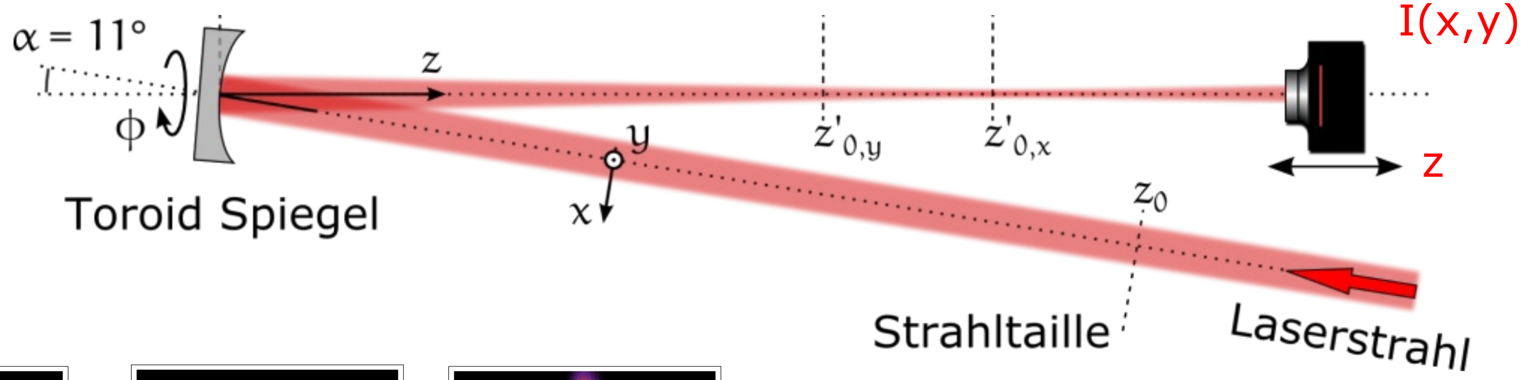
# Beam Profile Analysis

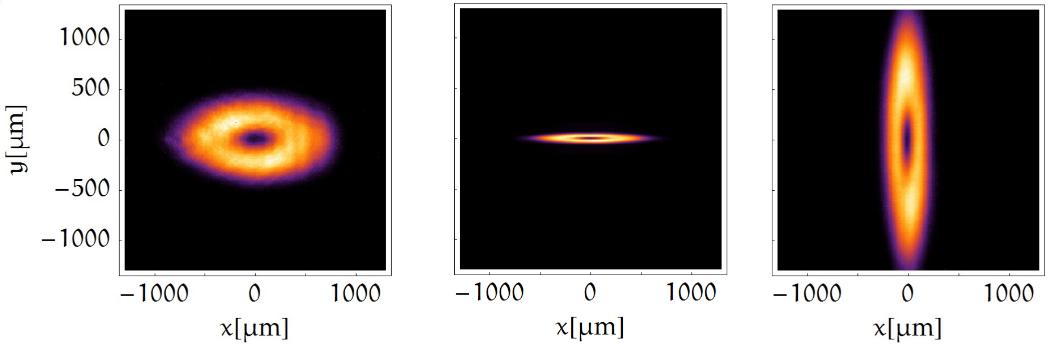
## Coherence Determination by Wigner Distribution



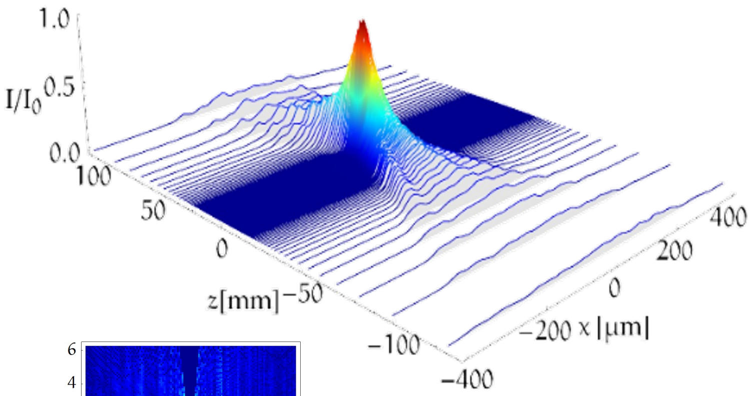
### "Tomographic analysis" of a laser beam

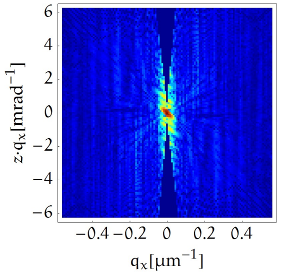


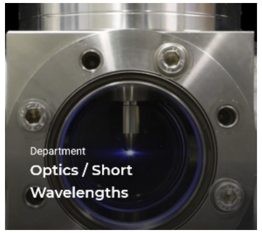




→ I(x,y, z, ϕ)

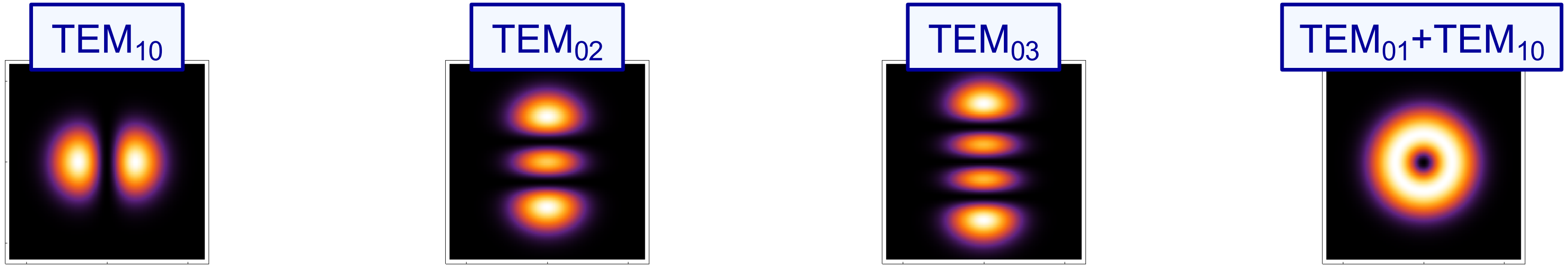





# Beam Profile Analysis

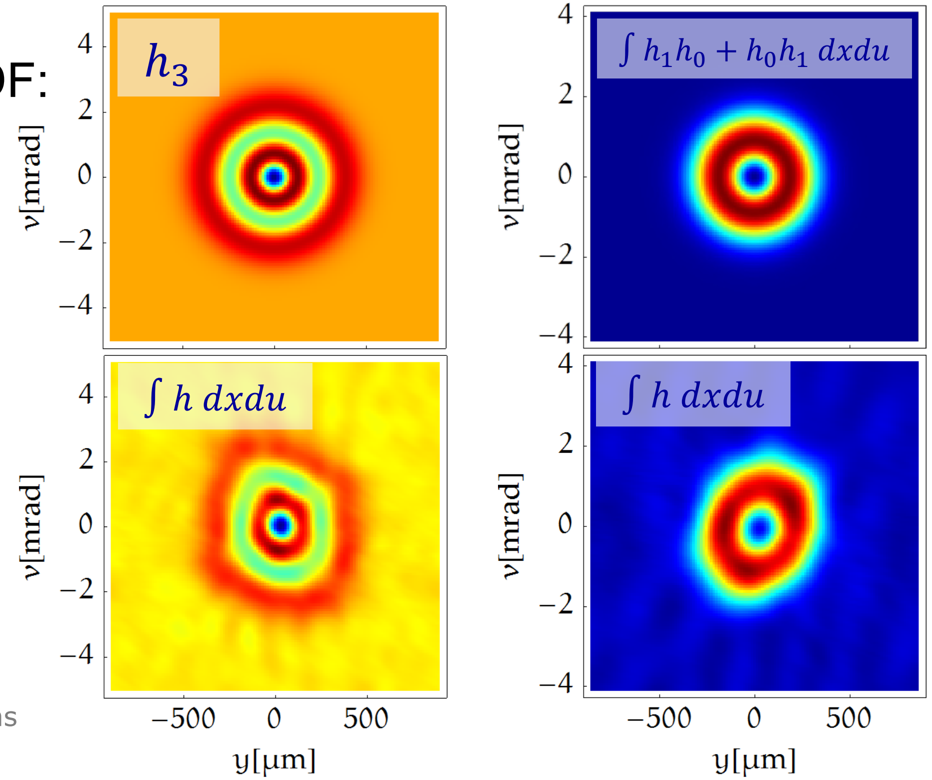
## Coherence Determination by Wigner Distribution



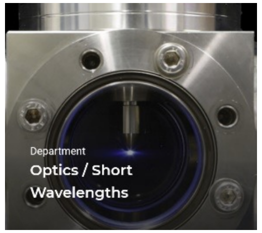

**Global degree of coherence K**

| | Theory | Experiment |
|---|---|---|
| $TEM_{00}$ | 1 | 0.95 |
| $TEM_{10}$ | 1 | 1.06 |
| $TEM_{02}$ | 1 | 0.98 |
| $TEM_{03}$ | 1 | 0.90 |
| $TEM_{01}$ $+TEM_{10}$ | 0.5 | 0.46 |

WDF:




T. Mey, "Measurement of the Wigner distribution function of non-separable laser beams employing a toroidal mirror," New J. Phys. **16**, 123042 (2014)
T. Mey, B. Schäfer, K. Mann, K. Tiedtke et al., Optics Express 2014




# Beam Profile Analysis

## 4D Wigner Measurement @ FLASH II

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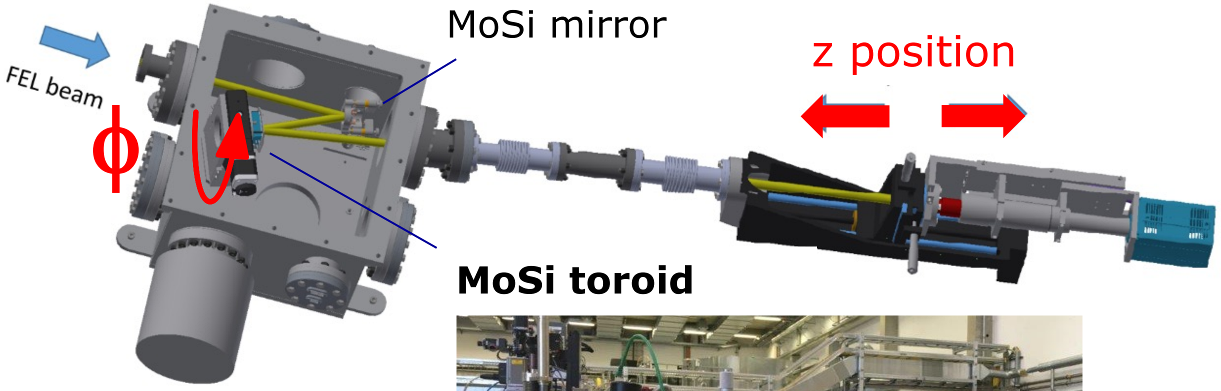
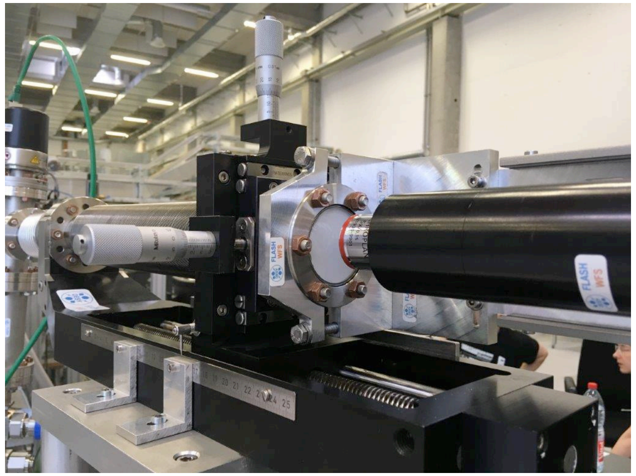
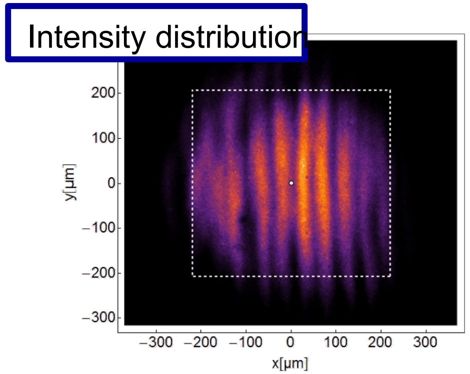
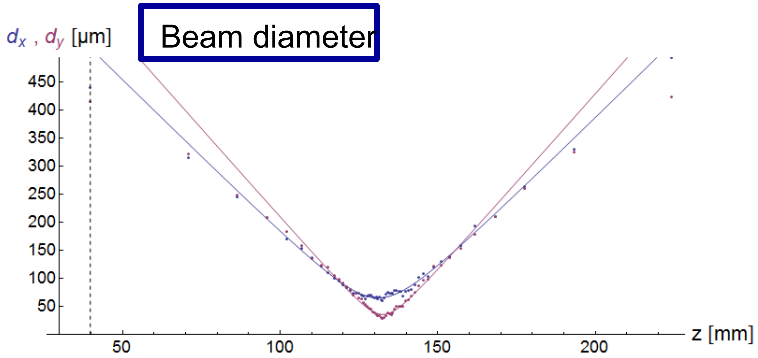


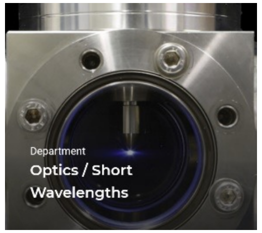



Coherence values from WDF evaluation:

| Parameter | Run 1 | Run 2 |
|---|---|---|
| # of Undulators | 12 | 9 |
| Global degree of coherence K | 5.9 % | 5.3 % |
| Horizontal/Vertical coherence* ($\sqrt{K}$ ) | 24 % | 23 % |
| Waist diameter | 2mm | 2.3mm |

very low!




# Beam Profile Analysis

## 4D Wigner Measurement @ FLASH II

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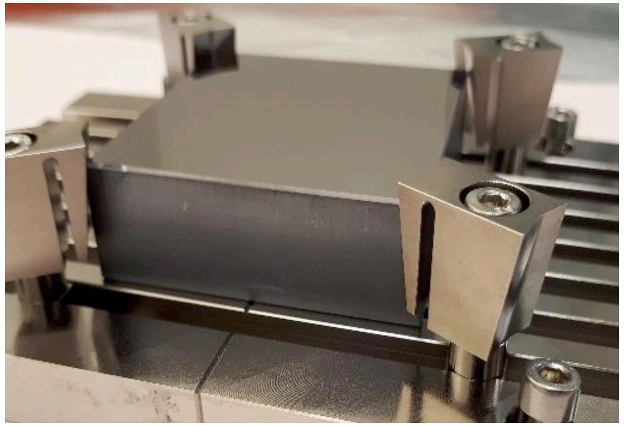
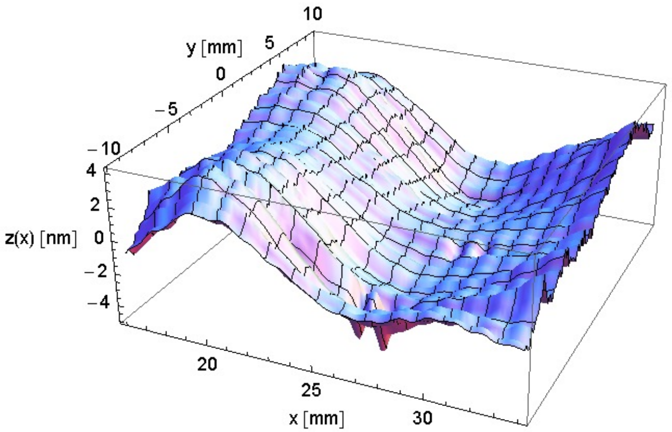
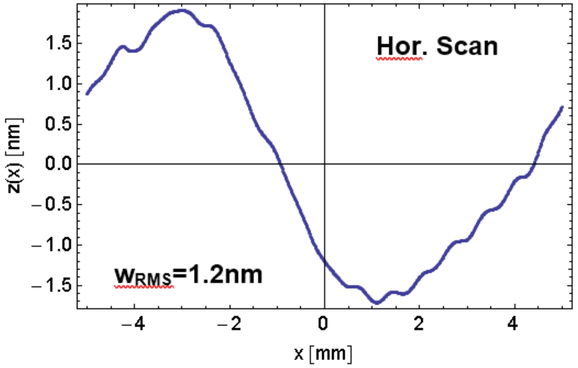
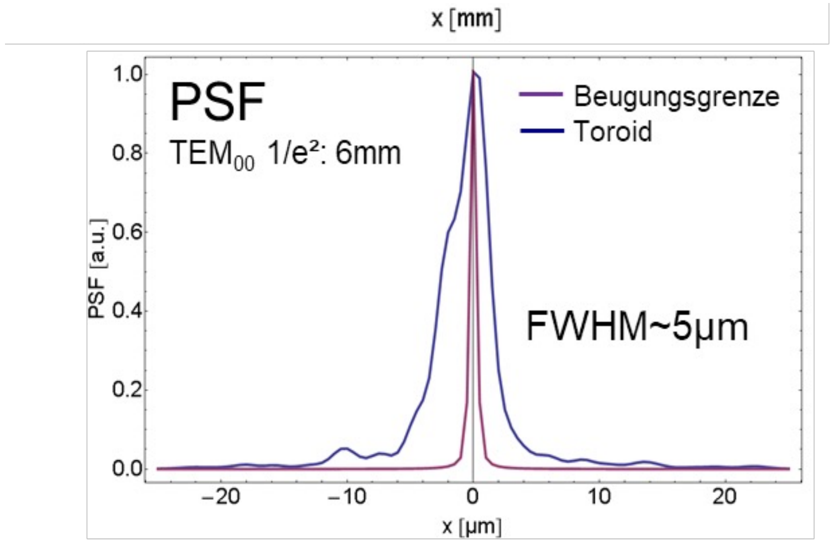
- Topographical Survey of Toroidal Mirror
  - Coated with Mo/Si multilayer @ 13.5 nm
  - Surface figure: Deflectometry (Frank Siewert / BESSY)



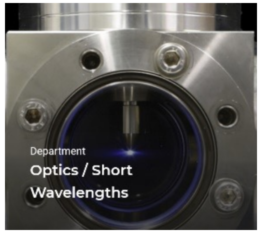



Simulated PSF from topography:




- ➢ Reason for low coherence
- ➢ Wigner technique can be applied, but better optics needed




# Beam Profile Analysis

## FELfocus Project: Automated Adjustment based on Wavefront Sensing

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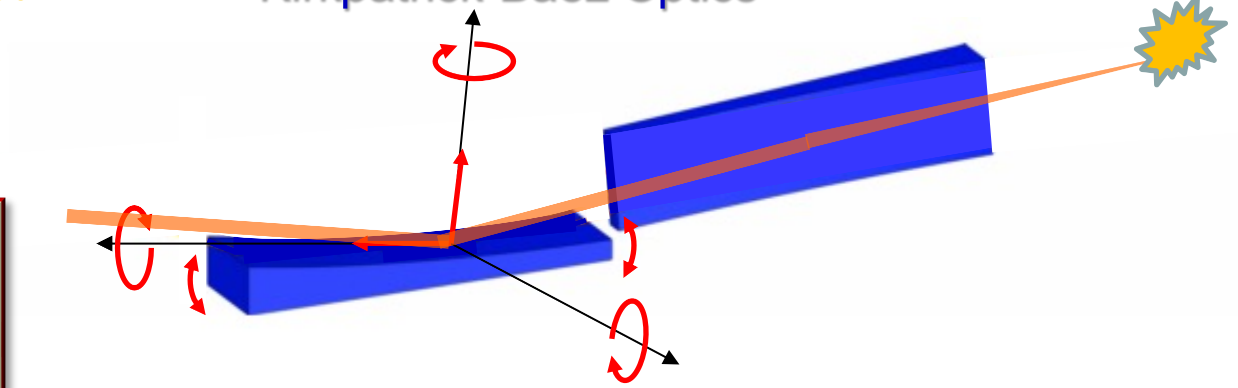
- Motivation
  - Many Degrees of Freedom (KB: ~ 10 - 14)
    - High Dimensional Parameter Space
      Beam Position, Focus diameter, Profile orientation, aberrations etc.
  - Manual Adjustment very Time consuming
    → Optimum configuration is usually not achieved!

Kirkpatrick-Baez Optics



**Advantage:**

- ➢ More beam-time for Users
- ➢ Higher beam quality
- ➢ More flexible adaption to experimental requirements

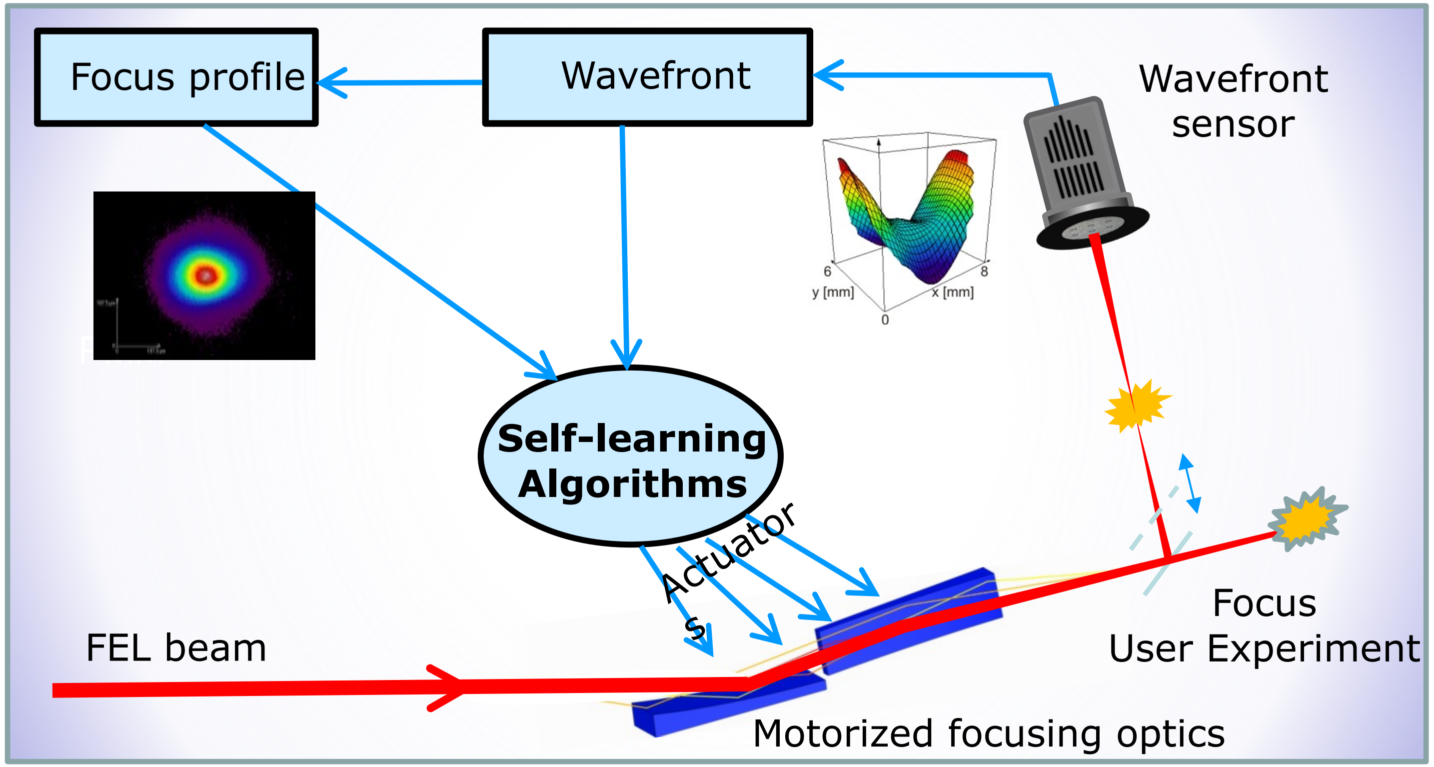
**Relevant Beam Parameters**

Focus position (3 Parameter)
Focus dimension (2 Parameter)
Orientation (1 Parameter)
Aberrations (N Parameter)

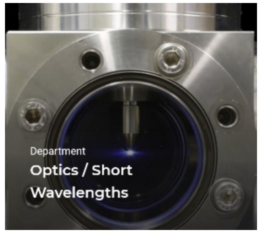
# Beam Profile Analysis

## FELfocus Project: Automated Adjustment based on Wavefront Sensing

- Partners:
  - Institut für Nanophotonik Göttingen e.V.
  - University of Göttingen, Math Dept.
  - DESY
  - European XFEL
  - Carl Zeiss SMT




Poster 13/35 Barbara Keitel et al.
→ quasi-parasitic wavefront and focus monitoring possible!




# Beam Profile Analysis

## FELfocus Project: Automated Adjustment based on Wavefront Sensing

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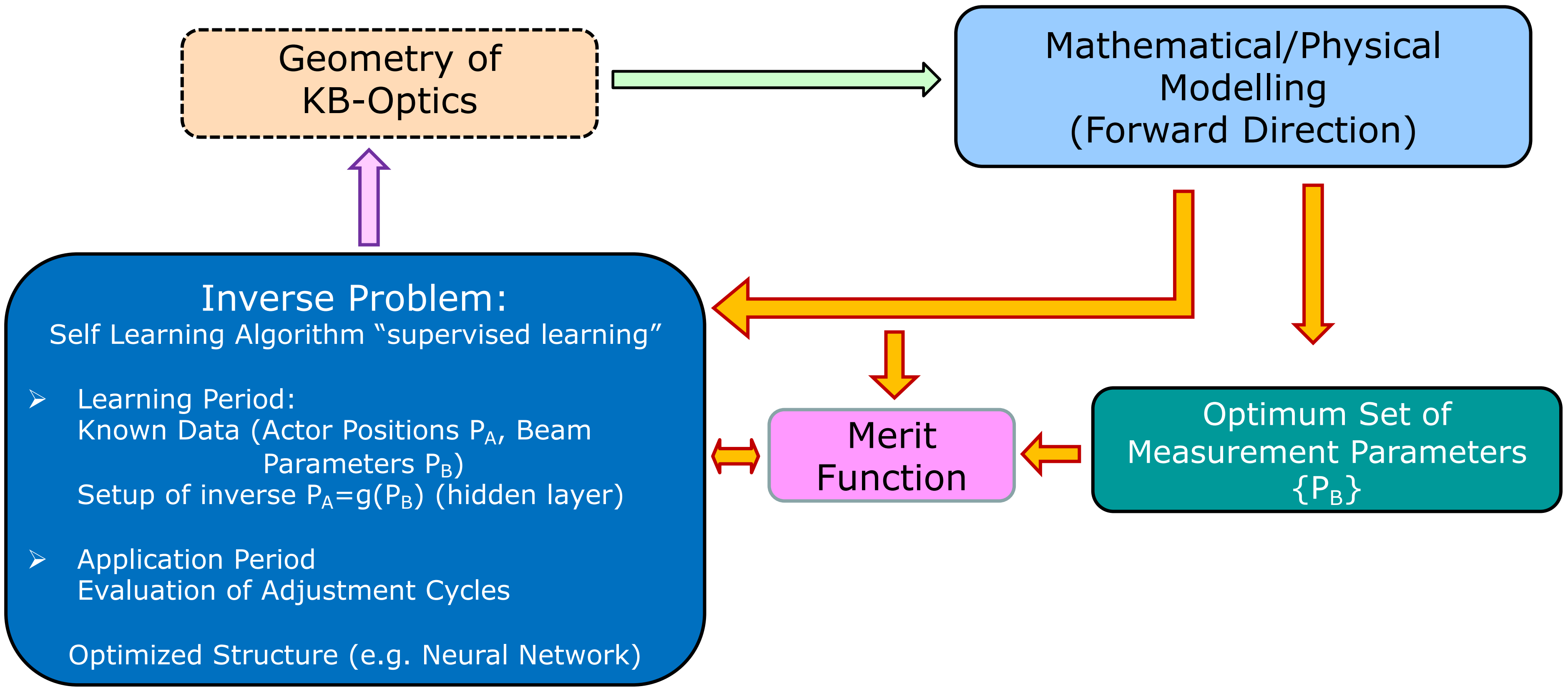
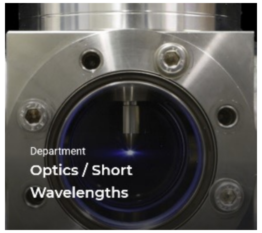
Block Diagram of Sub-Systems and Dependencies within the Policy for optimized and automated Adjustment






# Beam Profile Analysis

## FELfocus Project: Automated Adjustment based on Wavefront Sensing

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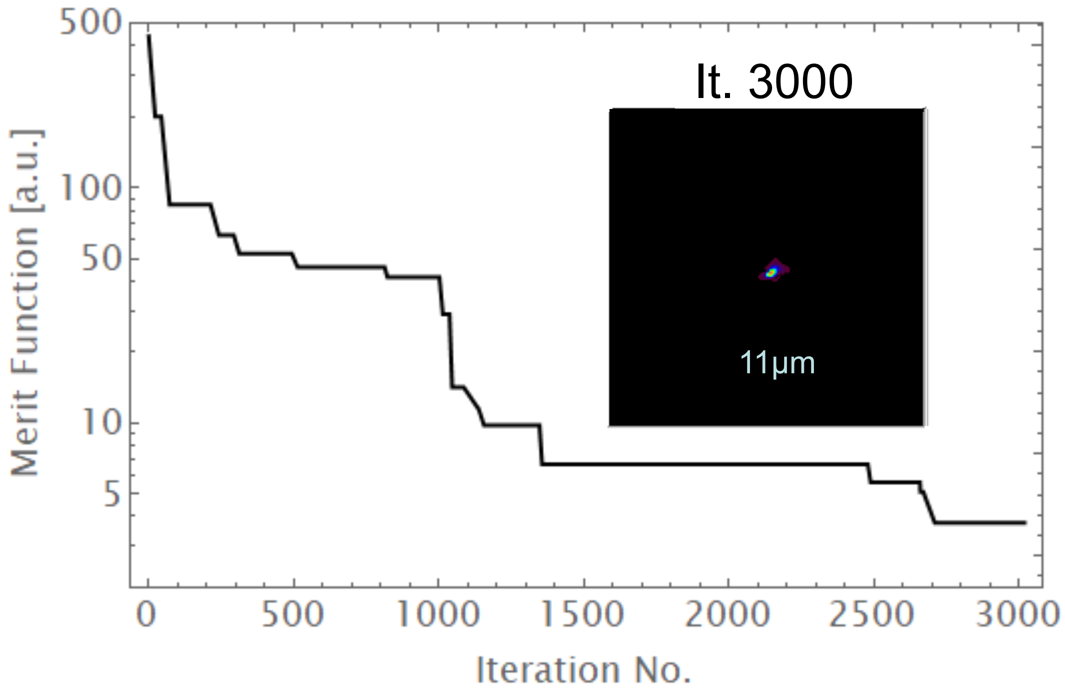
### Model

**Input Beam**
Gaussian Schell-Model Beam
(incl. Pos/Pt Instabilities)

**Propagation through KB Optics**
Ray-Tracing + Fresnel-Back-Propagation
(incl. „virtual“ Hartmann Wavefront Sensor)

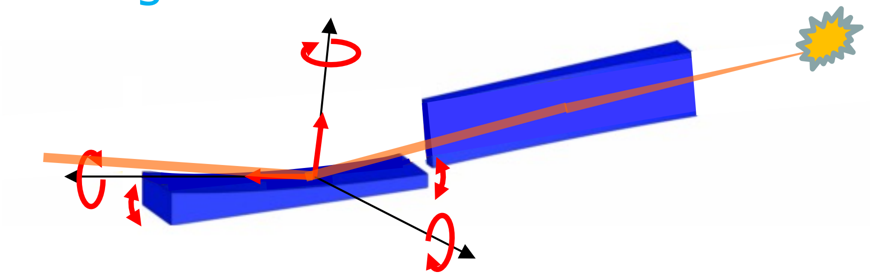
**Evaluation of Merit Function**
@ Focus and Sensor Position

**Optimization**
via Downhill-Simplex Algorithm
(+ Simulated Annealing)



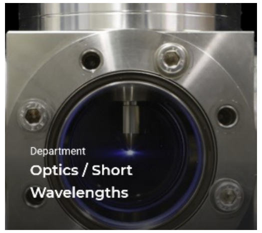
## What we have

- Hartmann Sensors for VUV / EUV / soft X-rays
- Numeric handling of partially (spatial) coherent beam
  - quasi real-time propagation
  - coherence determination using Wigner Distribution
- On-Line focus monitoring



## What we're aiming for

- (Automated) A.I. based KB-Optics adjustment at FLASH II
- Approaching the hard X-ray regime...




# PhotonMEADOW 2023

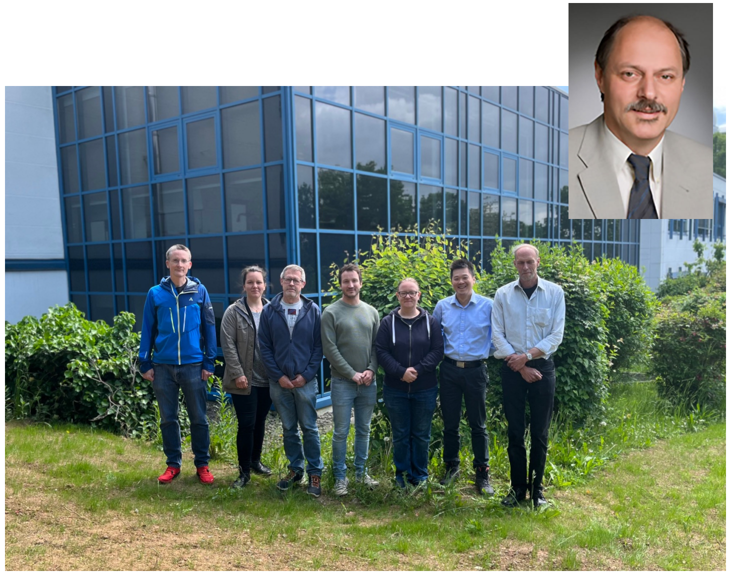
## Wavefront metrology and beam propagation in the EUV/X-ray spectral range

IFNANO
INSTITUT FÜR NANOPHOTONIK

### Former Coworkers

- B. Flöter
- T. Mey
- J. Holburg
- J.O. Dette

### The Group



### BMBF projects ProWave & FELFocus

- B. Keitel, DESY
- E. Plönjes, DESY
- G. Plonka-Hoch, Univ. Göttingen

### Partners & Collaboration

- Michael Meyer
- Tommaso Mazza

European XFEL

- Frank Scholze

PTB Physikalisch Technische Bundesanstalt

- Frank Siewert

HZB Helmholtz Zentrum Berlin