Hartmann Measurements and Comparative Beam Characterization at Free Electron Lasers

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Motivation

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Wavefront measurements for

- Beamline commissioning
  - Mirror alignment
  - Effect of gas absorbers, solid filters
- FEL characteristics
  - FEL source position and size
  - Beam position and stability
- Diagnostic for user experiments
  - Online-monitoring of wavefront quality, focus size and position
  - Single-pulse wavefront monitoring

Near- / Farfield moments for

- Direct comparison of phase measurement-type (Hartmann, interferometry, holographic, iterative) and caustic-related (ablation, phosphor…) techniques
- Generalized formalism in 4D phase space for Rayleigh length, waist parameters etc., Gaussian beam as special case

Hartmann Principle of Phase Measurement

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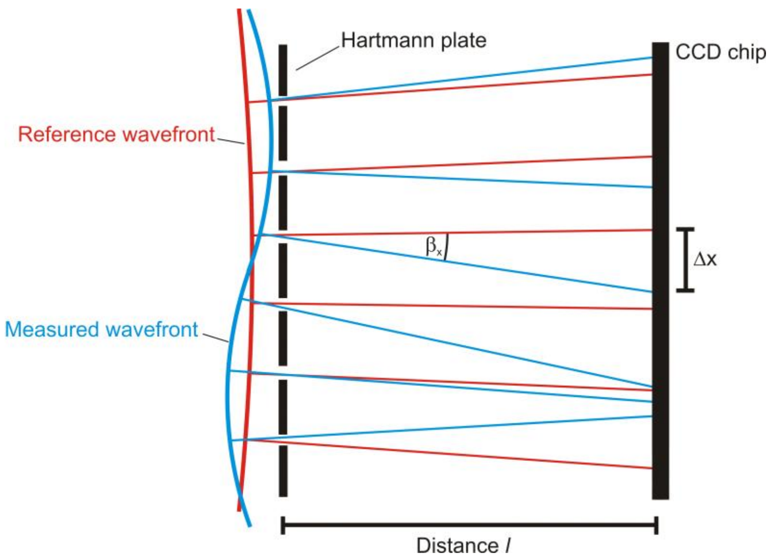
The Hartmann test



St

SSimultaneous measurement of intensity and phase

- A pinhole array divides the (partially) coherent beam into subrays
- Spot pattern deviation divided by CCD distance yields relative local wavefront gradient
- Wavefront gradient approximates the local transverse Poynting vector

$$\mathbf{S}_{\perp} \propto \nabla_{\perp} w_{ij} = \boldsymbol{\beta}_{ij}^{ref} + \boldsymbol{\beta}_{ij} = \boldsymbol{\beta}_{ij}^{ref} + \frac{\Delta \mathbf{x}_{ij}}{l}$$

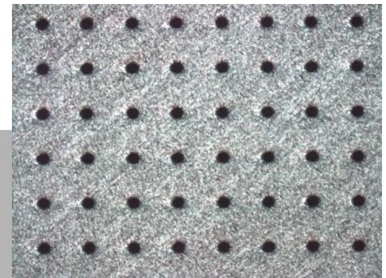
Intensity and wavefront reconstruction

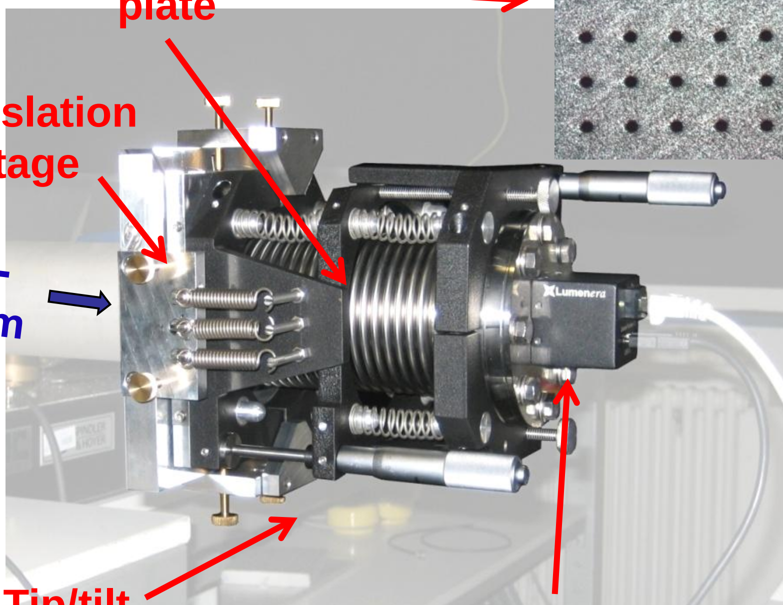
- Modal reconstruction of the wavefront by polynomial fit (e.g. Zernike polynomials)

$$\boldsymbol{\beta}(\mathbf{x};z) = \nabla_{\perp} w(\mathbf{x};z) = \sum_{k=1}^{N} c_k(z_0) \nabla_{\perp} P_k(\mathbf{x})$$

- Sum over all pixels within one subaperture samples intensity

LLG Hartmann Sensor





Wave front sensor

CCD: field of view = 8.2 x 6.6 mm
1279 x 1023 pixels
quantum converter
Hartmann plate: 33 x 30 laser drilled holes

Tilt range: ±10°
x/y translation range: ±10mm

Capabilities

- Accuracy approx. λ/15 PV for EUV
- Wavefront reconstruction
- Zernike coefficients
- Second moment beam parameters
- Intensity profile
- Pointing stability

Self-supporting wavefront sensor attachable behind user experiments

Hartmann Sensor Accuracy

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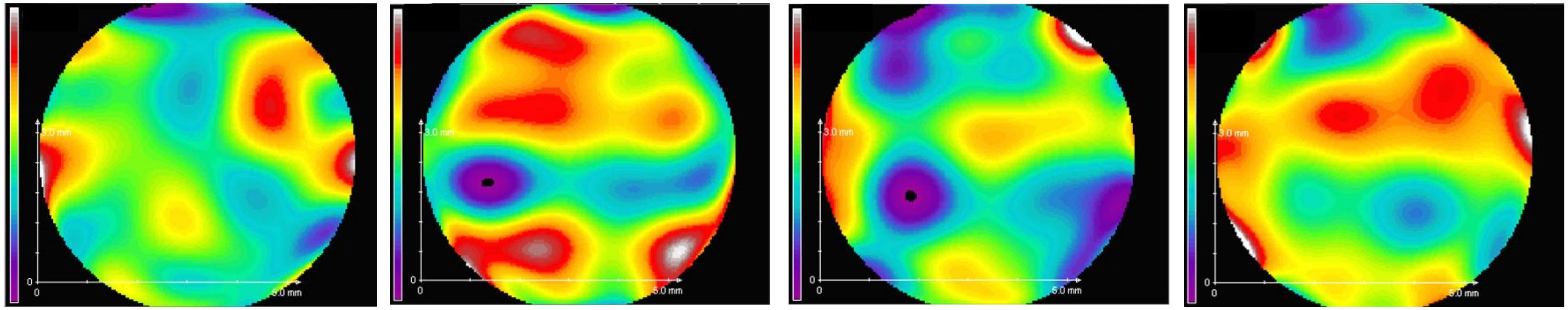
Series of single frames with a 5µm pinhole at BL1



$w_{pv}=0.074\lambda$ $w_{pv}=0.069\lambda$ $w_{pv}=0.056\lambda$ $w_{pv}=0.092\lambda$

Relative accuracy

Reference	λ_{EUV}/w_{PV}	w_{PV} [nm]
Lab source reference	1.1	11.9
Reference FLASH (after 6 month)	3.3	4.1
Accuracy for a single frame	15.3	0.9

FLASH– Experimental Setup

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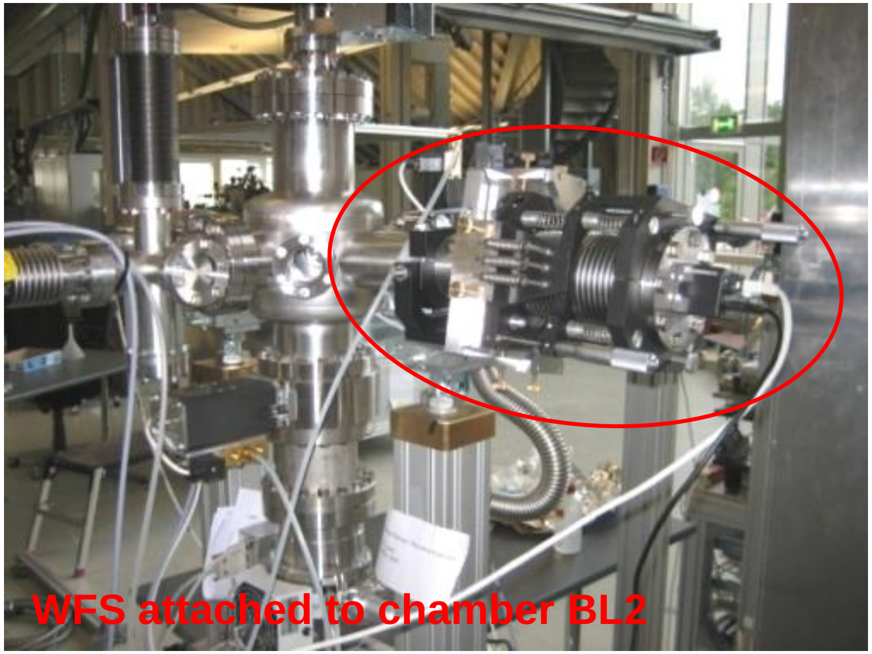
- BL2 mirror alignment
- Comparative caustic scans (phosphor, PMMA) and Hartmann sensor measurement at BL2



FLASH – Calibration BL1

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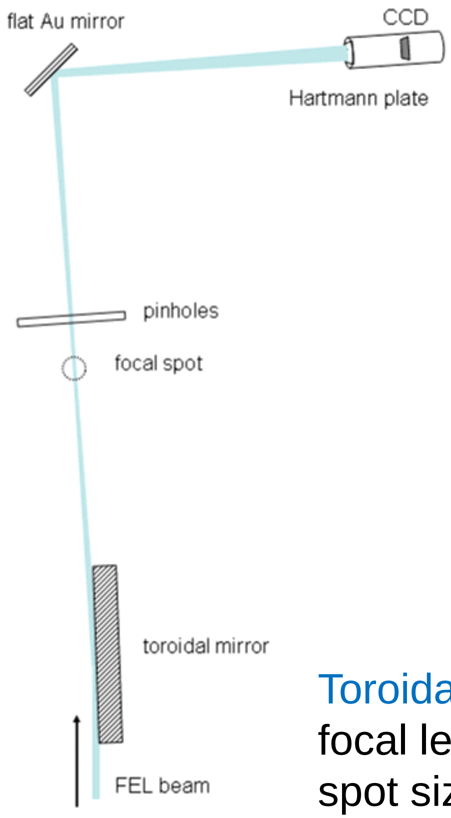
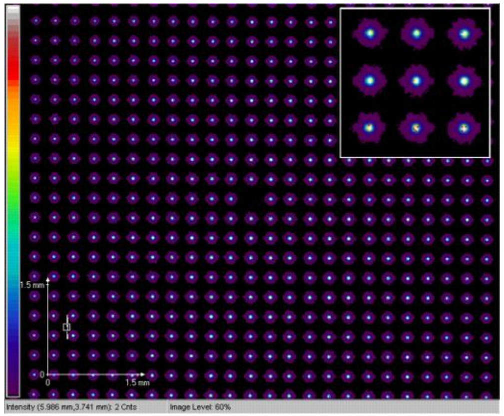
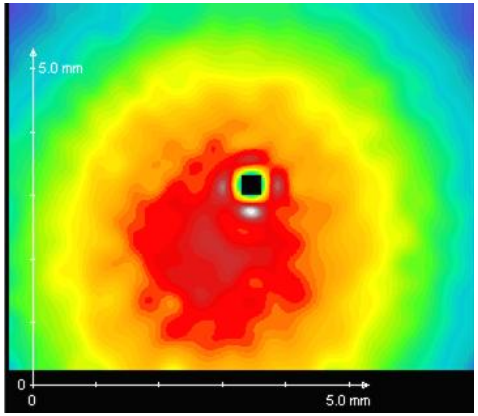


Hartmann Sensor Calibration BL1:

- Generation of a spherical wave by spatial filtering with a 5µm pinhole
- Distance sensor - pinhole c. 4m
- Wavelength 13.5nm





Toroidal Mirror

focal length → 10m
spot size design value (FWHM) → 100µm
distance to theoretical source → 68m

FLASH– Mirror Alignment

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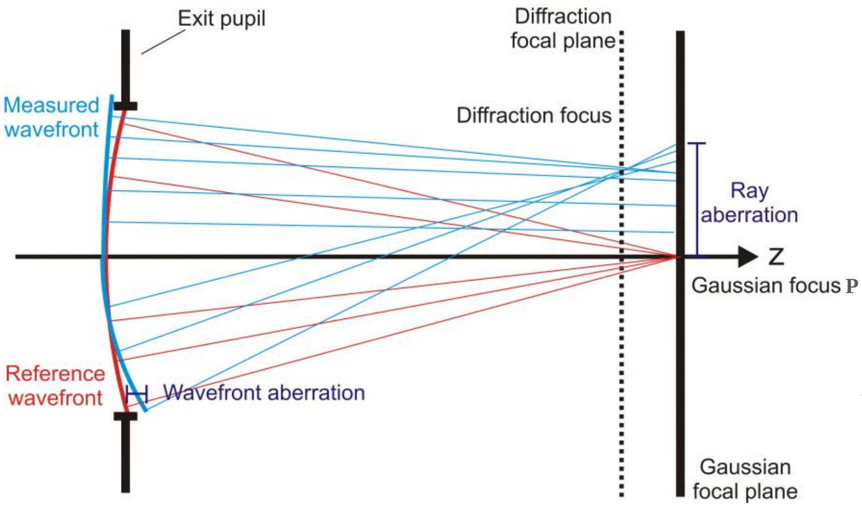
Wavefront and Ray Aberrations



Wavefront aberrations

Zernike polynomials suitable for FLASH beamlines

- Orthogonal on a circular aperture
- Typical mirror aberrations are well represented

$$w(\rho,\theta)=\sum_{n=0}^{\infty}\sum_{\substack{m=0\\ n-m\ even}}^{n}\left(A_{nm0}R_n^m(\rho)\cos(m\theta)+A_{nm1}R_n^m(\rho)\sin(m\theta)\right)$$

Higher order terms in the wavefront are known as aberrations

$$w(\mathbf{r},t)=\underbrace{A_{000}}_{\text{Piston}}+\underbrace{A_{100}x+A_{101}y}_{\text{Tilt}}-\underbrace{\frac{4a^2}{R}(x^2+y^2)}_{\text{Gaussian}}+\underbrace{A_{220}(x^2-y^2)+A_{221}2xy+\mathrm{O}^3}_{\text{Aberrations }\Phi}$$

Wavefront implications for focal spot quality

$$i(P)\approx 1-\left(\frac{2\pi}{\lambda}\right)^2 w_{rms}^2$$

$$i(P)\approx 1-\frac{2\pi^2}{\lambda^2}\sum_{n=1}^{\infty}\sum_{m=0}^{n}\frac{A_{nm}^2}{n+1}$$

- w_{rms} lowers the normalized intensity at the Gaussian focus (intensity at the Gaussian focus in the aberrated case over the nonaberrated case)
- Maréchal criterion: Optical system well corrected when i(P)≥0.8, which equals $w_{rms}\leq\lambda/14$
- Lower order Zernike aberration cannot correct for higher orders

FLASH – Mirror Alignment

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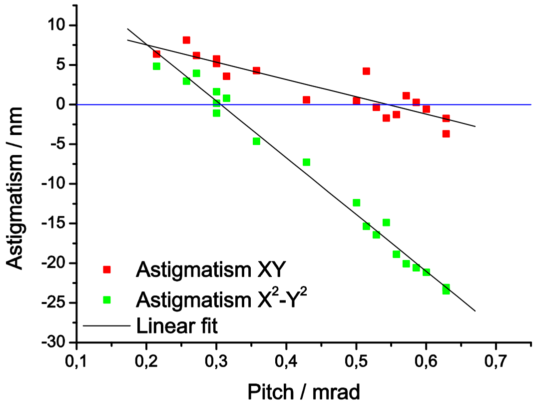
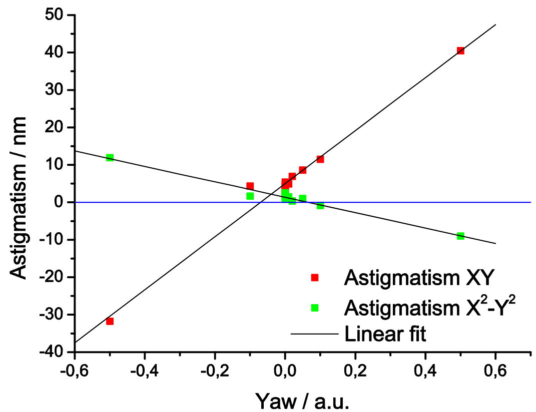
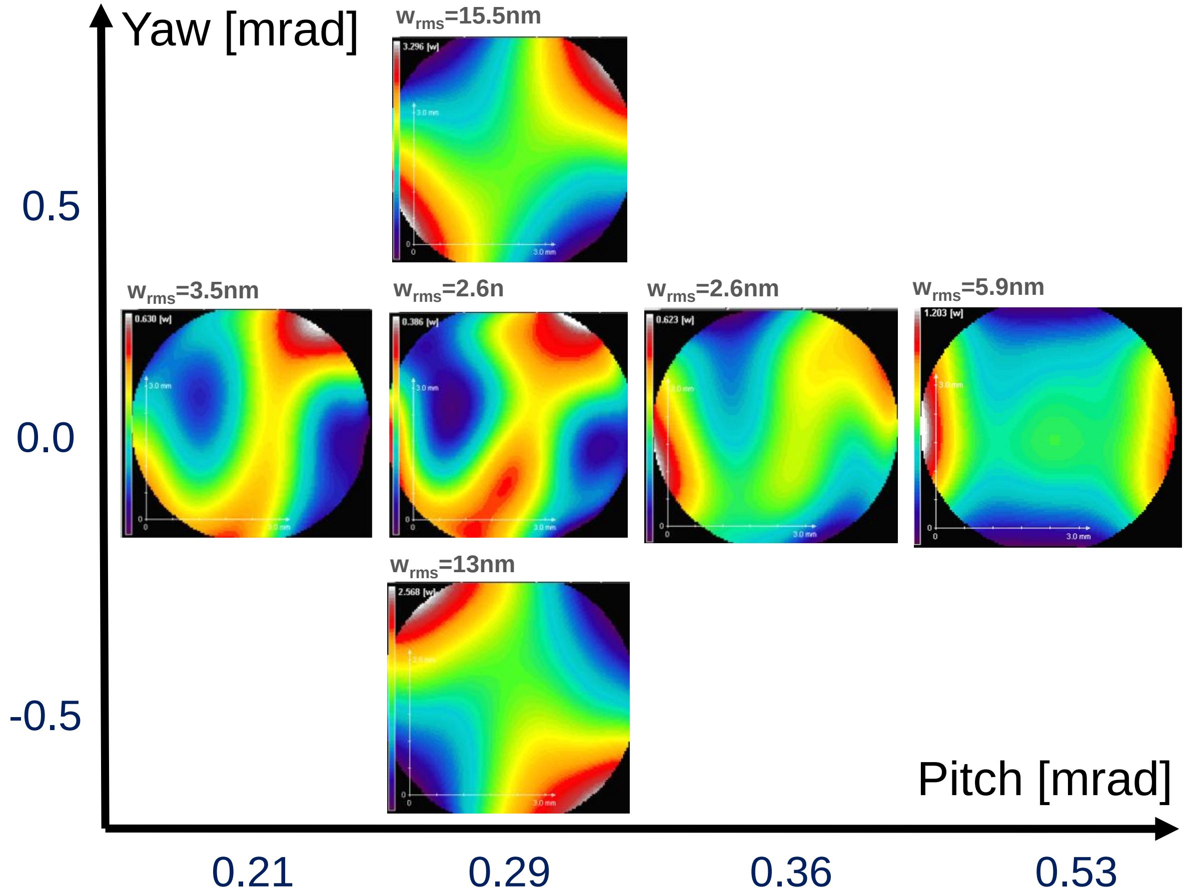
- Single Zernike coefficients are deduced from the local wavefront slopes
- Ellipsoidal mirror (f=2m)







FLASH – Mirror Alignment

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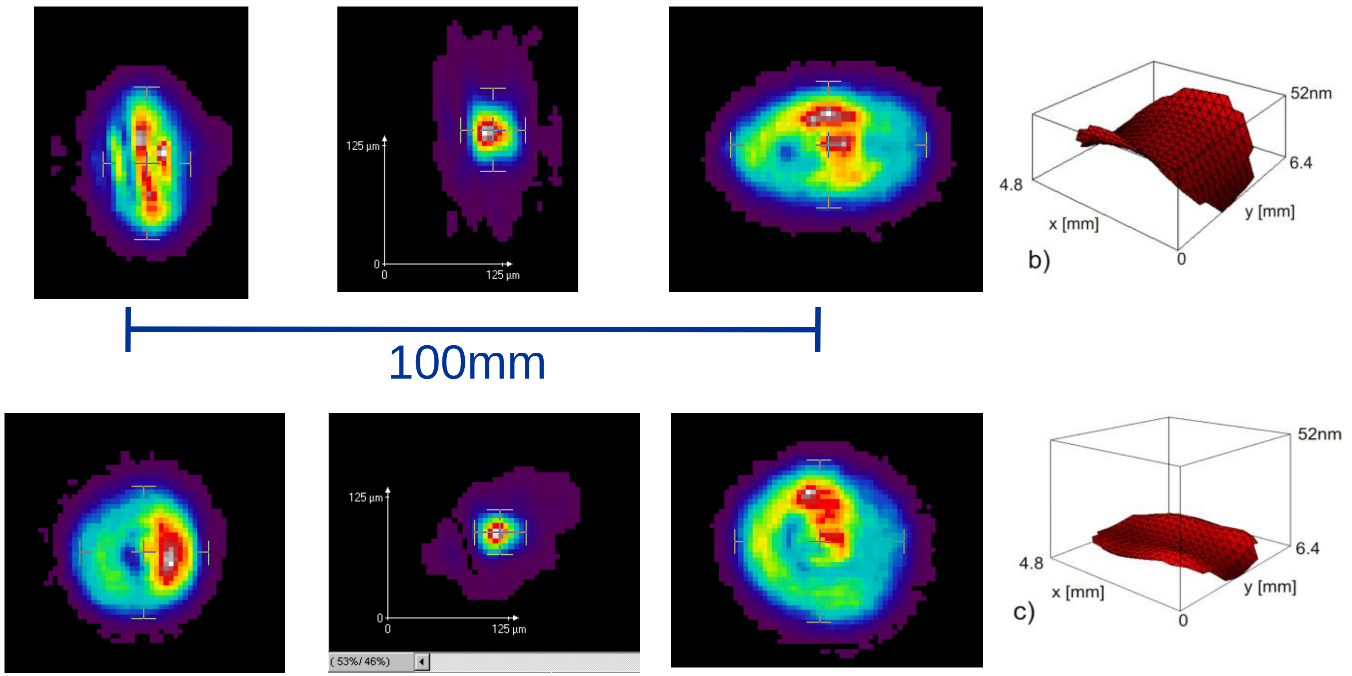
pre alignment

post alignment



- w_{pv} reduced from 52nm (λ_{26nm}/0.5) to 12nm (λ_{26nm}/2.2)
- w_{rms} reduced from 9.2nm (λ_{26nm}/2.8) to 2.6nm (λ_{26nm}/10)

Comparative Caustic Scans

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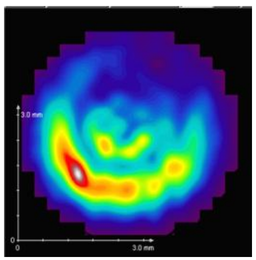
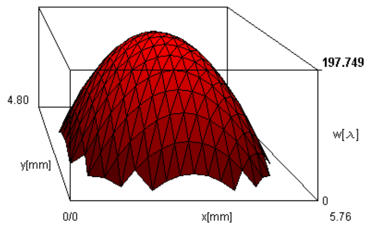
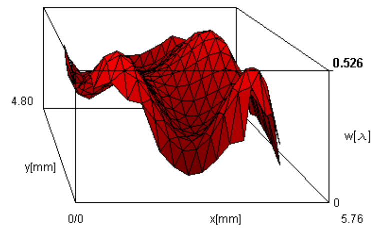
Second near-/farfield moments from Hartmann data







$$P = \begin{pmatrix} <x^2> & <xy> & <xu> & <xv> \\ <xy> & <y^2> & <yu> & <yv> \\ <xu> & <yu> & <u^2> & <uv> \\ <xv> & <yv> & <uv> & <v^2> \end{pmatrix}$$

$$\langle x^2 \rangle = \frac{\sum_{ij} (x_{ij} - <x>)^2 I_{ij}}{\sum_{ij} I_{ij}}, \quad \langle xu \rangle = \underbrace{\frac{\sum_{ij} (\beta_{x,ij} - <\beta_x>)(x_{ij} - <x>) I_{ij}}{\sum_{ij} I_{ij}}}_{\text{wavefront curvature}}, \quad \langle u^2 \rangle = \underbrace{\frac{\sum_{ij} (\beta_{x,ij} - <\beta_x>)^2 I_{ij}}{\sum_{ij} I_{ij}}}_{\text{wavefront slope term}} + \underbrace{\frac{1}{k^2} \frac{\sum_{ij} (\partial_x I_{ij})^2 / I_{ij}}{4 \sum_{ij} I_{ij}}}_{\text{diffraction term}}$$

- Hartmann data consists of intensity and wavefront gradient at each subaperture
- Complete second moment matrix in 4D phase space computed from Hartmann data
- Second moments used for computation of well-known beam parameters: waist size and position, divergence, beam propagation factor M^2, Rayleigh length

$$d_x = 4\sqrt{<x^2>}, \quad \theta_x = 4\sqrt{<u^2>}, \quad M_x^2 = 2k\sqrt{<x^2><u^2> - <xu>^2}, \quad d_0 = \frac{4M^2\lambda}{\pi\theta}, \quad z_R = \frac{d_0}{\theta}, \quad z_0 = \frac{<xu> z_R}{|<xu>|}\sqrt{\left(\frac{d}{d_0}\right)^2 - 1}$$

Comparative Caustic Scans

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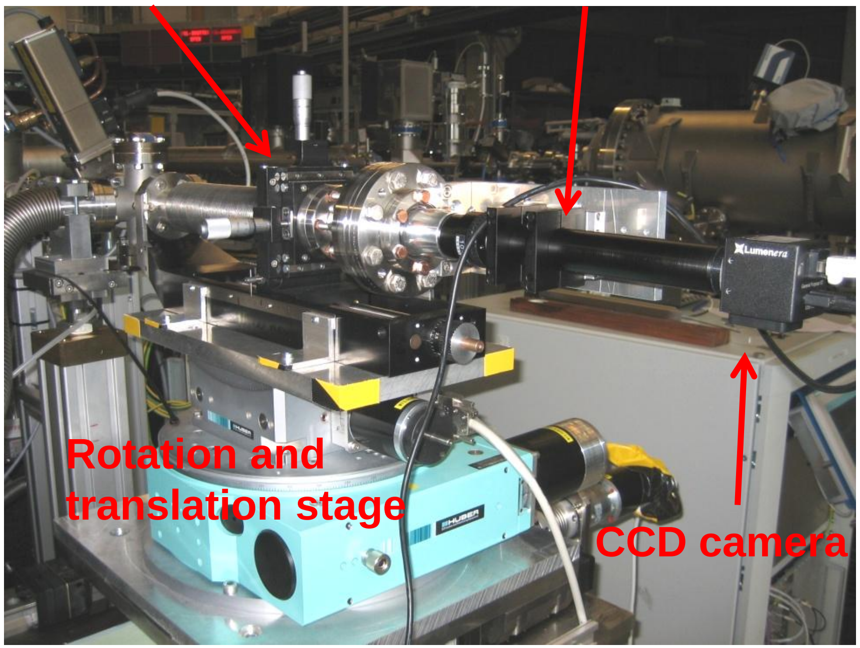
Second near-/farfield moments from EUV camera

Phosphor coated screen / PMMA

Long working distance microscope

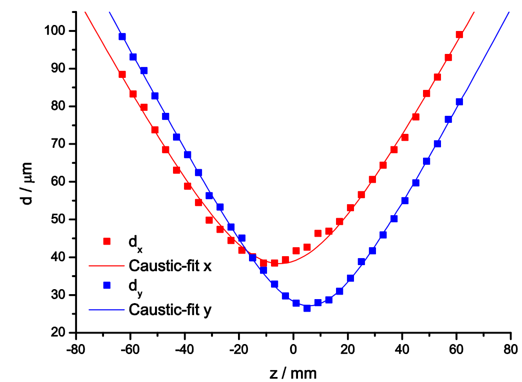


- Phosphor-coated screen inside the vacuum
- Screen imaged onto CCD chip via long working distance-microscope (47mm)
- Second Moment beam diameter from pixel count

$$d_x = 4\sqrt{<x^2> - <x>^2}$$

EUV camera caustic: quadratic fit

$$d^2 = cz^2 + bz + a$$



Waist position and size, Rayleigh length, divergence, M_x^2, M_y^2

Comparative Caustic Scans

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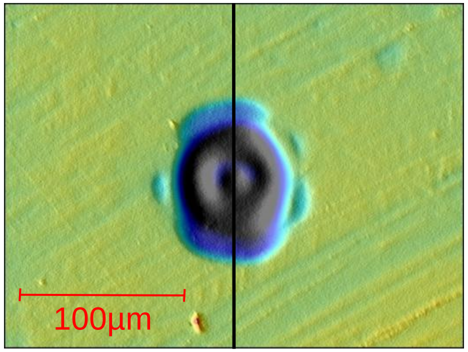
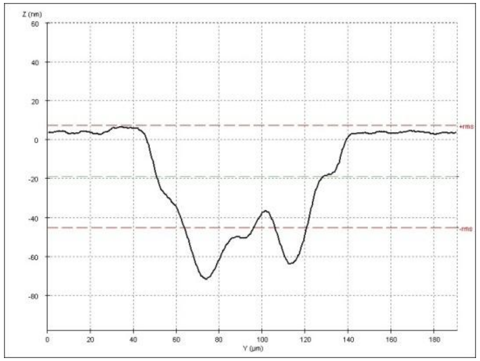
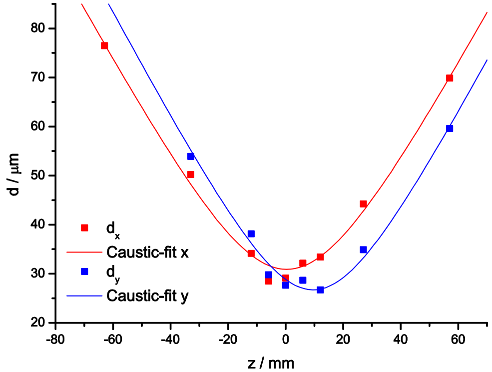
Second moment beam diameter from PMMA



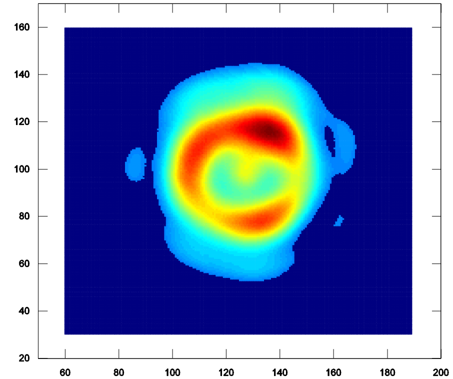


Ablative PMMA imprint, white-light interferometer,

- Bulk PMMA sample at same position as phosphor
- Single pulses
- Assuming Lambert-Beer’s law with
  - Ablation threshold 7.2mJ/cm2
  - Attenuation length 55.2nm
- Second moment beam diameter



PMMA caustic



Beam profile

Comparative Caustic Scans

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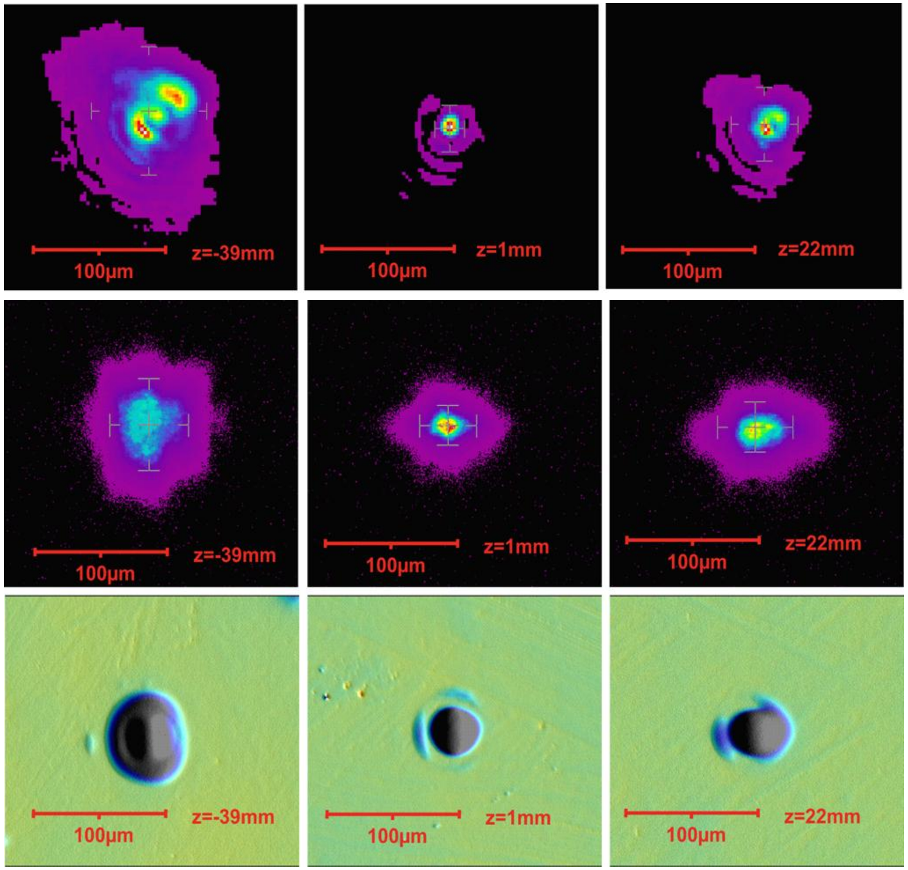

	Hartmann sensor	Phosphor with EUV camera	PMMA
$z_{R,x}$[mm]	34	29	28
$z_{R,y}$[mm]	30	22	24
$z_{0,x}$[mm]	2060	1985	1991
$z_{0,y}$[mm]	2068	1996	2000
$d_{0,x}$[µm]	53 31 FWHM	42 25 FWHM	31 18 FWHM
$d_{0,y}$[µm]	45 27 FWHM	32 19 FWHM	27 16 FWHM
M^2_x	4.7	4.6	-
M^2_y	3.9	3.4	-

Hartmann Measurements at LCLS

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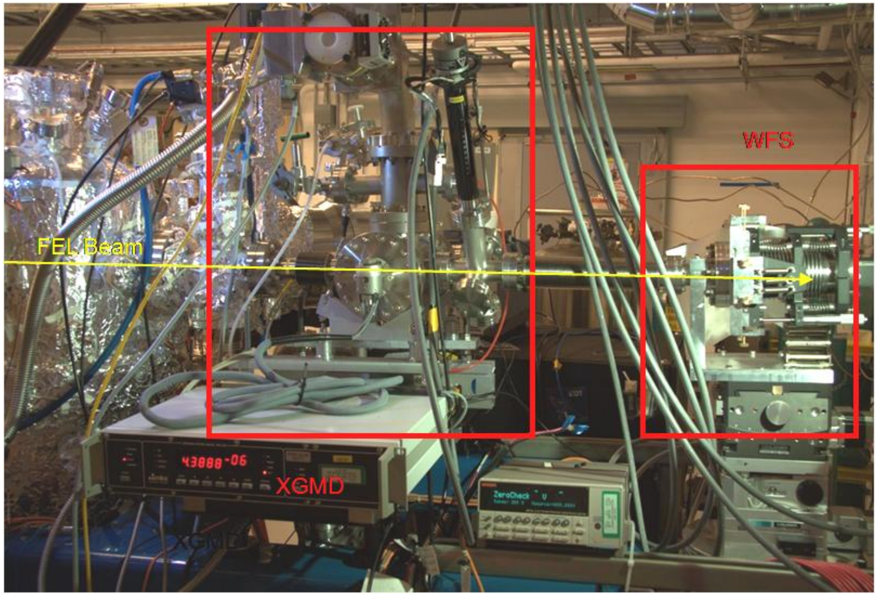
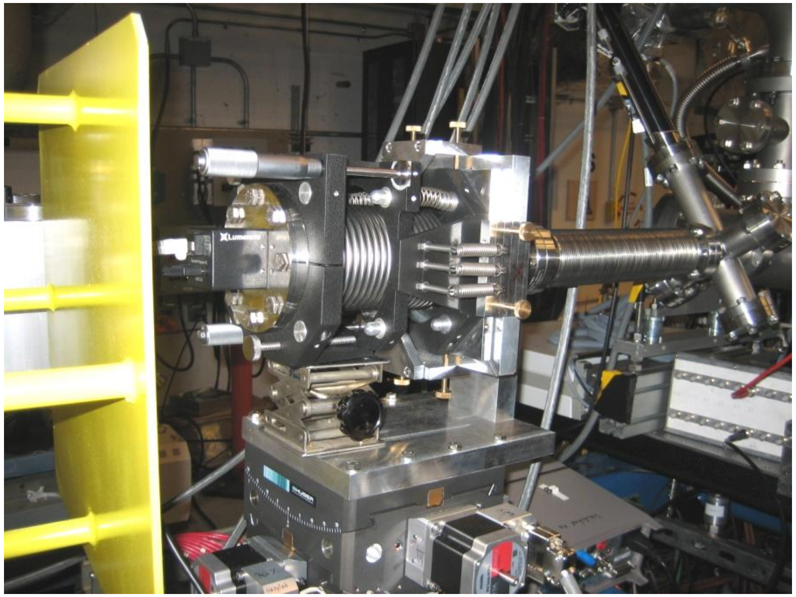
- LLG Hartmann sensor for beamline commissioning at LCLS AMO station
- AMO station features KB optic
- Combined experimental setup XGMD + WFS





Hartmann Measurements at LCLS

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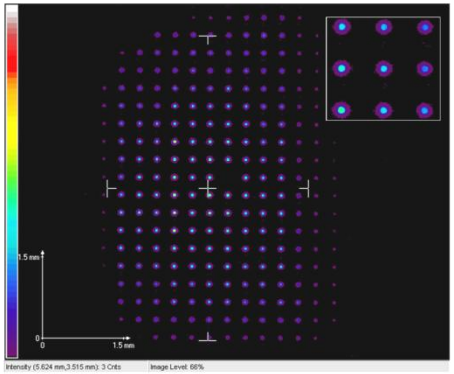
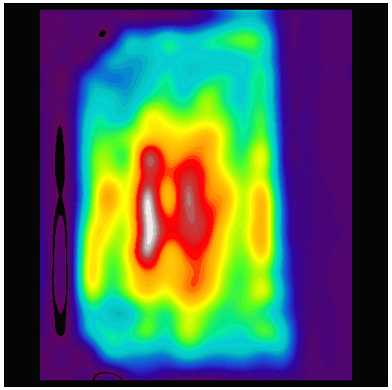
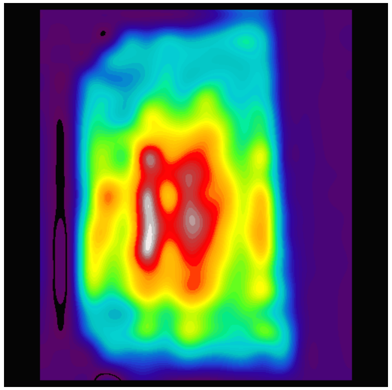
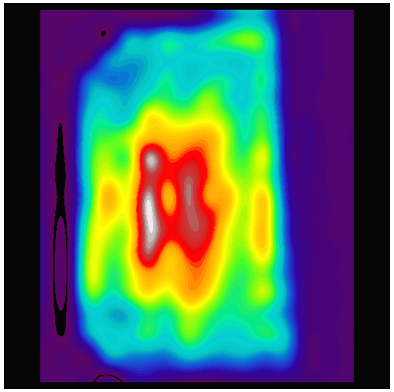
- Hartmann measurements at E_{ph}=821eV
- Reference taken at FLASH (13.5nm)
- Hartmann test not chromatic (in nondiffractive regime)
- Hartmann sensor spot pattern (left) shows sharp, well defined spots
- Interpolated beam profiles (bicubic spline) show the beam profile









Hartmann measurements at LCLS

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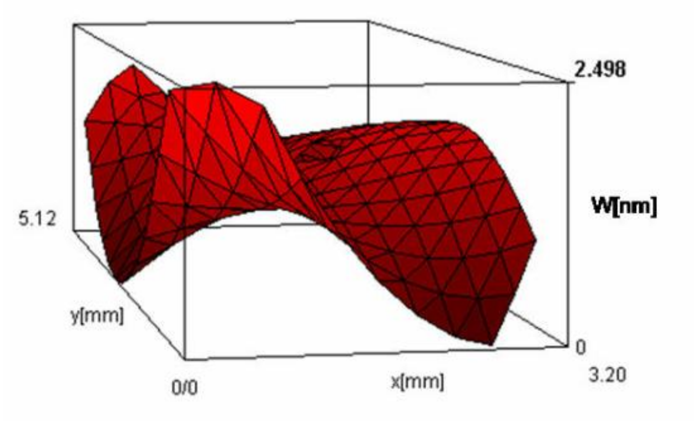
- Wavefront reconstructed using Legendre polynomials
- No on-site and at-wavelength calibration

	Measured (Legendre 2)	**predicted**
Beam width	3.5mm x 5.2mm (2nd moment)	
Pointing stability	23µm x 53µm (sensor position)	
Wavefront	5nm PV, 9Å rms	
Divergence	x: 1.04 mrad y: 1.56 mrad	1.04 mrad 1.58 mrad
Waist position	-3370mm / -3345mm	-3365mm
Spot size	7.3µm x 7.7µm 4.3µm x 4.53µm FWHM	1-3µm



Single-pulse wavefront at AMO station, Legendre degree 2

Summary

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- Wavefront measurements at FLASH BL1 and BL2 showing the feasibility of a compact Hartmann sensor with accuracy $\sim\lambda_{EUV}/15$
- Ellipsoidal at BL2 aligned. w_{rms} at BL2 reduced by more than a factor of three

- Waist sizes from caustic scans show general agreement with Hartmann measurements performed at BL2
- Other parameters may vary more

- Hartmann measurements performed during LCLS commissioning
- Hartmann sensor for ~800eV feasible
- Adjustments to the wavelength recommended

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Thank You!

White-light Interferometry for Imprints

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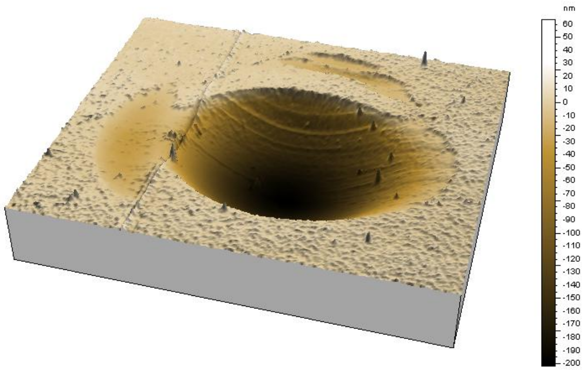
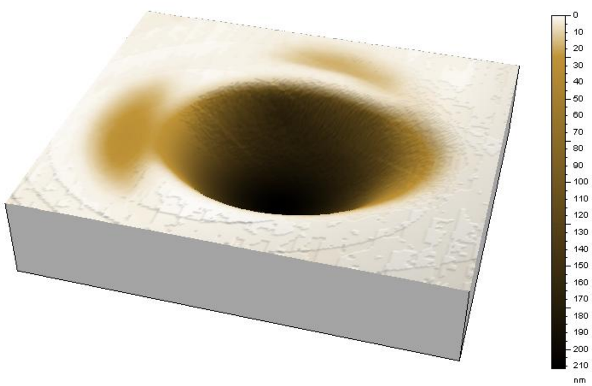
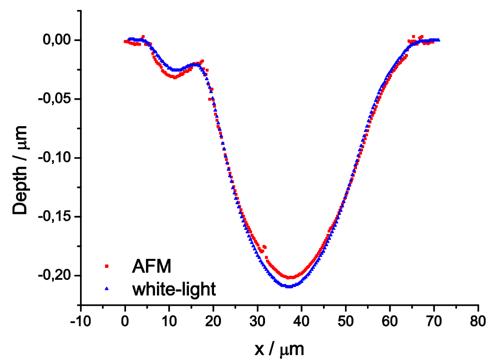


AFM scan



White-light interferometer



Line Scan

- White-light interferometry and AFM scans yield almost identical depth profiles
- Atomic force microscopy provides more high spatial frequency information