AT-WAVELENGTH METROLOGY OF X-RAY OPTICS

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AT-WAVELENGTH (X-RAY) METROLOGY

- INTRODUCTION
- PENCIL BEAM DEFLECTOMETRY
- GRATING INTERFEROMETRY
- HARTMANN SENSING
- SPECKLE-BASED METHODS
- DISCUSSION & CONCLUSION

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AT-WAVELENGTH METROLOGY

Development of X-ray sources (FEL, SR and others...) stimulate progress in optics

- minimize beam wavefront errors caused by optics
- correct incoming wavefront imperfections in view, e.g., of perfect collimation, focusing or otherwise
- diffraction-limit as ultimate goal, dimensions ~ several tens of nanometer down to 1 nm...

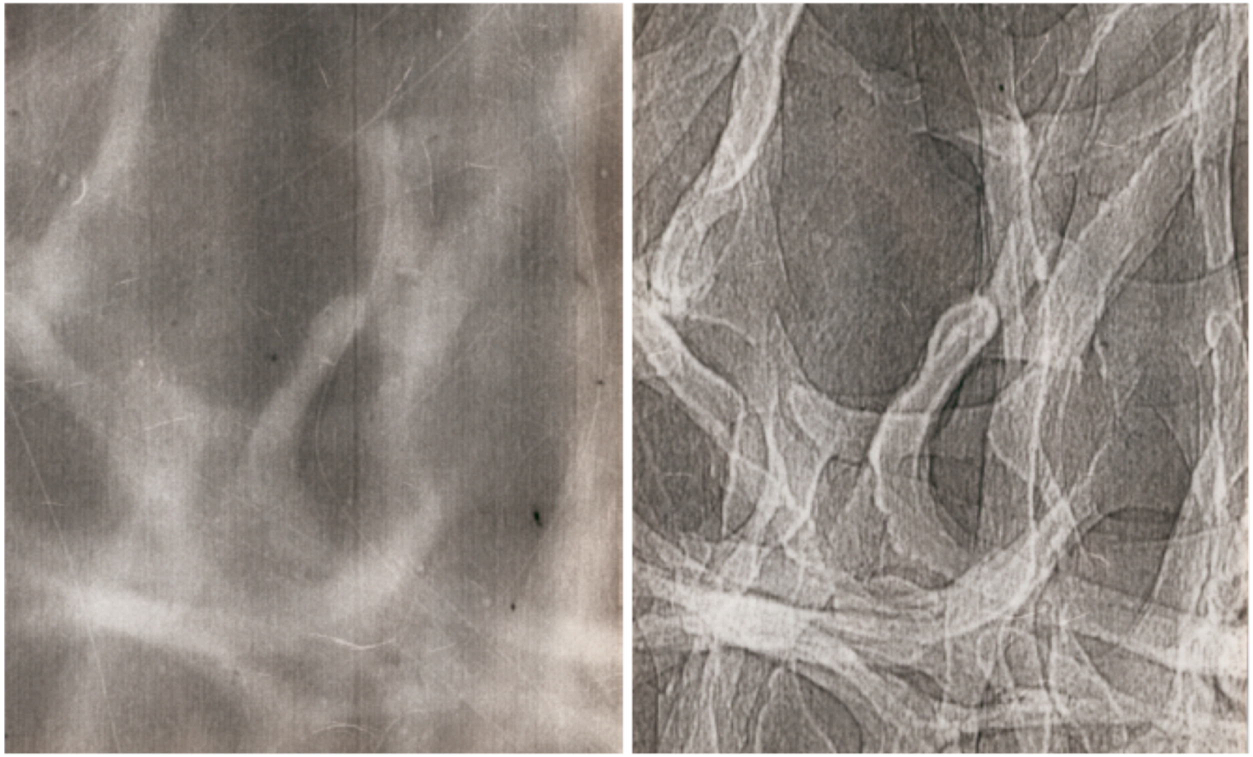
☆ **At-wavelength to monitor active optics or help manufacture optics**

☆ **At-wavelength to account for specificity of interaction with matter in X-XUV optics (coherence and scattering effects with surface and/or volume), as a way to integrate factors difficult to model or that may evolve with time**

- X-ray: short wavelength > precision metrology
- to take advantages of unique properties of X-XUV

Effect of beam propagation

HARD X-RAY PHASE CONTRAST IMAGING

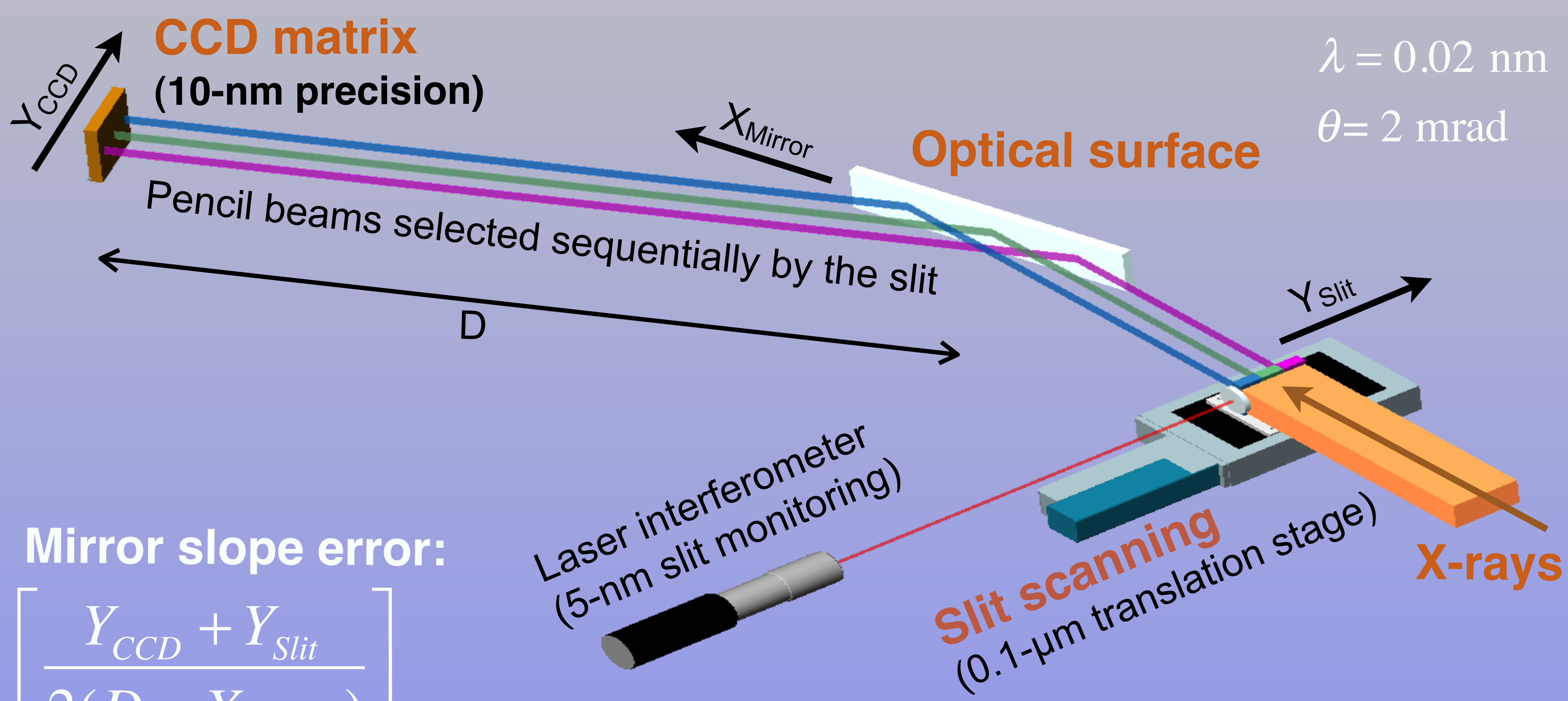


- X-ray images taken at ESRF BM5 (1994)
- Human vertebra with the detector located close and far from the sample

PENCIL BEAM X-RAY DEFLECTOMETRY

XLTP using X-ray SR beam as a wavefront reference

Ref. O. Hignette et al., SPIE Proc. vol. 3152 (1997); Review of Scientific Instruments, 76 (2005)



$\lambda = 0.02$ nm

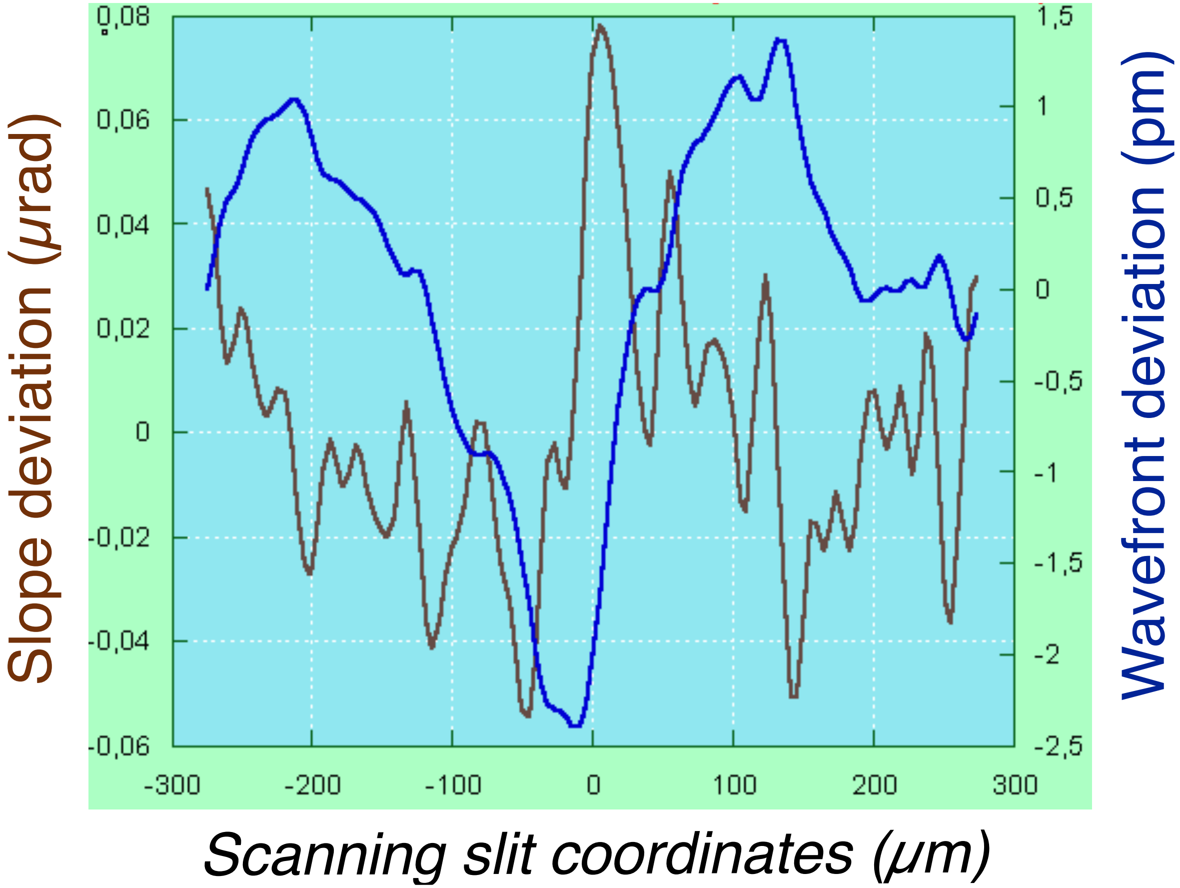
$\theta = 2$ mrad

Mirror slope error:

$$\left[\frac{Y_{CCD}+Y_{Slit}}{2(D-X_{Mirror})}\right]_{\text{linearly detrended}}$$

An X-ray slope error measuring device

- Reference wavefront: deviation from a sphere of radius 42.5 ± 0.1 m

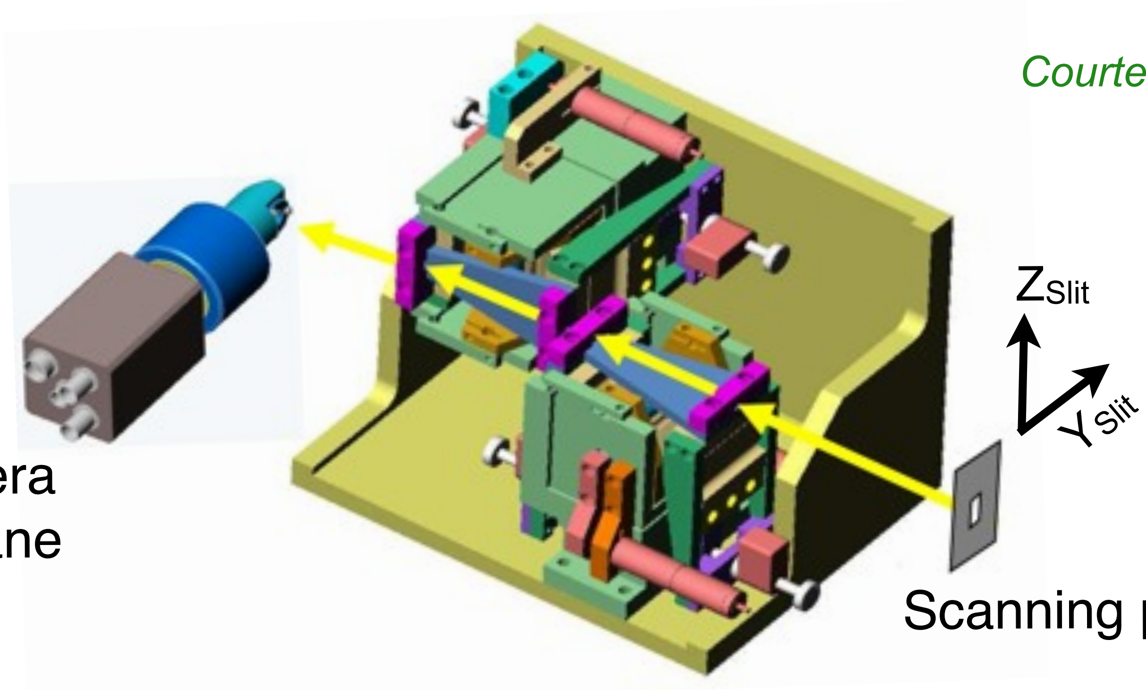


Courtesy: O. Hignette

- Slope standard deviation: 28 nrad (rms)
- Wavefront standard deviation: 0.9 pm (rms) [equiv. $\lambda / 100$]

Dynamical bending optimization of Kirkpatrick-Baez focusing optics

- Combination of two perpendicular off-axis elliptical cylinder mirrors


Courtesy: O. Hignette

CCD camera
in focal plane

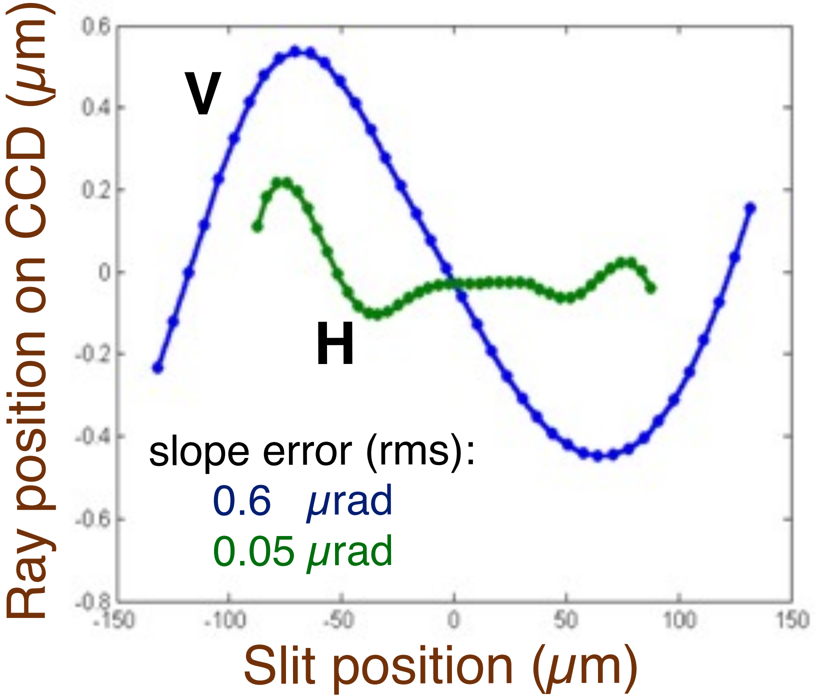
Scanning pinhole

- Goal: a spherical wavefront centered on the focus (CCD location)
- Deviations from ideal case are read sequentially on the X-ray CCD camera as a function of the slit position
- Mirror figure corrected by 2-moment bender based on flexural hinges

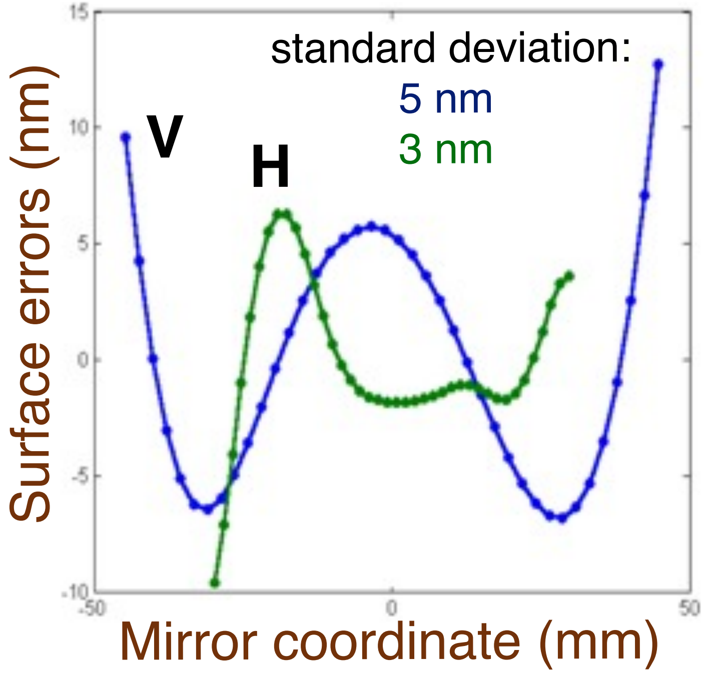
PENCIL BEAM X-RAY DEFLECTOMETRY

- **Interaction matrix** to describe bending requires 3 wavefront measurements (unit displacement on each actuator) & linear procedure

Camera reading after optimization



Mirror shape errors (slope integration)



- **Precision of figure metrology**

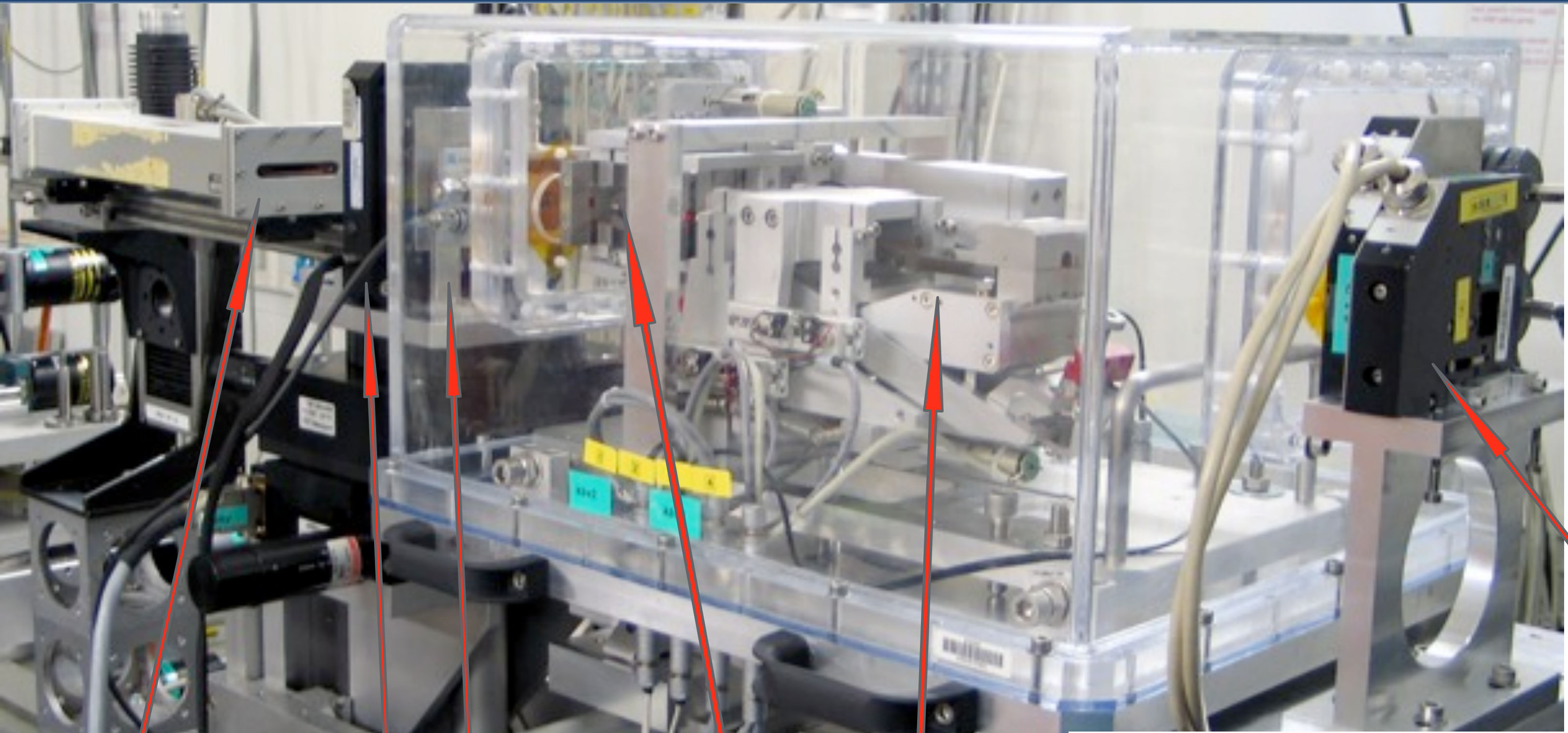
Courtesy: O. Hignette

on positioning: 20 nm

on shape: 0.25 nm on 100 mm mirror

Precision consistent with diffraction-limited operation

EXAFS MEASUREMENTS USING WIDE-BAND MULTILAYER KB OPTICS



Beam direction

sampling slits

I_1 ion chamber

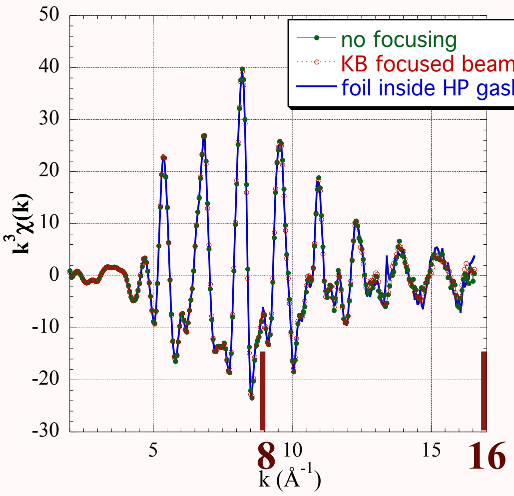
y-z piezo stages

I_0 ion chamber

horizontal foc. mirror

vertical foc. mirror

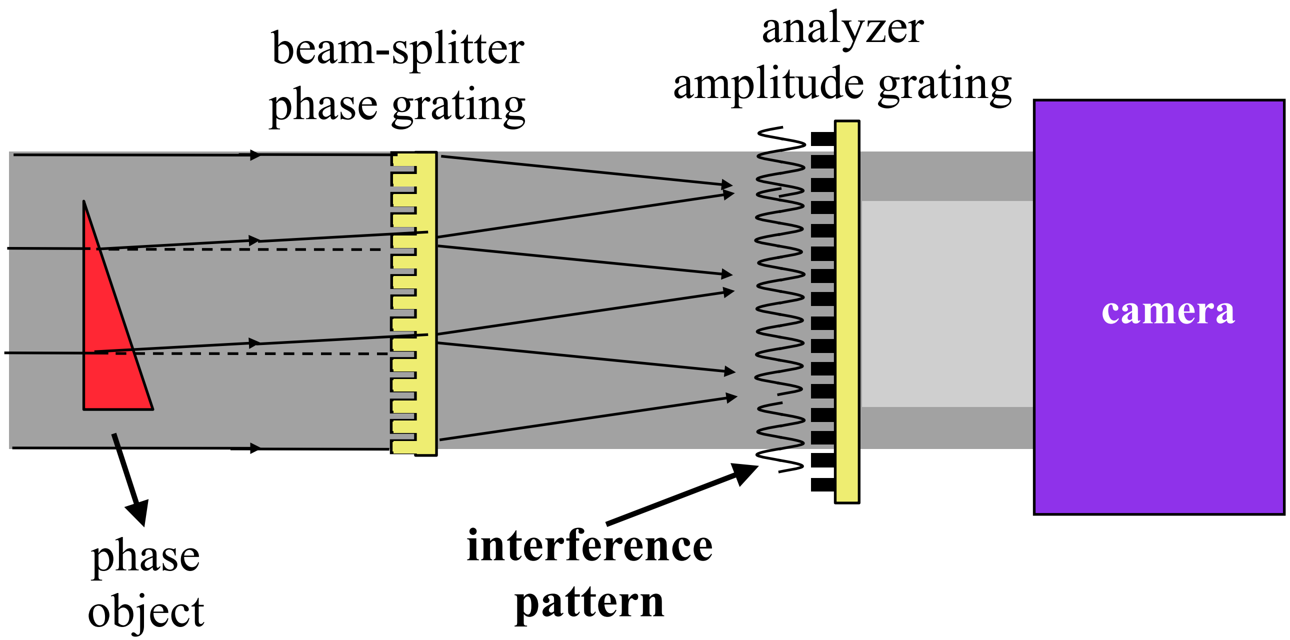
E. Ziegler, G. Aquilanti, O. Mathon, S. de Panfilis, P. van Vaerenbergh, X-Ray Spectrometry (2009)



2 x 2 µm at BM29

Fe K-edge focused vs unfocused

GRATING INTERFEROMETRY



beam-splitter phase grating

analyzer amplitude grating

camera

phase object

interference pattern

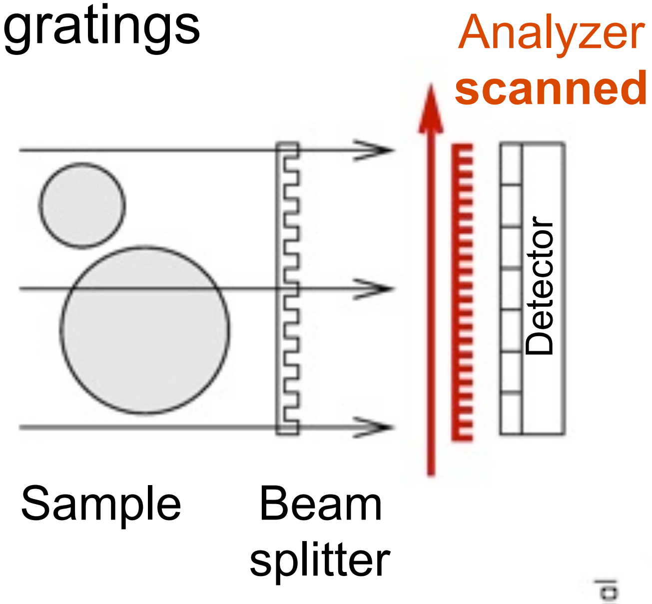
Si grating (4 μm pitch)

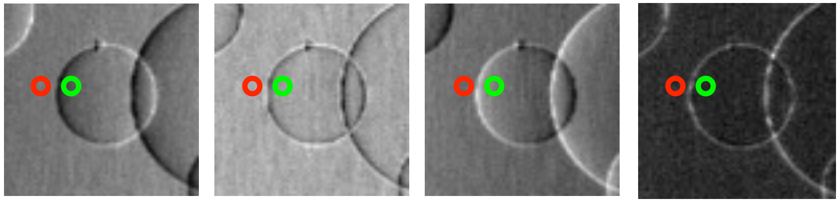
Au grating (2 μm pitch)

- presence of object distorts wavefront > deflects the beam > local displacement of the fringes > different intensity at the detector
- intensity correlated to first derivative of wavefront phase > differential phase contrast
- phase-stepping interferometry allows to separate absorption from phase: phase gradient image and transmission signal

Ref. T. Weitkamp et al. Optics Express, 13 (2005)

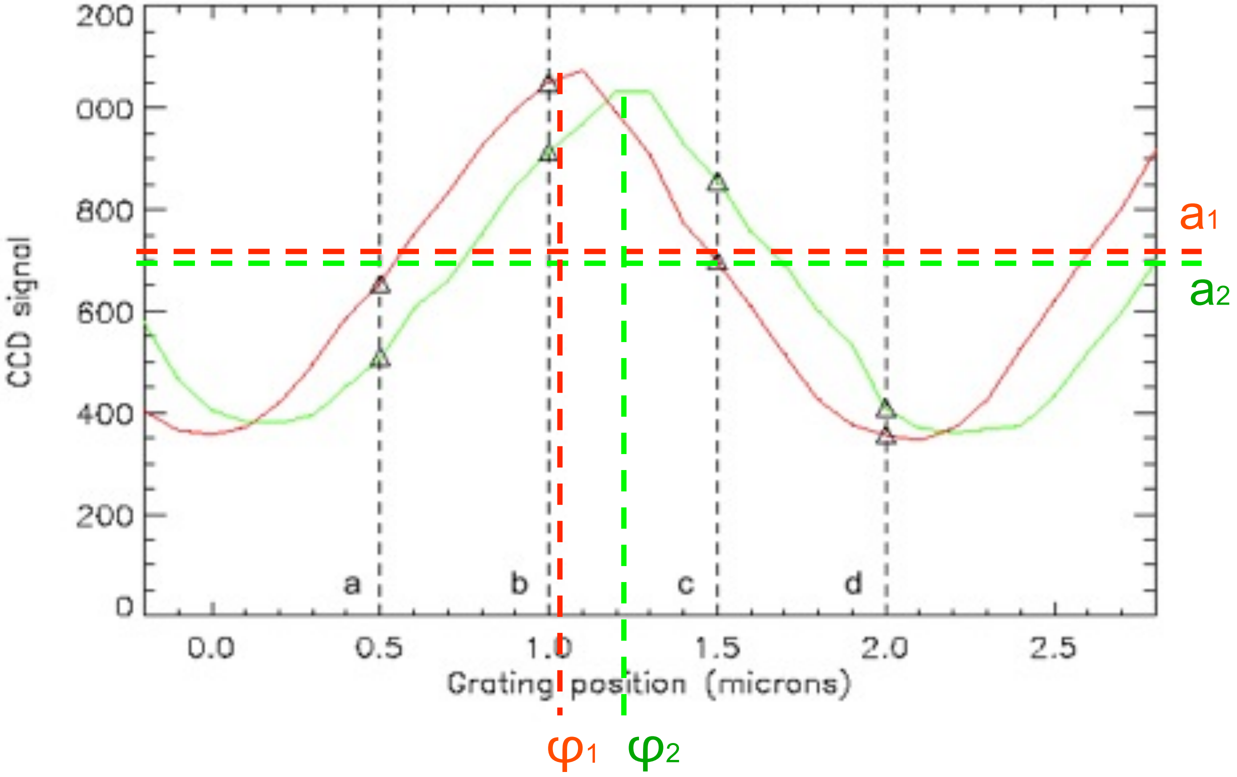
- Phase stepping interferometry: linear transverse scan of one of the gratings

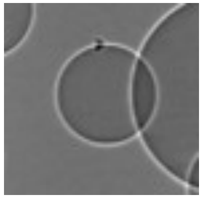




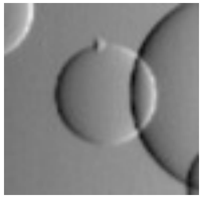
Ref. T. Weitkamp et al. Optics Express, 13 (2005)

Intensity oscillates





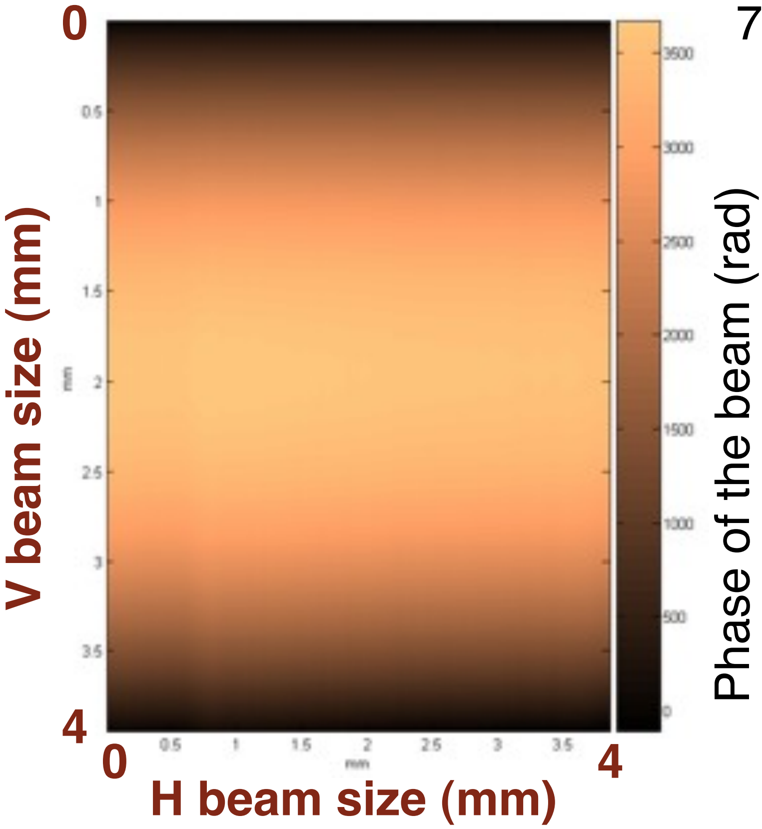
a_{ij}



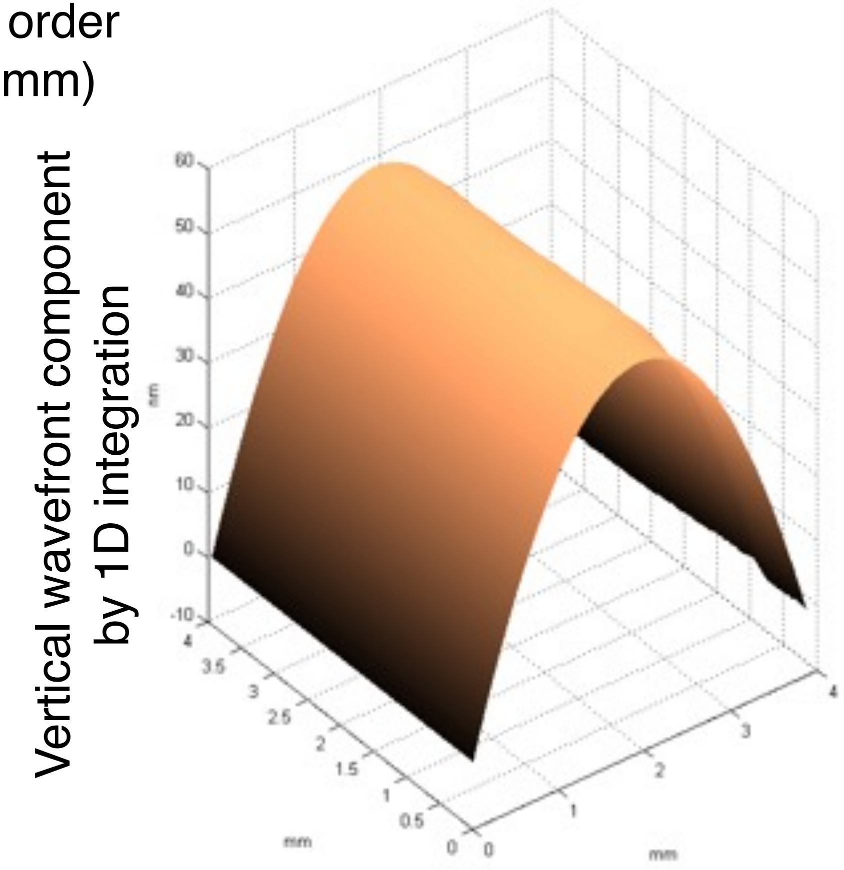
φ_{ij}

GRATING INTERFEROMETRY

Phase stepping interferometry: measure of BM5 beam wavefront



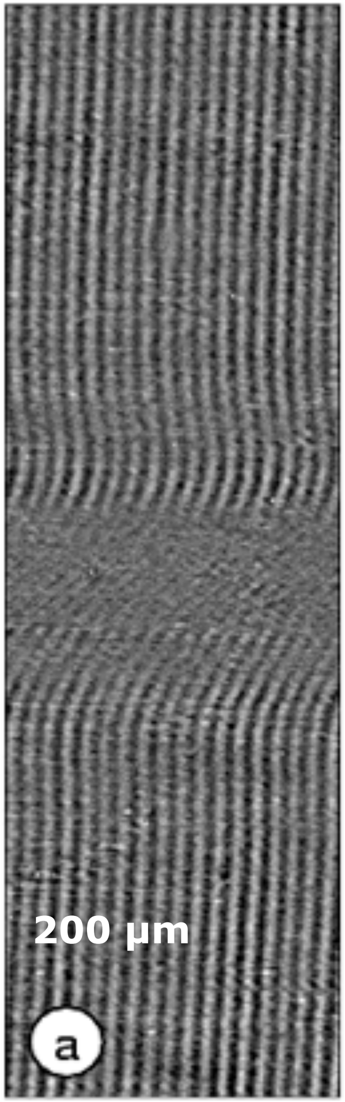
7th Talbot order
(d= 163 mm)



g_2: pitch 2nd grating; d: inter-grating distance; φ : fringe phase in the image

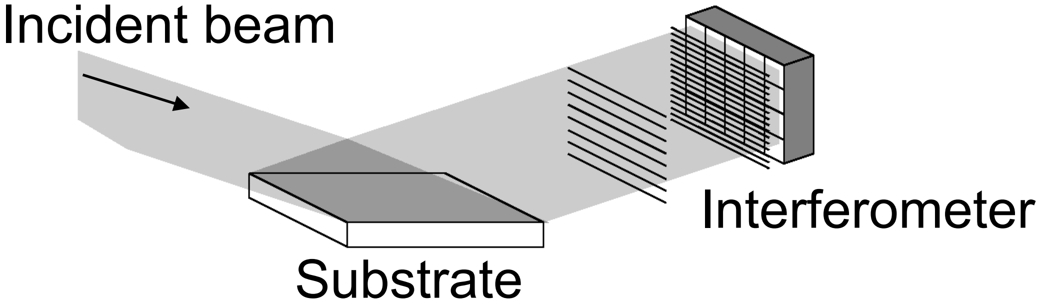
Phase gradient in x-direction: $\frac{\partial\Phi(x,y)}{\partial x} = \frac{g_2}{\lambda d}\varphi(x,y)$ **> Radius$_V$: 37.203 m**

GRATING INTERFEROMETRY

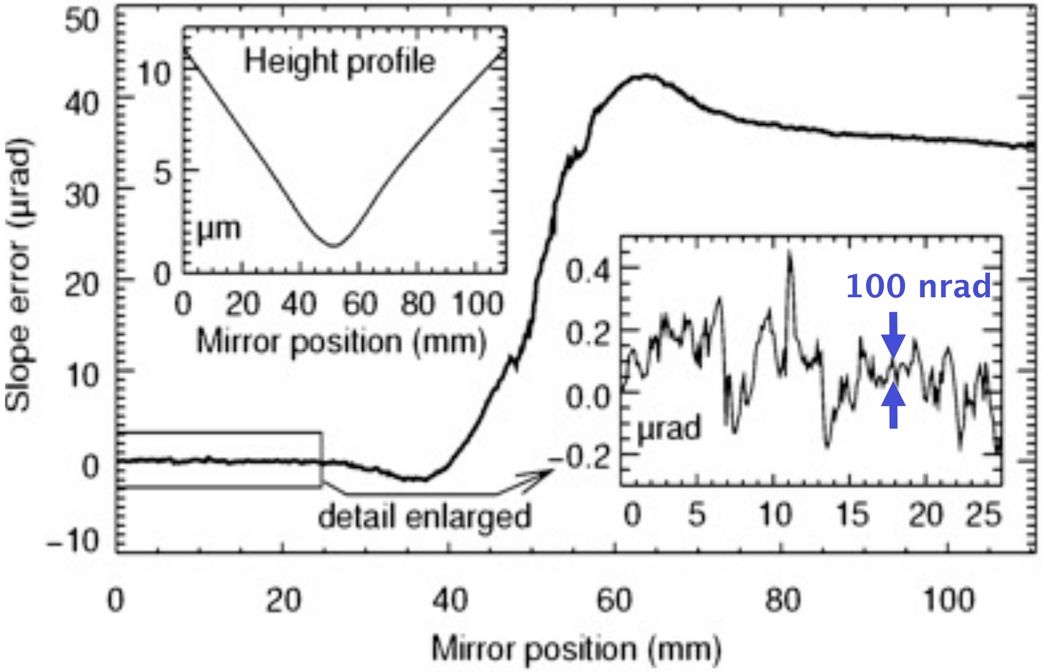


detected interferogram

analyze main Fourier component



W/Si multilayer, 13.4 mrad, E: 12.4 keV

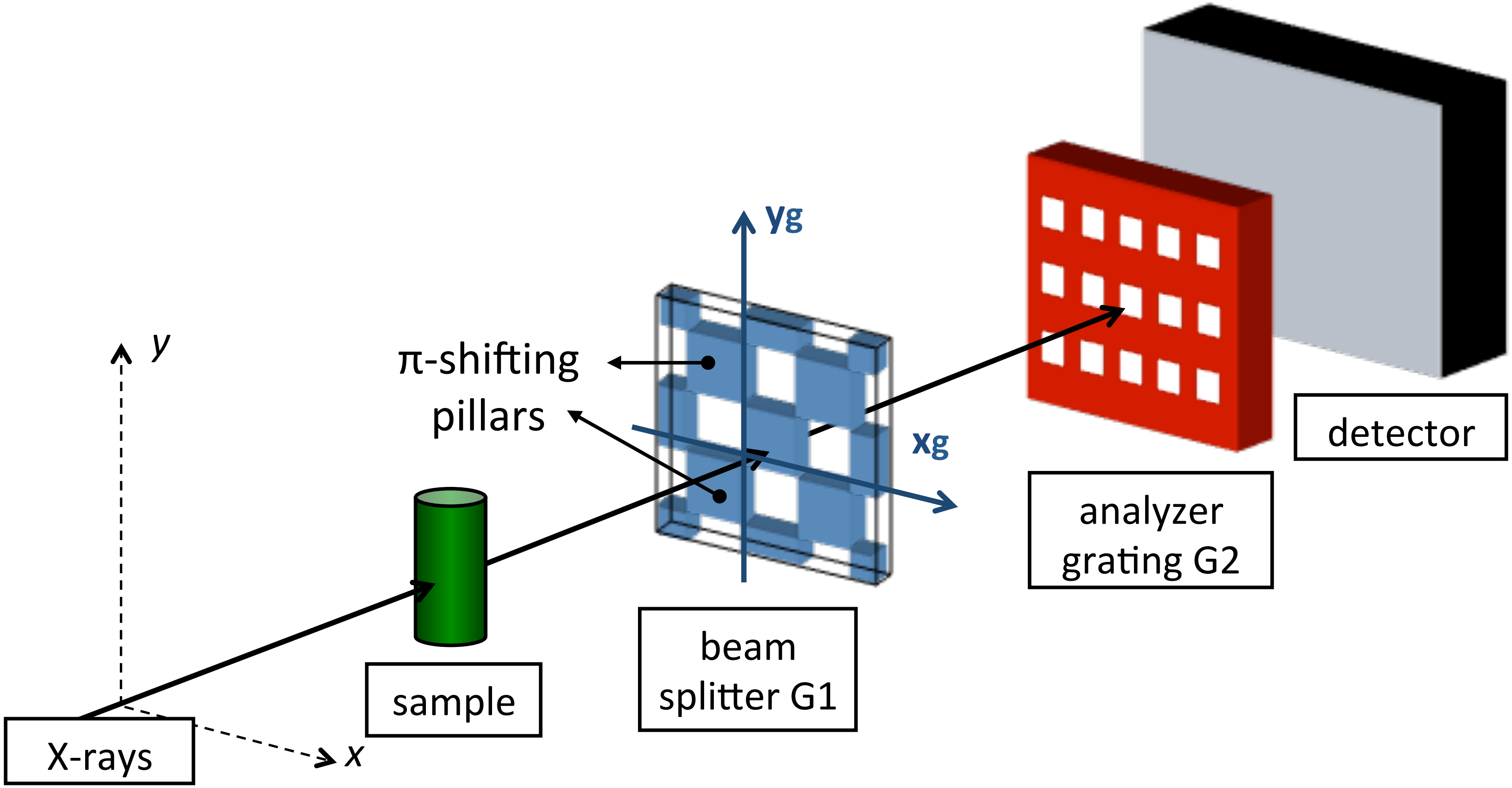


Accuracy better than 0.1 *µrad*

Ref. T. Weitkamp et al., APL 86 (2005)

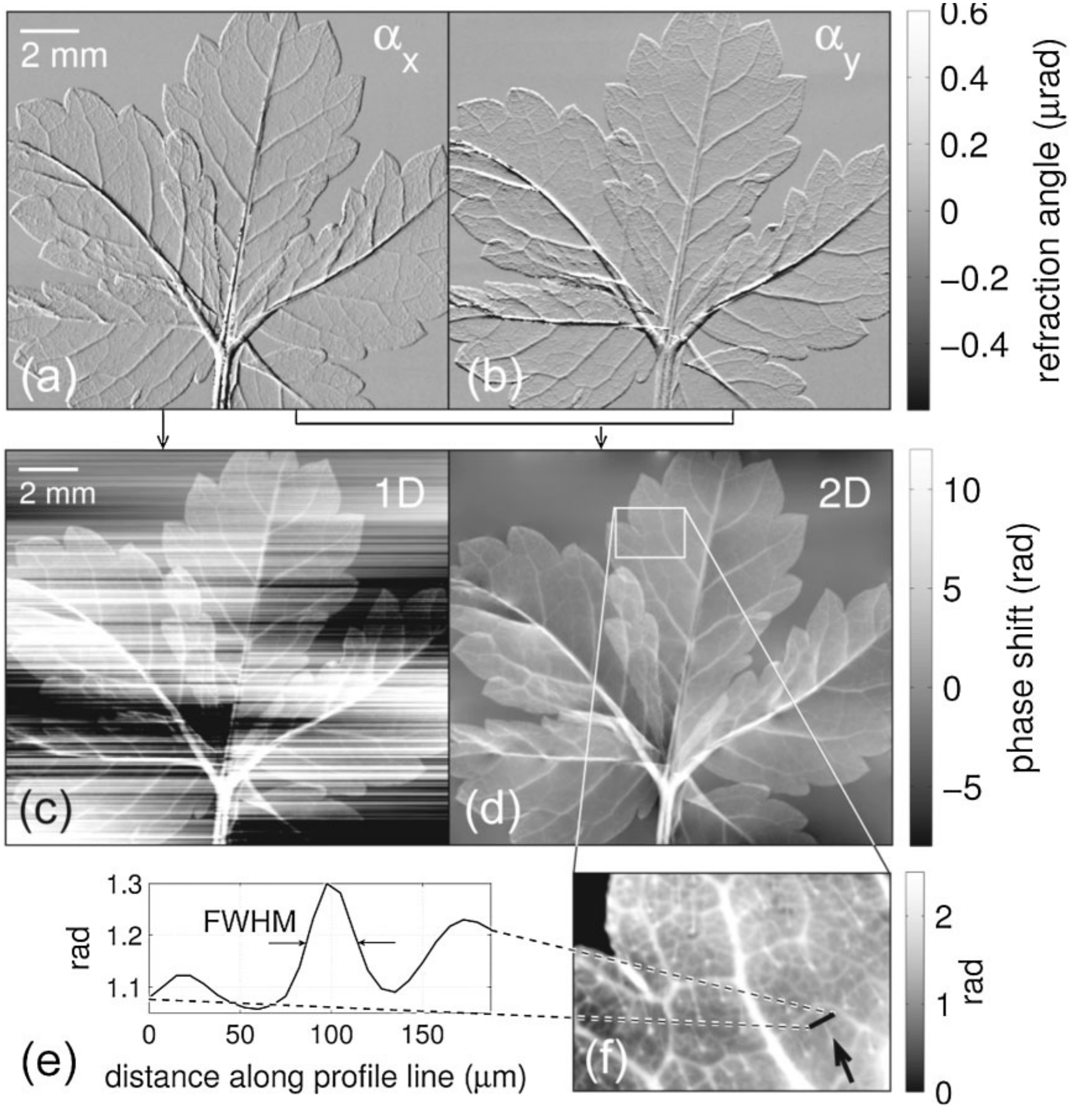
2D-GRATING INTERFEROMETER

- Scattering signal and phase derivative in x and y directions
- Helps overcoming limitations due to presence of a blind direction

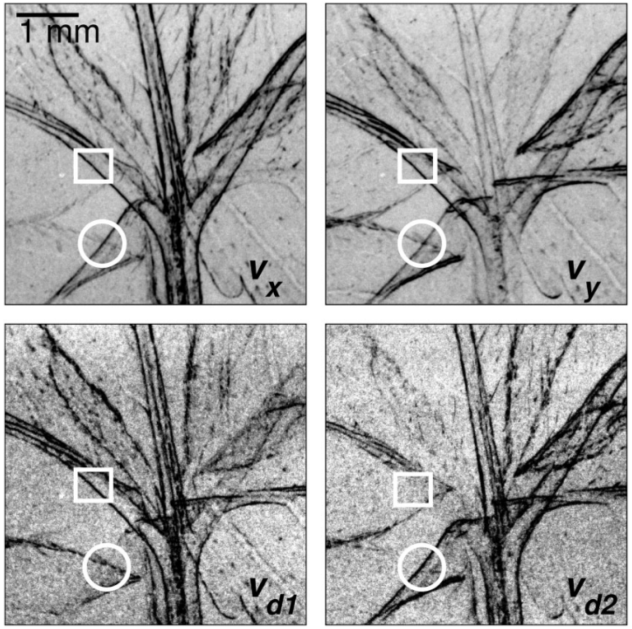


Ref. I. Zanette, T. Weitkamp, T. Donath, S. Rutishauser, C. David, PRL, 105 (2010)

2D-GRATING INTERFEROMETER



Scattering images

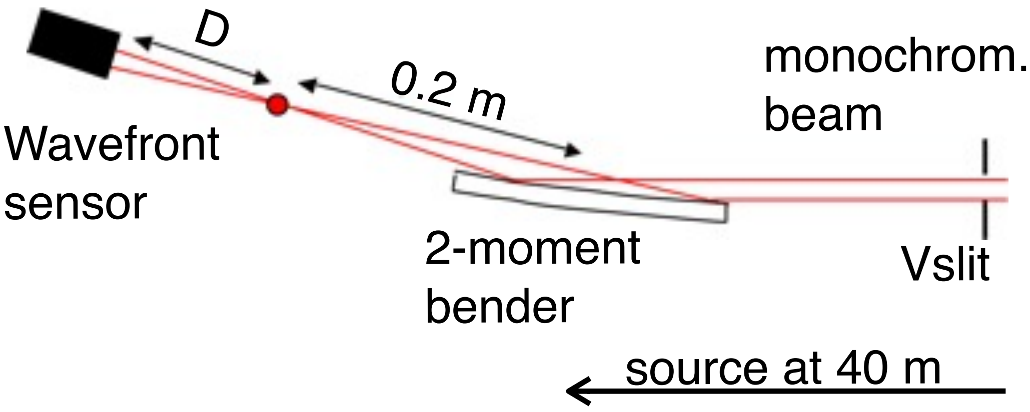


Ref. I. Zanette, T. Weitkamp, T. Donath, S. Rutishauser, C. David, PRL, 105 (2010)

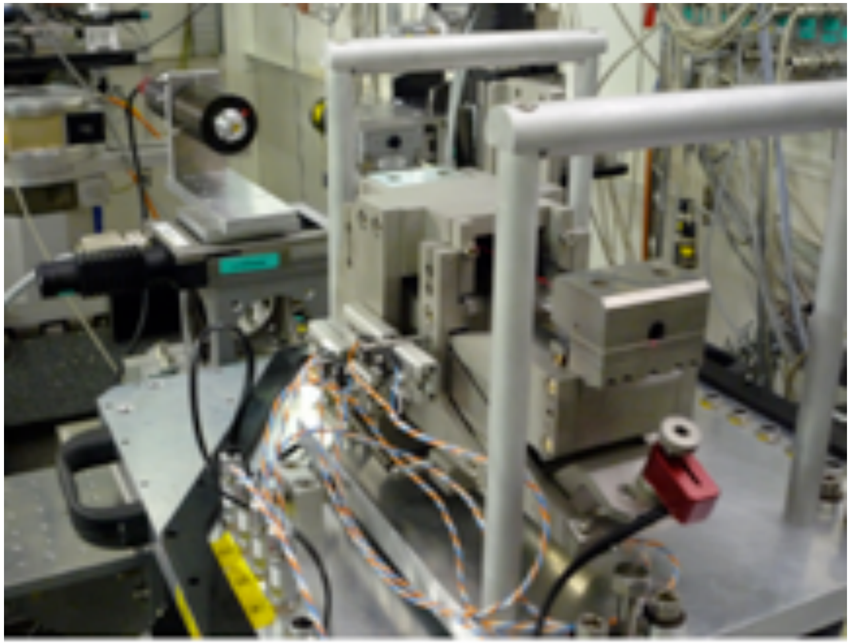
HARTMANN SENSING

- **Wavefront sensing and adaptive optics in X-ray range**
  - Schack-Hartmann wavefront sensor from Imagine Optic (HASO)
  - Automatic KB alignment already achieved using soft X-rays (3 keV)

    Ref. P. Mercère, M. Idir, T. Moreno, G. Cauchon, G. Dovillaire, X. Levecq, L. Couvet, S. Bucourt, P. Zeitoun, Optics Letters, 31, 2 (2006).
  - Hartmann grid for hard X-rays (E= 14 keV)



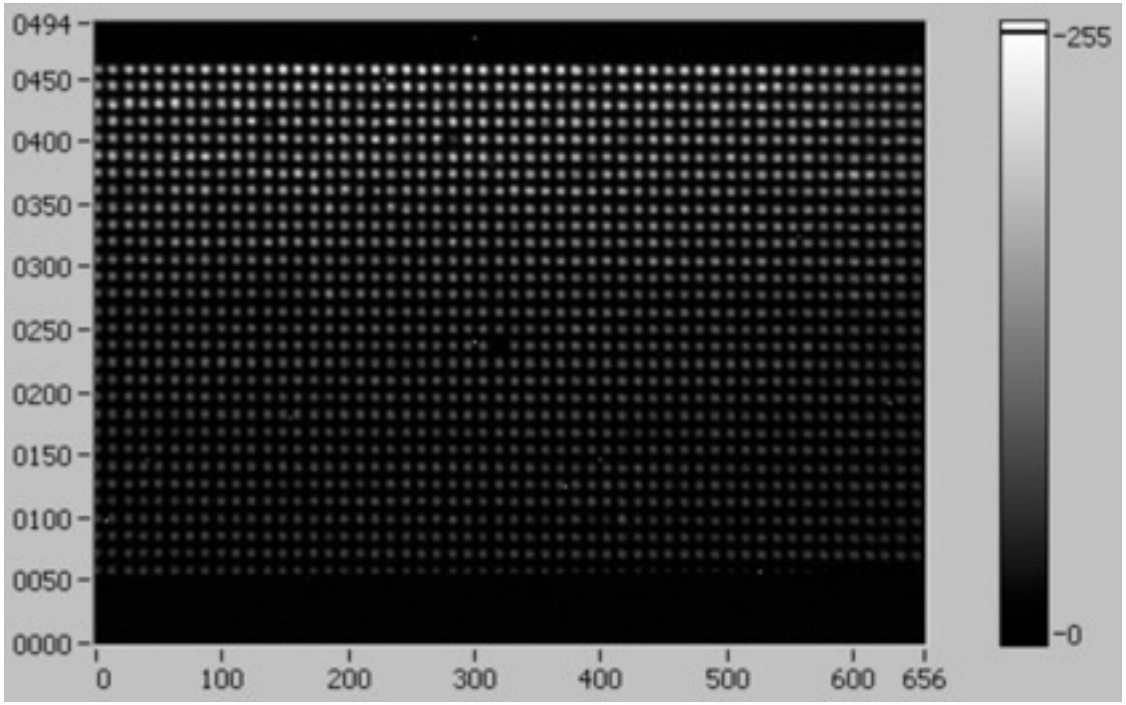
Multilayer-coated mirror, 170 mm, 8.1 mrad at 14 keV, trapezoidal shape



HARTMANN SENSING

- access to wavefront local slopes (derivative) by sampling the incoming beam through a Hartmann grid
  - each sub-aperture providing its own spot on a CCD camera, the sensor delivers a set of {x,y} spot centroid positions or Hartmann pattern

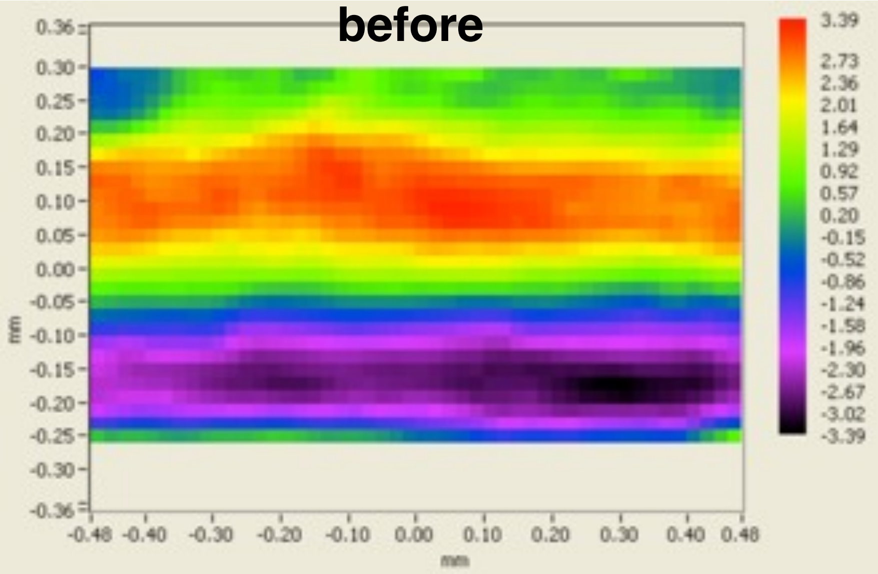
Vslit= 1.15 mm
L_{mirror}= 142 mm
D= 0.10 m
expo time: 1.3 s

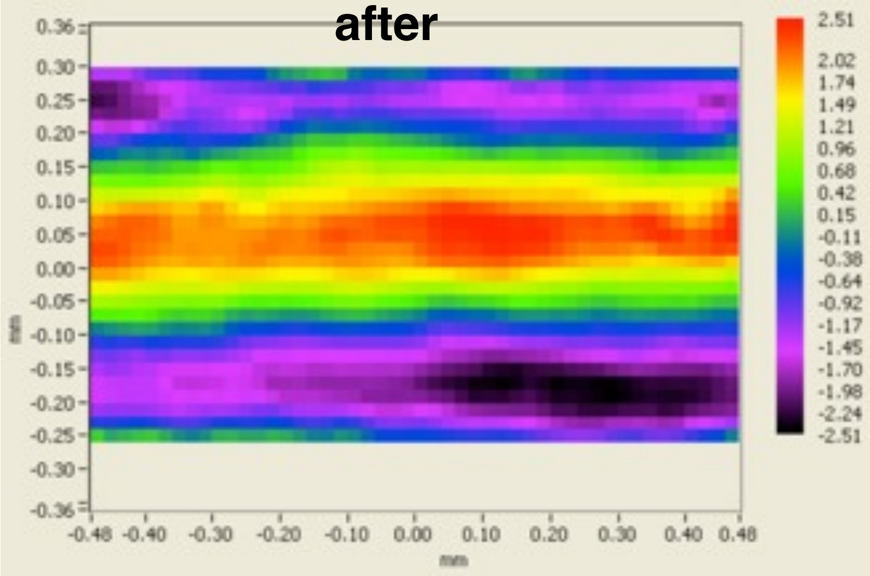


  - wavefront obtained by integration of the local slope, quality depending on the number of sub-apertures (higher is better but must avoid overlapping)

HARTMANN SENSING

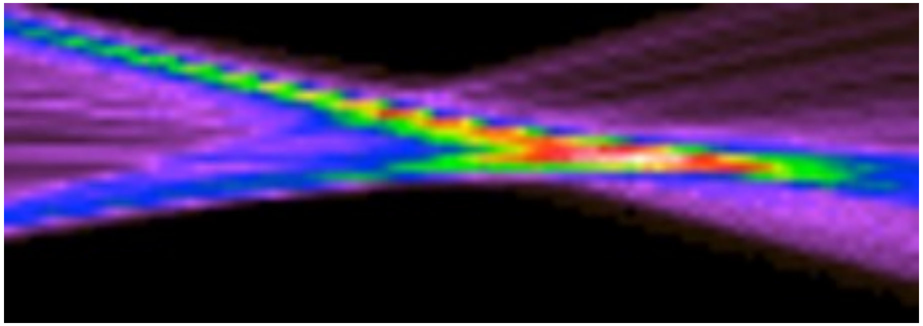
Vslit= 1.15 mm



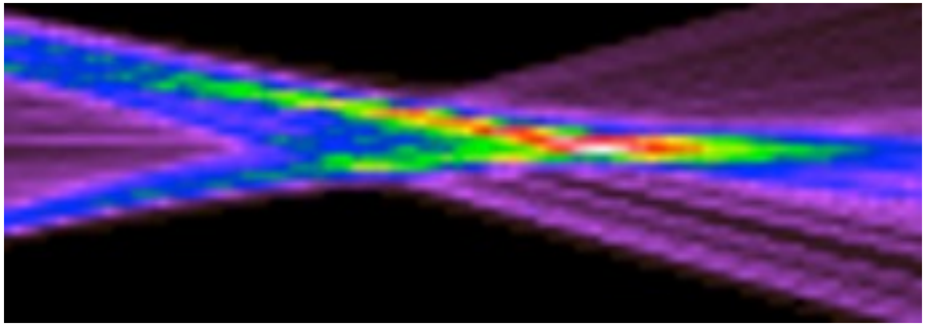


Residual wavefront allows to calculate intensity profile at the focus

Before correction:
2.0 nm rms, 6.8 nm PV

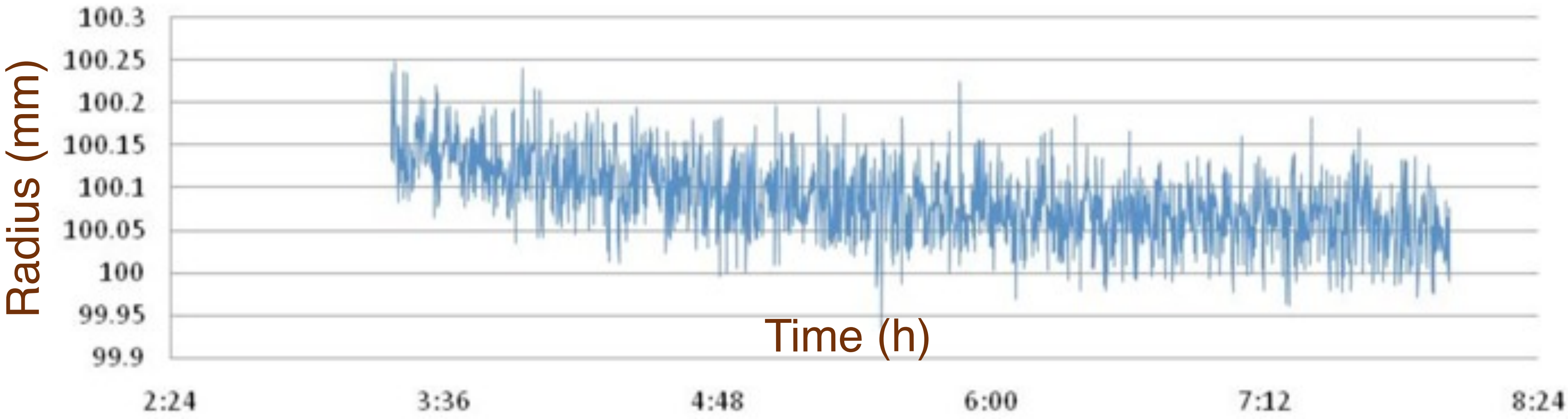


After correction:
1.4 nm rms, 5.0 nm PV



HARTMANN SENSING

- results on reflected wavefront expected to be better by liberating constraint on the tilt
- overnight monitoring of the wavefront sagittal radius of curvature:



Fluctuation ~ 0.1 mm corresponding to wavefront change ~ 0.3 nm

X-RAY SPECKLE

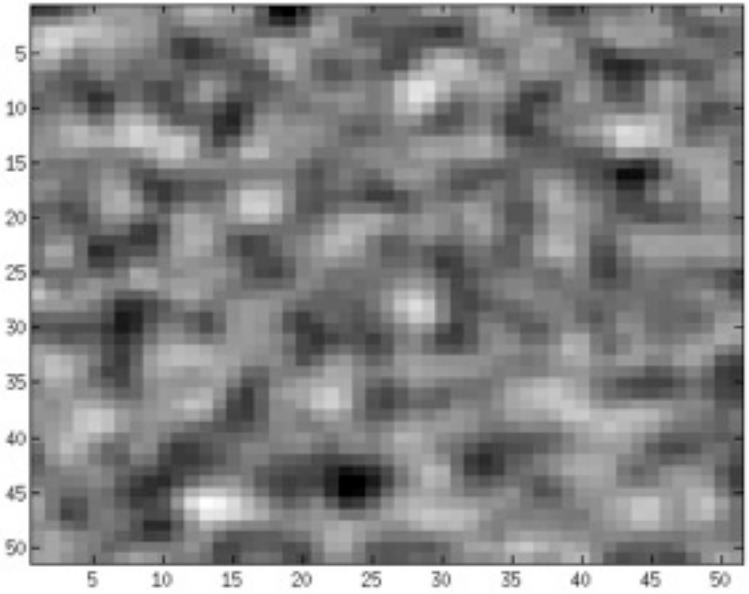
- X-ray speckle: random intensity pattern created by irradiation of a scattering object with a partially coherent light
- Near-field regime: speckle grains do not change in size and shape over a distance $z_{NF} \sim dD^2 / \lambda$

d: speckle grain size
D: transverse coherence

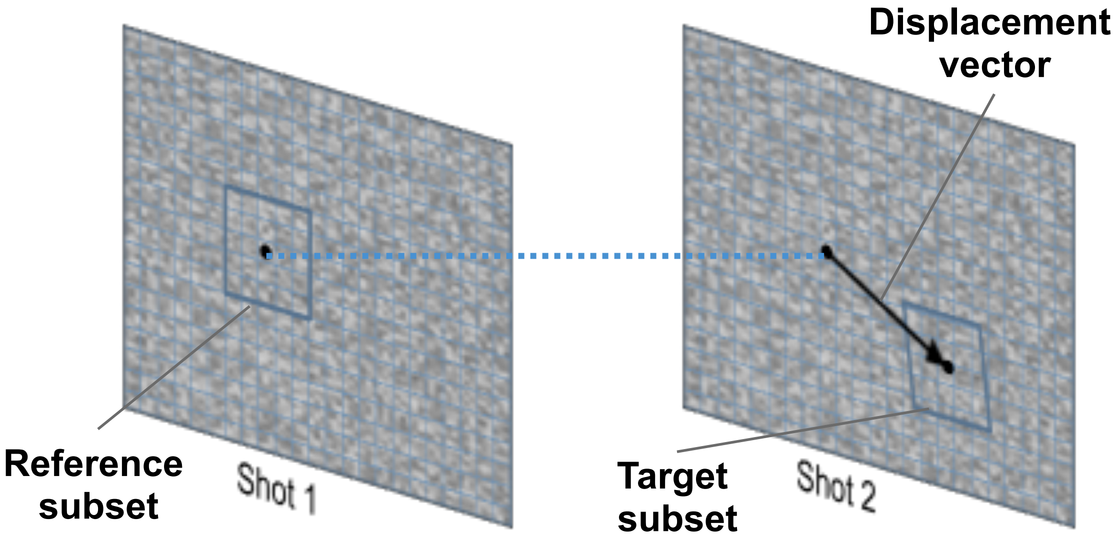
Ref. R. Cerbino, L. Peverini, M. Potenza, A. Robert, P. Bösecke, M. Giglio, Nature Physics 4 (2008)

- Generation of a static speckle pattern: solid membrane containing phase objects (e.g., cellulose)

ESRF BM5 beamline: speckle pattern behind scattering membrane located downstream crystal monochromator beam and Be windows



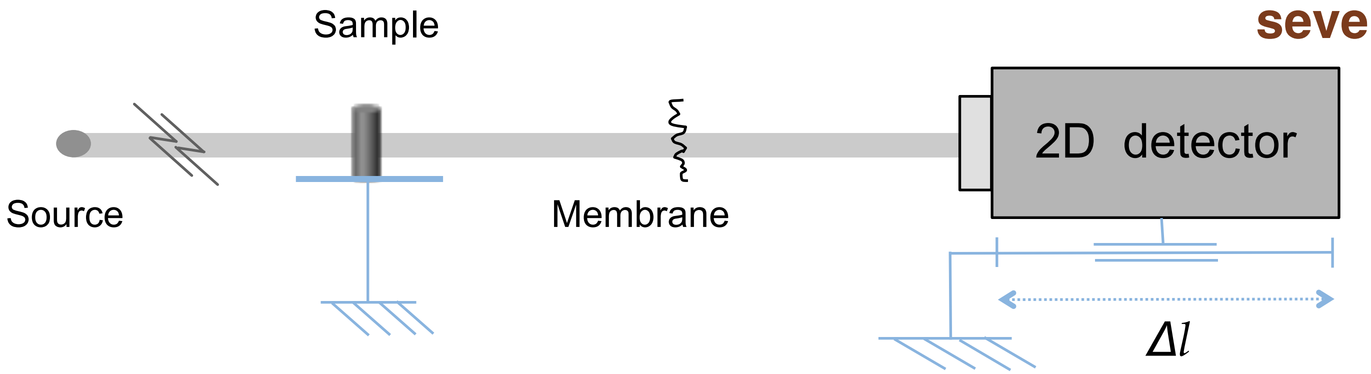
Tracking the speckle pattern using digital image correlation



Subset tracking between images with 0.01 pixel accuracy

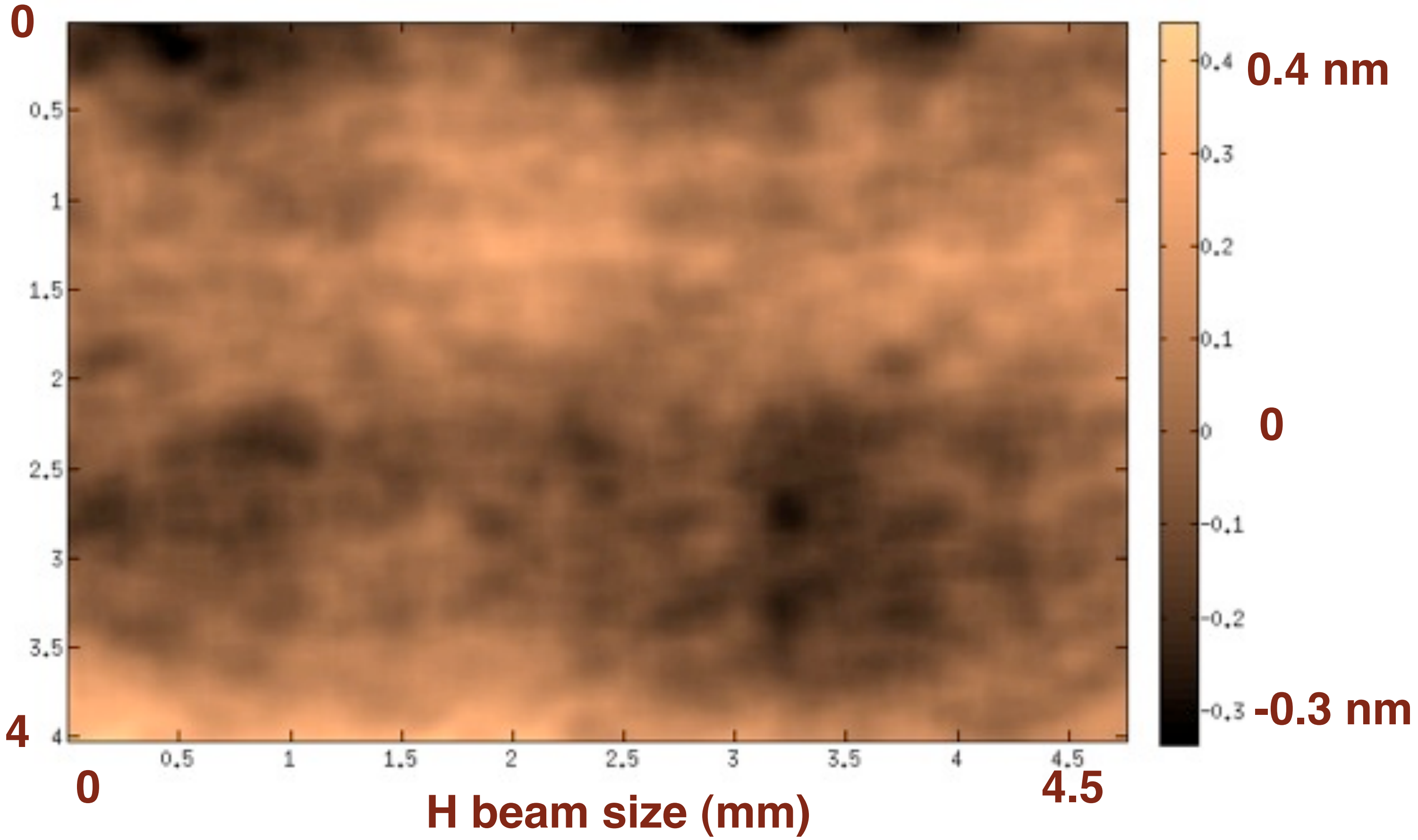
Absolute configuration

Measurement of the wavefront state at several detector planes



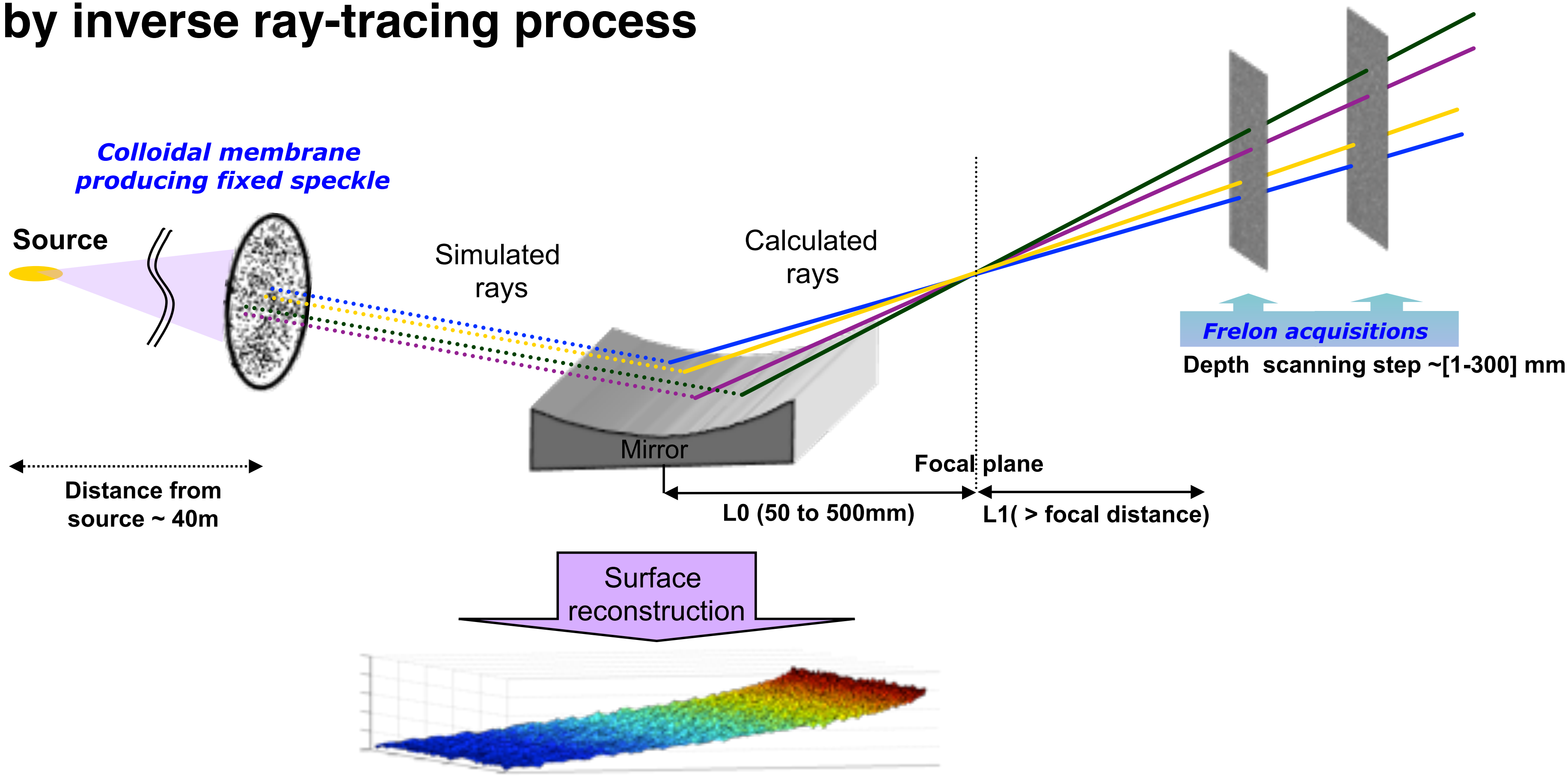
2D WAVEFRONT CHARACTERIZATION

Deviation from ellipsoid (in nm) E: 17 keV, two images distant 500 mm



- **Wavefront radius: R_V= 37.43 m, R_H= 40.37 m with picometer precision**
- **Spatial resolution: 5.8 *μ*m over 4 mm x 4.6 mm**
- **Precision on slope: better than 0.1 *μ*rad**

☆ 2D reconstruction of the mirror surface by inverse ray-tracing process



PhD thesis of Sebastien Berujon

CONCLUSION

☆ **At wavelength metrology:**

- easier if end user/application based at large research facility source
- shearing interferometry used at laboratory source *(Röntgen award 2010)*
- speckle tracking: simplicity of the instrumentation *(work in progress)*

☆ **In-situ at-wavelength metrology** to enable accurate measurements on:

- beamline optical elements
- mirror figure correction (active optics or mirror surface figuring)
  - out-of-focus metrology desired (user experiments and routine performance control, on line mirror figuring,)
  - mirror figuring: surface profile needed

CONCLUSION

- ☆ **Precision on slope error can reach 0.1 to 0.03 μrad**
- ☆ **Limits of some at-wavelength methods**
  - sampling limits with short mirrors or viewed at small angle (e.g., hard x-rays on uncoated mirror surface)
  - 2D observation vs one direction at a time
  - shearing interferometry: strongly curved surfaces
  - XST: minimum curvature to benefit from beam magnification and gain sensitivity
- ☆ **Complementarity with other techniques** (calibration, limited access to X-XUV...)
  - access to NOM, LTP, stitching interferometry... is important