Laser beam characterization and thermal wavefront distortions in optical components

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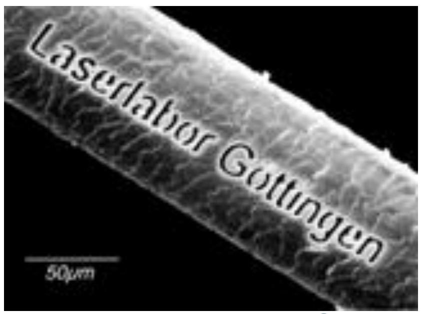
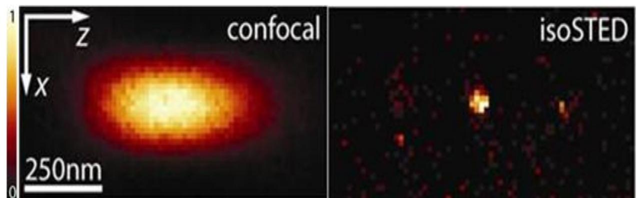
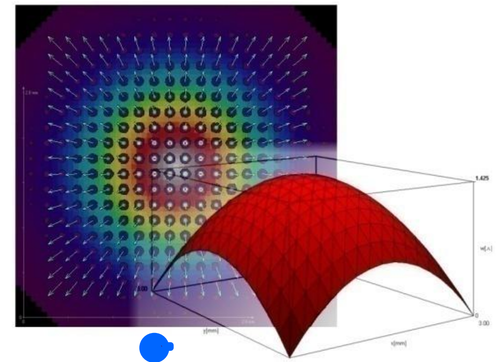
**Micro
Material processing**

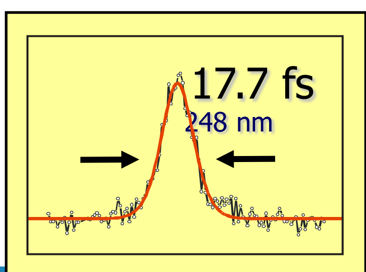


Nanoscopy



**Optics /
Short wavelengths**





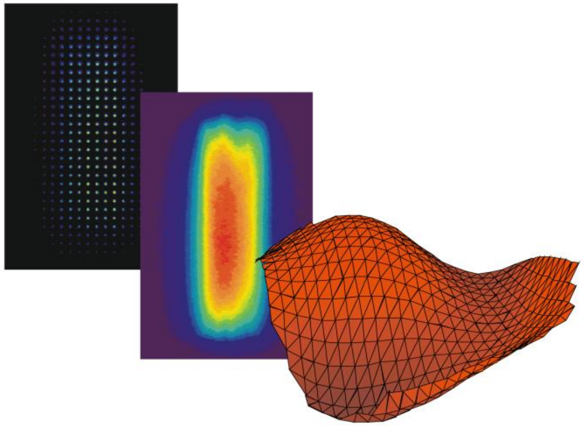
**Short pulse laser
technology**

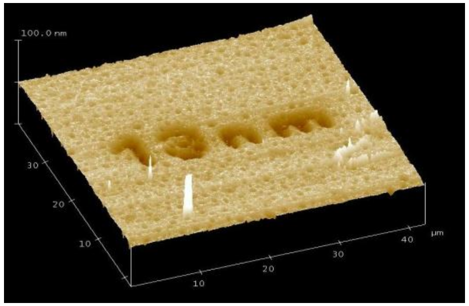
**Spectroscopy /
Sensorics**

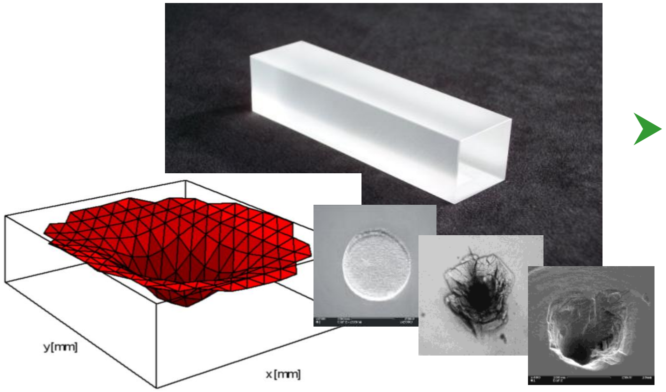
Dept.
“Optics / Short Wavelengths”

- Beam and Optics Characterization

  - **Optics test** (351…**193 nm**)
    - *(Long term) degradation (10^9 pulses)*
    - *Non-linear processes*
    - *LIDT*
    - ***Absorption** / Scatter losses*
    - *Wavefront deformation*







  - **Beam propagation**
    - *Wavefront*
    - *coherence*
    - *M²*

  - **EUV/soft x-ray technology**
    - *Source & Optics*
    - *Metrology*
    - *Material interaction*

Spectrum of electromagnetic radiation

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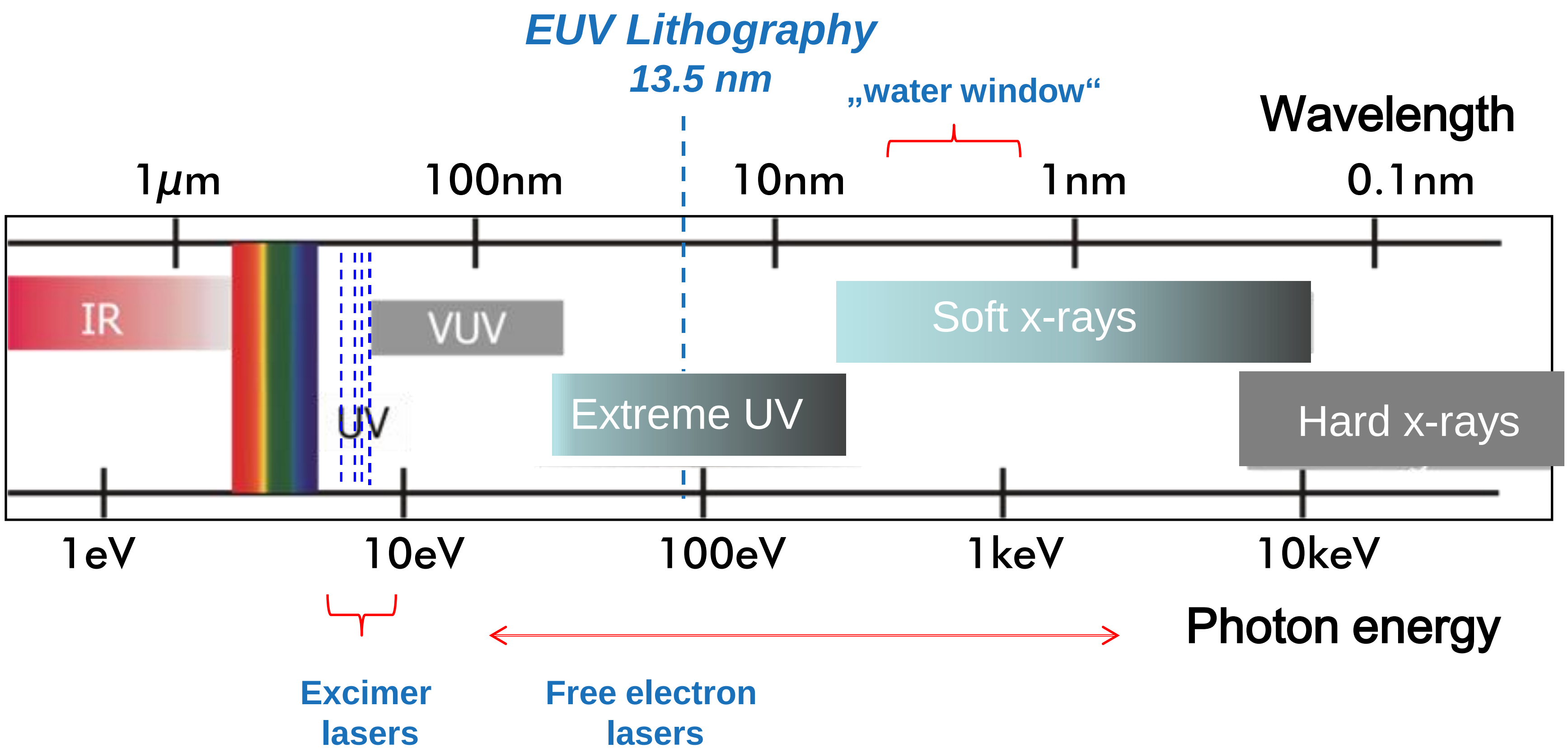
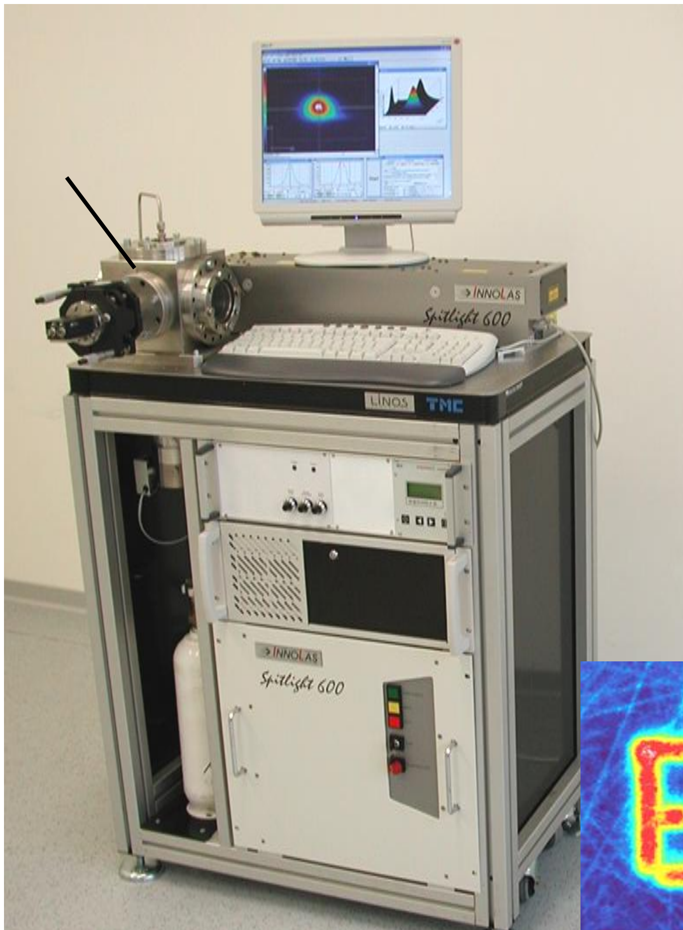
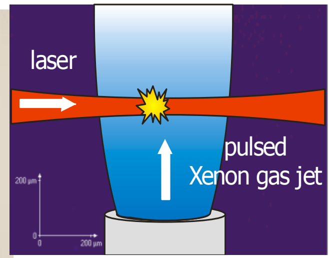
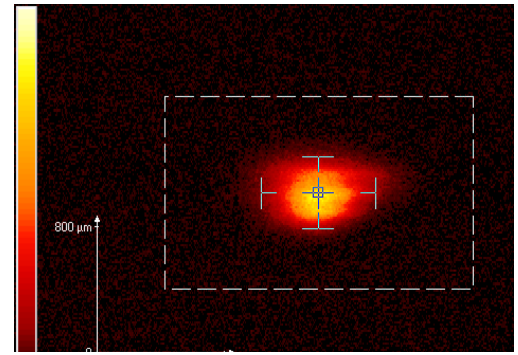
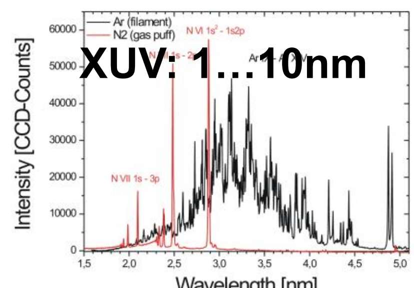


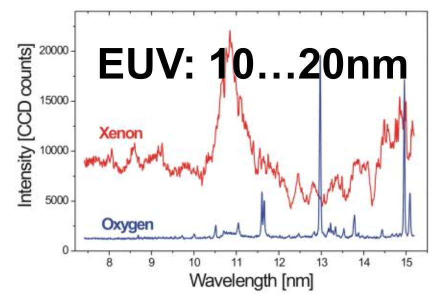
Table-top EUV source

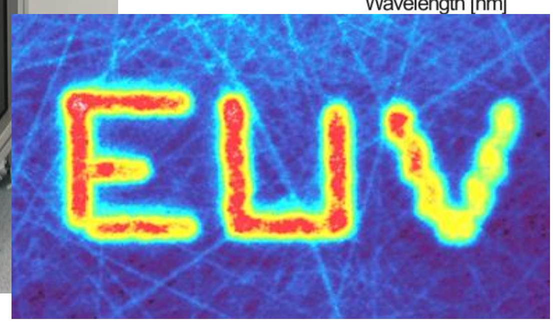


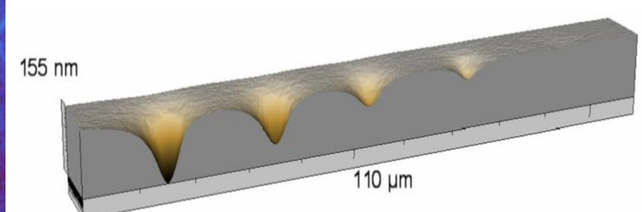












Ablation / damage thresholds @13.5nm

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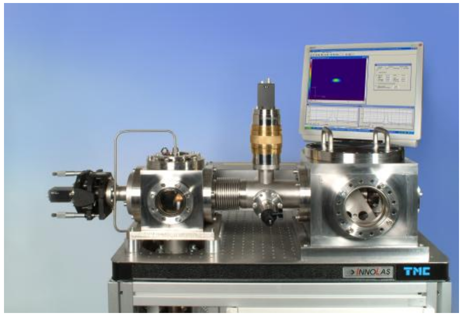
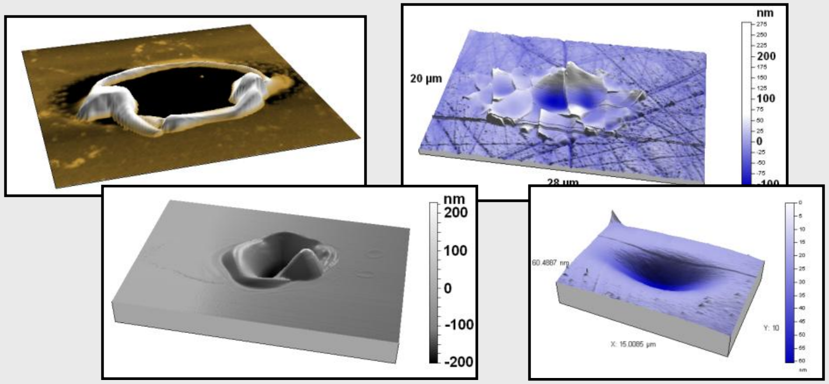
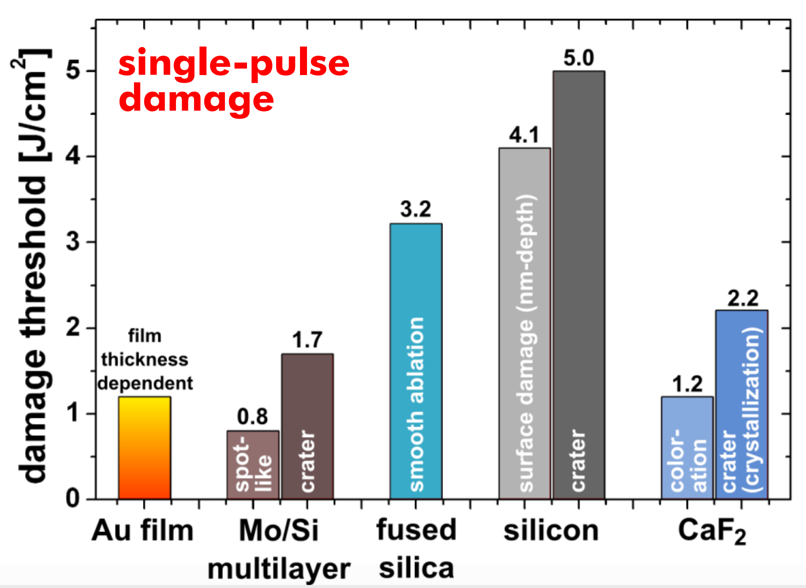
- Laser driven EUV/XUV plasma source setup
  - 1.2 J/cm^2 (@ 13,5 nm, 2 % bandwidth)
  - 7.4 J/cm^2 (filtered by 2 Mo/Si mirrors)



- Damage thresholds of mirrors / substrates





KLA Tencor

F. Barkusky, K. Mann et al., Optics Express 18, 4347 (2010)

Outline:

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- Introduction
- Determination of beam parameters (ISO standards)
- Wavefront measurement / analysis of beam propagation
- Wavefront distortion in high power laser optics
- Thermal lensing / Focus shift

Relevant laser parameters:

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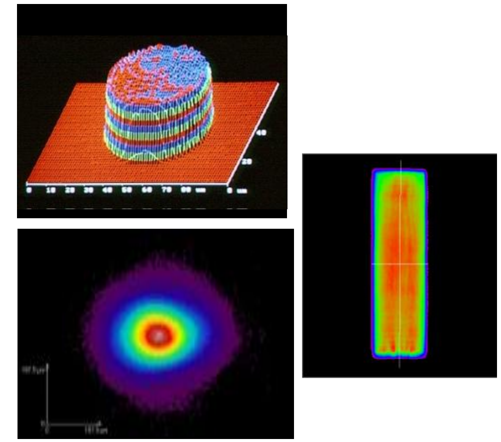
Parameters	Standard
Average power / pulse energy	ISO 11554
Wavelength / spectral band width	ISO 13695
Pulse length	ISO 11554
Polarization	ISO 12005
Beam diameter	ISO 11146
Divergence	ISO 11146
Beam profile	ISO 13694
Pointing / pos. stability	ISO 11670
M² / focusability	ISO 11146
Wavefront / phase distribution	ISO 15367
coherence	-

Propagation



Spatially resolved measurement

Excimer laser beam characterization

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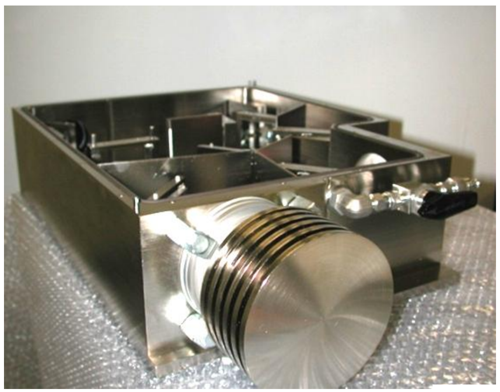
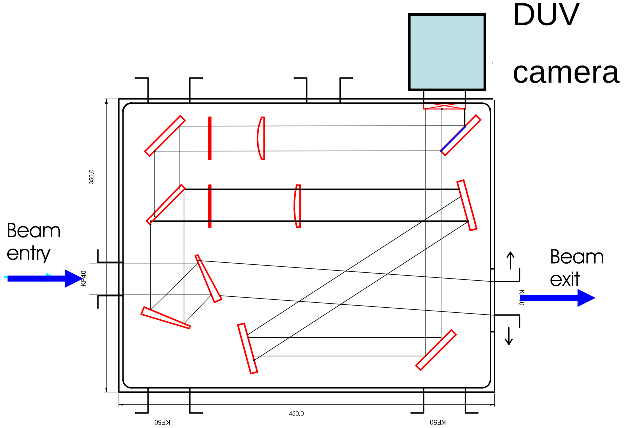
ASML

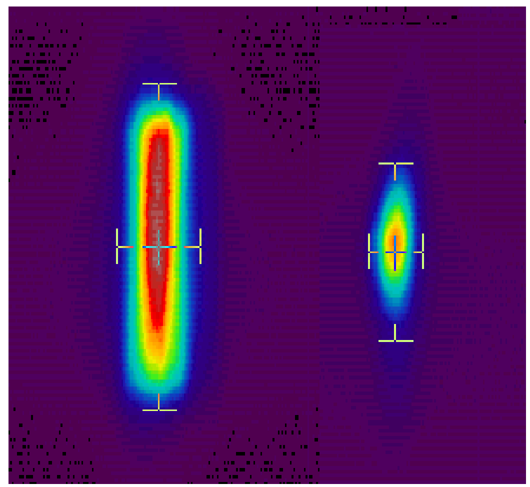
ZEISS CARL ZEISS SMT

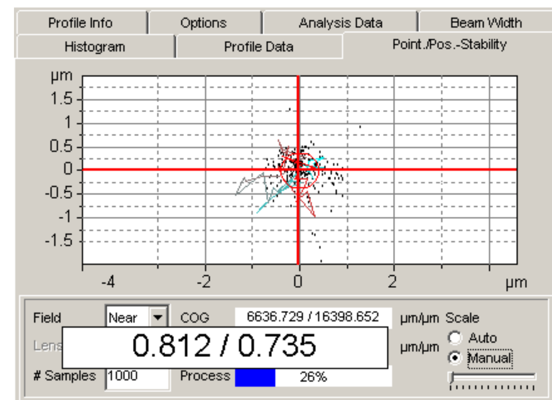
- Simultaneous near- and far-field analysis @193nm / 6kHz





Near-field far-field profile:





→ Beam width

divergence

pointing stability

Caustic measurement (ISO 11146)

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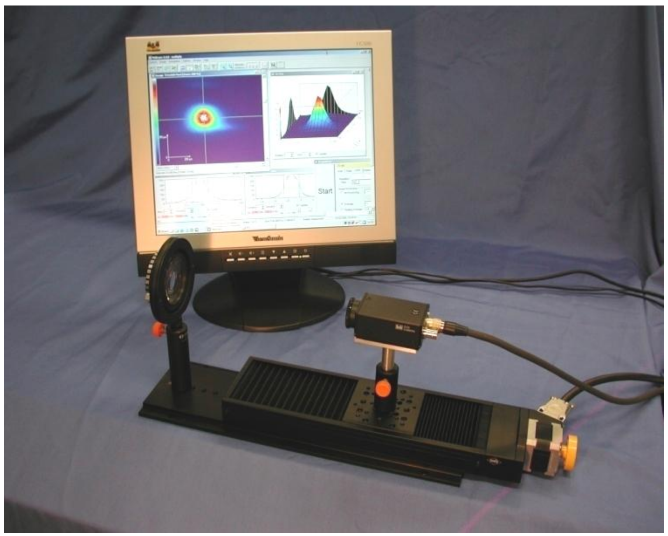
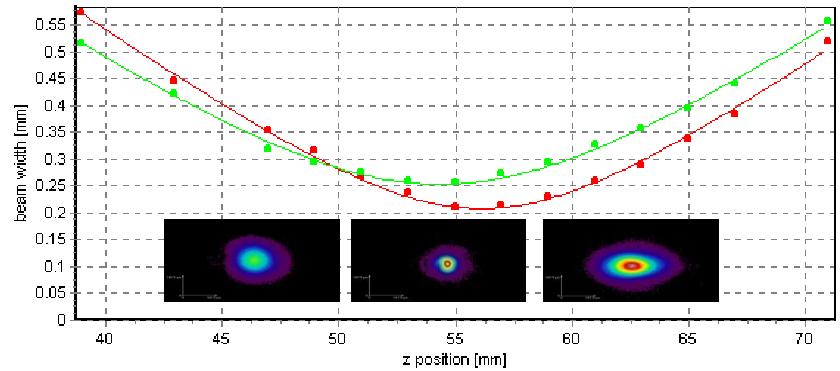
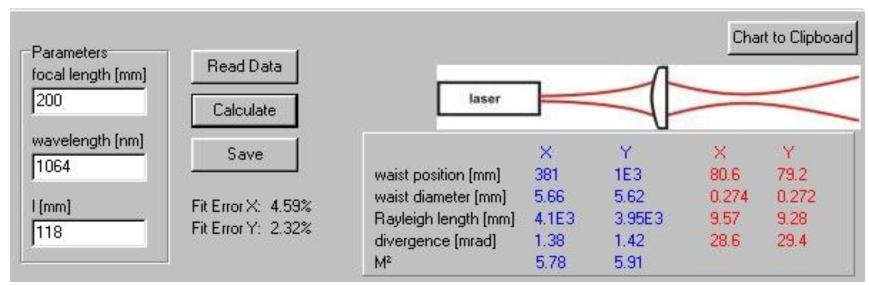
Example: Nd:YAG / 1064nm







- lens → beam waist
- $d_{\sigma,x,y}$ (2^{nd} moment) = f (z)
- hyperbolic fit

Beam parameters
- propagation factor M²
- divergence
- Rayleigh length
- waist diameter / position

→ all lasers

Caustic of Free Electron Laser FLASH / DESY

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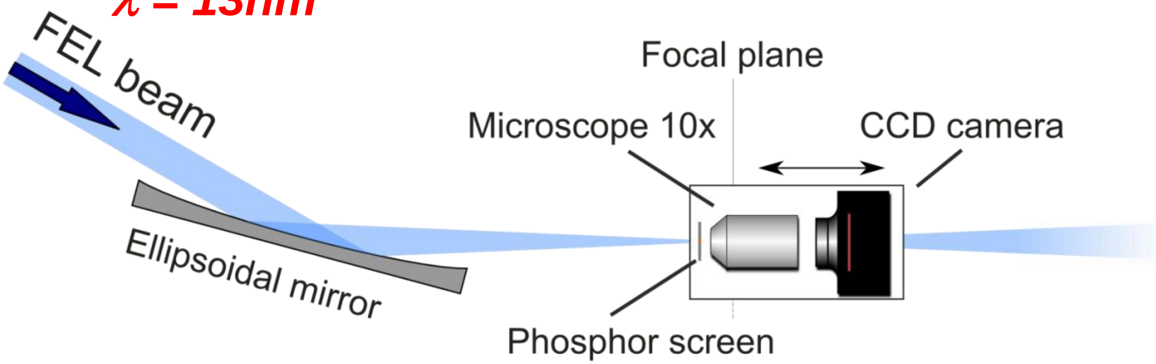
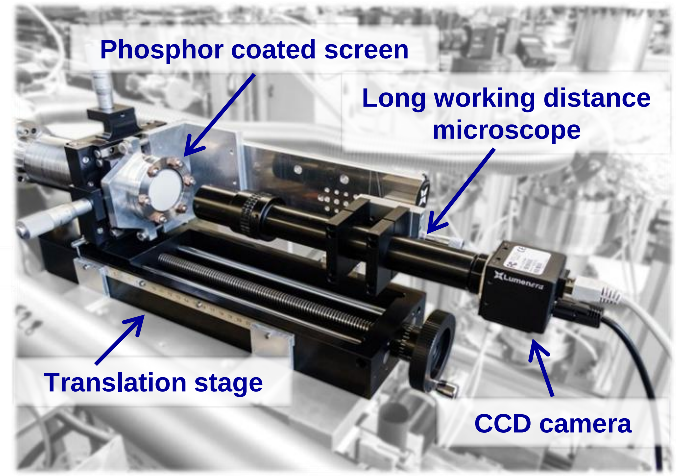
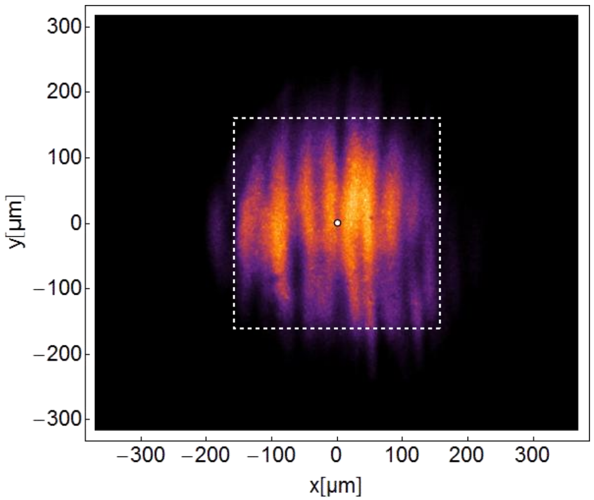
λ = 13nm

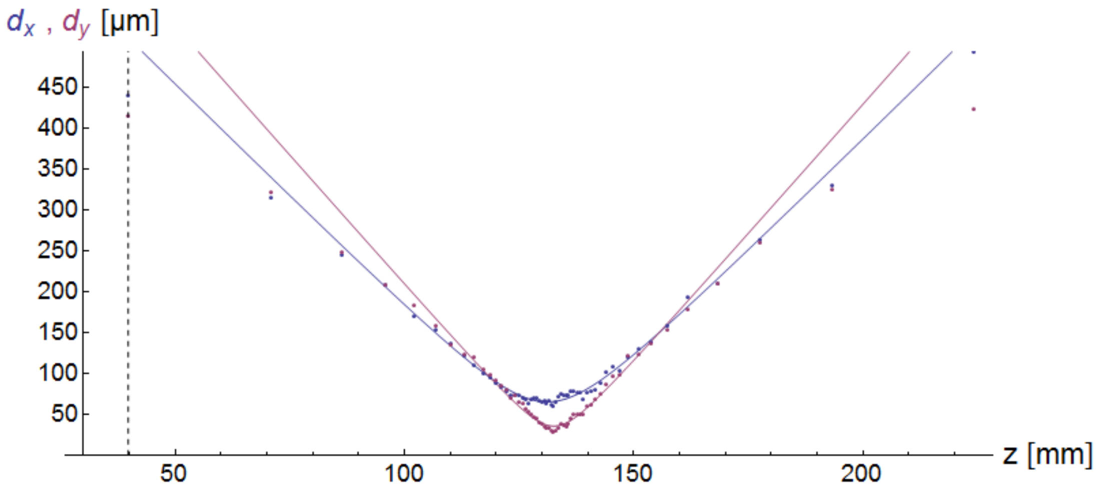




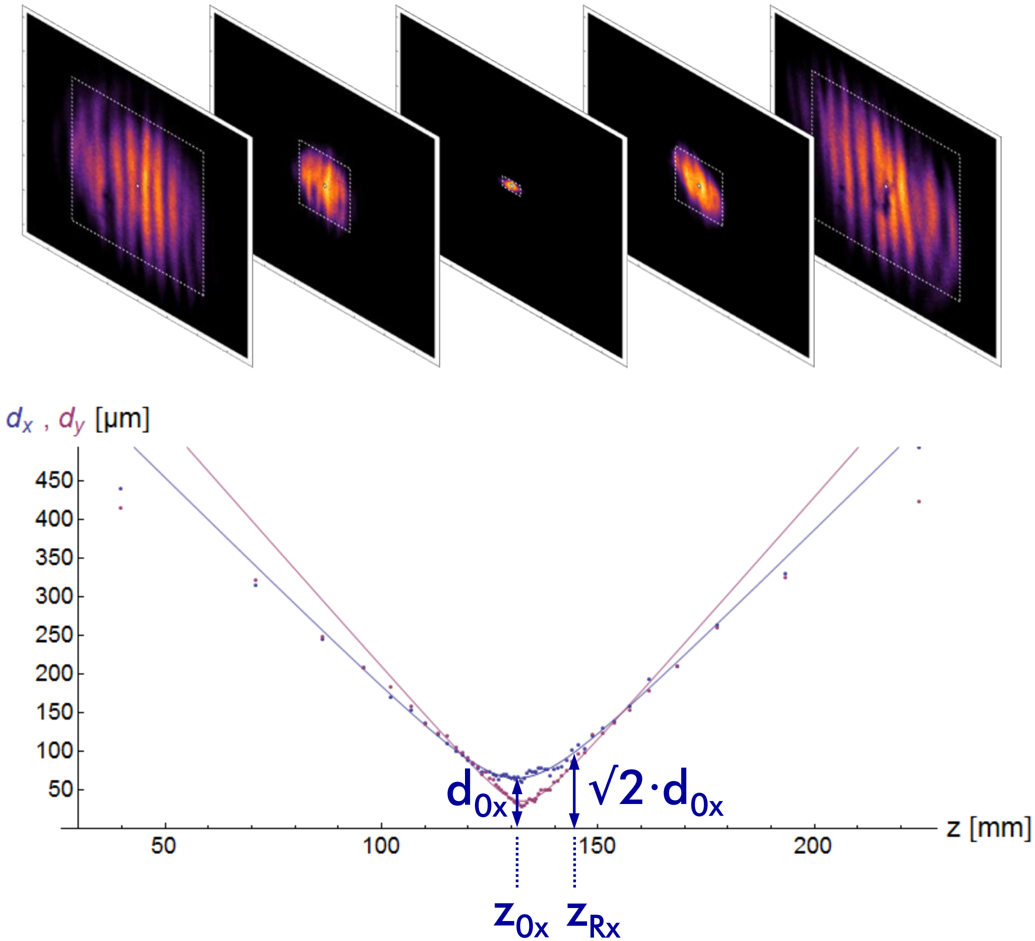
Intensity distribution



Beam diameter



Caustic of Free Electron Laser FLASH / DESY



Beam parameter	Value
Waist position z_{0x} / z_{0y} [mm]	131.1 / 132.6
Waist diameter d_{0x} / d_{0y} [µm]	65.5 / 35.9
Rayleigh length z_{Rx} / z_{Ry} [mm]	11.8 / 5.7
Beam propagation factor M^2_x / M^2_y	21 / 13
coherence	???

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Focusing of laser-induced soft x-ray plasma

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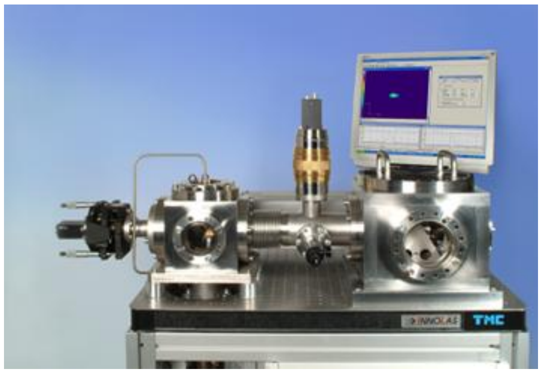
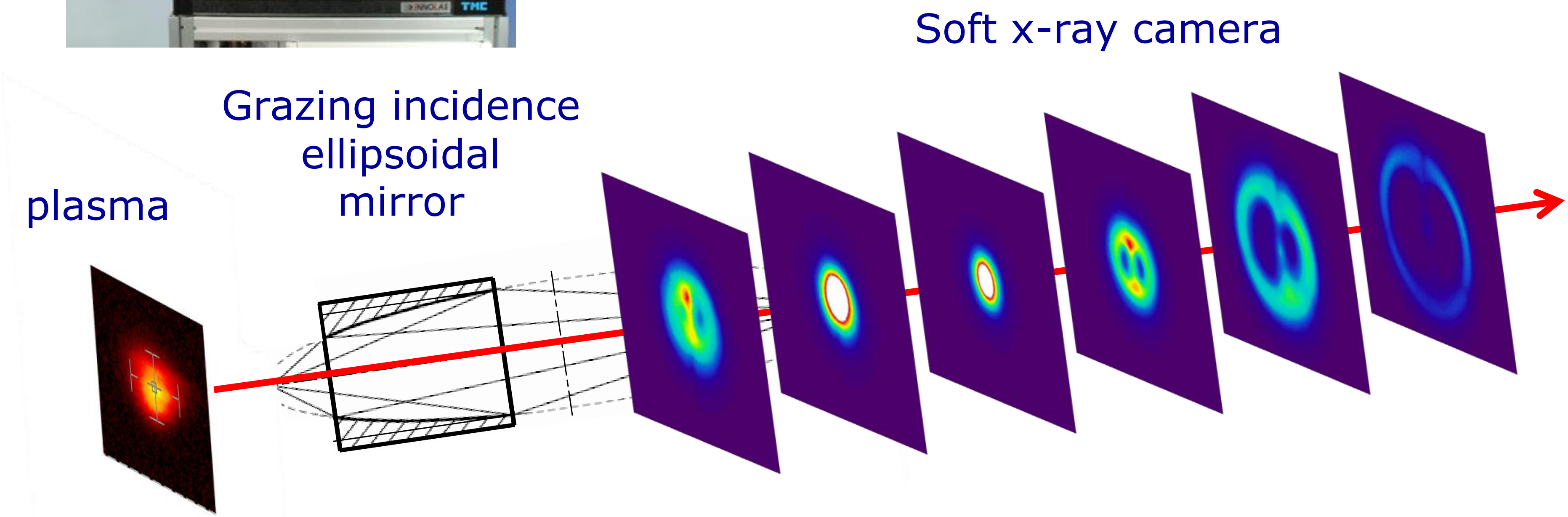


- λ = 2.88nm (monochromatic)
- → waist dia. ~ 500µm



…time-consuming…

Hartmann-Shack wavefront sensor:

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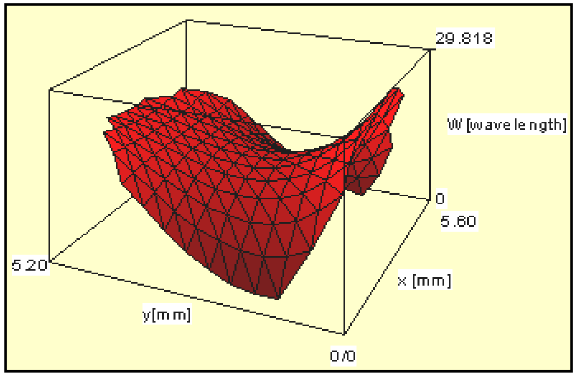
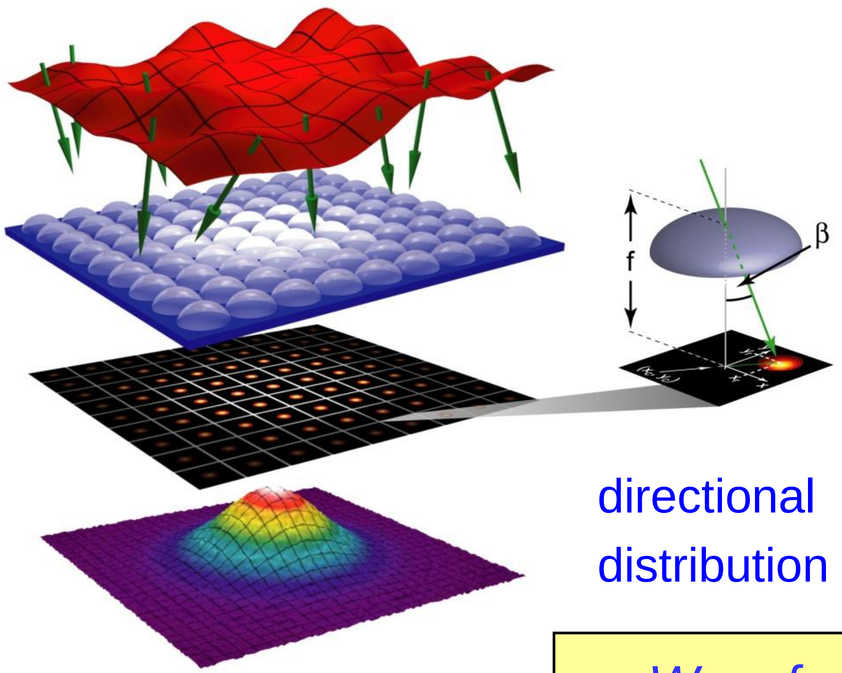
wavefront:





directional
distribution

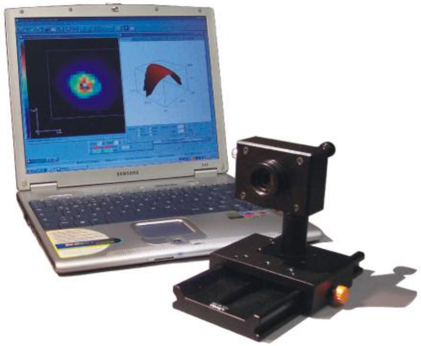
intensity
distribution

$\Rightarrow$ *Wavefront* w(x,y)

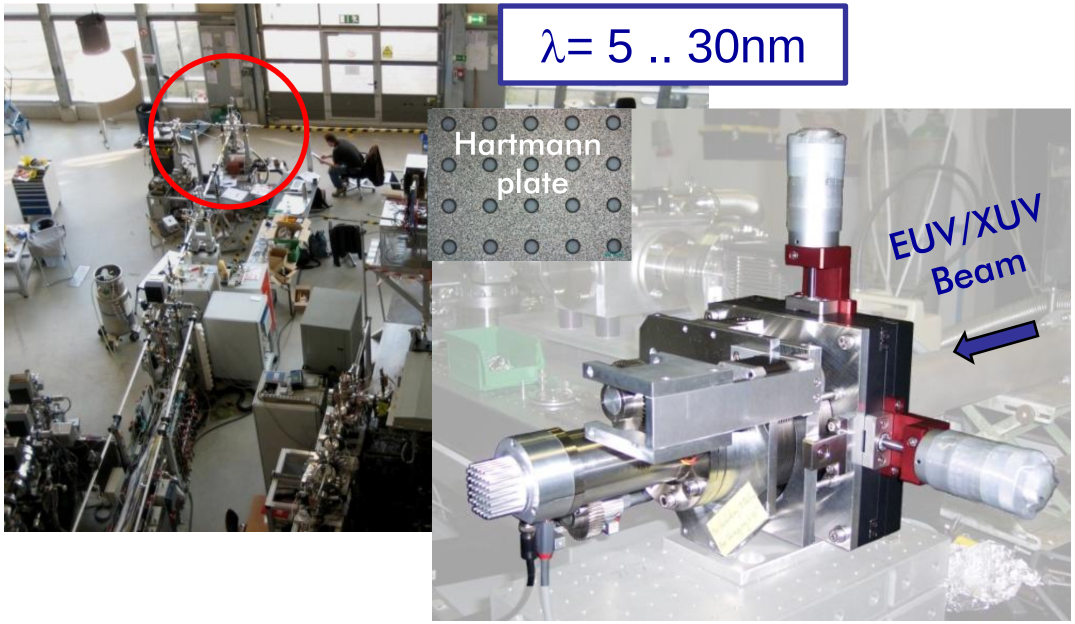
= surface ⊥ Poynting-Vektor S(x,y)

(ISO 15367-2)

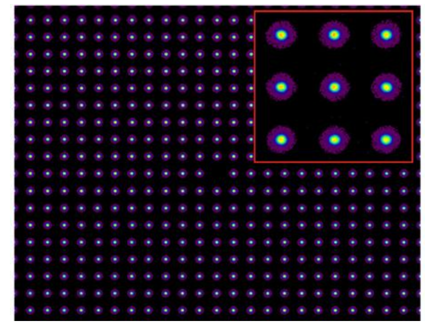
LOT
LOT ORIEL GRUPPE EUROPA



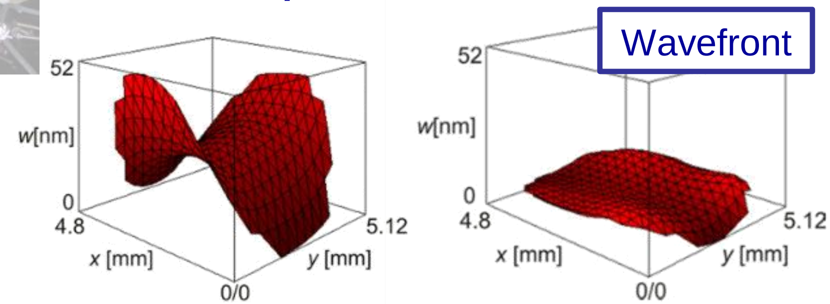
EUV wavefront sensor: Optics adjustment at FLASH FEL



Spot distribution:



Wavefront before and after mirror adjustment:



w_{rms}~ 10nm

w_{rms}~ 2.5nm ~ λ/10

Experimental setup (BL2):

B. Flöter, K. Mann, K. Tiedtke et al. NIM **A 635**, S108–S112 (2011)

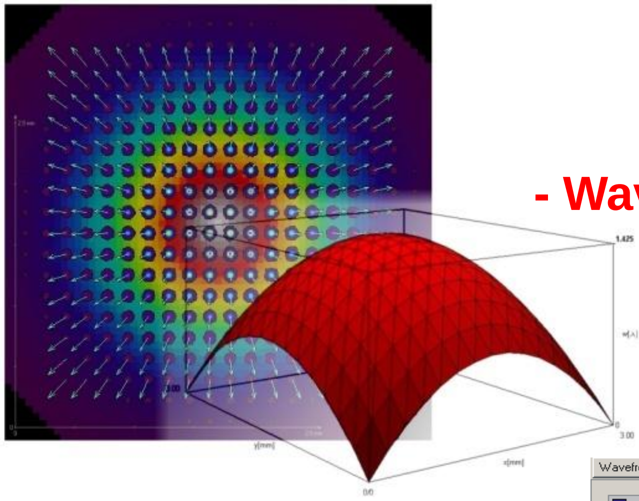
Beam characterization:

Hartmann-Shack wavefront sensor

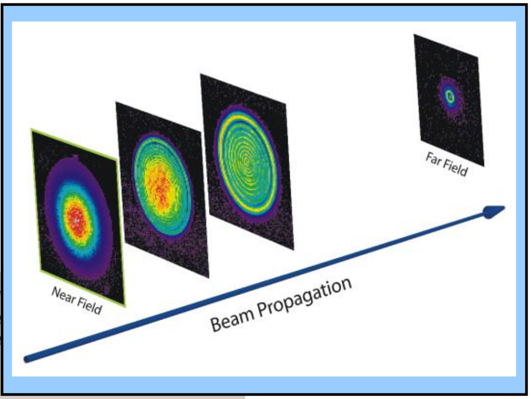
Spot distribution →

- Beam profile

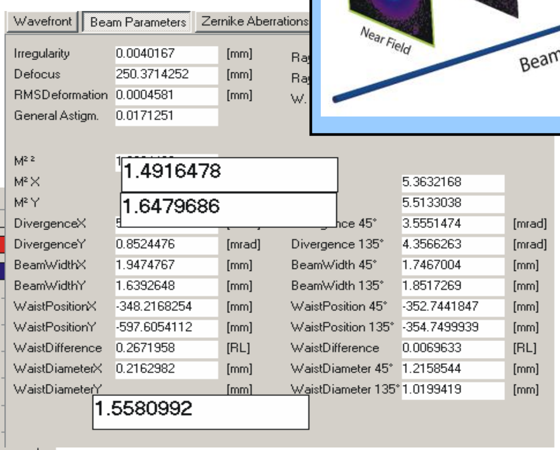
- Wavefront



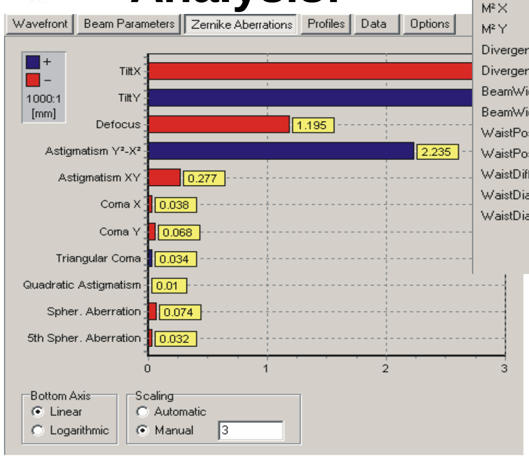
Propagation analysis



Beam parameters:



Zernike Analysis:



$$M_x^2 = \frac{4\pi}{\lambda}\sqrt{\langle x^2\rangle\langle \beta^{x^2}\rangle - \langle x\beta^x\rangle^2}$$

B.Schäfer, K. Mann, Rev. Sci. Instr. 77, 053103 (2006)

Collimated Diode Laser Beam

650 nm, cw, 2 mW

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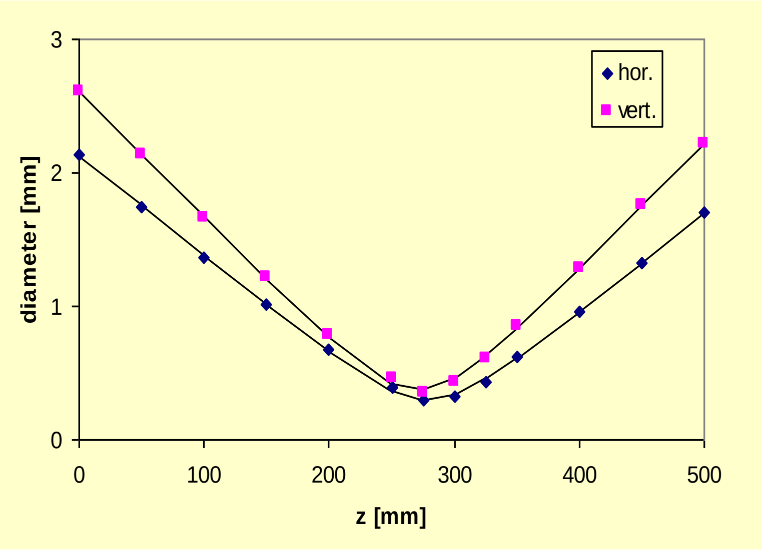
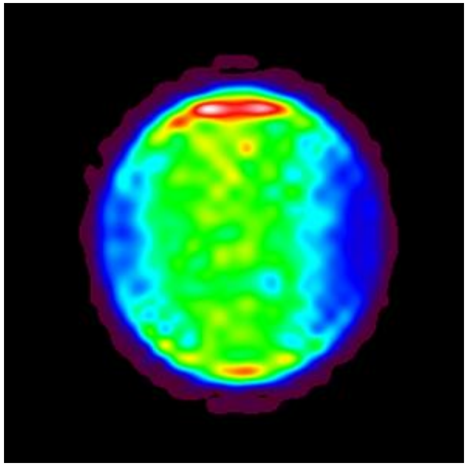
Caustic measurement



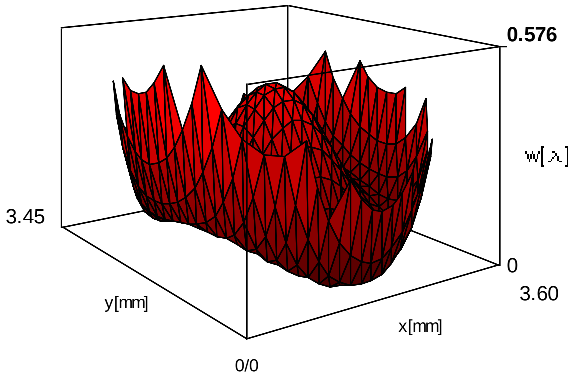
M²=2.68 / 4.26
θ_σ=7.56 / 9.55 mrad

Hartmann-Shack (single measurement)

Profile:



Wavefront aberrations:



M²=2.52 / 4.23
θ_σ=7.16 / 10 mrad

Prediction of beam propagation:

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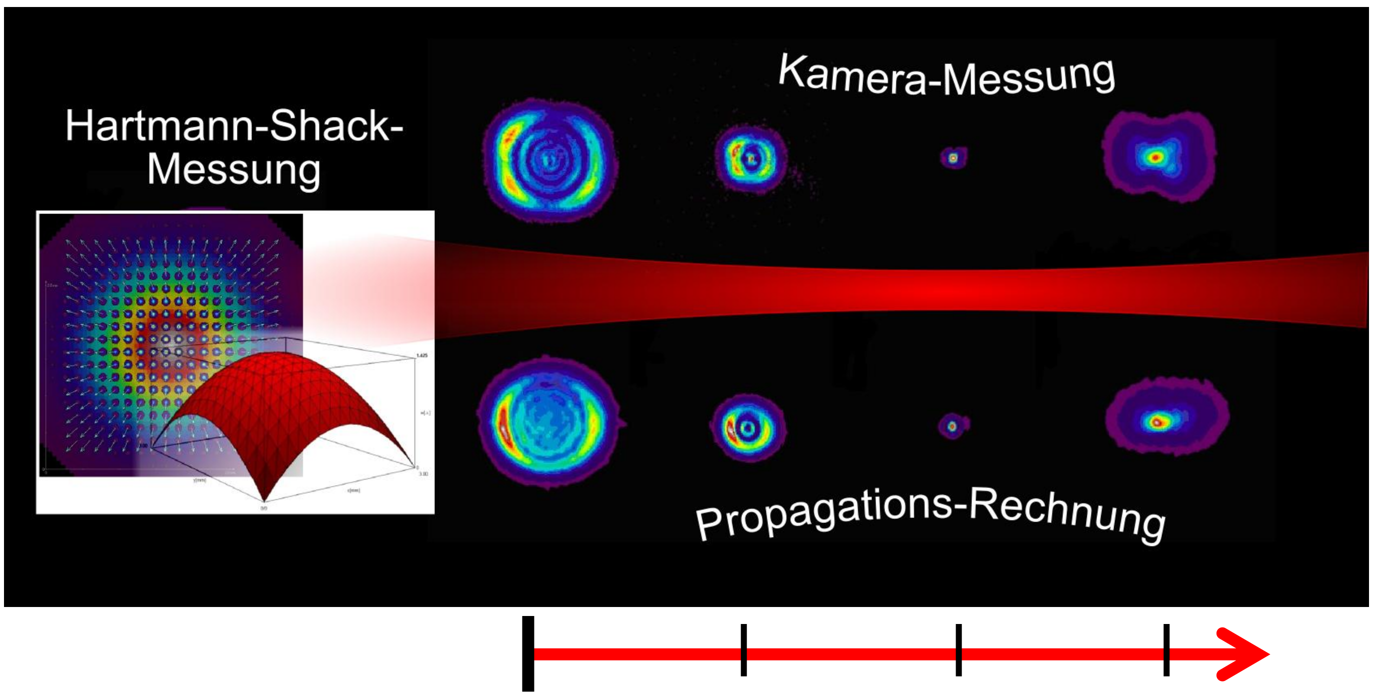
Single Hartmann-Shack Measurement → **Wavefront w(x,y)**

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

Fresnel-Kirchhoff integral

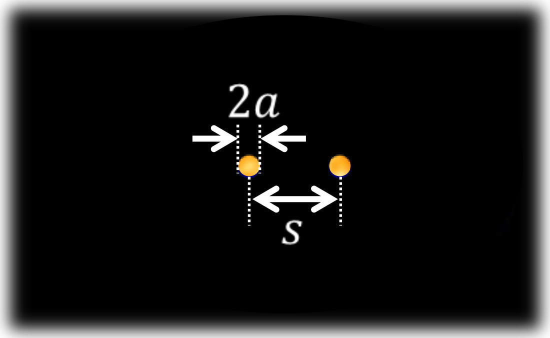
collimated diode laser:



z=0

….only fully coherent beams !

Spatial coherence:

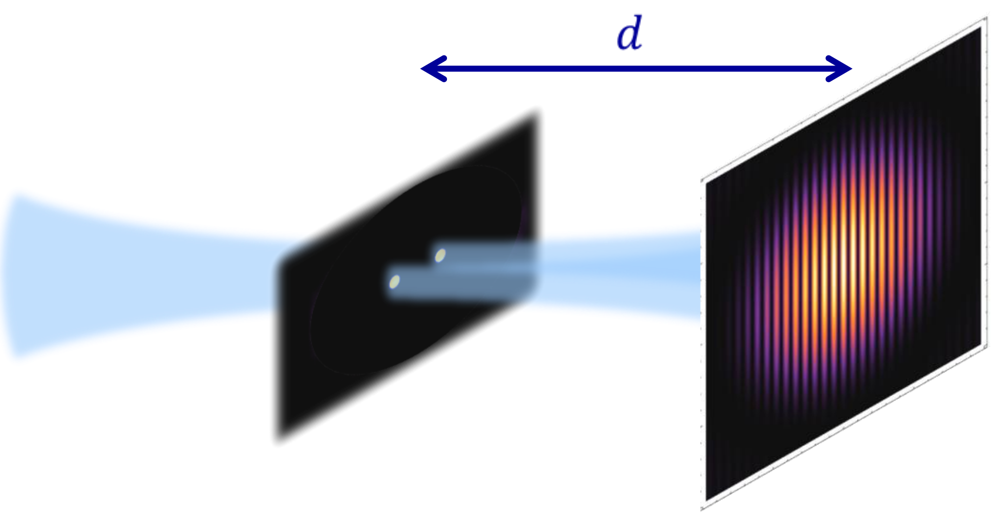


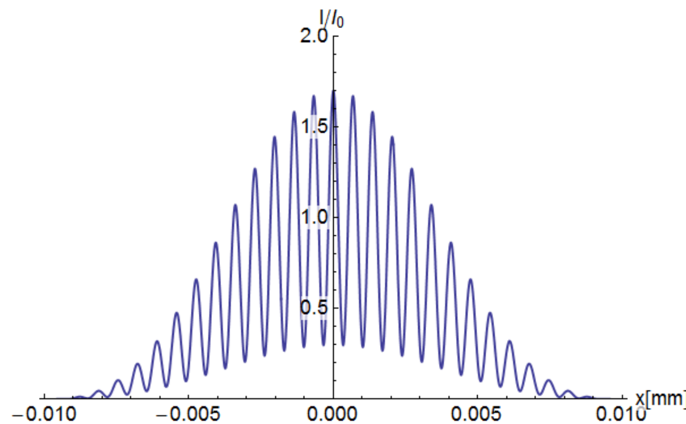
Young´s experiment:

interference of elementary waves

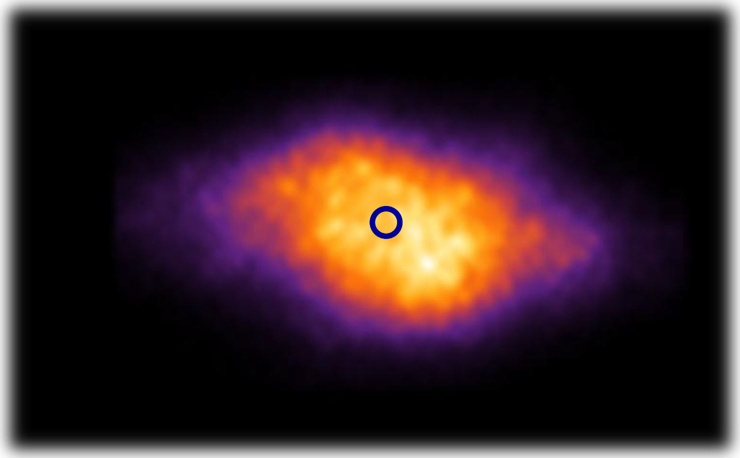
Contrast of fringes

→ local degree of coherence $\gamma(\vec{x}, \vec{s})$:

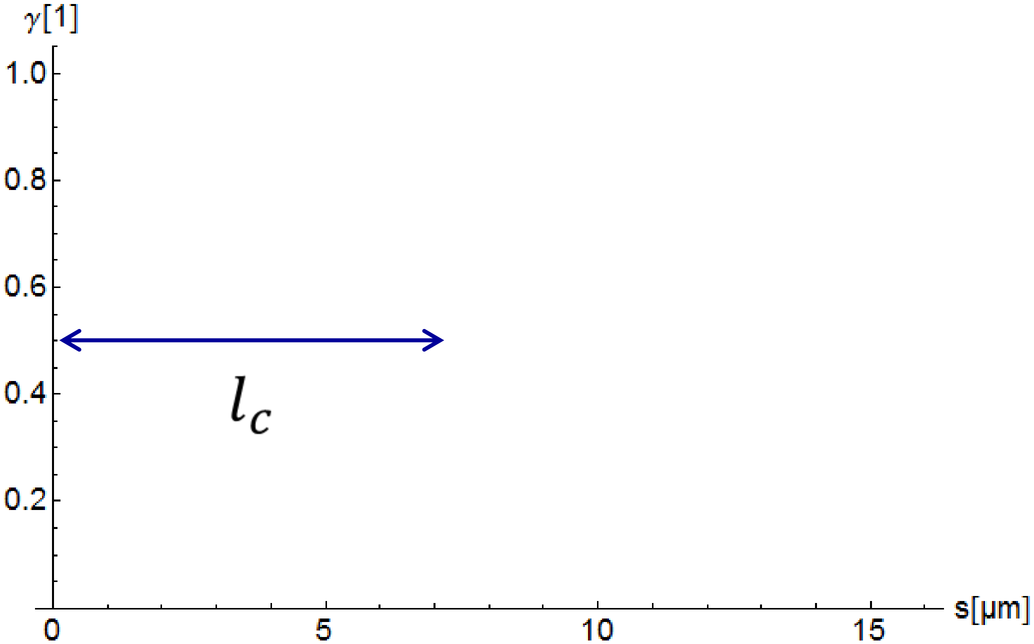




Mutual coherence function



$$\gamma(0, s_x) = \frac{\Gamma(0, s_x)}{\sqrt{I(-s_x/2) \cdot I(s_x/2)}}$$



coherence length l_c

Wigner distribution

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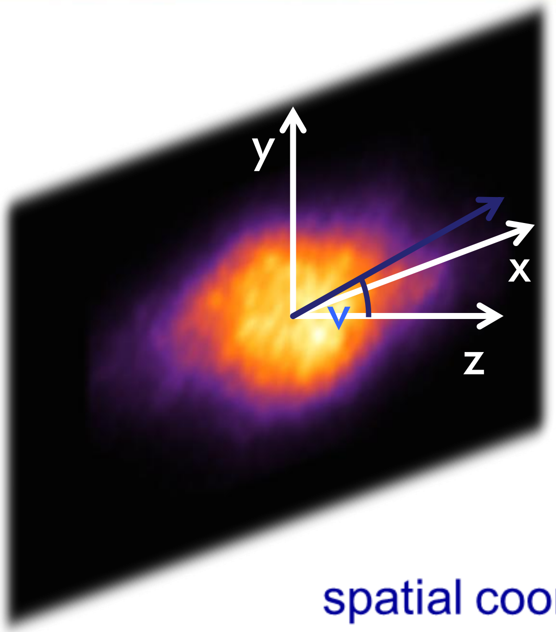

h = Fourier transform of Mutual Coherence Function:

Wigner distribution

mutual coherence function

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

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

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

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

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

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

Partially coherent beams: Measurement of Wigner Distribution

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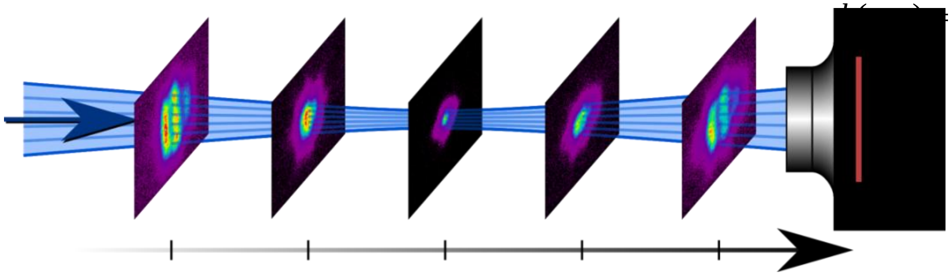
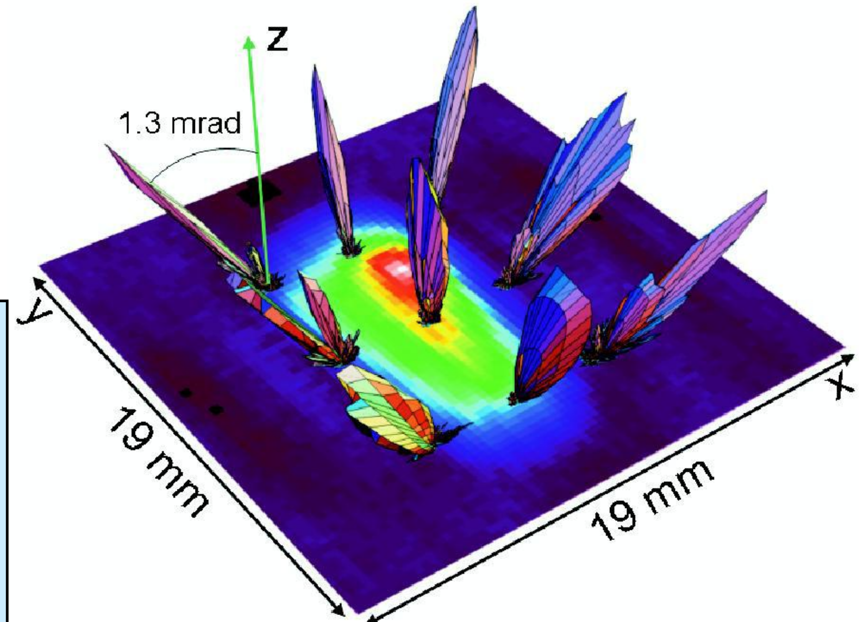
Mapping of 4D phase space:



Example:
*Spatially resolved angular distribution of **excimer laser @193nm***



⇔ Tomographic analysis of a laser beam

⇒ **comprehensive beam characterization**

- *beam parameters*
- *coherence function*
- *mode content*
- *wavefront*
- *angular characteristics*

B. Schäfer, K.Mann, New J. Phys. 2011

Optics characterization:

Photo-thermal lens effect $\leftrightarrow$ Absorption

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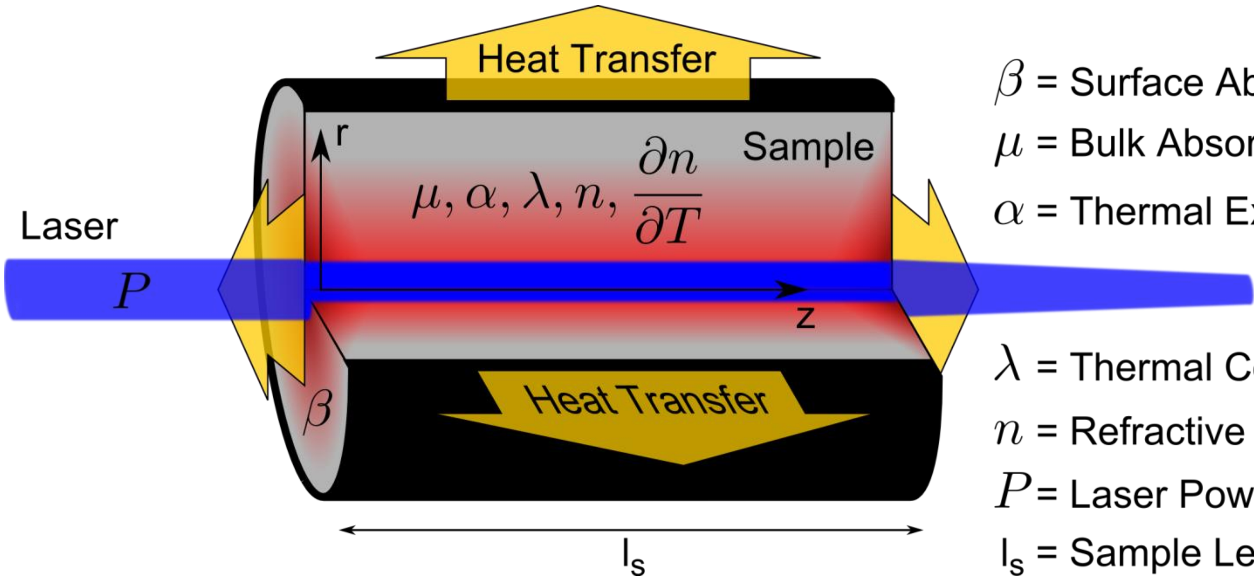


β = Surface Absorption Coefficient
μ = Bulk Absorption Coefficient
α = Thermal Expansion Coefficient

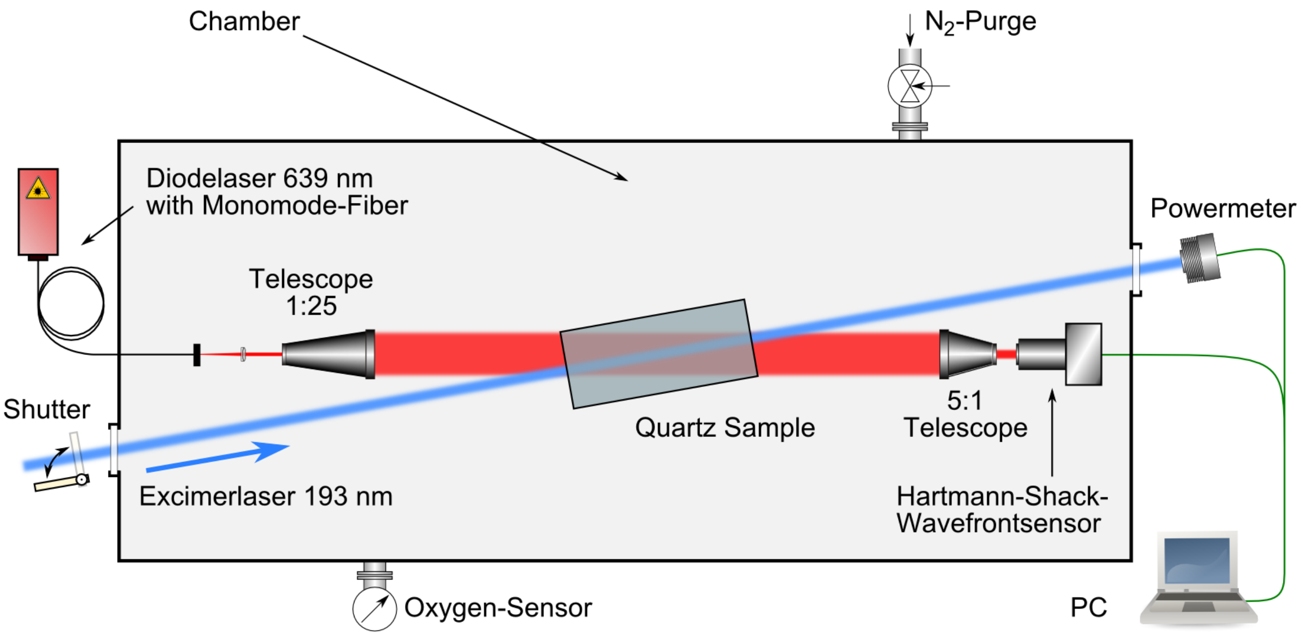
λ = Thermal Conductivity
n = Refractive Index
P = Laser Power
l_s = Sample Length

$\frac{\partial n(T)}{\partial T}$

irradiation → Absorption *bulk + surface* → heating → Refractive index / Expansion → Thermal lens

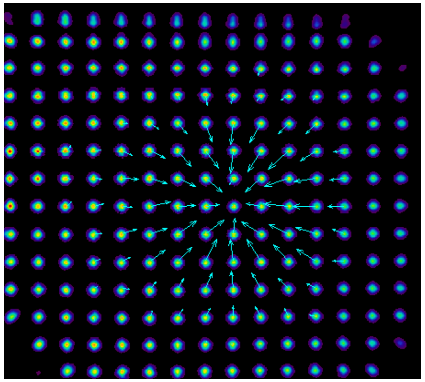
$$\delta w(r) = \left(\frac{\partial n}{\partial T}(T) + \alpha\, n(T) \right) \cdot l_s \cdot \delta T(r) \propto P \cdot (A_{bulk} + A_{surf})$$

Monitoring of ´Thermal lenses´:

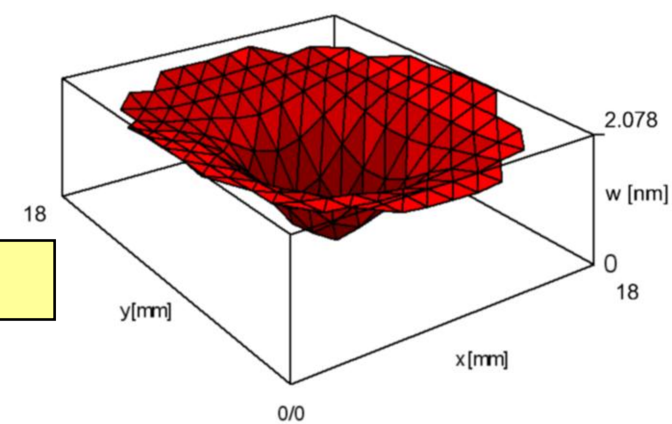


- *quartz plate ∅ 25 x 45mm*
- *irradiated @193nm, ~100mW/cm²*

Spot diagram:



Wavefront:



⇒ Formation of thermal lens

⇔ Wavefront sensor of extreme sensitivity

(~ λ / 10000)

$\Delta w_{p\text{-}v}$ ~ 1nm ⇒ Defocus ~ 10km !

Thermal lens in fused silica

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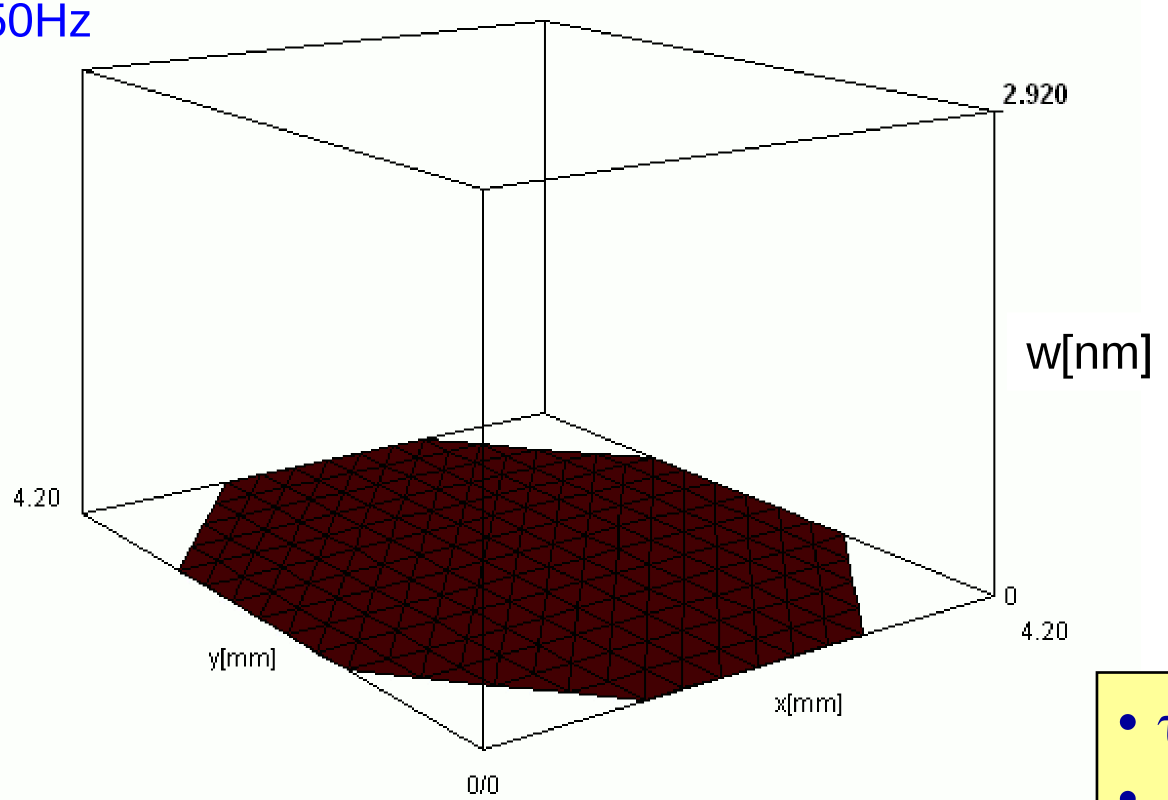
Quartz sample
@ 193nm / 150Hz
H ~ mJ/cm²



- τ ~ sec
- Δw ~ nm

Photothermal setup
for quantitative absorption measurement

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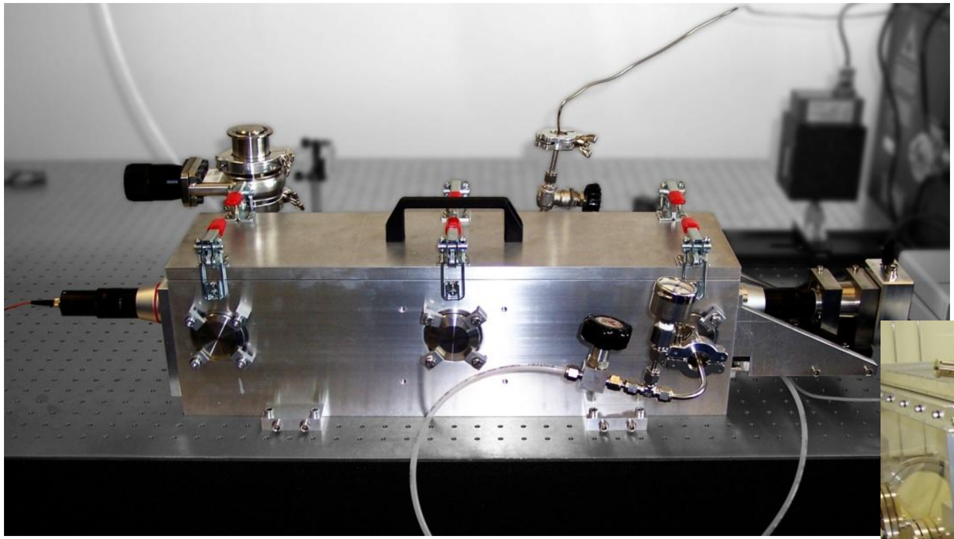
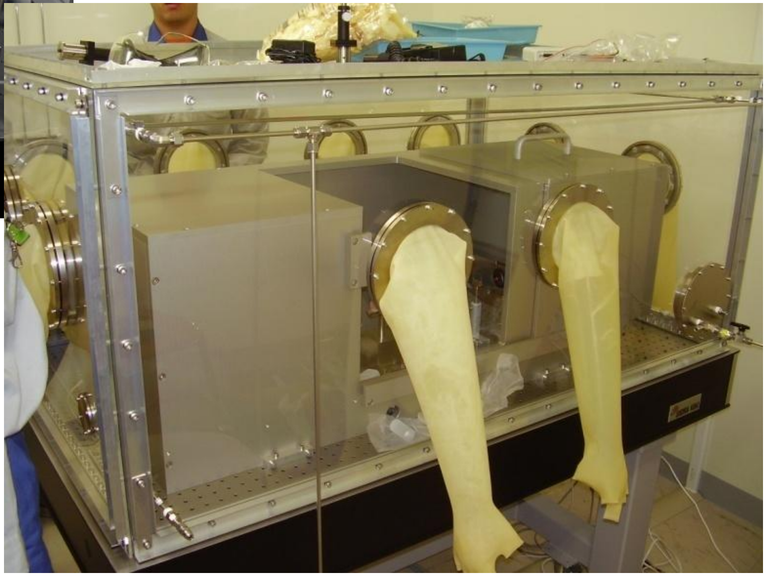


- fused silica
- HR / AR coatings



- 193nm: p (O_2) < 50ppm

ZEISS
AGC
Heraeus
ShinEtsu

Absorption of NIR optics:

Thermal Lens in AR coated BK7 glass

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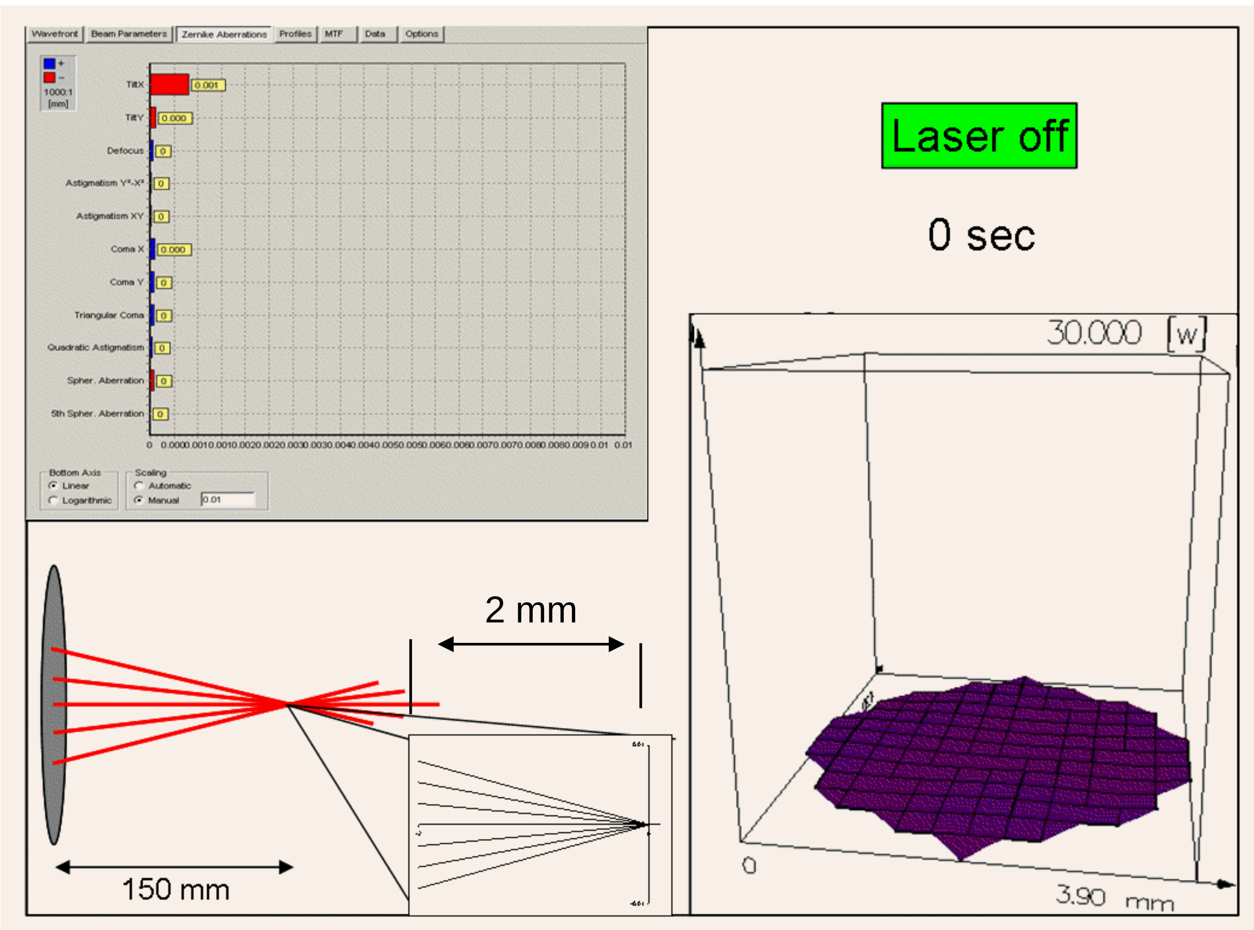
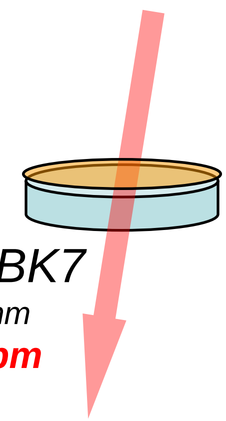
Fiber laser @1070nm / 100W



Fiber laser
Ø1.6mm
P=100W
1070 nm



Substrate BK7
Ø31,5mm, l=2mm
$\mu l + 2\beta \approx$ 65 ppm

Focus shift:

$$\Delta f = \frac{d^2}{d + 0.5 C_{20}^{-1}} \approx 1mm$$

Thermal wavefront distortion in beam delivery optics

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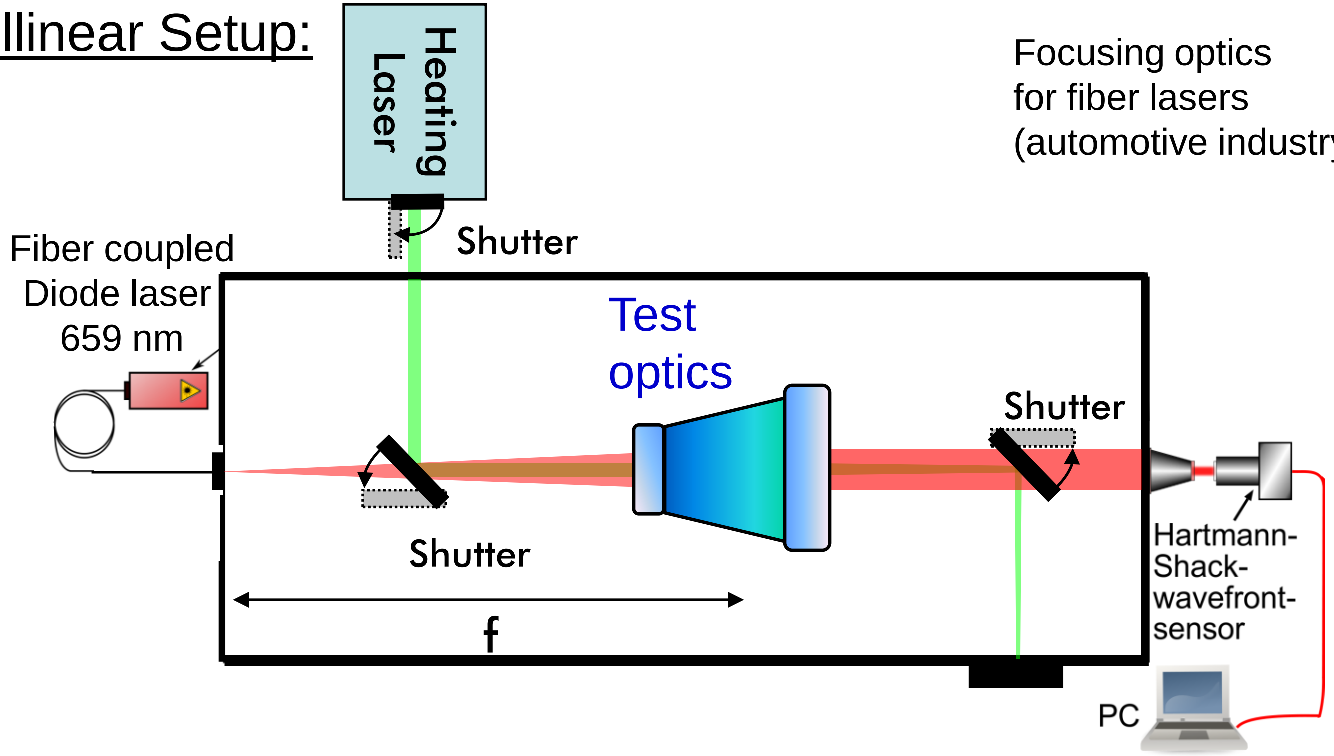
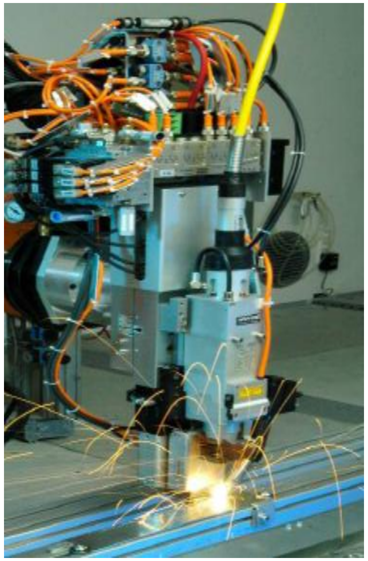
Collinear Setup:



Focusing optics
for fiber lasers
(automotive industry)



- Measurement during cooling intervals
- Investigation of complex optical systems

patented

Focus shift in F-Theta objective @532nm:

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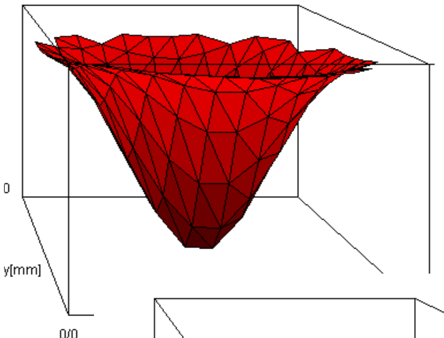
Wavefronts during cooling period:



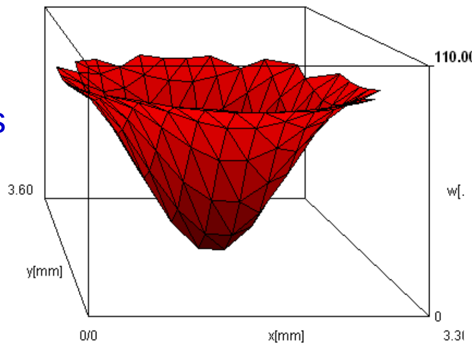
110nm
~ λ/4

w[nm]

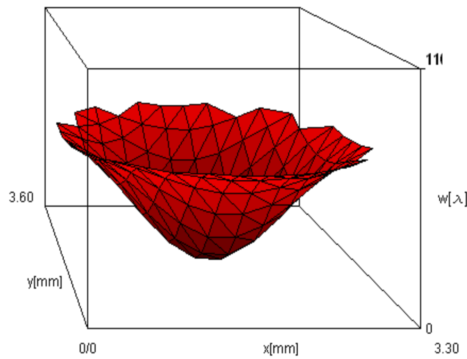
P=3.5W
λ=532nm

⇒ Focus shift
= - 0.7mm

t=1 sec
Defocus
=19m

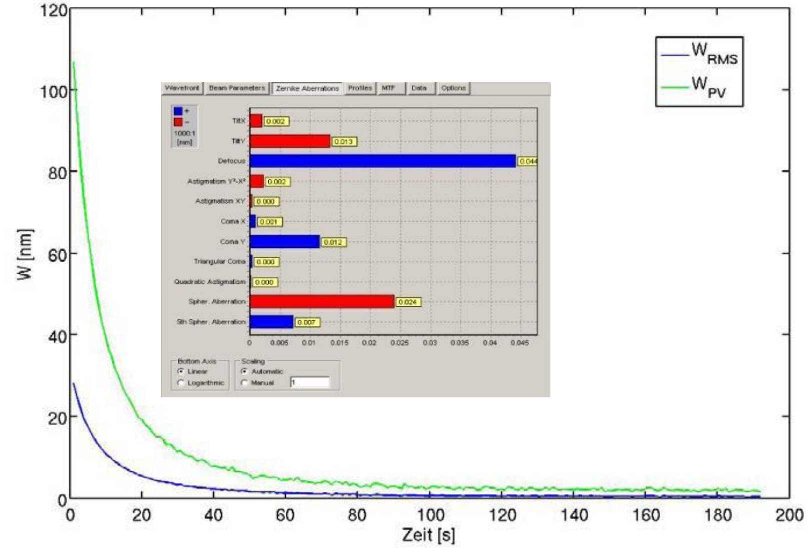


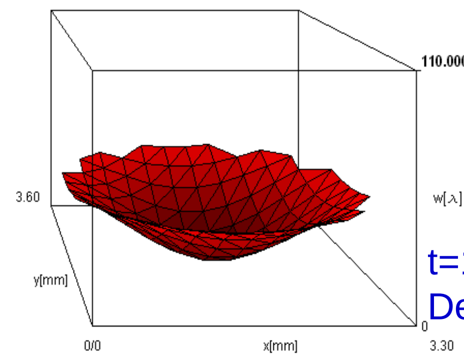
t= 2 sec
Defocus = 22.6m



t=5 sec
Defocus= 32.7m

Wavefront deformation vs. time:



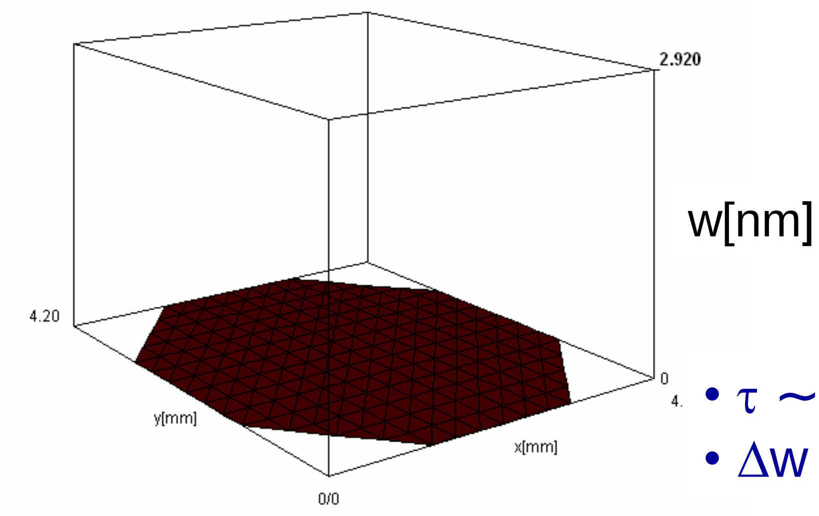


t=10 sec
Defocus= 52.5m

Photothermal absorption measurement

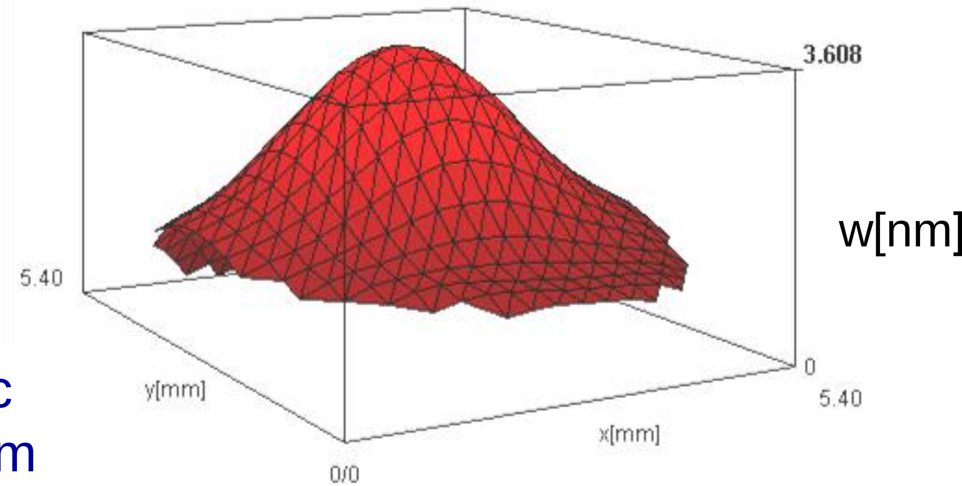
Comparison Quartz - CaF_2

Quartz:



- $\tau \sim$ sec
- $\Delta w \sim$ nm

CaF_2:



dn/dT: $8.5 \cdot 10^{-6}$ [1/K] $-10.5 \cdot 10^{-6}$ [1/K]

- Reversal of wavefront deformation
- → possibility for compensation of thermal lensing !

Summary:

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- **Laser beam characterization**

  - ISO standards

- **Hartmann-Shack wavefront sensor**

  - beam propagation for single pulses (M^2, Strehl, $\Delta < 5\%$)

  - Wigner distribution $\Rightarrow$ partially coherent beams

- **Thermal lensing in beam delivery optics**

  - New photothermal technique for measurements of ***absorption*** and ***focus shift***

  - high sensitivity wavefront sensor

  - Examples: wavefront distortions @193nm, @1070nm, @532nm F-Theta obj.

Wavefront Curvature Sensor

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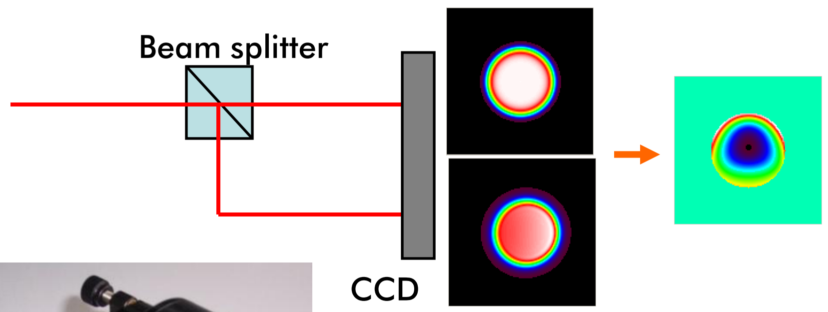
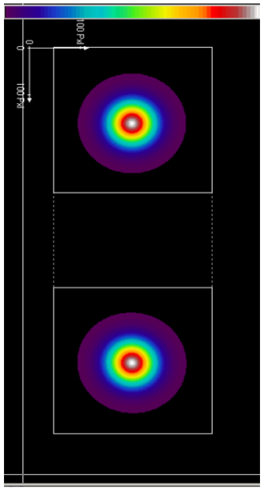
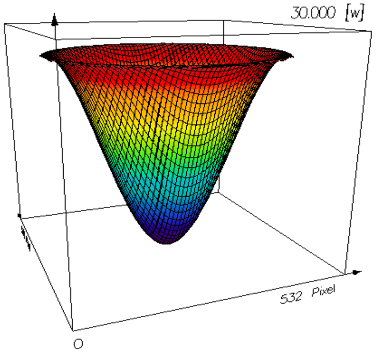
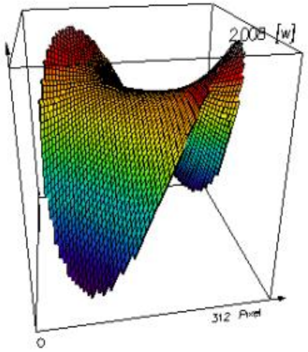
Wavefront Reconstruction from **Intensity Transport Equation**:

$$-\partial_z I = \nabla_\perp I \cdot \nabla_\perp w + I \cdot \Delta_\perp w \rightarrow w(x,y)$$









- High spatial resolution (pixel size)
- Self-referencing

Thank You !

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Coworkers:

- *Dr. B. Schäfer*
- *Dr. U. Leinhos*
- *J.O. Dette*
- *W. Hüttner*
- *F. Kühl*
- *M. Lübbecke*
- *T. Mey*
- *M. Müller*
- *G. Steinert*
- *J. Sudradjat*
- *M. Stubenvoll*

Outlook:

- Separation of surface and bulk effects
- Measurement at other wavelengths: NIR, EUV, x-ray (FEL)
- Prevention of thermal lensing

  - Reduction of absorption

  - compensation → adaptive optics