Wigner distribution measurement of the spatial coherence properties of FLASH

Tobias Mey

Laser-Laboratorium Göttingen e.V.
Hans-Adolf-Krebs Weg 1
D-37077 Göttingen

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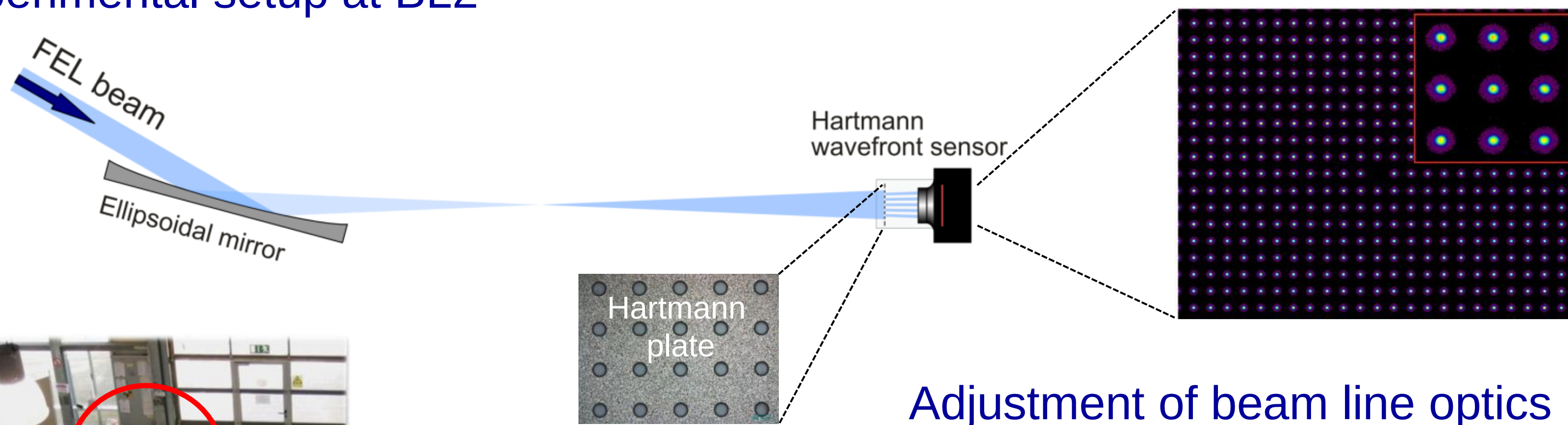
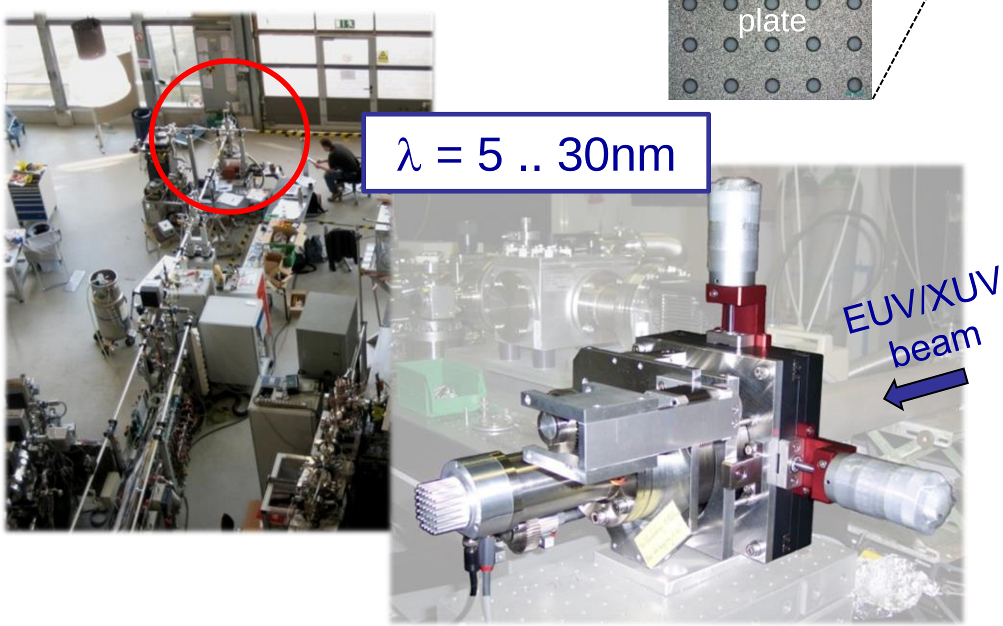
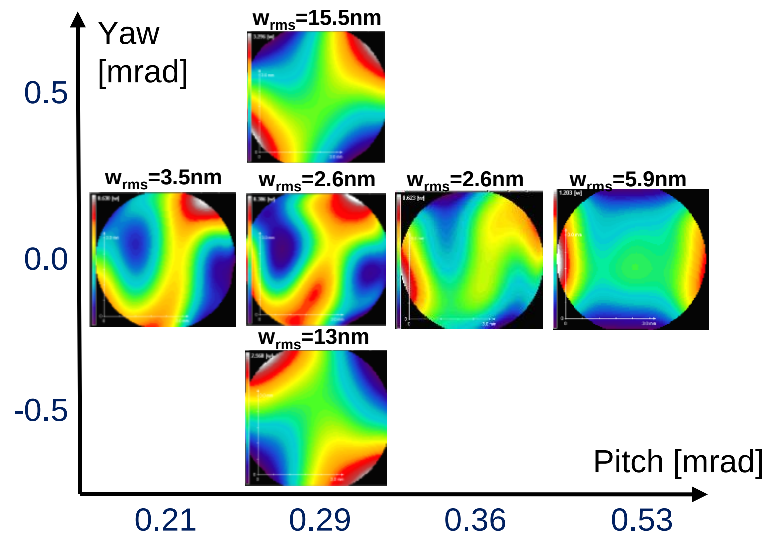
EUV wavefront sensor

Experimental setup at BL2





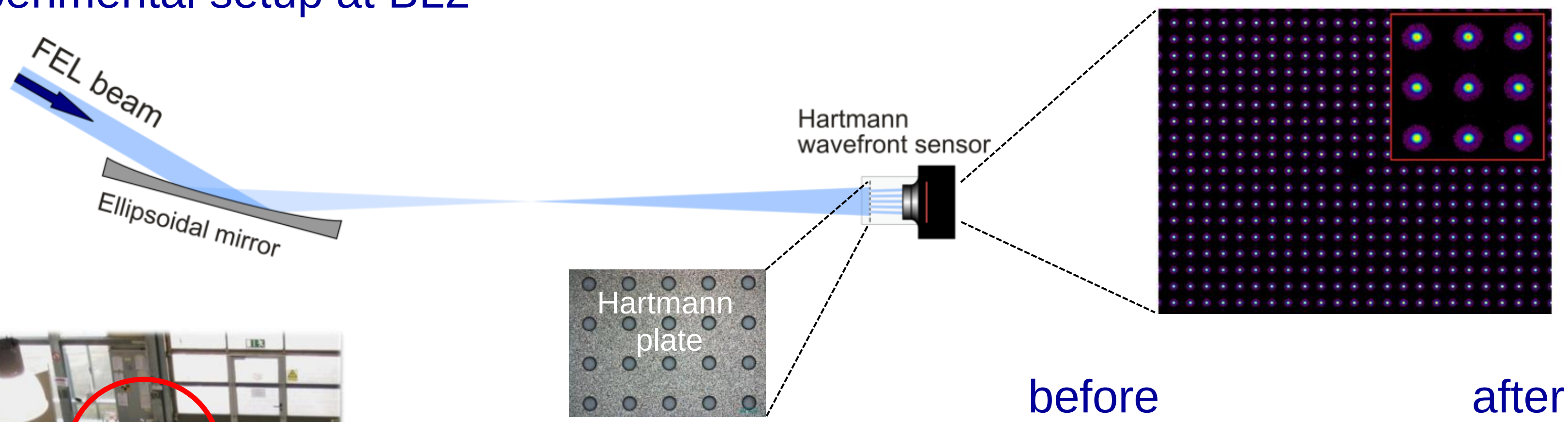
Adjustment of beam line optics by online wavefront monitoring

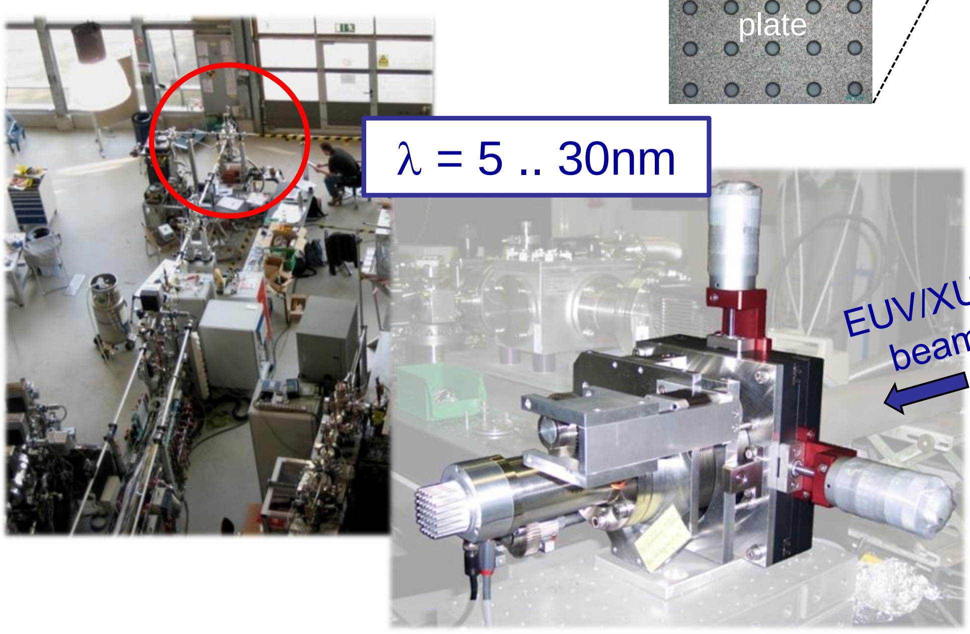


[1] B. Flöter *et al*, *Beam parameters of FLASH beamline BL1 from Hartmann wavefront measurements*, Nucl. Instrum. Meth. A 635 (2011) 5108-5112

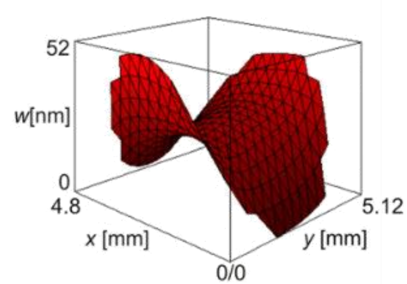
EUV wavefront sensor

Experimental setup at BL2



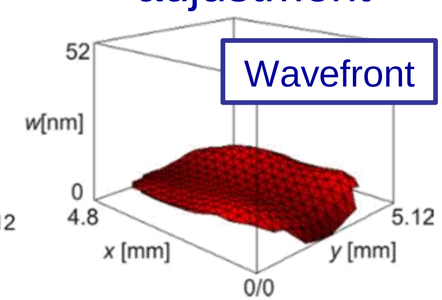


before adjustment



w_{rms}~ 10nm

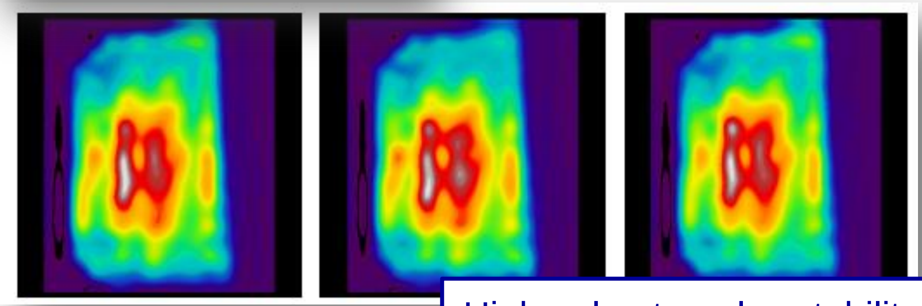
after adjustment



w_{rms}~ 2.5nm ~ λ/10

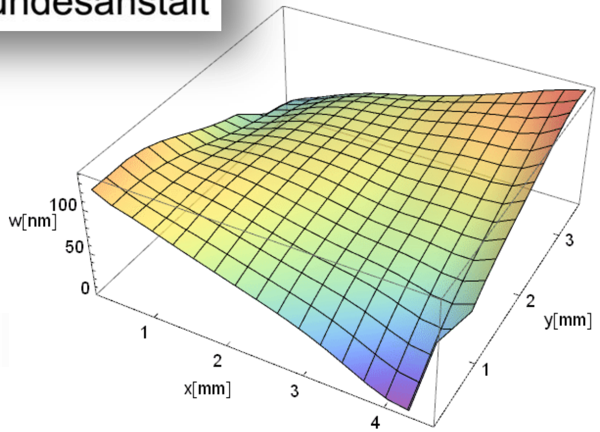
[2] B. Flöter *et al*, *EUV Hartmann sensor for wavefront measurements at the Free-electron LASer in Hamburg*, New J. Phys. 12 (2010) 083015

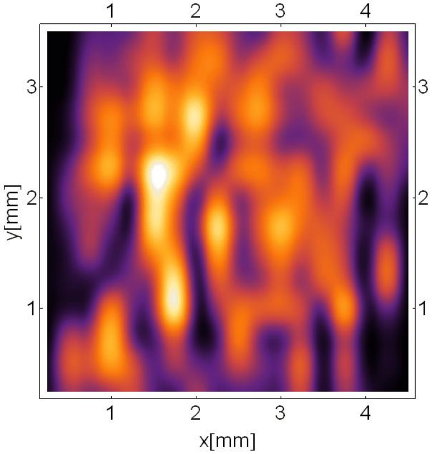
EUV wavefront sensor



High pulse-to-pulse stability!

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





Online optics alignment
at MLS synchrotron
at 13.5 nm

Motivation

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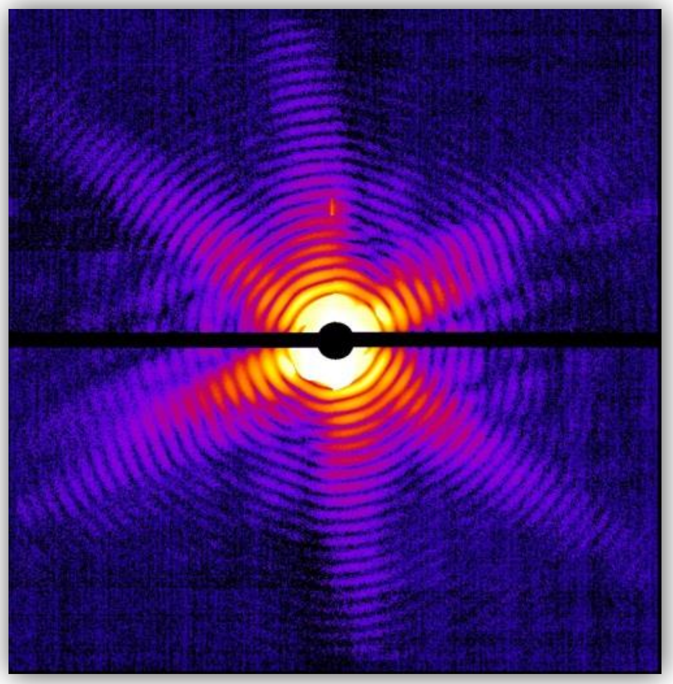
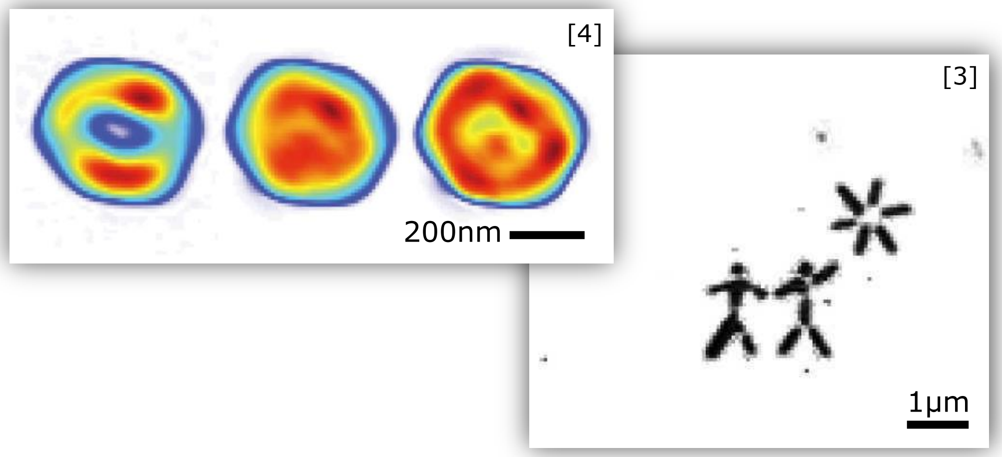
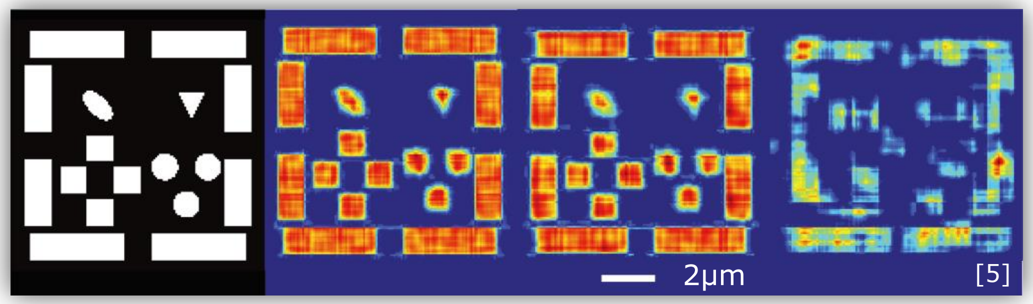
Laboratorium
Göttingen e.V.

Coherent diffractive imaging



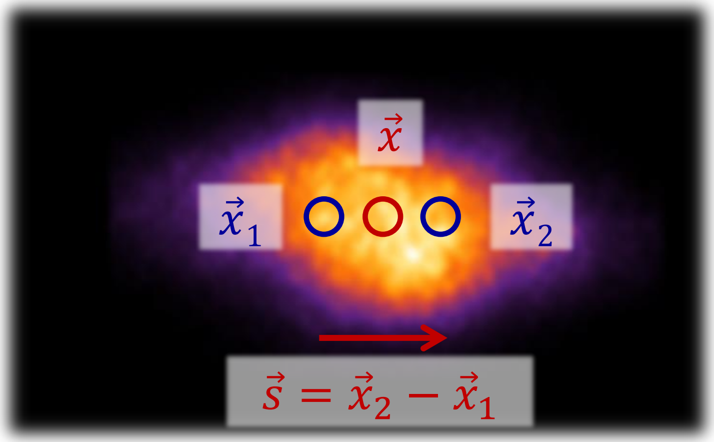




Decreasing coherence

[3] H. N. Chapman *et al.*, "Femtosecond diffractive imaging with a soft-X-ray free-electron laser," Nature Phys. **2**, 839-843 (2006)
[4] M. M. Seibert *et al.*, "Single mimivirus particles intercepted and imaged with an X-ray laser," Nature **470**, 78-82 (2011)
[5] B. Chen *et al.*, "Diffraction imaging: The limits of partial coherence," Phys. Rev. B **86**, 235401 (2012)

Coherence



Mutual coherence function

$$\Gamma(\vec{x},\vec{s}) = \langle E(\vec{x}_1,t)\cdot E^*(\vec{x}_2,t)\rangle$$
$$= \langle E(\vec{x}-\vec{s}/2,t)\cdot E^*(\vec{x}+\vec{s}/2,t)\rangle$$

Local degree of coherence

$$\gamma(\vec{x},\vec{s}) = \frac{\Gamma(\vec{x},\vec{s})}{\sqrt{I(\vec{x}-\vec{s}/2)\cdot I(\vec{x}+\vec{s}/2)}}$$

Global degree of coherence

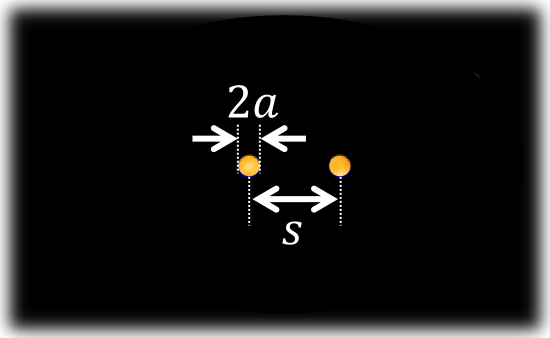
$$K = \frac{\iint \Gamma(\vec{x},\vec{s})^2 d\vec{x}d\vec{s}}{\left(\iint \Gamma(\vec{x},0)d\vec{x}\right)^2}$$

→ required for interference effects

[6] M. Born and B. Wolf, *Principles of Optics,* Cambridge University Press (1980)

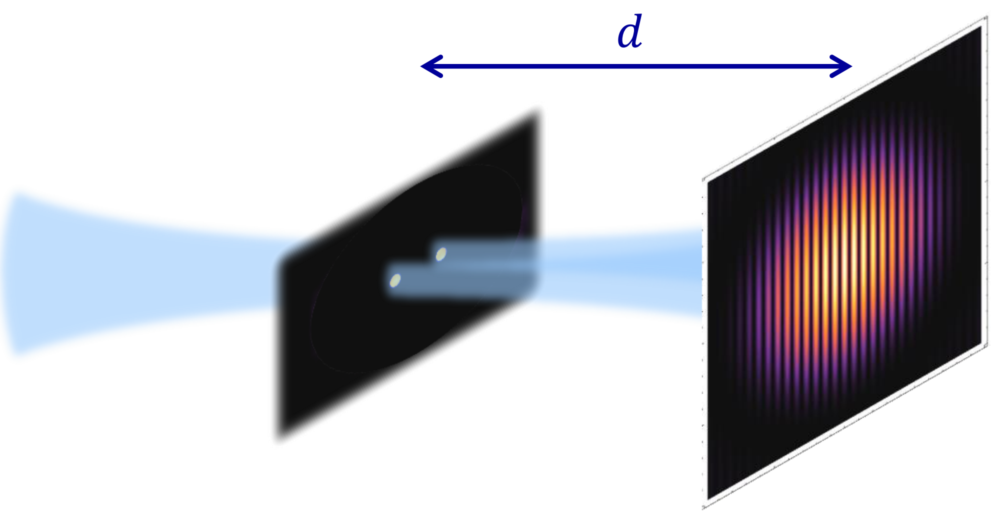
Coherence

Interference of elementary waves → $\gamma(\vec{x},\vec{s})$

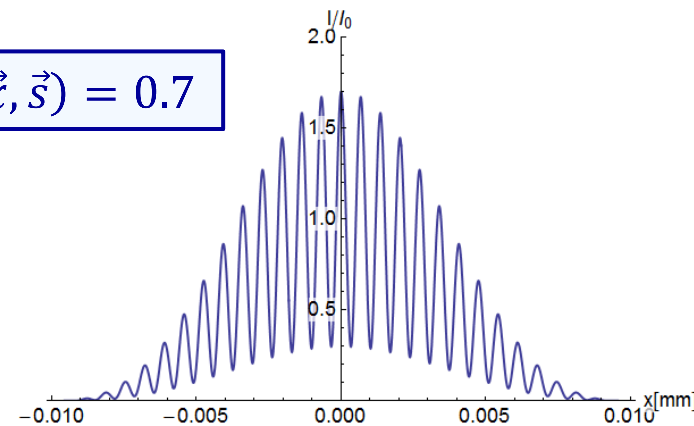


$$I(x,y) = I_0 \cdot \left(J_1\left(\frac{2\pi a r}{\lambda d}\right) \Big/ \frac{2\pi a r}{\lambda d} \right)^2 \cdot \left[1 + \gamma(\vec{x},\vec{s}) \cdot \cos\left(\frac{2\pi s}{\lambda d} x\right)\right]$$ [6]

$$r = \sqrt{x^2 + y^2}$$



$$\gamma(\vec{x},\vec{s}) = 0.7$$



[6] M. Born and B. Wolf, *Principles of Optics,* Cambridge University Press (1980)

Coherence

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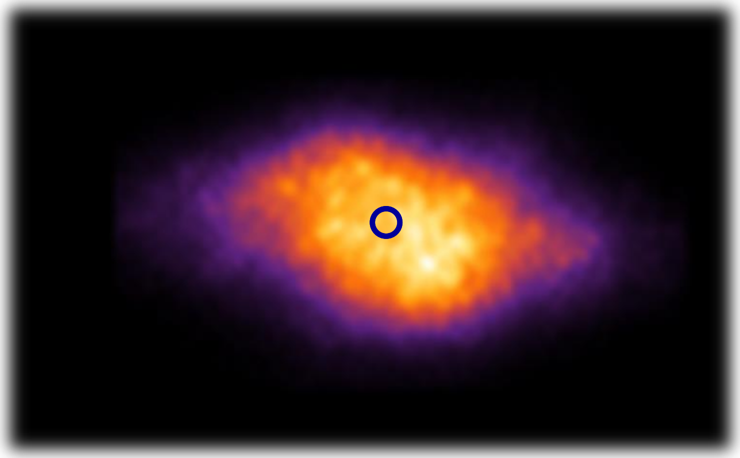
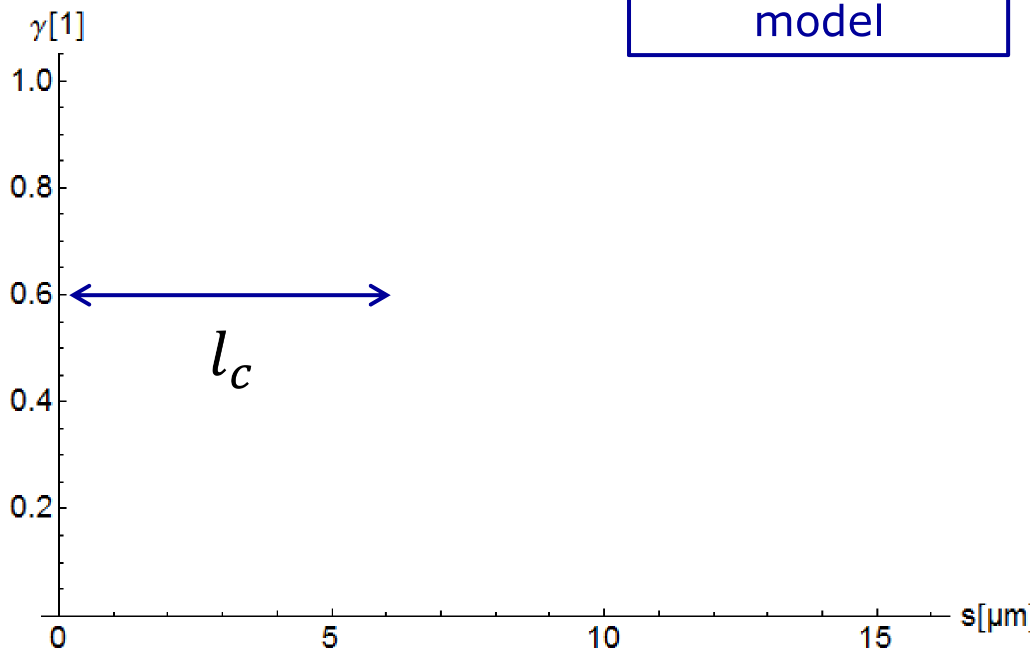


$$\gamma(0,0,s_x,0) = \exp\left[\frac{s_x^2}{2\,l_c^2}\right]$$

Gaussian Schell model



Coherence length l_c

Coherence

Spatial and temporal coherence properties of single free-electron laser pulses

A. Singer[1], F. Sorgenfrei[2], A. P. Mancuso[3], N. Gerasimova[1], O. M. Yefanov[1], J. Gulden[1], T. Gorniak[4,5], T. Senkbeil[4,5], A. Sakdinawat[6], Y. Liu[7], D. Attwood[7], S. Dziarzhytski[1], D. D. Mai[8], R. Treusch[1], E. Weckert[1], T. Salditt[8], A. Rosenhahn[4,5], W. Wurth[2*] and I. A. Vartanyants[1,9*]

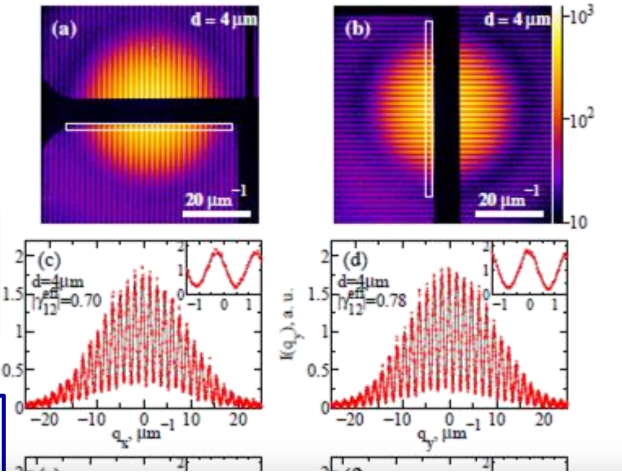
[1] Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, D-22607 Hamburg, Germany
[2] Institut für Experimentalphysik and CFEL, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[3] European XFEL GmbH, Albert-Einstein-Ring 19, 22761 Hamburg, Germany
[4] University of Heidelberg, Im Neuenheimer Feld 253, 69120 Heidelberg, Germany
[5] Institute of Functional Interfaces, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[6] SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025-7015, USA
[7] University of California, Berkeley, CA 94720, USA
[8] Institut für Röntgenphysik, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany
[9] National Research Nuclear University, "MEPhI", 115409 Moscow, Russia
*Ivan.Vartaniants@desy.de, Wilfried.Wurth@desy.de

Abstract: The experimental chara[…] coherence properties of the free-ele[…] wavelength of 8.0 nm is presented. […] single femtosecond pulses focused […] measured. A transverse coherence le[…] and 8.7 ± 1.0 μm in the vertical dir[…] coherent pulses. Using a split and […] pulses produced in the same operati[…] to be 1.75 ± 0.01 fs. From our exp[…] parameter of the FLASH beam to b[…] exceeds the values of this parameter […] range by many orders of magnitude.

OCIS codes: (000.0000) General.

References and links

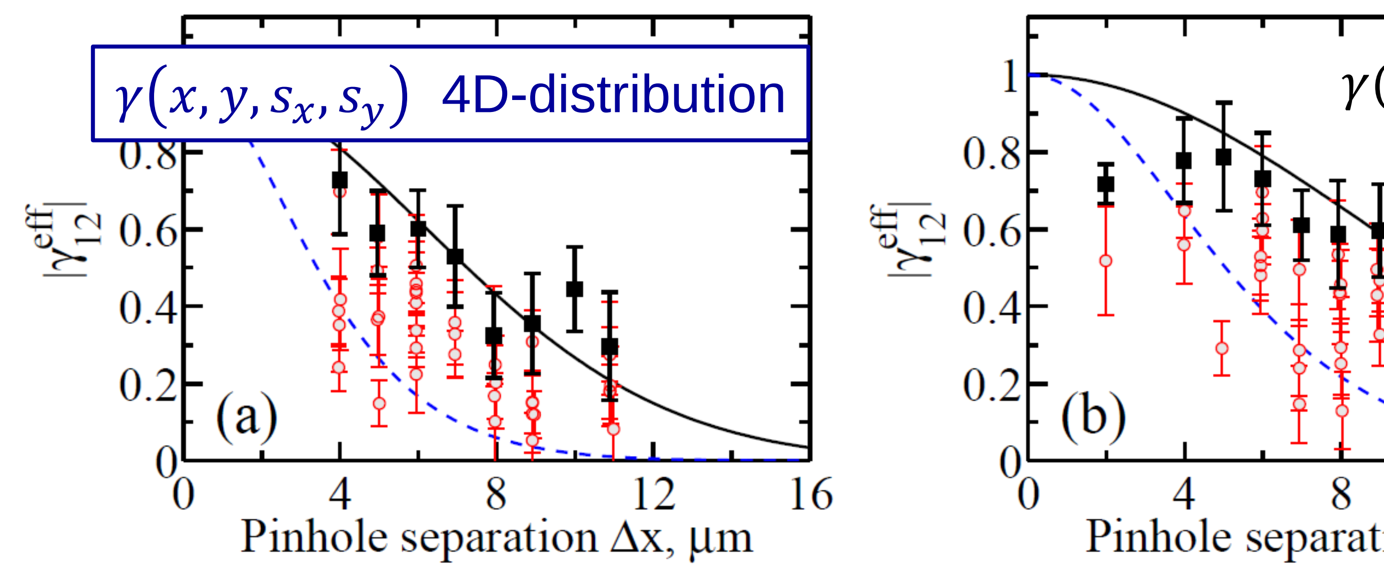
1. W. Ackermann, G. Asova, V. Ayvazyan, A. Azima, N[…] mann, R. Brinkmann, O. I. Brovko, M. Castellano, […] J. T. Costello, D. Cubaynes, J. Dardis, W. Decking, […] S. Dsterer, A. Eckhardt, H. T. Edwards, B. Faatz, J. […] Gensch, C. Gerth, M. Görler, N. Golubeva, H. J. G[…] Han, K. Honkavaara, T. Hott, M. Hüning, Y. Ivanise[…] V. Katalev, K. Kavanagh, E. T. Kennedy, S. Khodya[…]



Gaussian Schell model

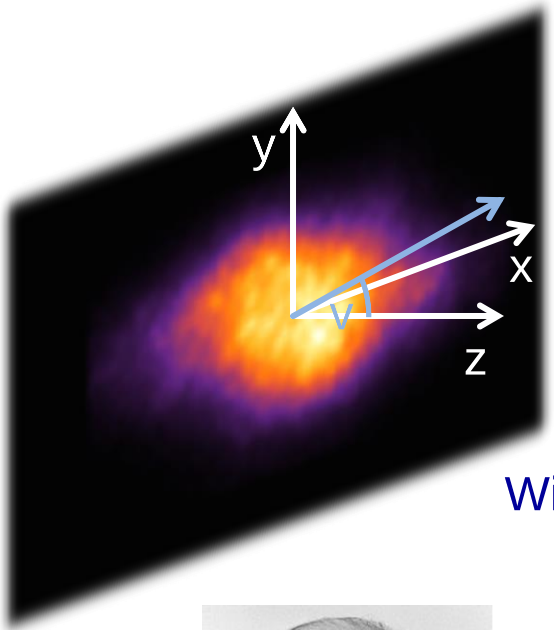
$K = 0.42 \pm 0.09$

$\gamma(x, y, s_x, s_y)$ 4D-distribution



[7] A. Singer *et al.*, "Spatial and temporal cohere

Wigner distribution function



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

Mutual coherence function

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

Wigner distribution

Radiation angle $\vec{u} = \binom{u}{v}$

“Ge

anc

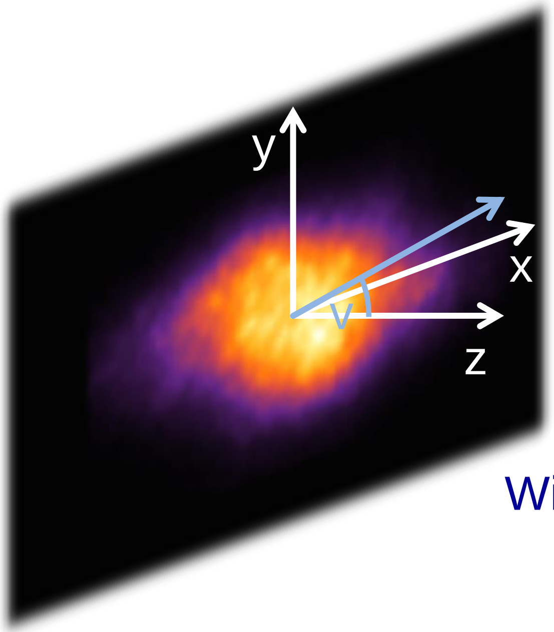
Eugene Paul Wigner
Nobel price 1963
(with J. H. D. Jensen and M. Goeppert-Mayer)

Wilhelm-Weber-Straße 22, Göttingen ►

sitior

[8] M. J. Bastiaans, “Application of the Wigner distribution function to partially coherent light,” J. Opt. Soc. Am. A **3**, 1227-1238 (1986)

Wigner distribution function



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Wigner distribution

Radiation angle $\vec{u} = \binom{u}{v}$

Irradiance

$$I(\vec{x}) = \iint h(\vec{x},\vec{u}) du dv$$

→ Near field

Radiance

$$\hat{I}(\vec{u}) = (2\pi)^{-2} \iint h(\vec{x},\vec{u}) dx dy$$

→ Far field

Global degree of coherence

$$\mathrm{K} = \lambda^2 \frac{\iint h(\vec{x},\vec{u})^2 dx^2 du^2}{\iint h(\vec{x},\vec{u}) dx^2 du^2}$$

[8] M. J. Bastiaans, "Application of the Wigner distribution function to partially coherent light," J. Opt. Soc. Am. A **3**, 1227-1238 (1986)

Gaussian Schell-model

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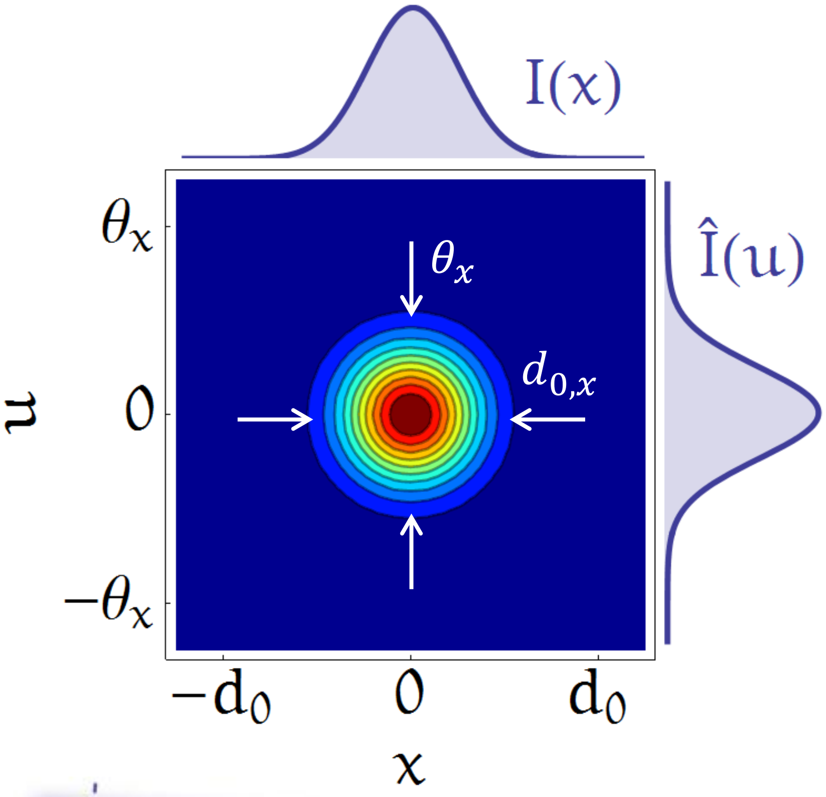


Separability

$$h(\vec{x},\vec{u}) = h_x(x,u) \cdot h_y(y,v)$$

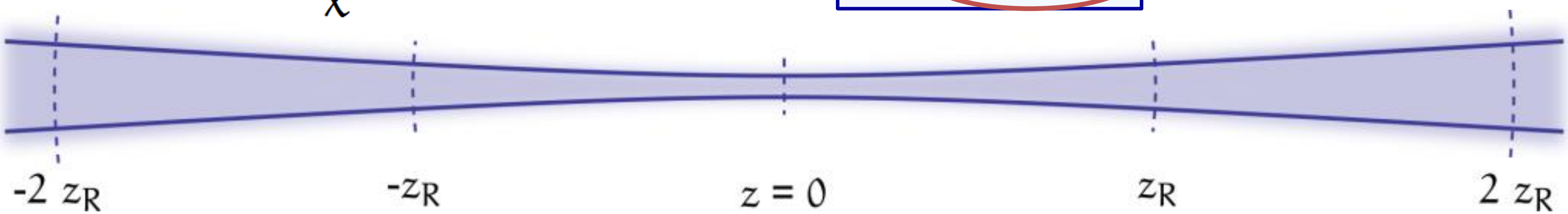
Wigner distribution at waist position

$$h_x(x,u) = h_0 \exp\left[-\frac{8\,x^2}{d_{0,x}^2}\right] \exp\left[-\frac{8\,u^2}{\theta_x^2}\right]$$

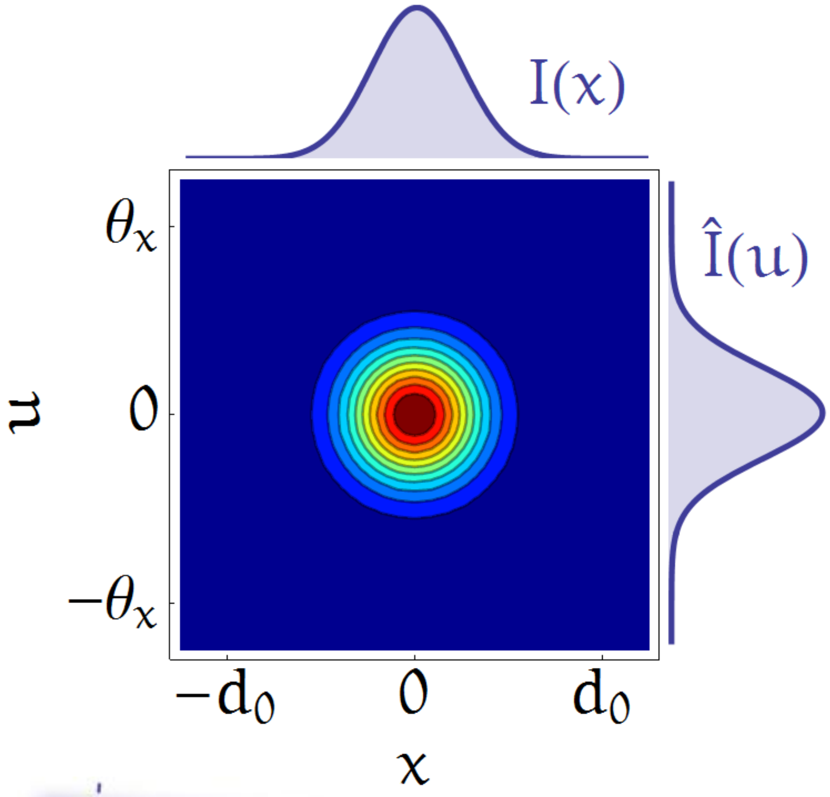
Global degree of coherence

$$K = \frac{4}{\pi} \cdot \frac{\lambda}{d_{0,x}\theta_x}$$

Phase space volume (constant after Liouville)



Gaussian Schell-model



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$$h(\vec{x},\vec{u}) = h_x(x,u)\cdot h_y(y,v)$$

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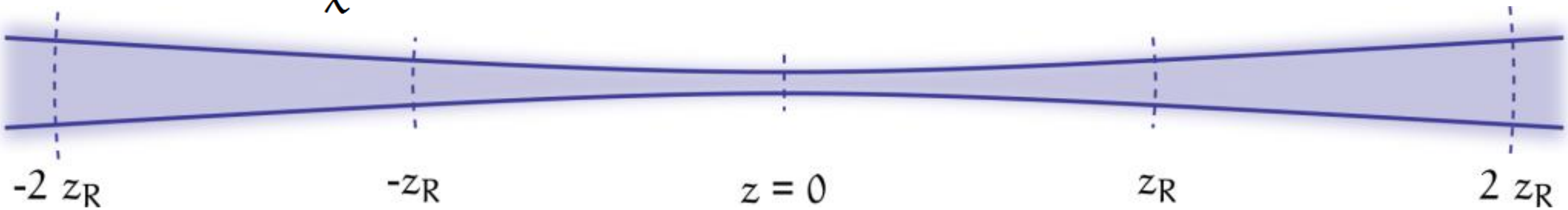
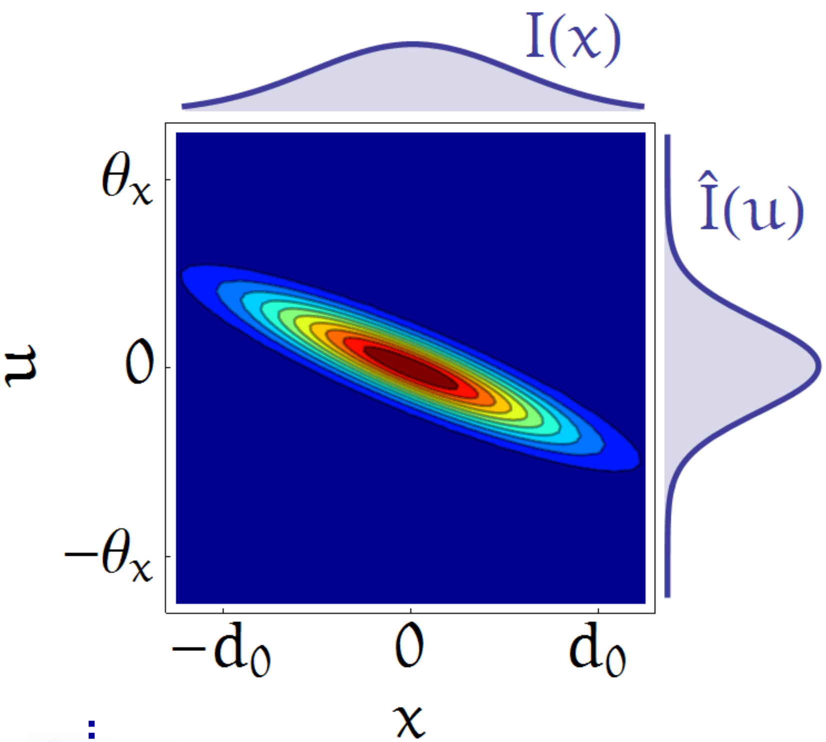
Propagation of the Wigner distribution

$$h_x(x,u)\Big|_z = h_x(x - z\cdot u, u)$$



Gaussian Schell-model



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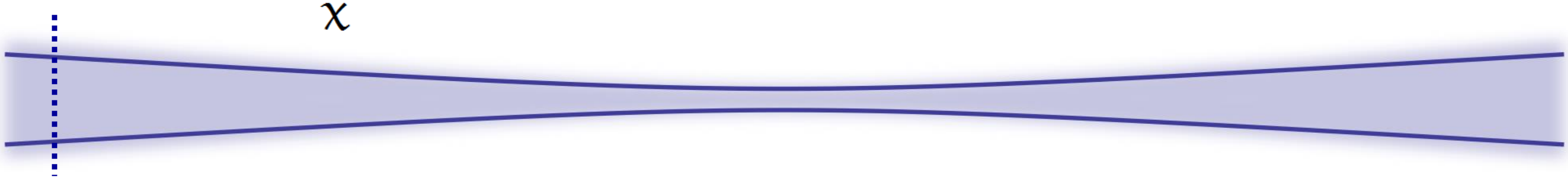
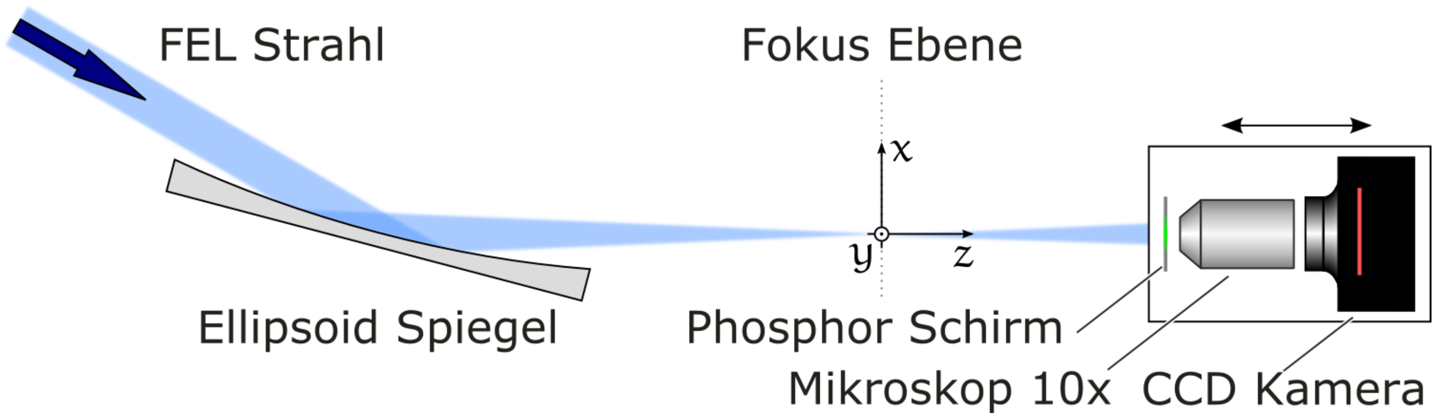
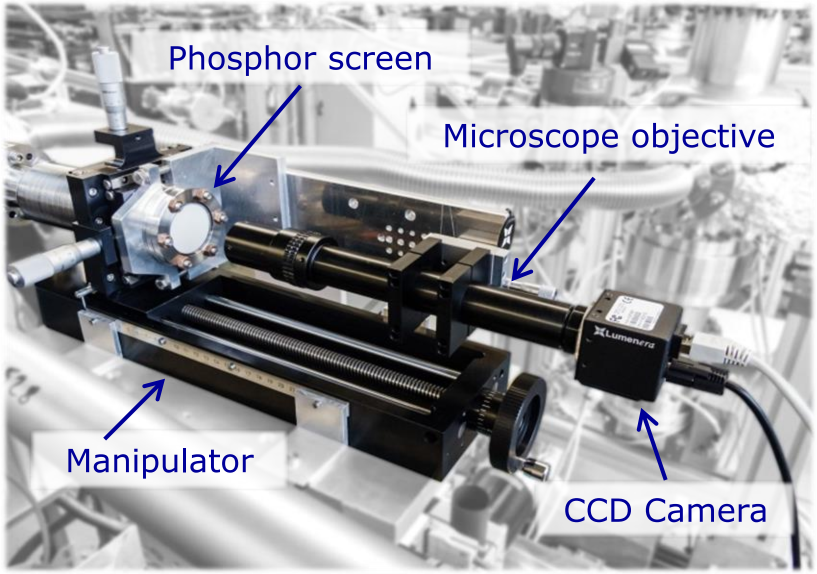


Caustic scan





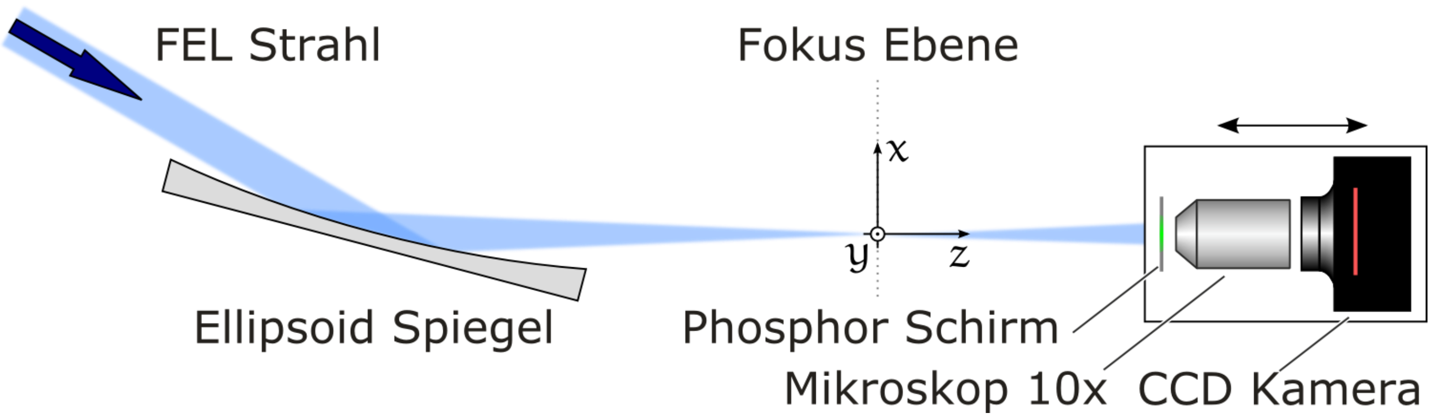
FLASH

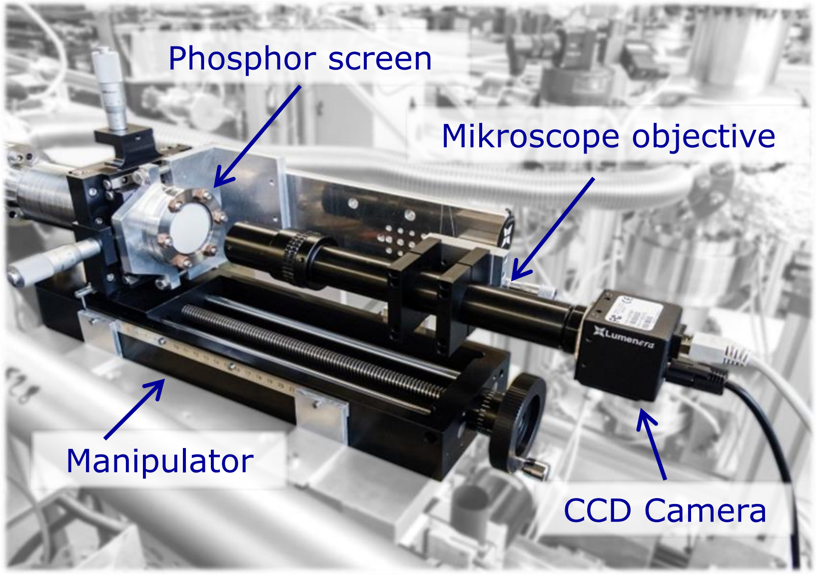
Wavelength	24.7 nm
Pulse energy	35 µJ
Repetition rate	10 Hz

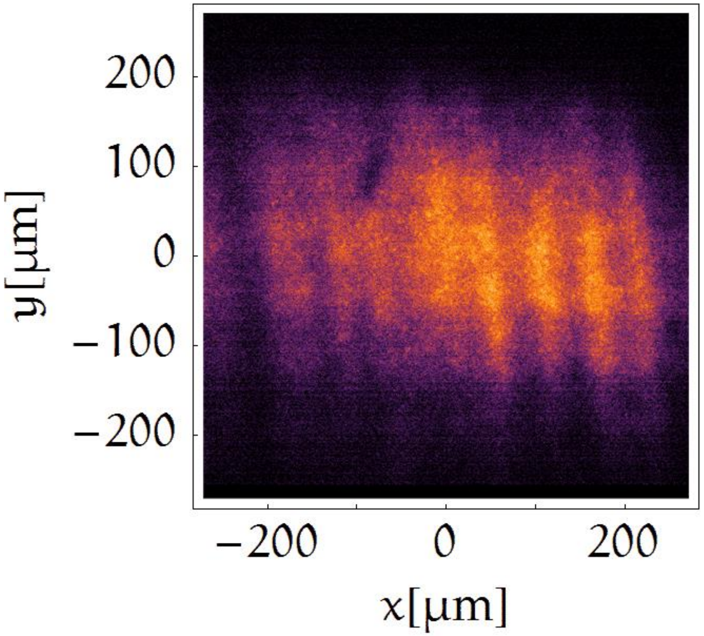
Camera

Eff. pixel size	0.645µm
Exposure time	1.5s

Caustic scan



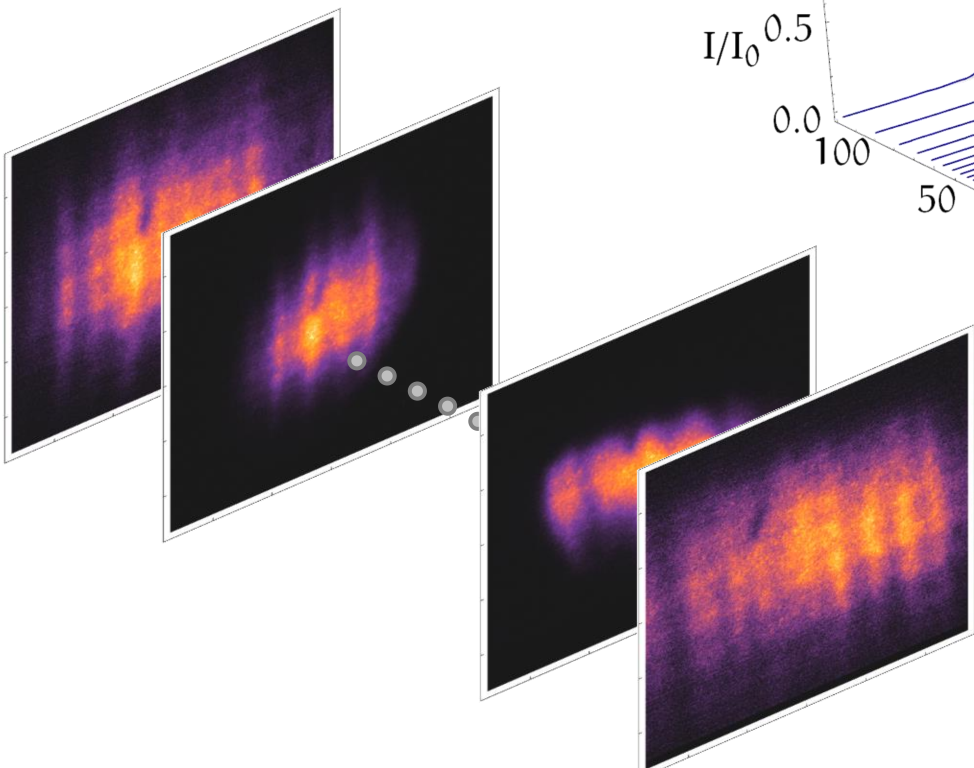


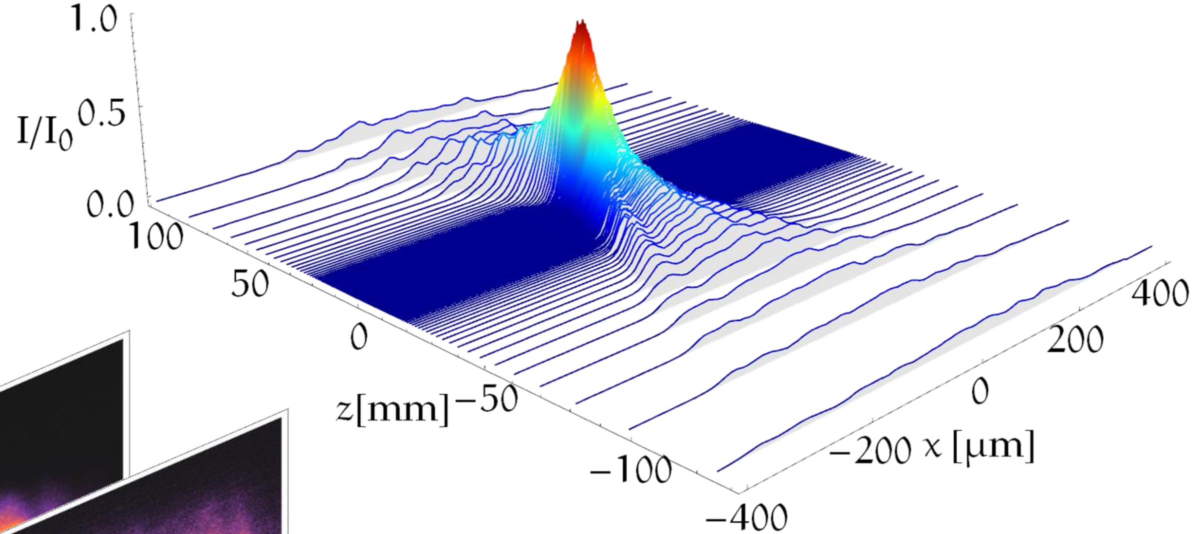


Wigner distribution

Projection-slice theorem [9]

$$\tilde{h}(q_x, z \cdot q_x) = \tilde{I}_z(q_x)$$





$$\int I(x,y)dy$$

[9] A. Torre, *Linear ray and wave optics in phase space,* Elsevier B.V. Netherlands (2005)

Wigner distribution

Projection-slice theorem [9]

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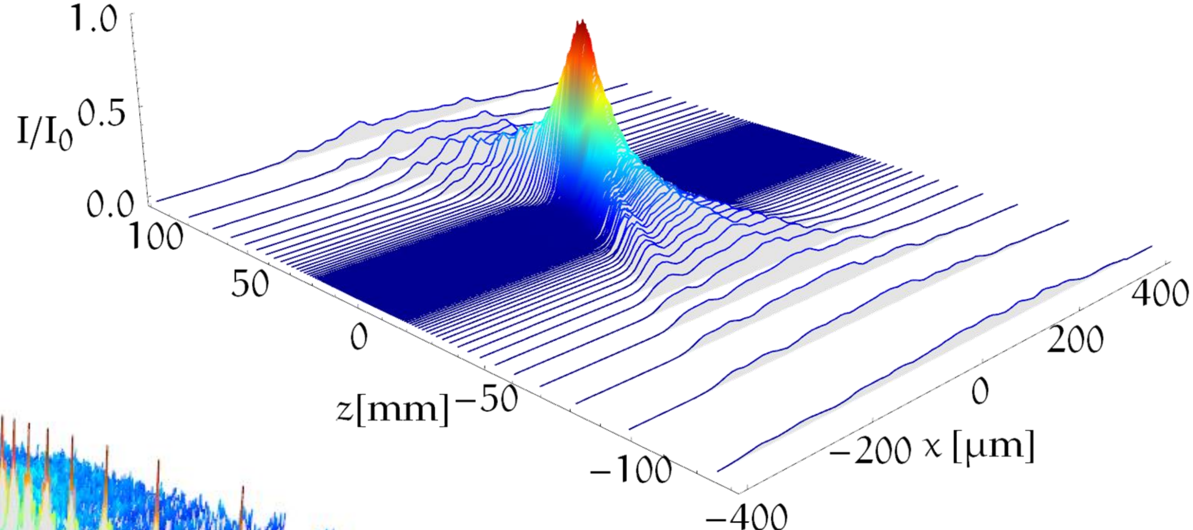
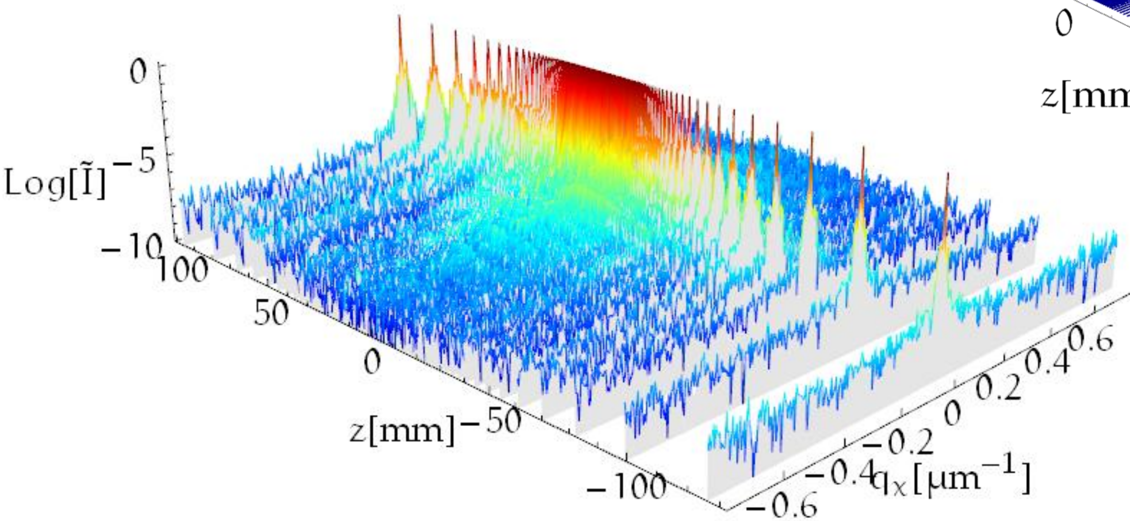




[9] A. Torre, *Linear ray and wave optics in phase space,* Elsevier B.V. Netherlands (2005)

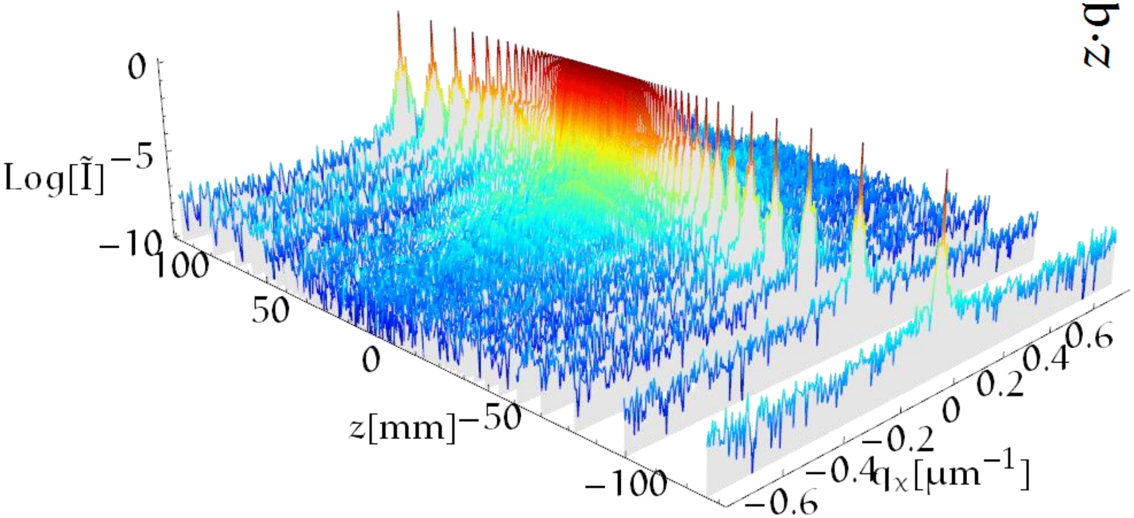
Wigner distribution

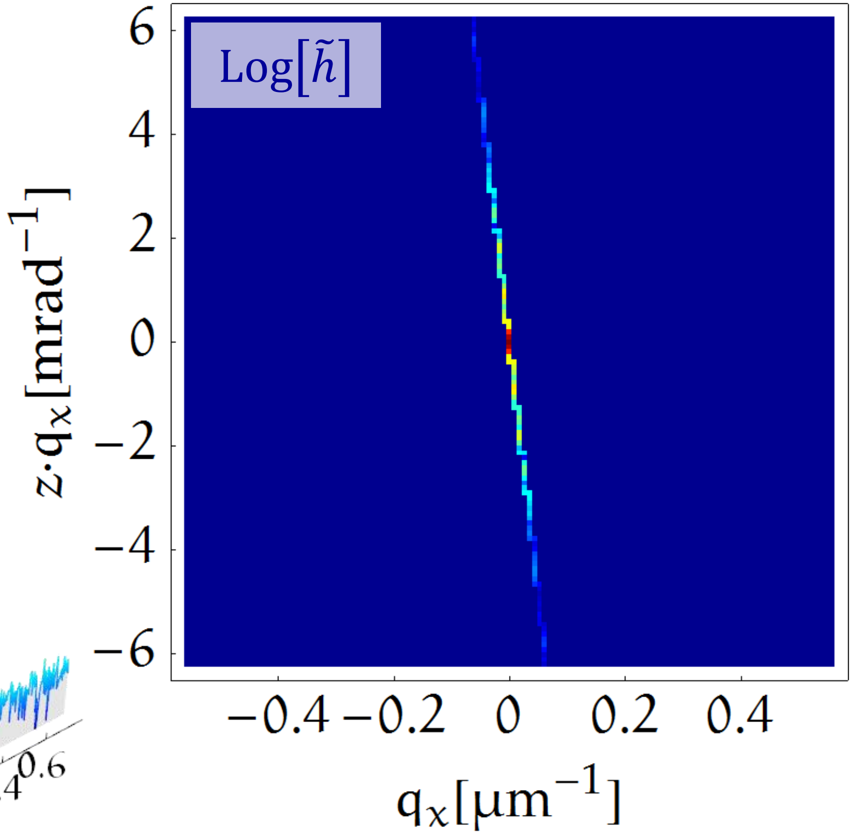
Projection-slice theorem [9]

$$\tilde{h}(q_x, z \cdot q_x) = \tilde{I}_z(q_x)$$

4D reconstruction

$$\tilde{h}(\vec{q}, z \cdot \vec{q}) = \tilde{I}_z(\vec{q})$$

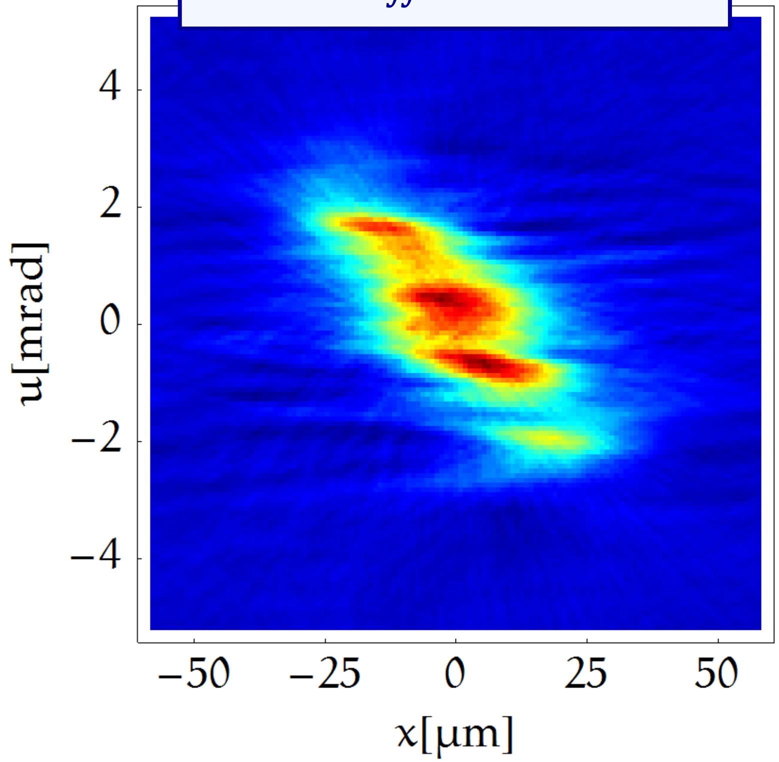




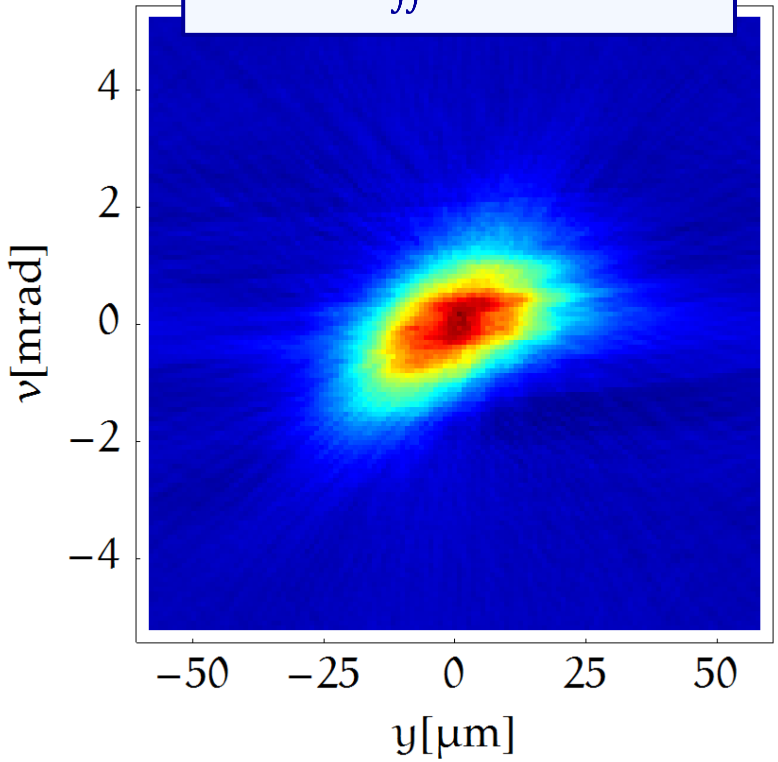
[9] A. Torre, *Linear ray and wave optics in phase space,* Elsevier B.V. Netherlands (2005)

Wigner distribution

$$h_x(x,u) = \iint h(x,y,u,v)\,dy\,dv$$

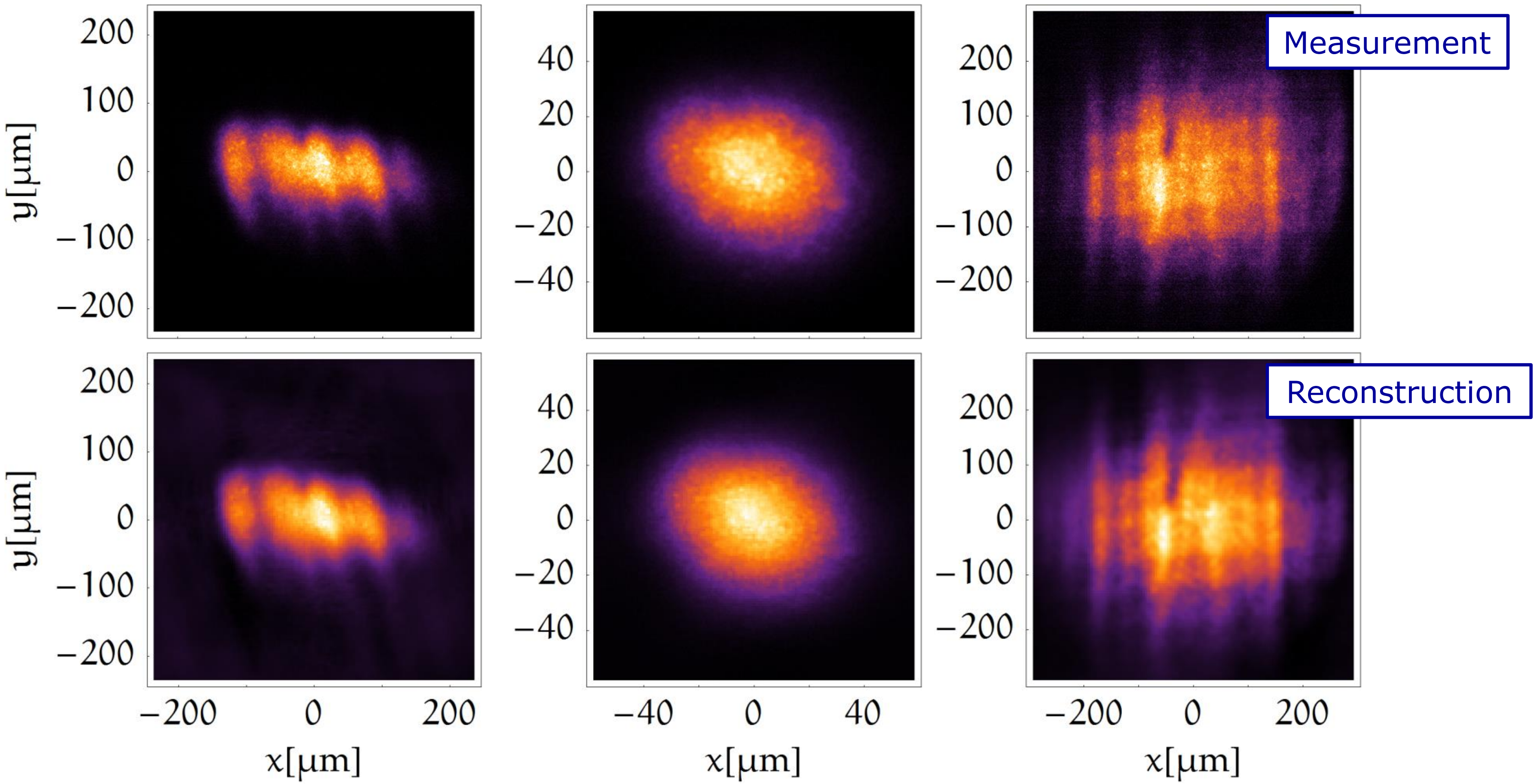


$$h_y(y,v) = \iint h(x,y,u,v)\,dx\,du$$

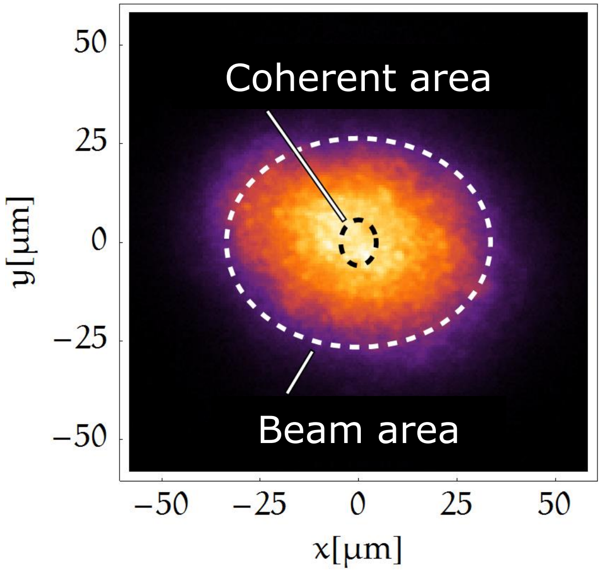


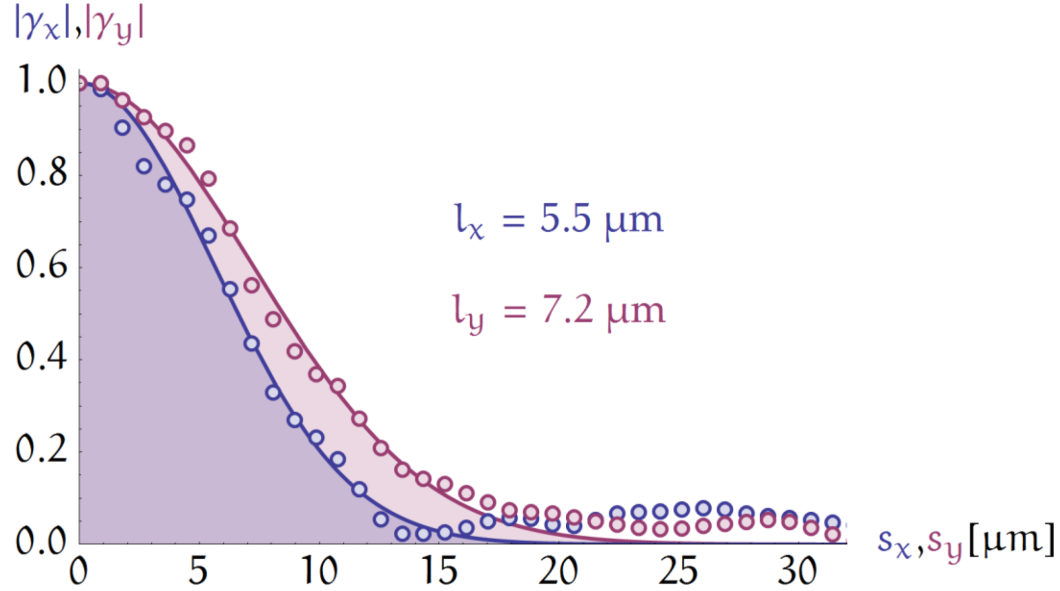
[10] T. Mey *et al.*, "Wigner distribution measurements of the spatial coherence properties of the free-electron laser FLASH," Opt. Expr. **22**, 16571-16584 (2014)

Wigner distribution



Coherence properties



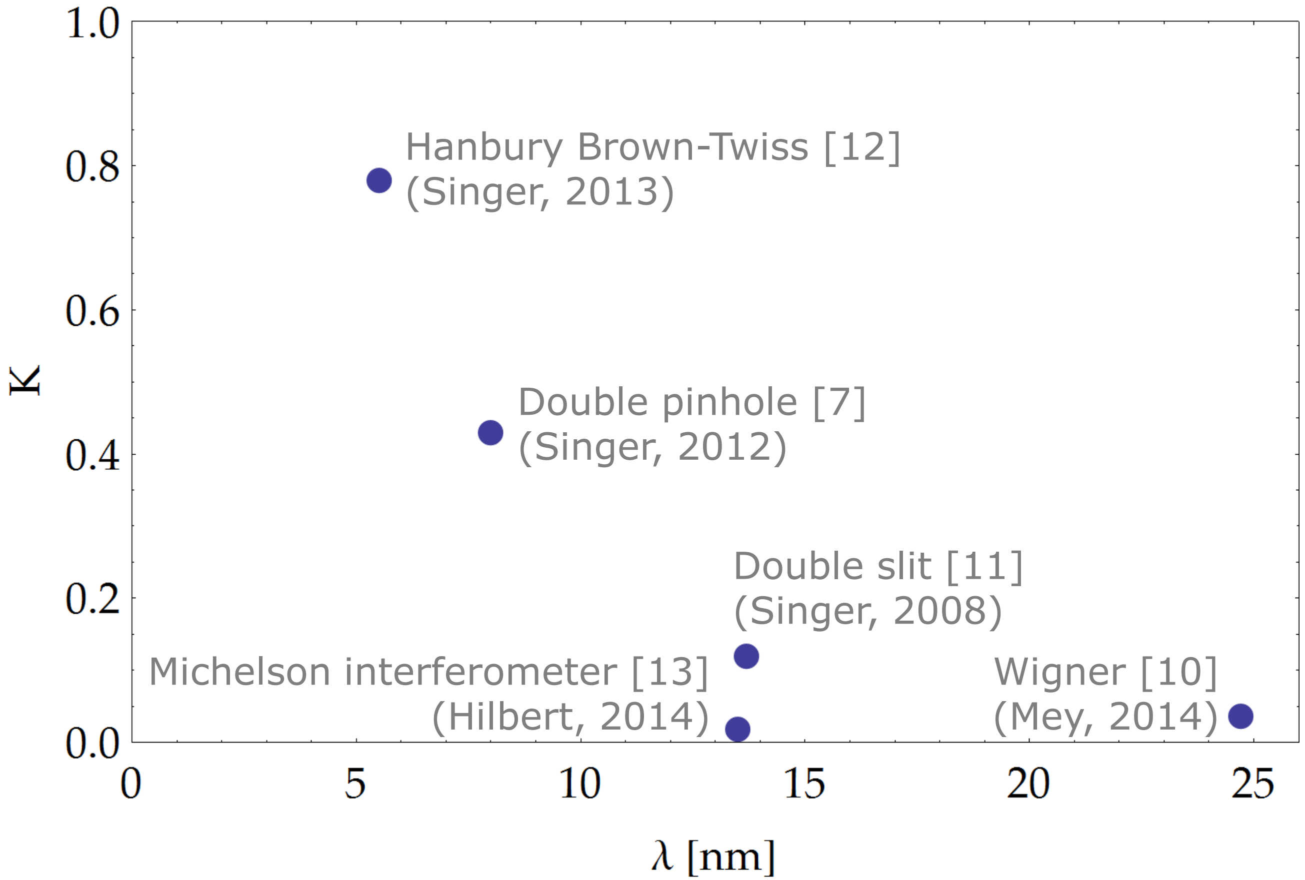


	Wavelength λ [nm]	Beam diameter d_x / d_y [μm]	Coherence length l_x / l_y [μm]	Global degree of coherence K
Wigner [10]	24.7	67 / 53	5.5 / 7.2	0.032
Double pinhole [7]	8.0	17 / 17	6.2 / 8.7	0.42

[7] A. Singer *et al.*, “Spatial and temporal coherence properties of single free-electron laser pulses,” Opt. Expr. **20**, 17480-17495 (2012)

[10] T. Mey *et al.*, “Wigner distribution measurements of the spatial coherence properties of the free-electron laser FLASH,” Opt. Expr. **22**, 16571-16584 (2014)

Coherence properties



[7] A. Singer *et al.*, Opt. Expr. **20**, 17480-17495 (2012)
[10] T. Mey *et al.*, Opt. Expr. **22**, 16571-16584 (2014)
[11] A. Singer *et al.*, Phys. Rev. Lett. **101**, 254801 (2008)
[12] A. Singer *et al.*, Phys. Rev. Lett. **111**, 034802 (2013)
[13] V. Hilbert *et al.*, Appl. Phys. Lett. **105**, 101102 (2014)

Thanks to…

Optics/Short Wavelengths

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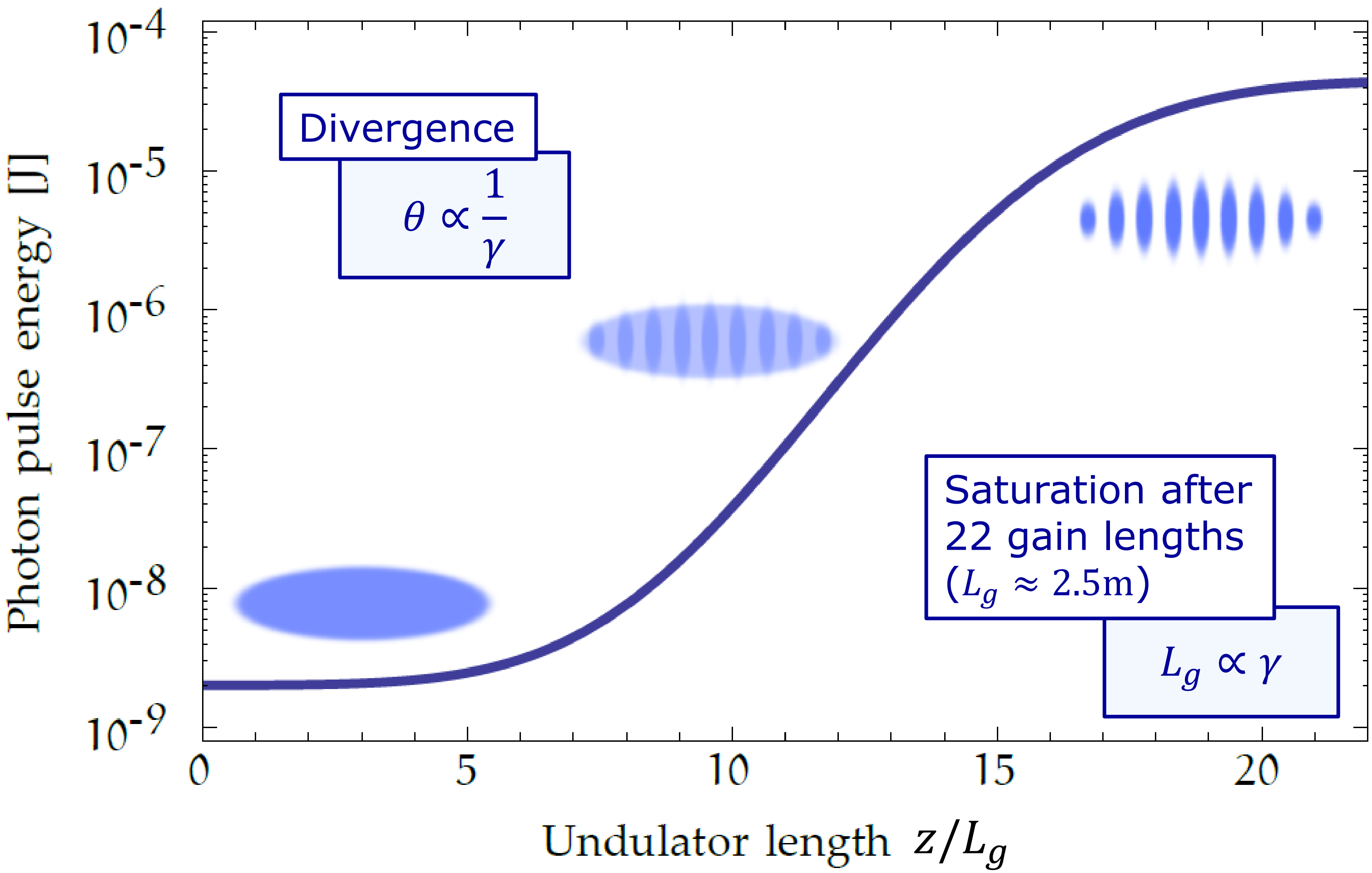
Dr. Bernd Schäfer

Dr. Barbara Keitel
Dr. Marion Kuhlmann
Dr. Elke Plönjes-Palm
…

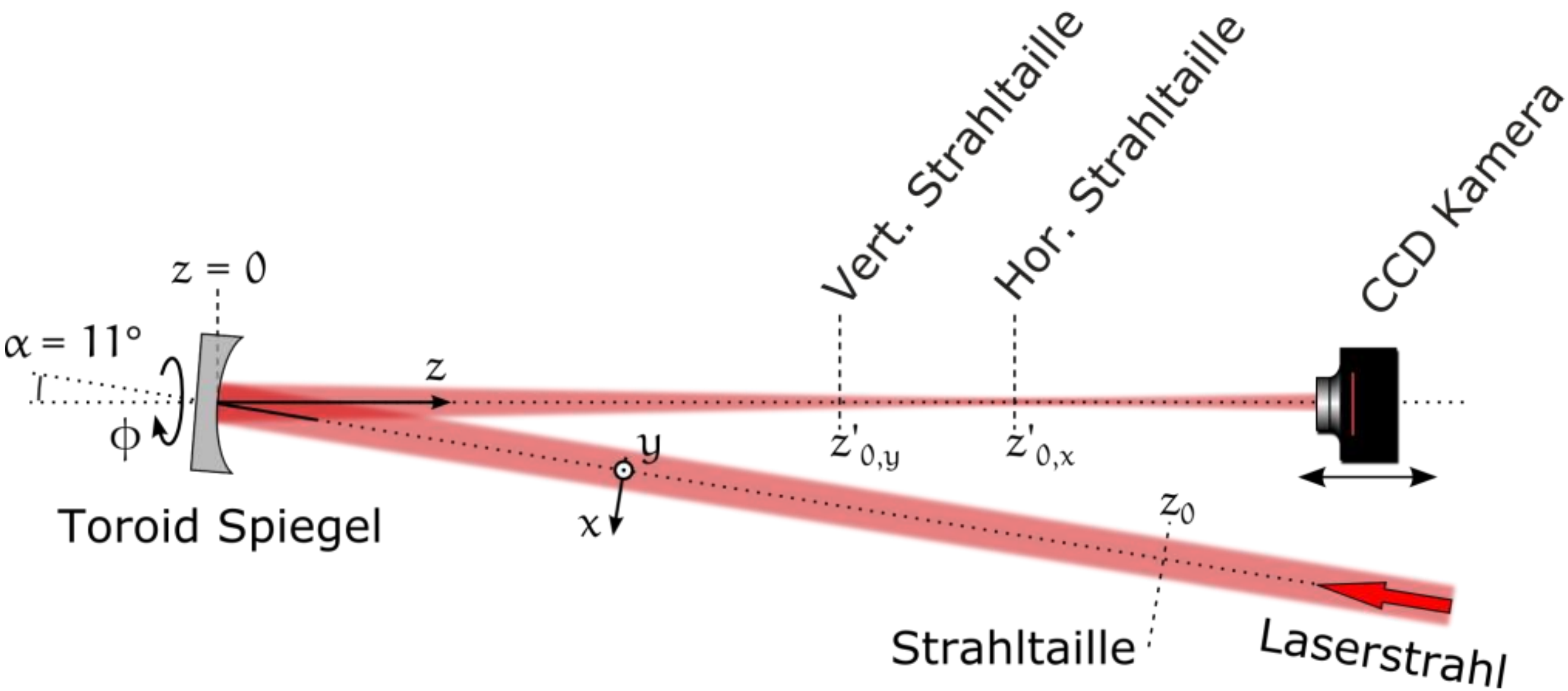
…and to you for your kind attention!

Saturation effects

Short wavelength → Raise electron energy γ



4D - Wigner distribution



4D - Wigner distribution

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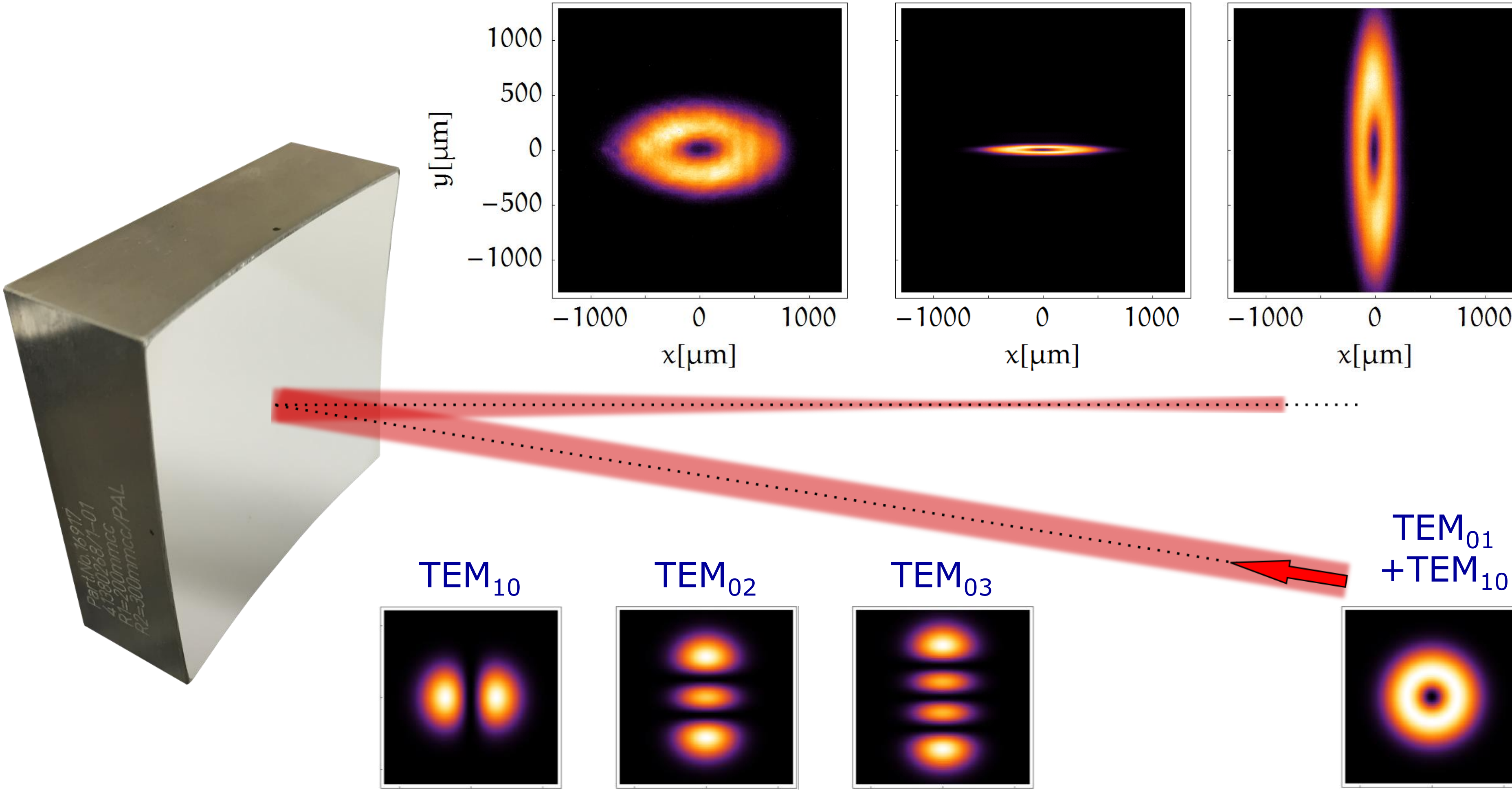
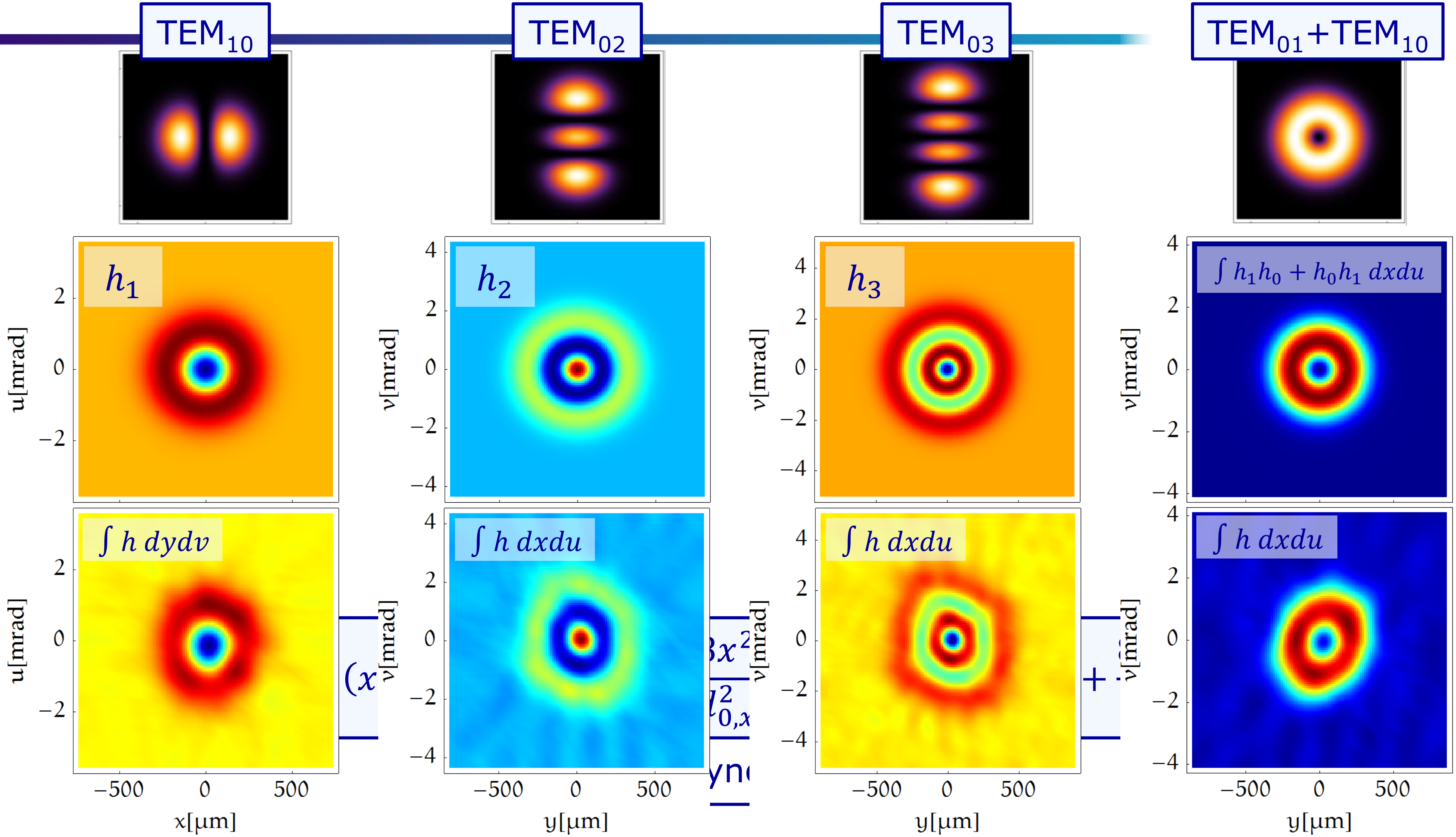


4D - Wigner distribution

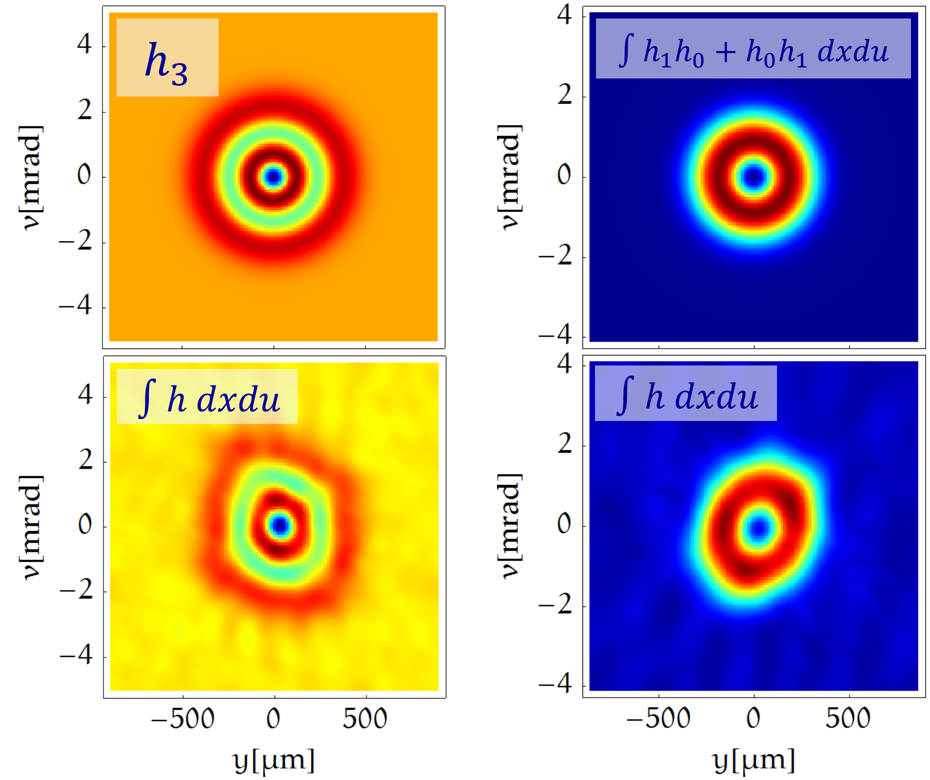


[7] A. Torre, *Linear ray and wave optics in phase space,* Elsevier B.V. Netherlands (2005)
[12] T. Mey, "Measurement of the Wigner distribution function of non-separable laser beams employing a toroidal mirror," New J. Phys. **16**, 123042 (2014)

4D - Wigner distribution

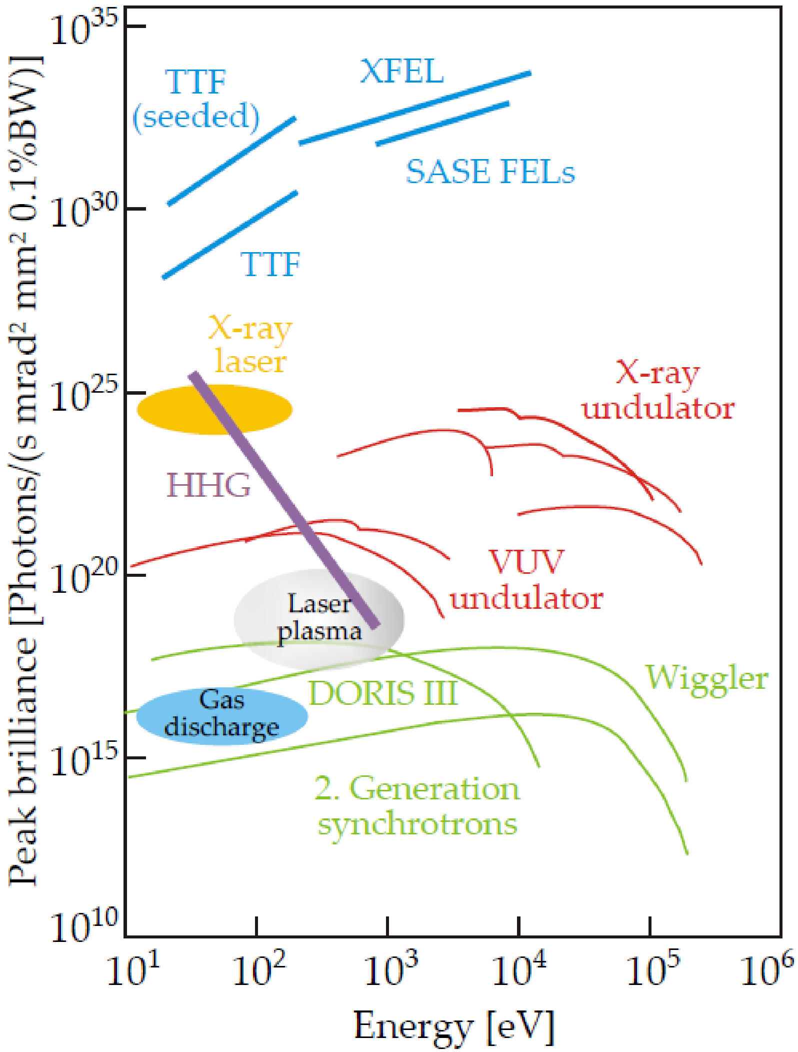
Global degree of coherence K

	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

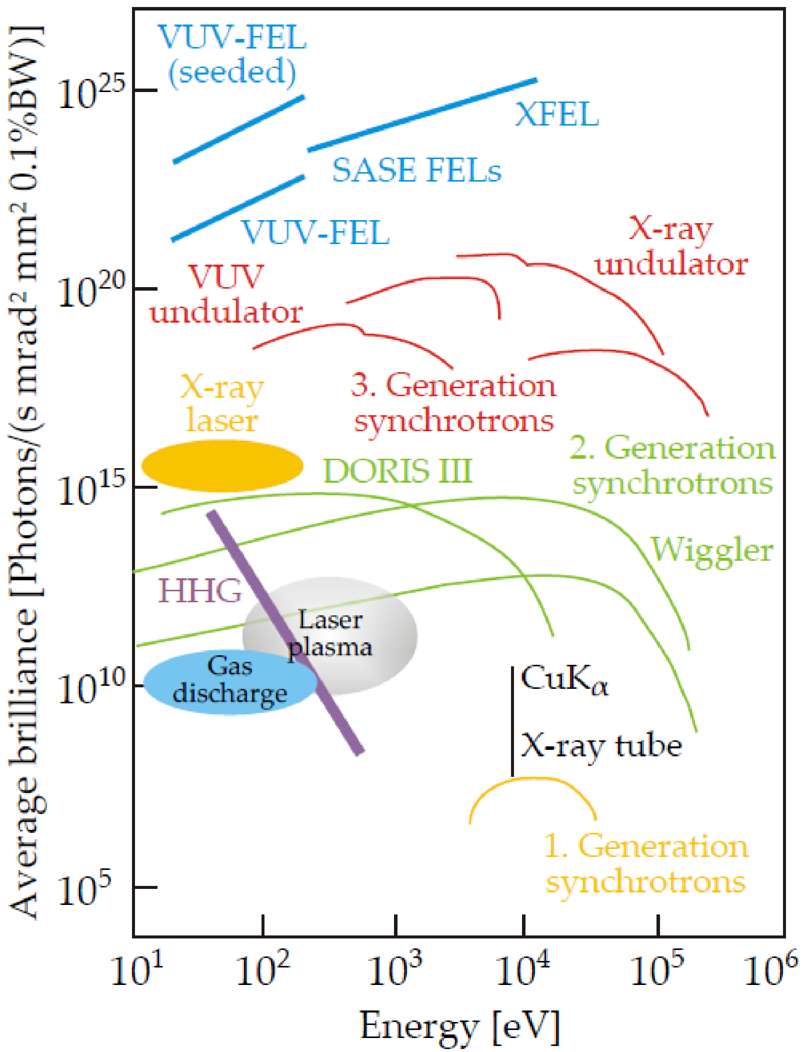


[7] A. Torre, *Linear ray and wave optics in phase space,* Elsevier B.V. Netherlands (2005)
[12] T. Mey, “Measurement of the Wigner distribution function of non-separable laser beams employing a toroidal mirror,” New J. Phys. **16**, 123042 (2014)

Brillanz

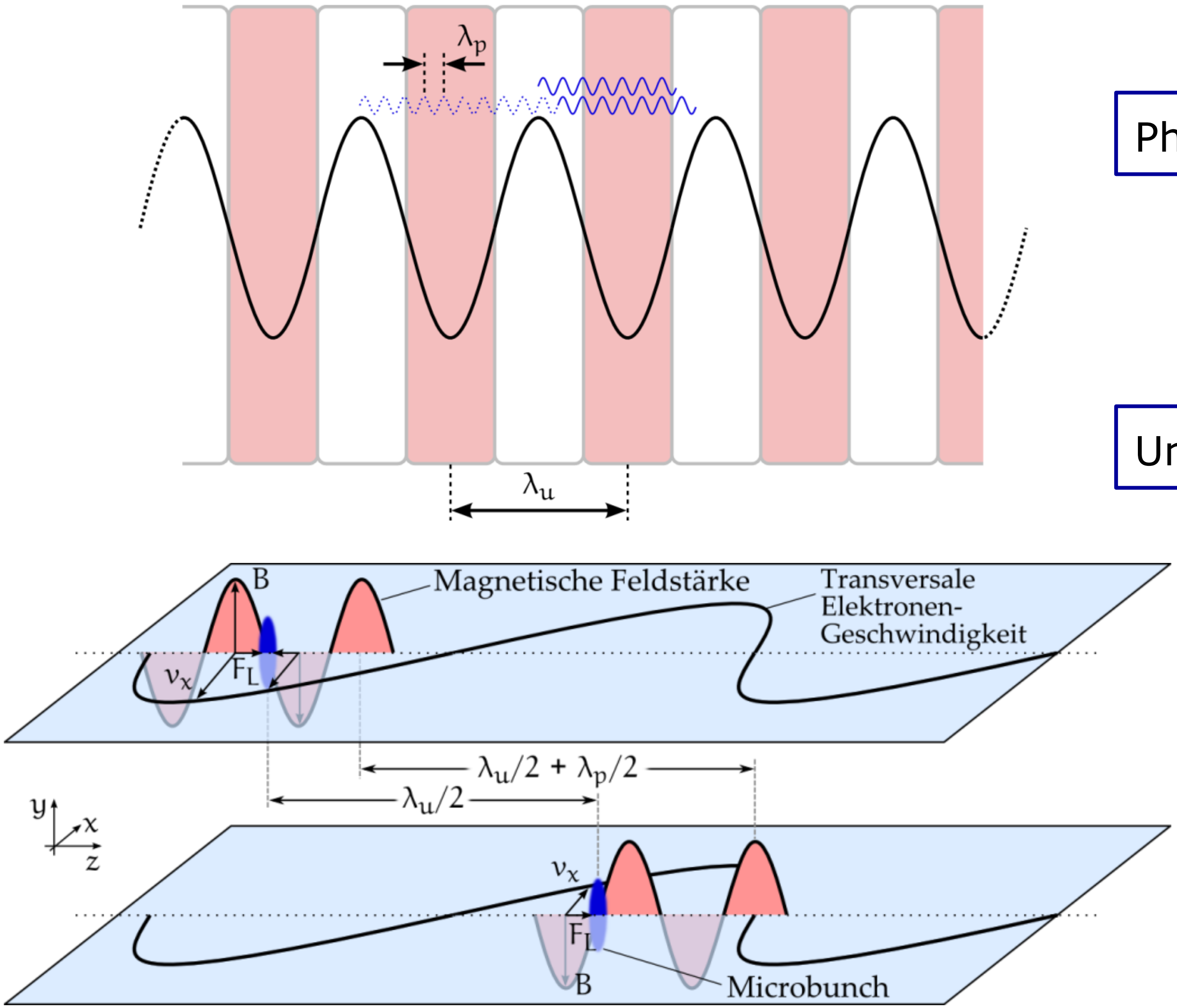


Peak brilliance [Photons/(s mrad² mm² 0.1%BW)]
Energy [eV]
TTF (seeded)
XFEL
SASE FELs
TTF
X-ray laser
HHG
X-ray undulator
VUV undulator
Laser plasma
Gas discharge
DORIS III
Wiggler
2. Generation synchrotrons



Average brilliance [Photons/(s mrad² mm² 0.1%BW)]
Energy [eV]
VUV-FEL (seeded)
XFEL
SASE FELs
VUV-FEL
VUV undulator
X-ray undulator
X-ray laser
3. Generation synchrotrons
DORIS III
2. Generation synchrotrons
Wiggler
HHG
Laser plasma
Gas discharge
CuKα
X-ray tube
1. Generation synchrotrons

Funktionsprinzip FEL



Photonen Wellenlänge

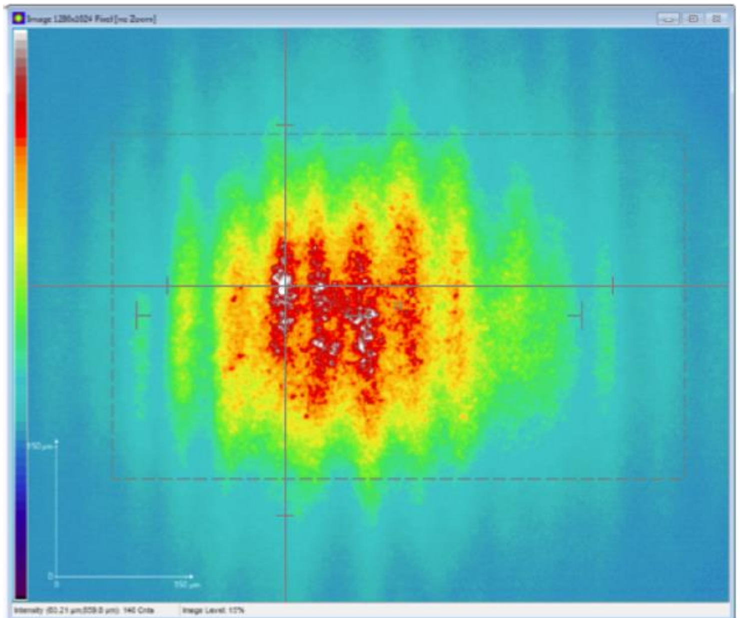
$$\lambda_p = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_u^2}{2}\right)$$

Undulator Parameter

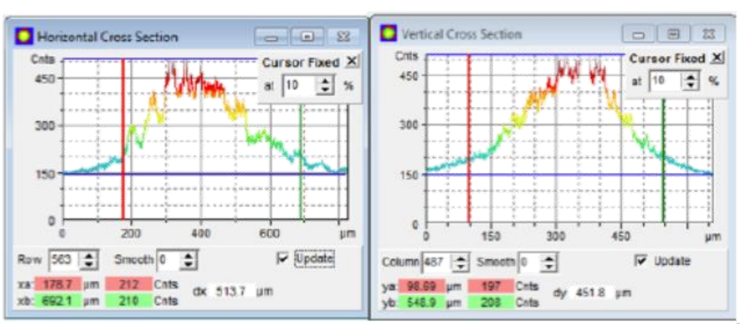
$$K_u = \frac{e\lambda_u B_0}{2\pi m_e c}$$

Streifen durch Spiegel

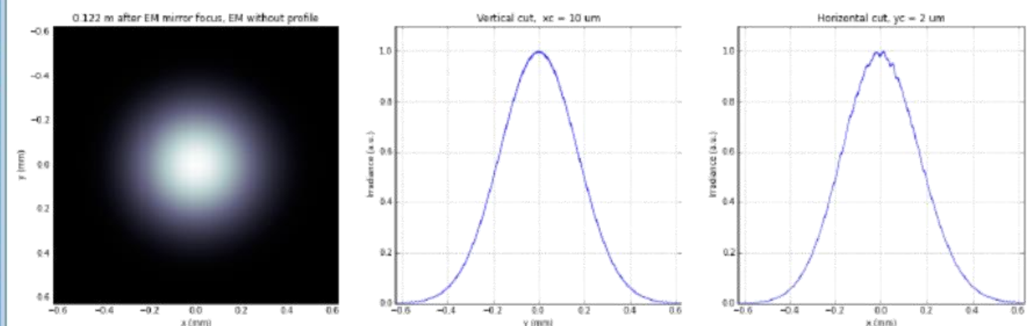
Both 10mm apertures in tunnel, 193nm Al filter



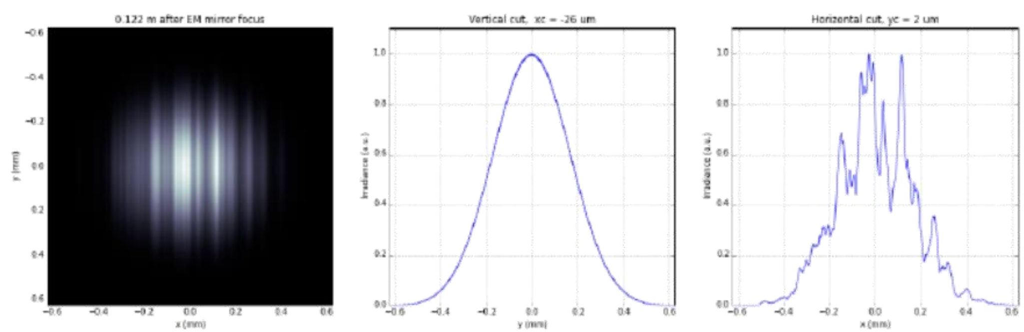
File: D:\Wiener2013_11\sequence62\seq.23.tif32
Position: 122mm behind focus position



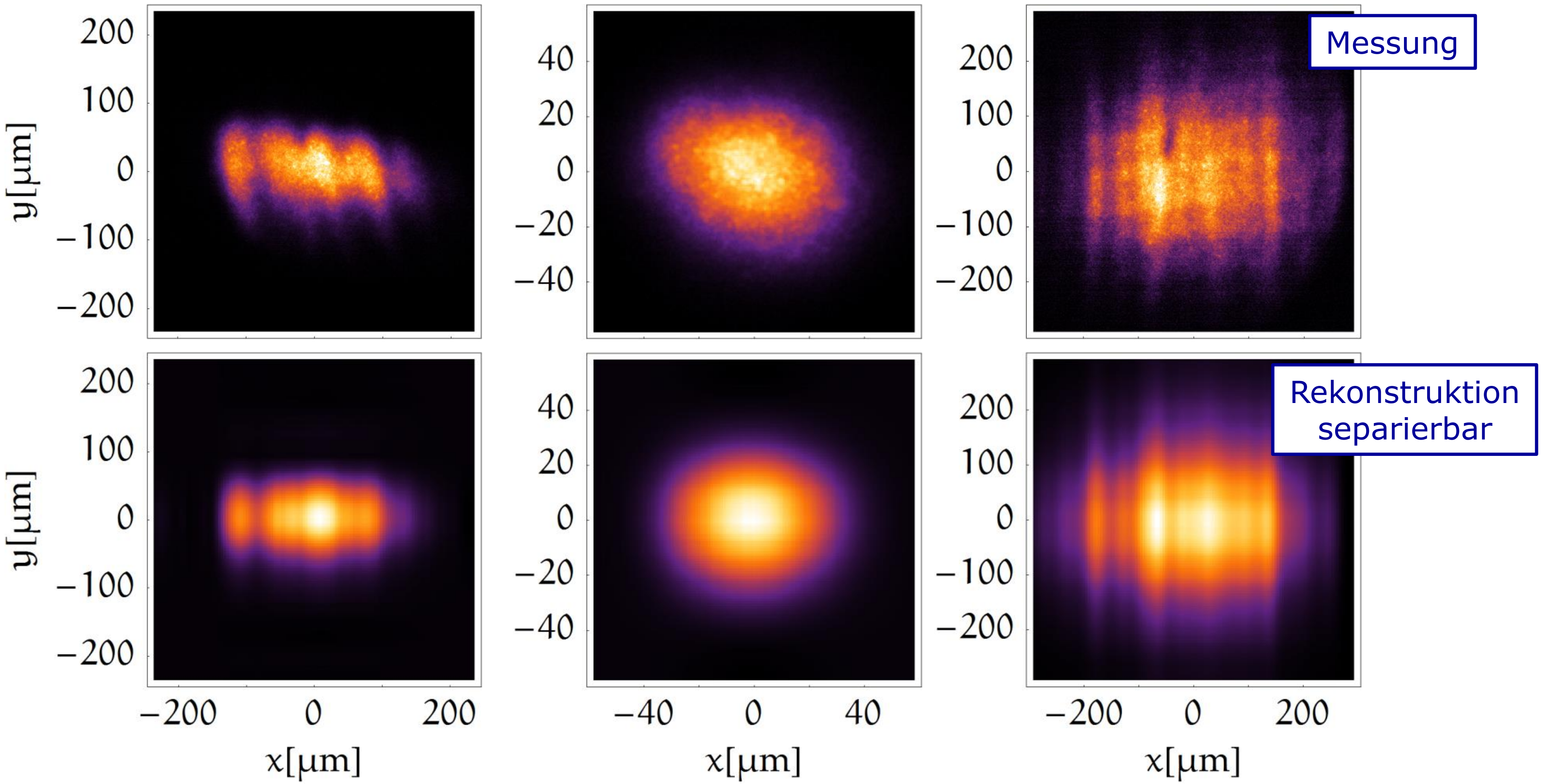
- no surface residual errors on EM



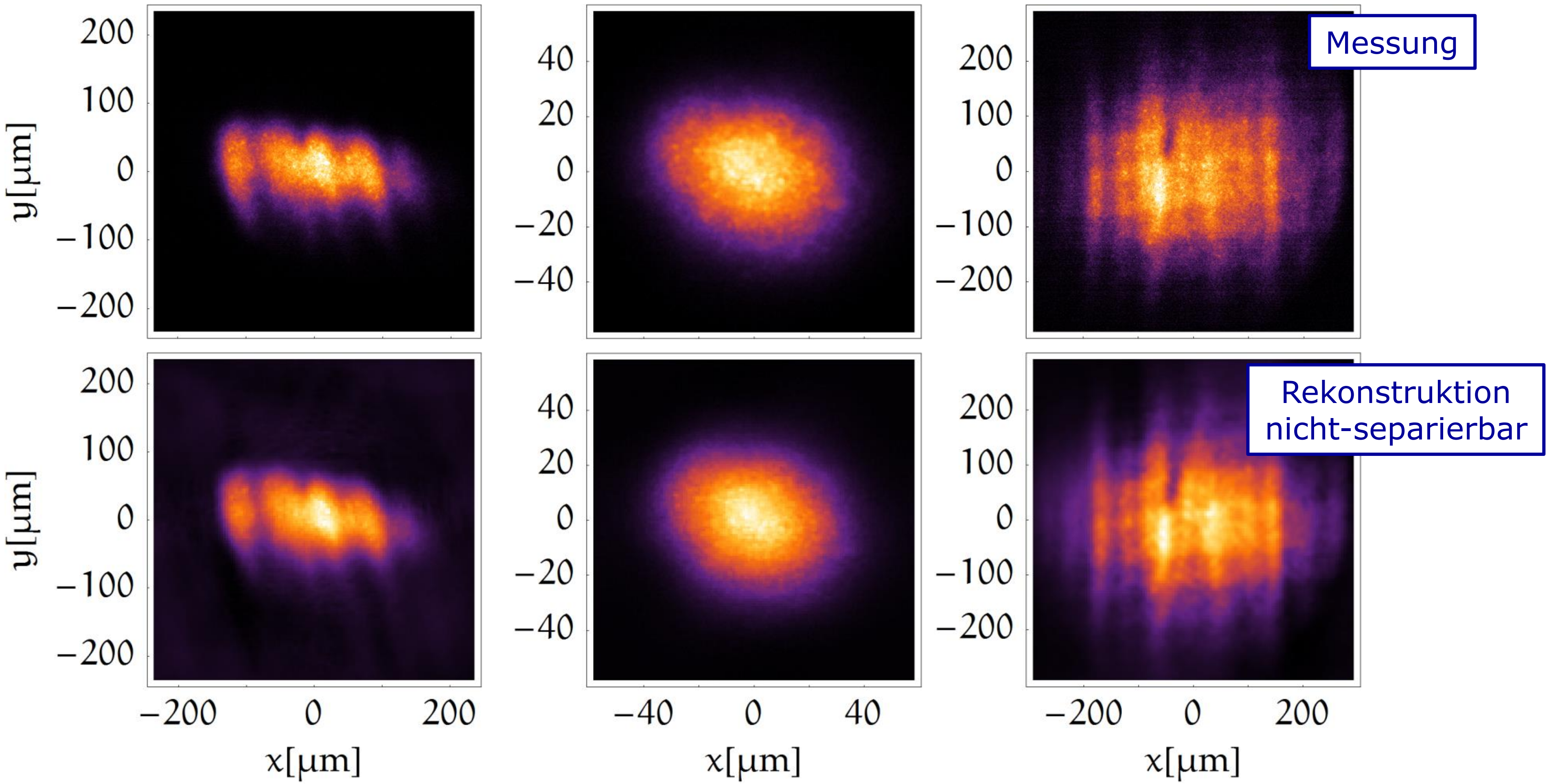
- with surface residual errors on EM:



FLASH - Wigner-Verteilung



FLASH - Wigner-Verteilung



FLASH - Wigner-Verteilung

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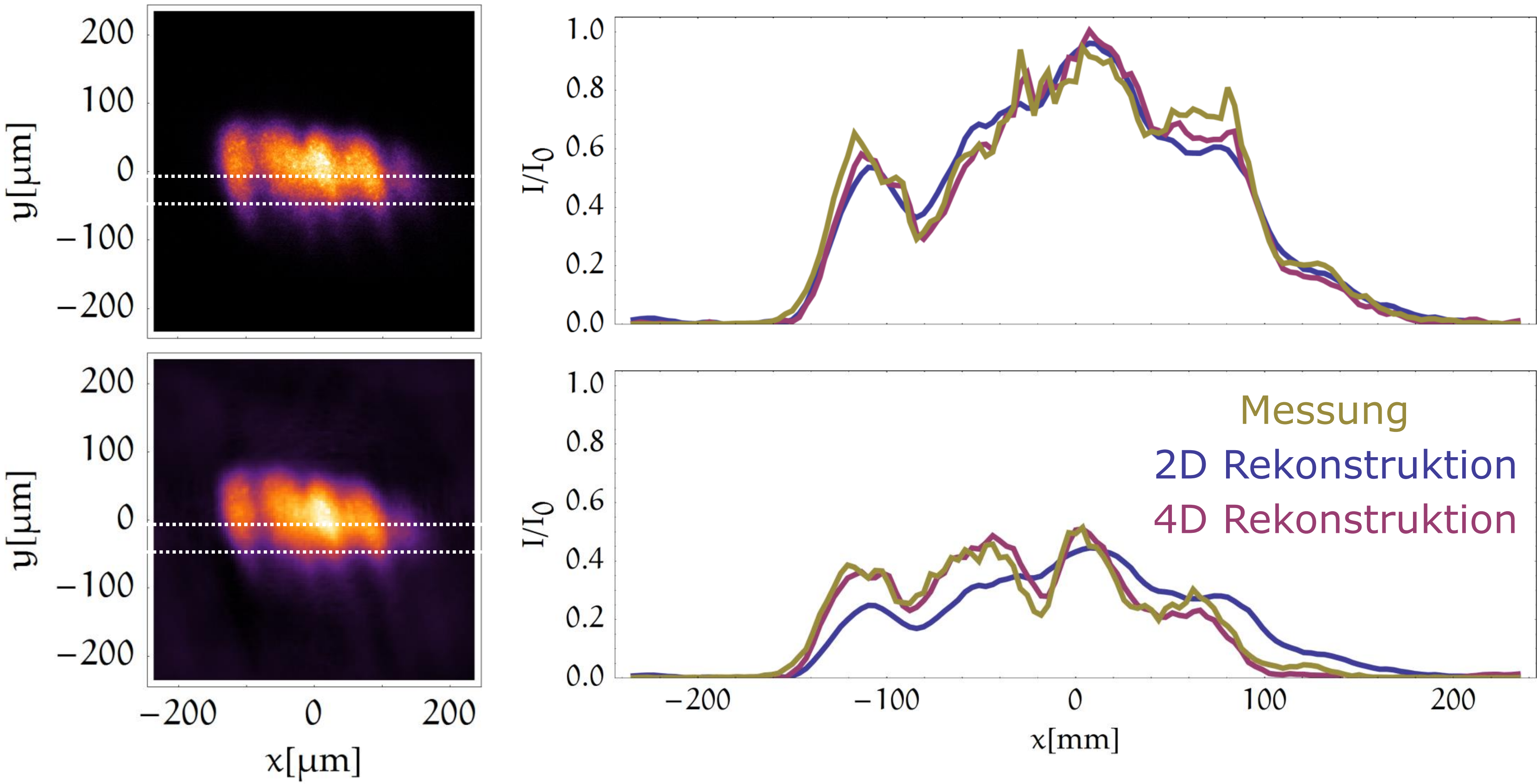
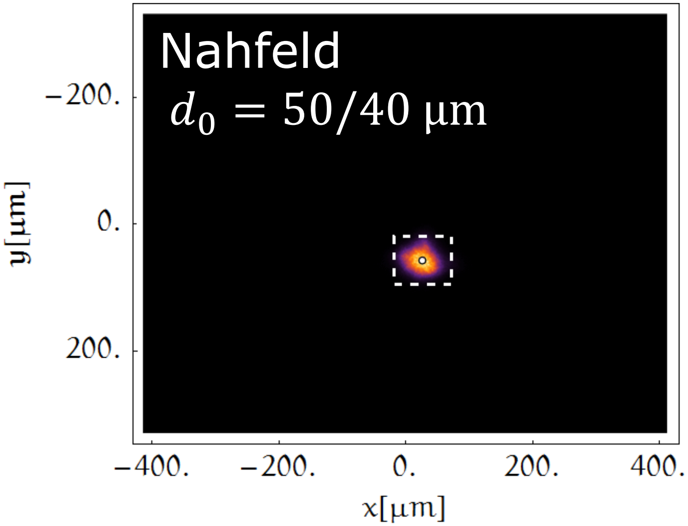
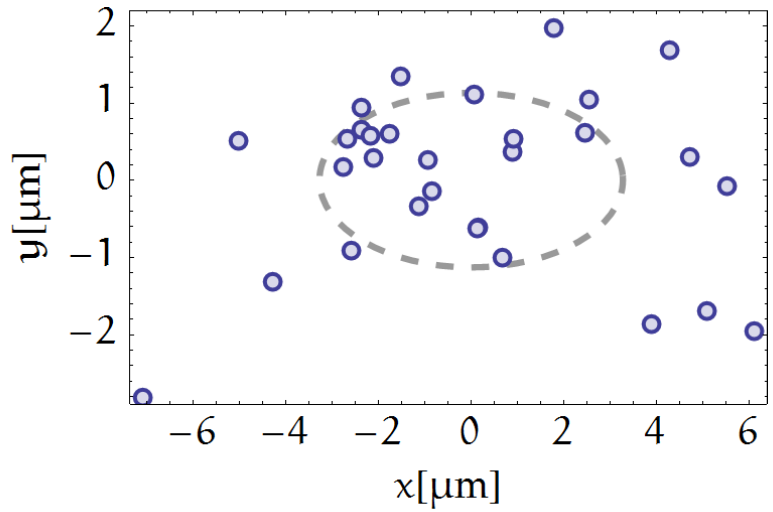
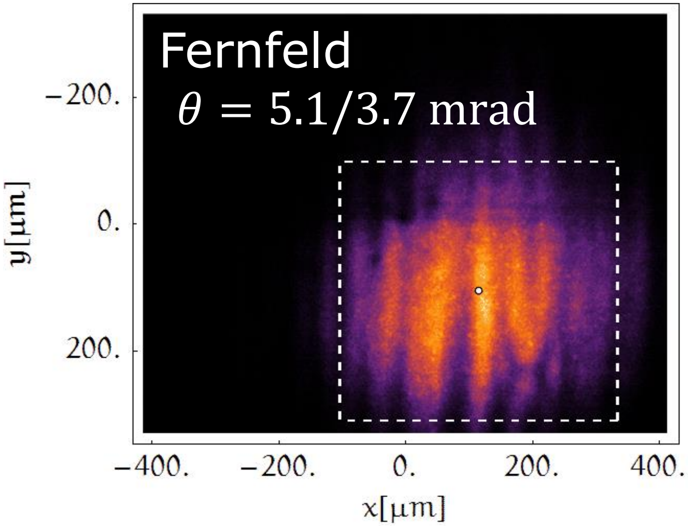
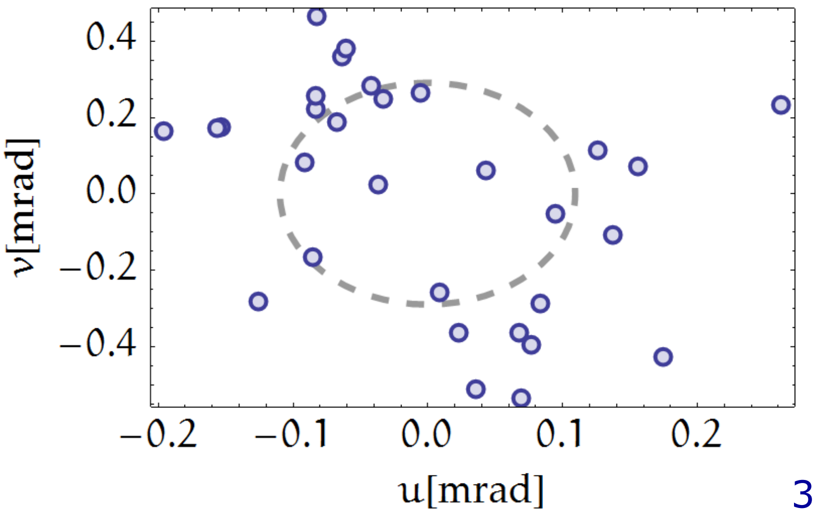


Fluktuationen FLASH - Schwerpunkt

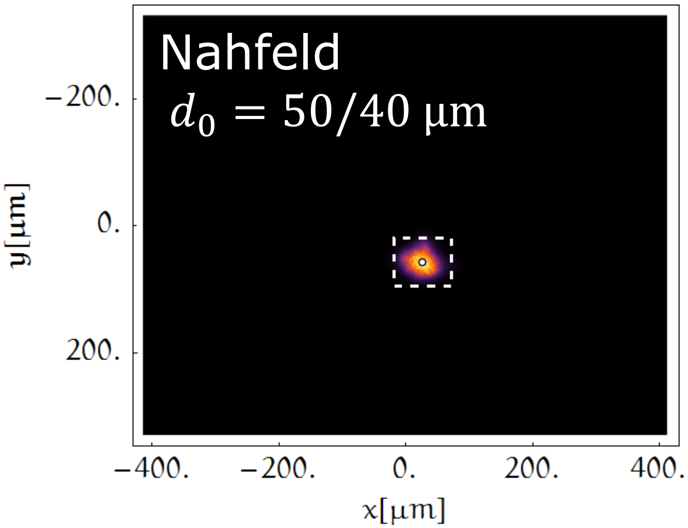


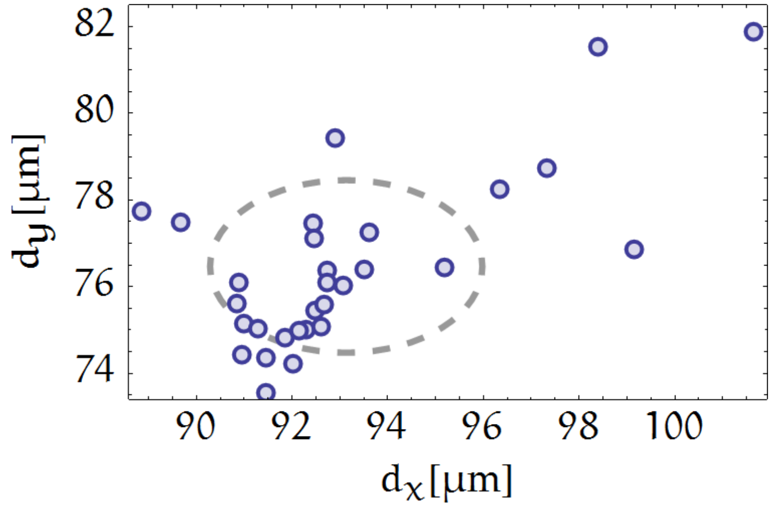


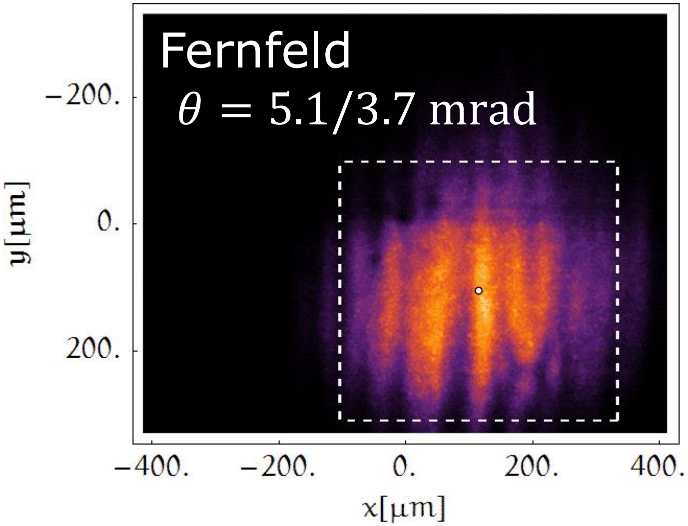


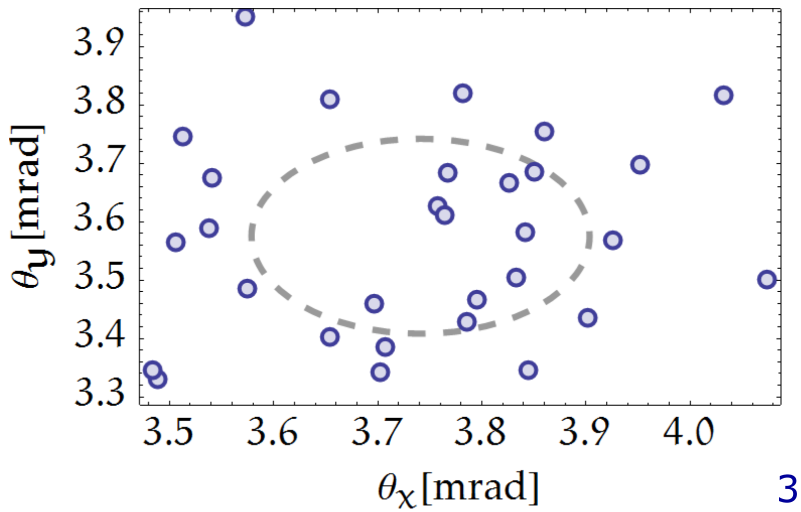


Fluktuationen FLASH - Durchmesser









Fluktuationen FLASH - Kohärenz

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$$K = \frac{16\lambda^2}{\pi^2} \cdot \frac{1}{d_{0,x}\, d_{0,y}\, \theta_x\, \theta_y}$$

$$\Delta K = \sqrt{\left(\frac{\Delta d_{0,x}}{d_{0,x}}\right)^2 + \left(\frac{\Delta d_{0,y}}{d_{0,y}}\right)^2 + \left(\frac{\Delta \theta_x}{\theta_x}\right)^2 + \left(\frac{\Delta \theta_y}{\theta_y}\right)^2} \cdot K$$

Durchmesser/Divergenz	$K \rightarrow 1.5 \cdot K$
Kohärenz-Fluktuation	$\Delta K = 0.08 \cdot K$

$$K = 0.048 \pm 0.004$$

Wigner-Verteilung und CDI

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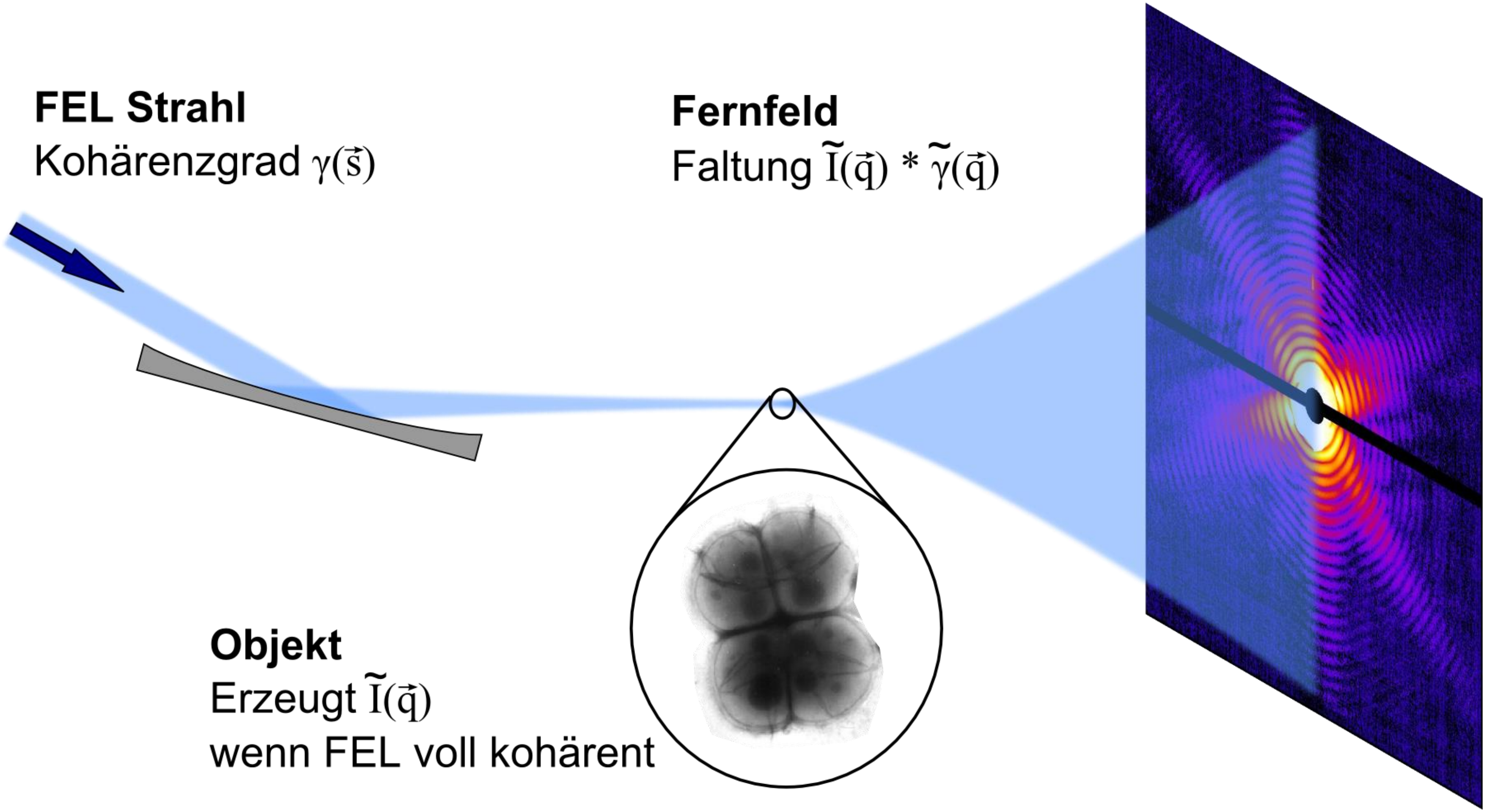
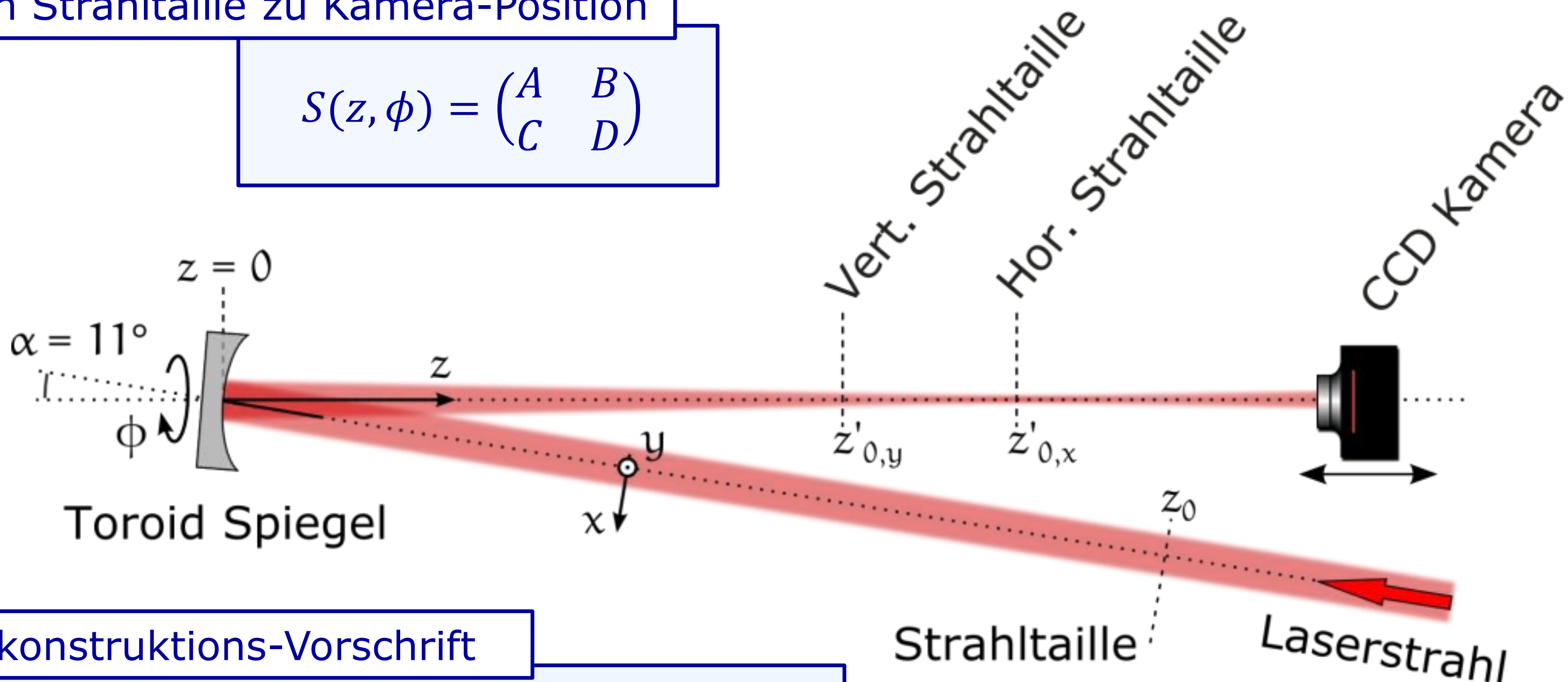


FLASH - Wigner-Verteilung

System-Matrix: Propagation
von Strahltaille zu Kamera-Position

$$S(z,\phi) = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

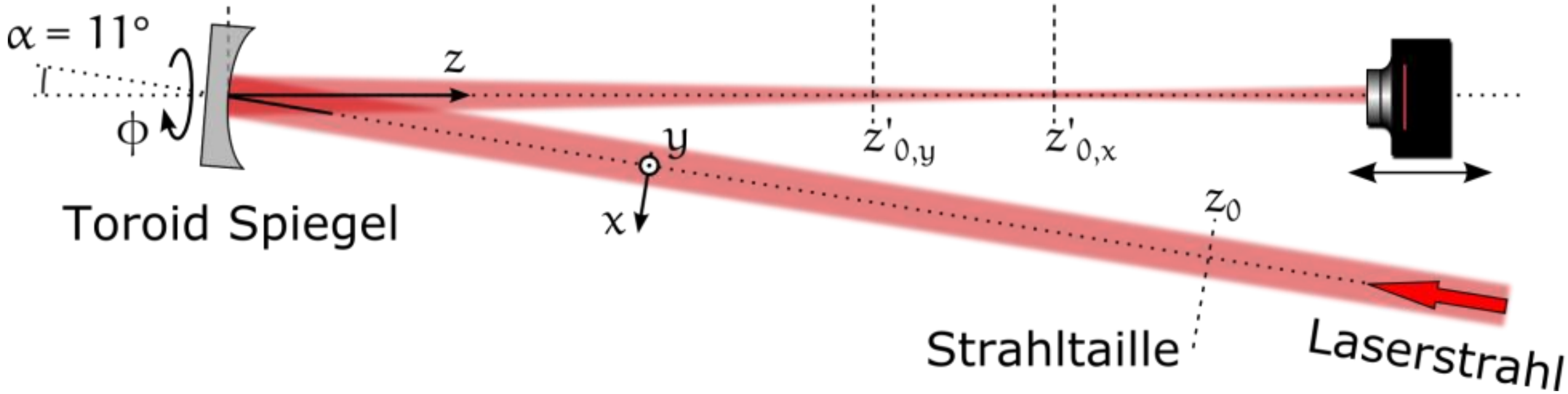


Rekonstruktions-Vorschrift

Freie Propagation: $\tilde{h}(\vec{q}_x, z \cdot \vec{q}_x) = \tilde{I}_z(\vec{q}_x)$

Allgemein: $\tilde{h}[A \cdot \vec{q}_x, B \cdot \vec{q}_x] = \tilde{I}_z(\vec{q}_x)$

Systemmatrix 4D Messung



$$S(z,\phi) = S_{\mathrm{prop}}(z) \cdot S_{\mathrm{tilt},\alpha} \cdot S_{\mathrm{rot}}(\phi) \cdot S_{\mathrm{toroid}} \cdot S_{\mathrm{rot}}(\phi)^{-1} \cdot S_{\mathrm{tilt},\alpha}^{-1} \cdot S_{\mathrm{prop}}(-z_0)$$

$$S_{\mathrm{prop}}(z) = \begin{pmatrix} 1 & 0 & z & 0 \\ 0 & 1 & 0 & z \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad S_{\mathrm{tilt},\alpha} = \begin{pmatrix} \sqrt{\cos\alpha} & 0 & 0 & 0 \\ 0 & 1/\sqrt{\cos\alpha} & 0 & 0 \\ 0 & 0 & 1/\sqrt{\cos\alpha} & 0 \\ 0 & 0 & 0 & \sqrt{\cos\alpha} \end{pmatrix}$$

$$S_{\mathrm{toroid}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -2/R_t & 0 & 1 & 0 \\ 0 & -2/R_s & 0 & 1 \end{pmatrix} \qquad S_{\mathrm{rot}}(\phi) = \begin{pmatrix} \cos\phi & -\sin\phi & 0 & 0 \\ \sin\phi & \cos\phi & 0 & 0 \\ 0 & 0 & \cos\phi & -\sin\phi \\ 0 & 0 & \sin\phi & \cos\phi \end{pmatrix}$$