MARX

Miroirs Actifs Rayons X

pour micro et nanofocalisation

X-ray Active Optics for micro and nanofocalisation

Outline

<u>Goal of the MARX Project</u> :

- To develop an X-ray active mirrors for micro or nano focalisation

1st part of the talk

- To develop at wavelength an in situ alignment system

2nd part part of the talk

- To validate the potential of X-ray active mirrors (for micro and nano focalisation)

Still in progress

MARX PROJECT Team and funding

- **Partners**
  - SOLEIL - project management and experimentation
  - ISP SYSTEM - development of the active mirror
  - IMAGINE OPTIC – development of wave front sensor
- **Finances**
  - 50% from the ANR (Agence Nationale pour la Recherche)
  - 50% partners financing

MARX main GOALS

– Elliptic shape error less than 0.5 µrad RMS
– Focal distance 300 to 350 mm
– High range of elliptic shapes
– Possibility to correct residual polishing defaults of the mirror
– Possibility to correct aberrations from the optical system

Active optics = Magic Mirror

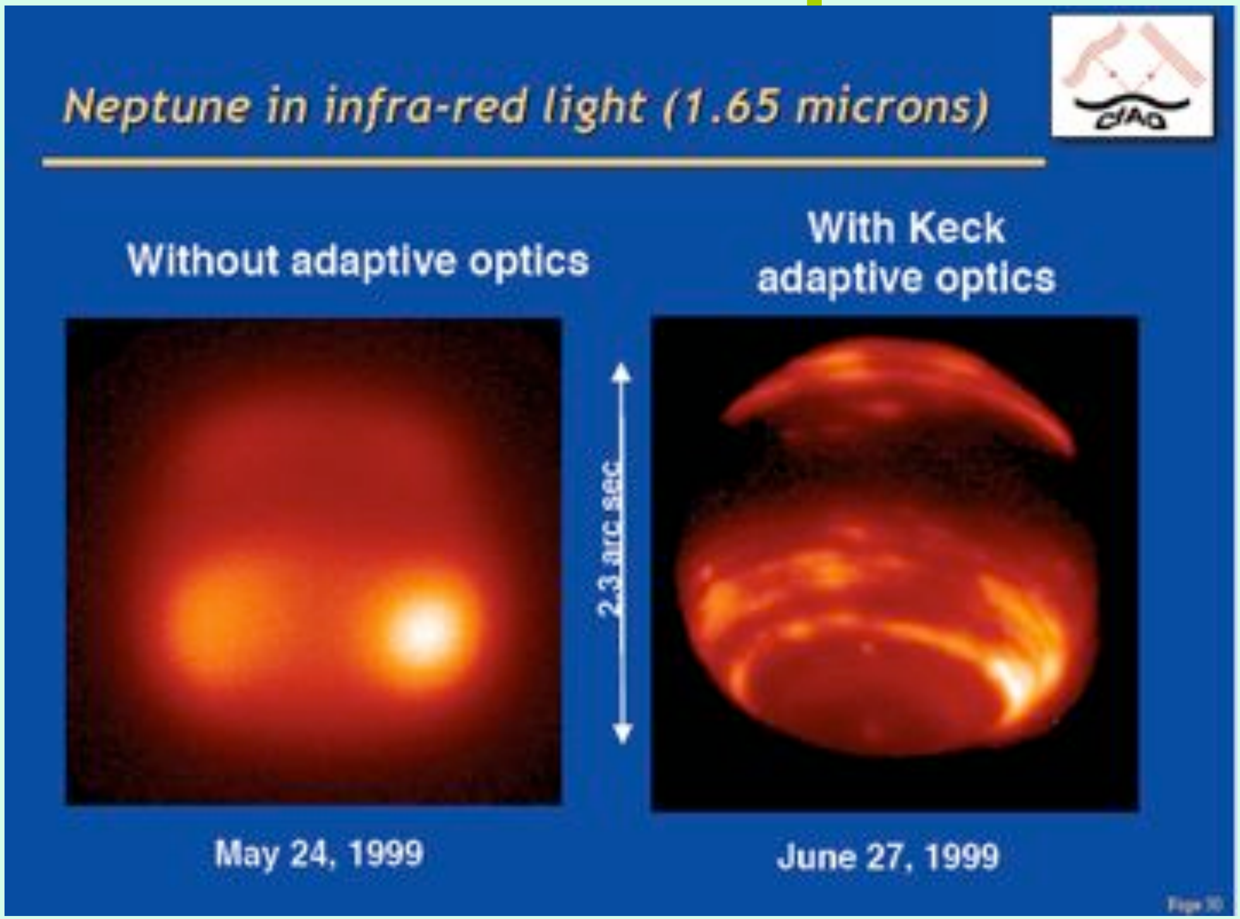
25 years old

45 years old

Adaptive mirrors is the solution

Active optics = Magic Mirror

Active optics = Magic Mirror true example

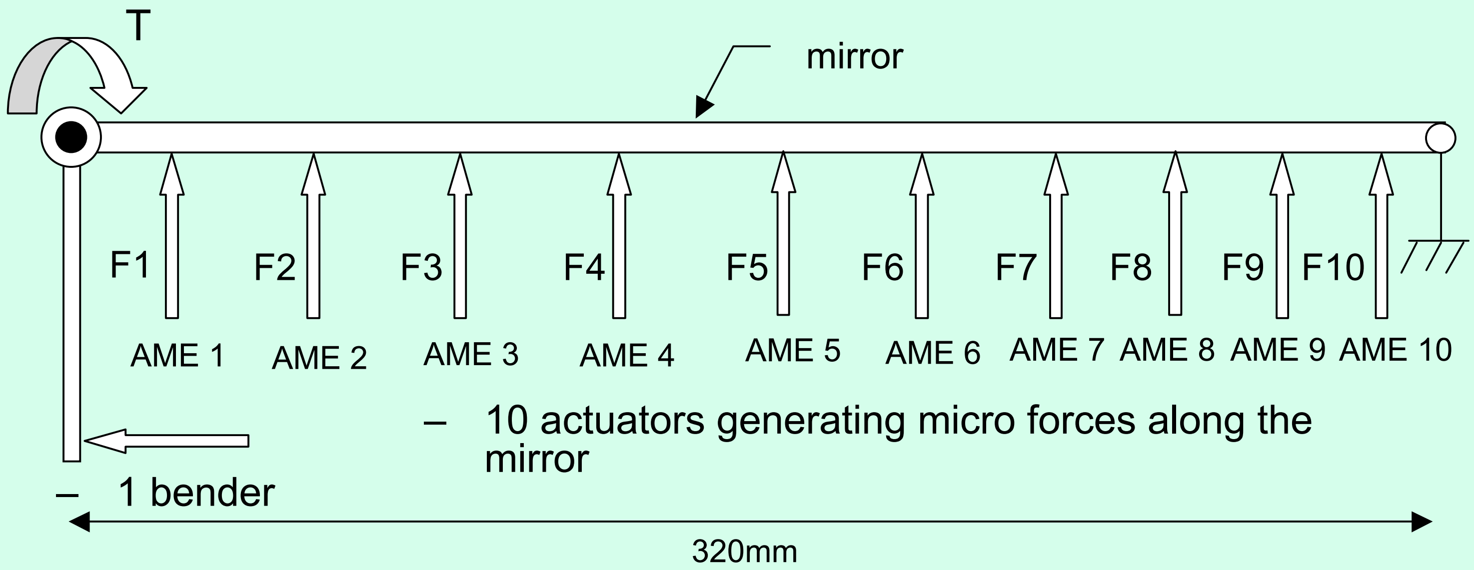


We can win a lot from the Astrophysics research and expertise in adaptive optics and wavefront analysis

MARX
1st Part
Active mirror

PRINCIPLE OF ACTIVE MIRROR

- The design of MARX permits to obtain naturally an elliptic shape with only 1 bender
- The AME actuators apply correction strengths to the initial form in order to obtain best focalisation and reduce the optical aberrations;
- Mirror characteristics:
  - Dimensions : 350x50x8mm
  - Material : Silicium
- The ISP SYSTEM original concept has been recently patented

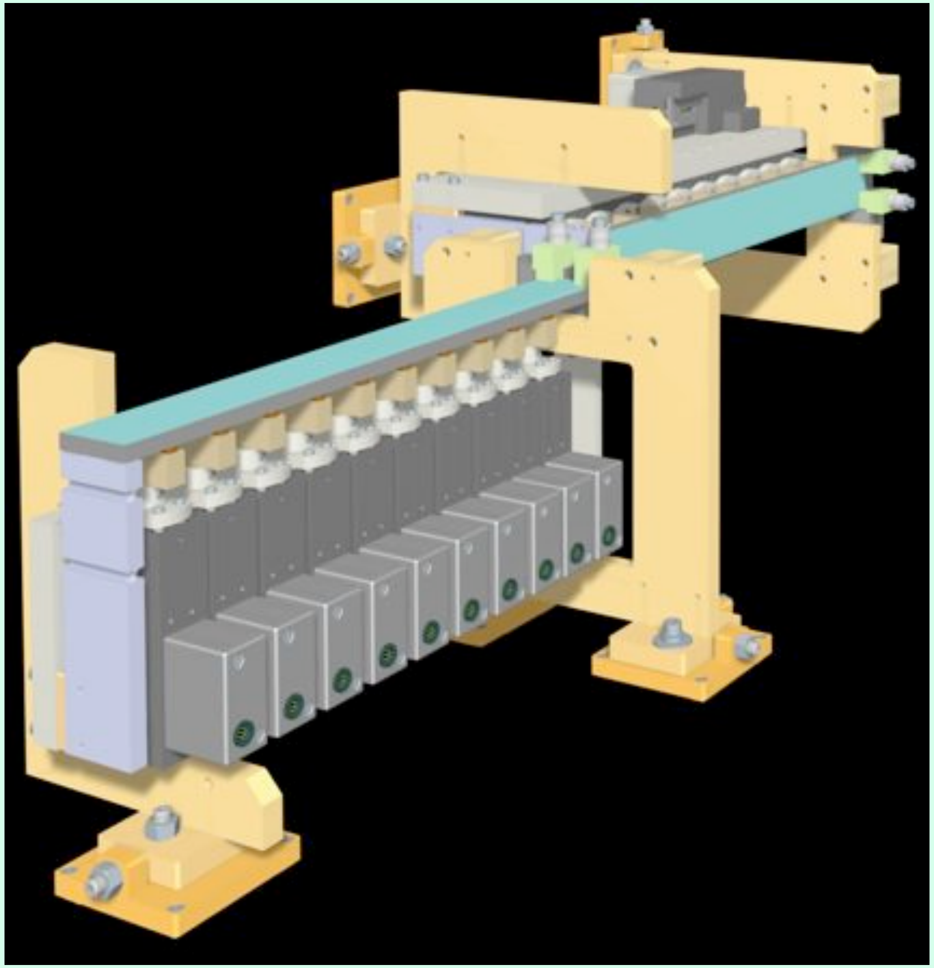


ISP SYSTEM DESIGN

- **<u>Active Kirckpatrick-Baez mirrors system :</u>**

  2 mirrors activated by

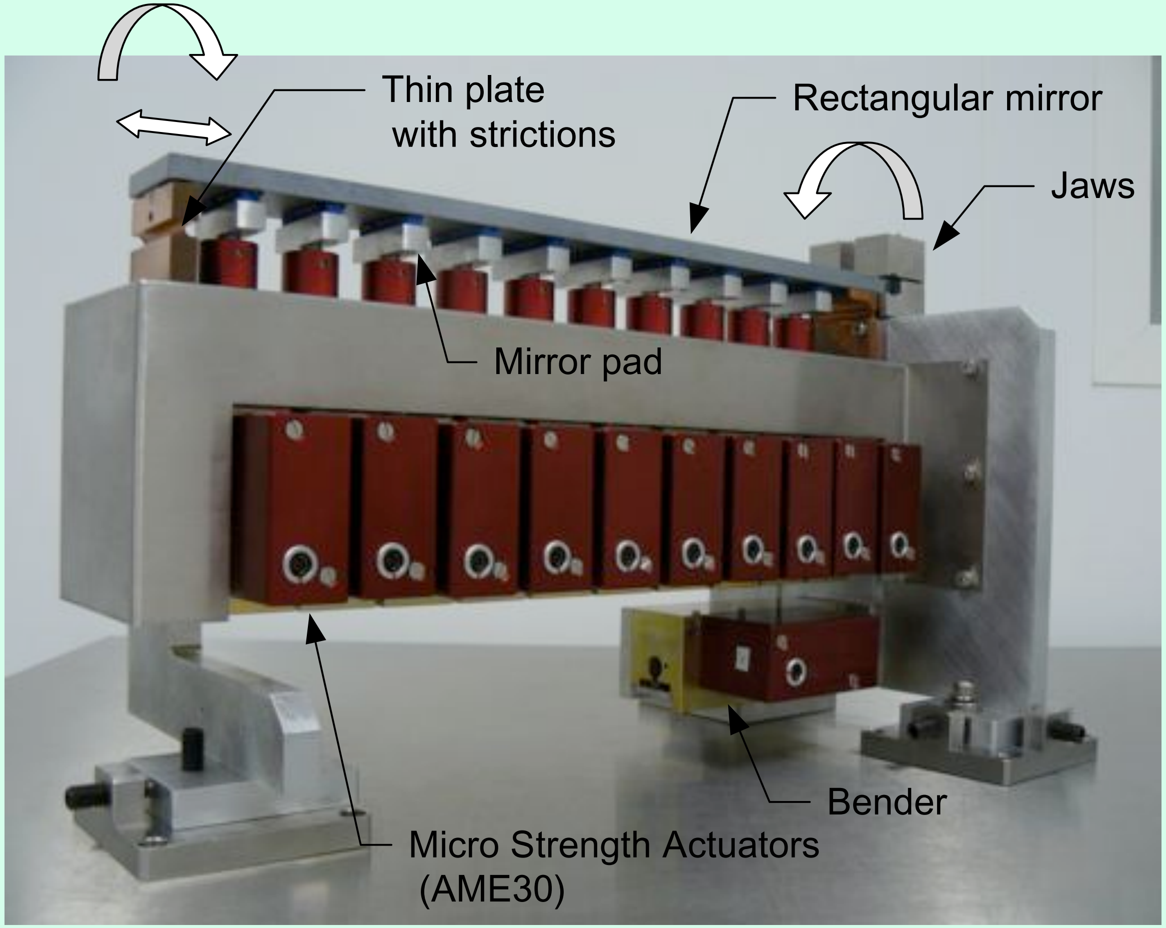
  – 2 kinds of actuators :
    - 1 bender
    - and 10 micro strength actuators (AME)



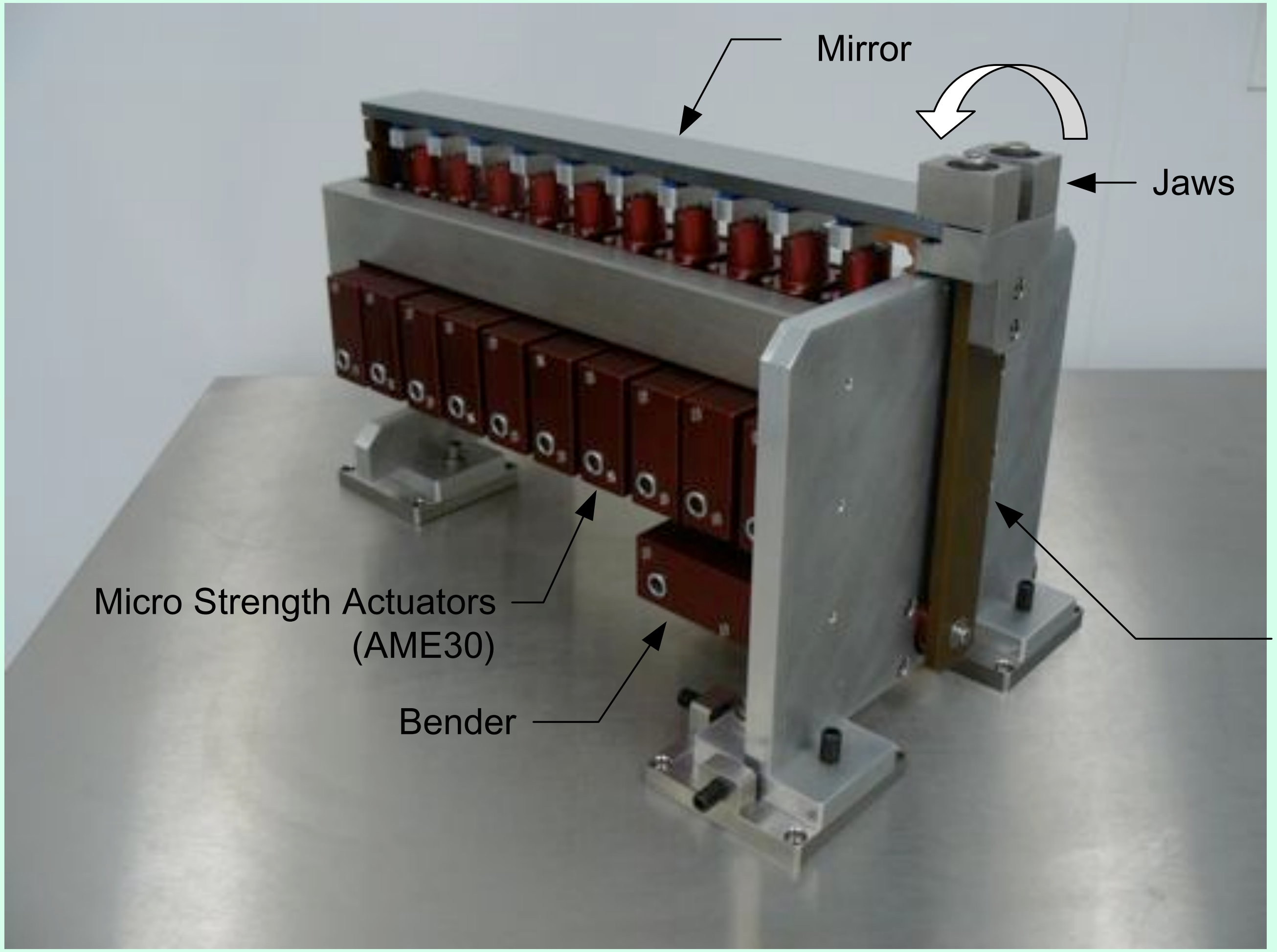
MARX Mirror DESCRIPTION

- The mirror is supported :
  - At the first extremity by a thin plate with strictions which allows 1 rotation and 1 translation. The joint is glued to the mirror
  - At the other side, by a pivot joint. The mirror is hold by a tightening controlled system (jaws).

- The AME are fastened to soft pads glued on the back face of the mirror. Soft pads are used to limit the “print effects” on the active face of the mirror.



MARX Mirror DESCRIPTION



MARX Mirror CONTROL RACK

- A dedicated Control Rack has been specially developed and realized for MARX application.
- The 19'' Rack includes :
  - 10 AME and 1 bender actuators controllers with integrated microcontroller et power driver
  - Interface communication from a PC via RS 232
  - Power supply

- Every actuator controller includes an algorithm of calibration with a dedicated mathematical grading

ISP SYSTEM's Micro Strength Actuator (AME)

- ***AME have been especially developed by ISP SYSTEM to be used in active optic systems which require very precise shapes (focalisation or wave front correction).***
- The concept, based on a calibrated strength generation, has been patented since 2002.
- The strength generation is obtained by coupling a screw-nut system energized by a bipolar stepping motor, with a floating head including springs.
- The strength range is about +/-30N with a repeatability of 10mN (others configurations are available for customer applications).

AME30 used for MARX

AME20 used for lasers, primed at MICRONORA 2006 (international exhibition of micro mechanic industry)

APPLICATION FOR LASERS Mégajoule
Laser example

- Laser wave front correction system

- Mirror : BK7
- shape : square mirror
- size :400x400mm
- material : BK7 glass

- Fitted of 39 ISP System's AME20 actuators

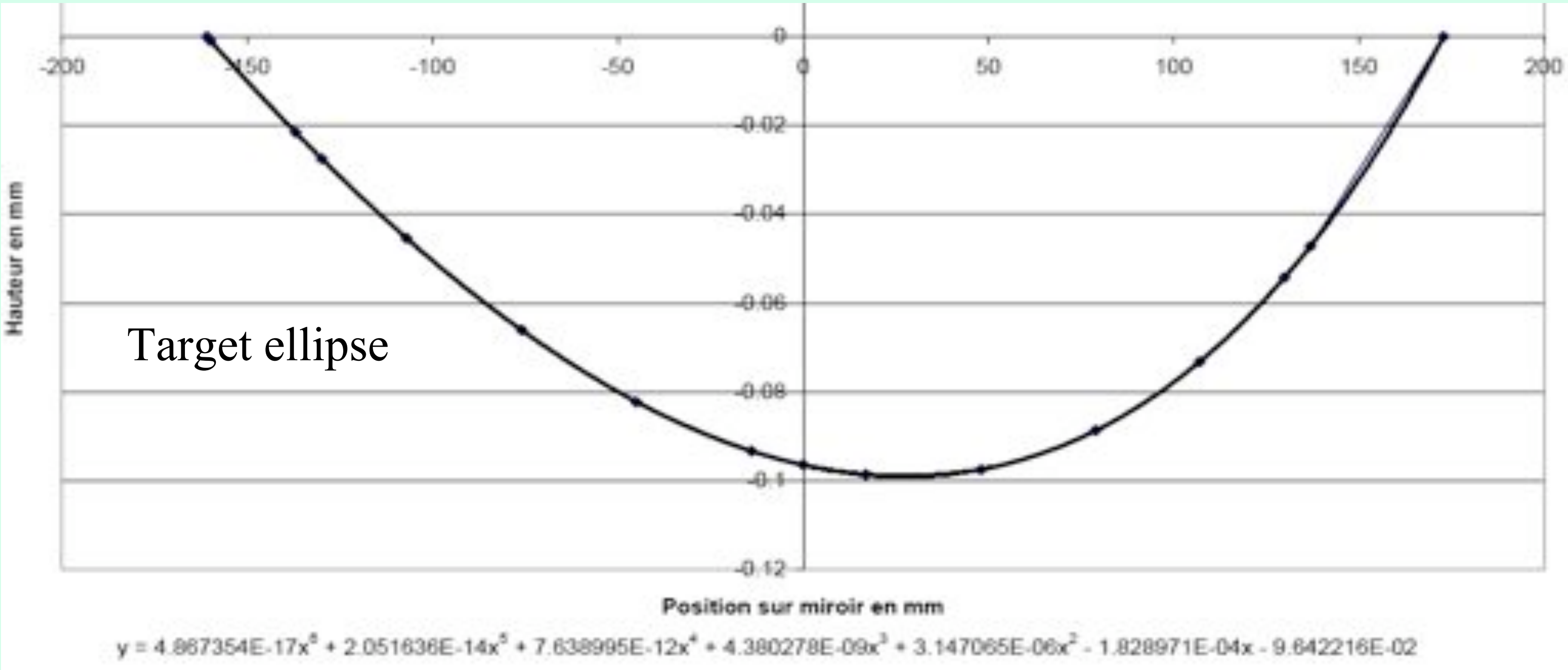
MARX Mirror targets

Mirror : Flat rectangular Silicon mirror (350 mm × 40 mm × 8 mm)
Slopes errors measured on LTP at 0.5 µrad rms over 340 mm pupil size

Working conditions : P = 35000 mm / Q = 300 à 350 mm / Θ = 0.35°

→ Working curvature from 100 to 115 m

→ Working sag about 100 µm

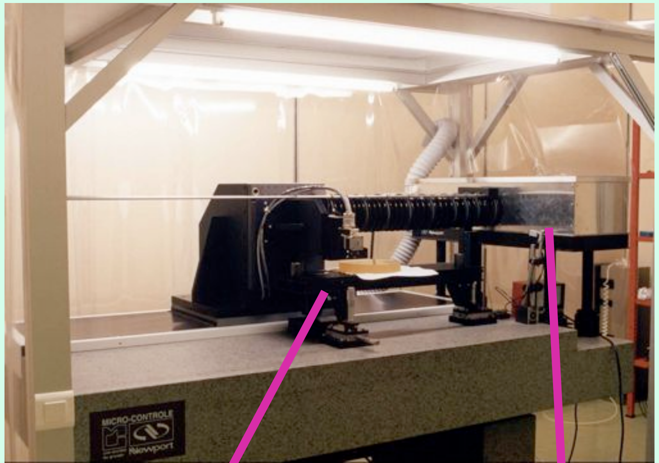


MARX
2nd Part
Active mirror
Metrology

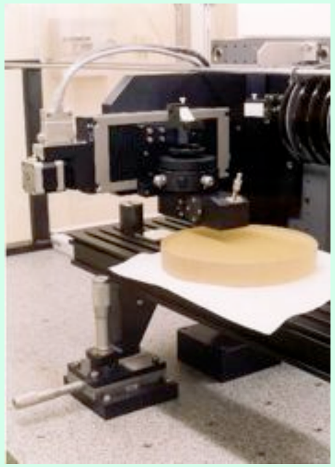
MARX MIRROR OFF-LINE METROLOGY

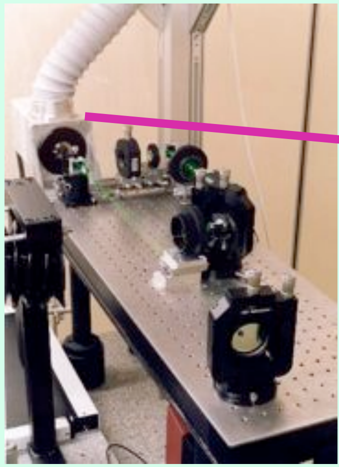
M. Thomasset, S. Brochet, F. Polack

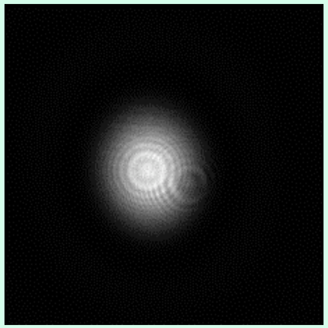
Long Trace Profiler (LTP) – Laboratoire de Métrologie Optique @ SOLEIL



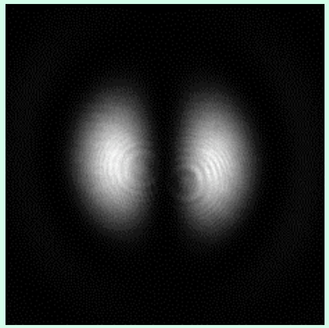
- 1D local slopes measurement.
- Active surface can be face-up, face-down or on the side.
- Maximum length : 1 m.
- Precision : Curvature 0.3%, slope errors 0.2 µrad r.m.s.
- Calibration : on a flat reference surface - precision : 0,1 %.
- Radii of curvature : from 3 m to infinite.
- Gratings groove density measurements.
- Shape reconstruction by Stitching algorithm available.

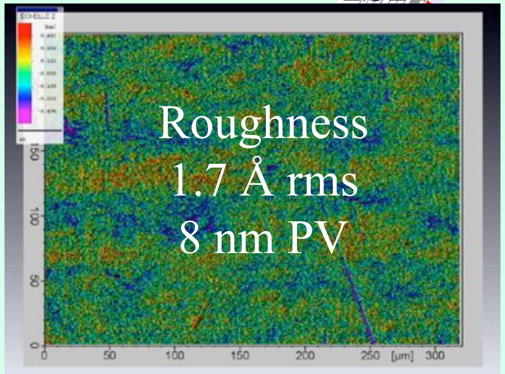






Polarization interferometer





<u>LTP measurement of the standing alone mirror</u>

Mirror dimensions: 350 mm × 40 mm × 8 mm

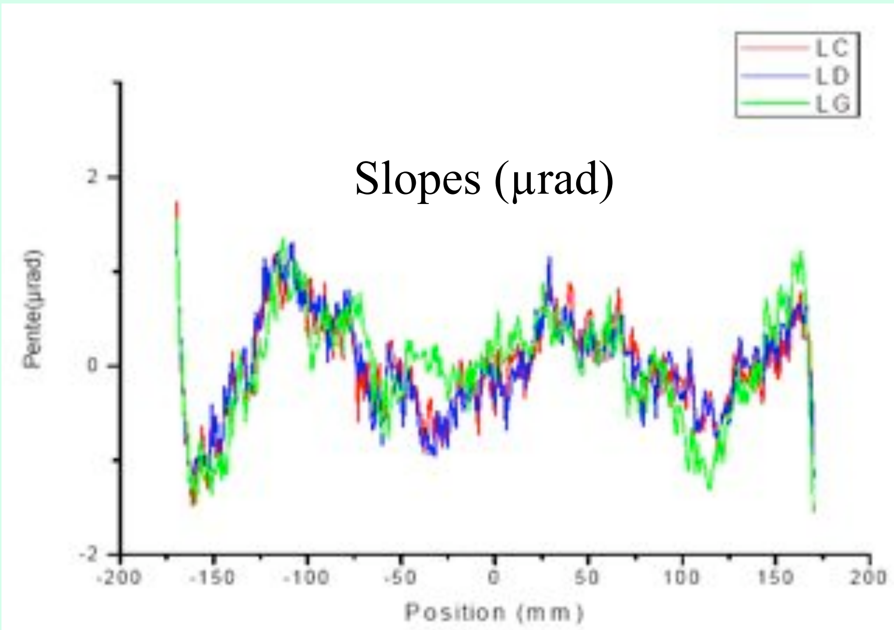
3 traces spaced by 10 mm

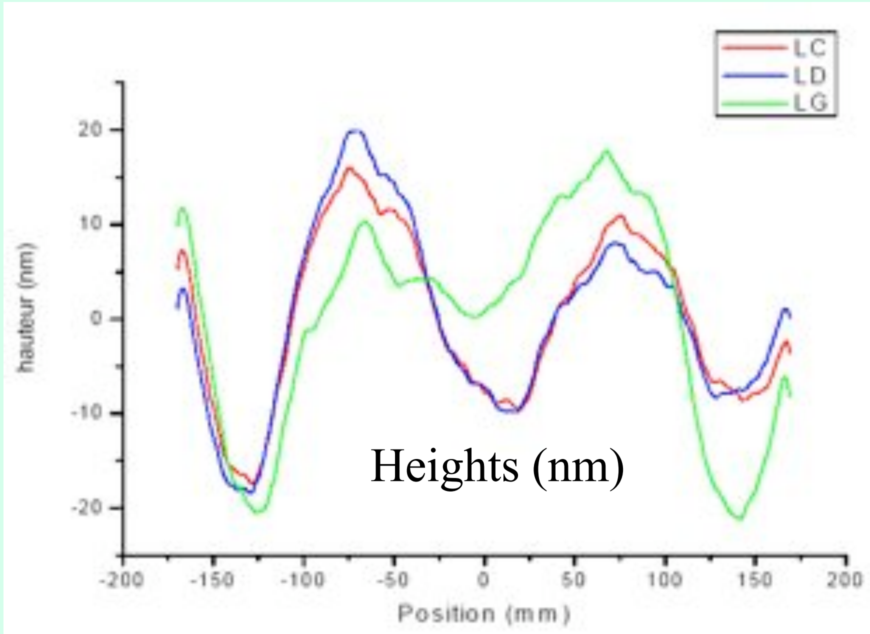
Measurement over 340 mm by 1 mm steps

LD: R = 22.2 km σ = 0.5 µrad rms

LC: R = 19.1 km σ = 0.5 µrad rms

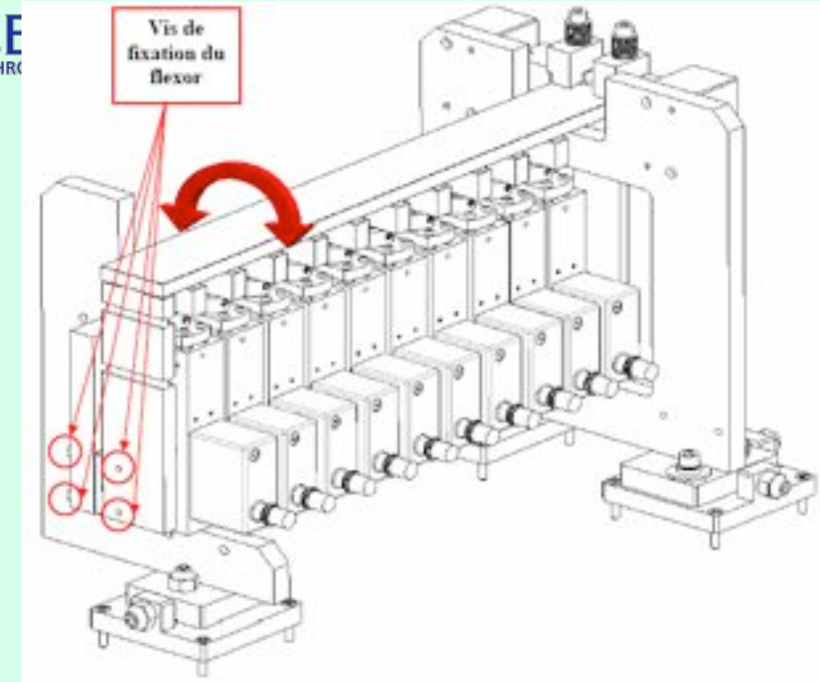
LG: R = 19.5 km σ = 0.6 µrad rms



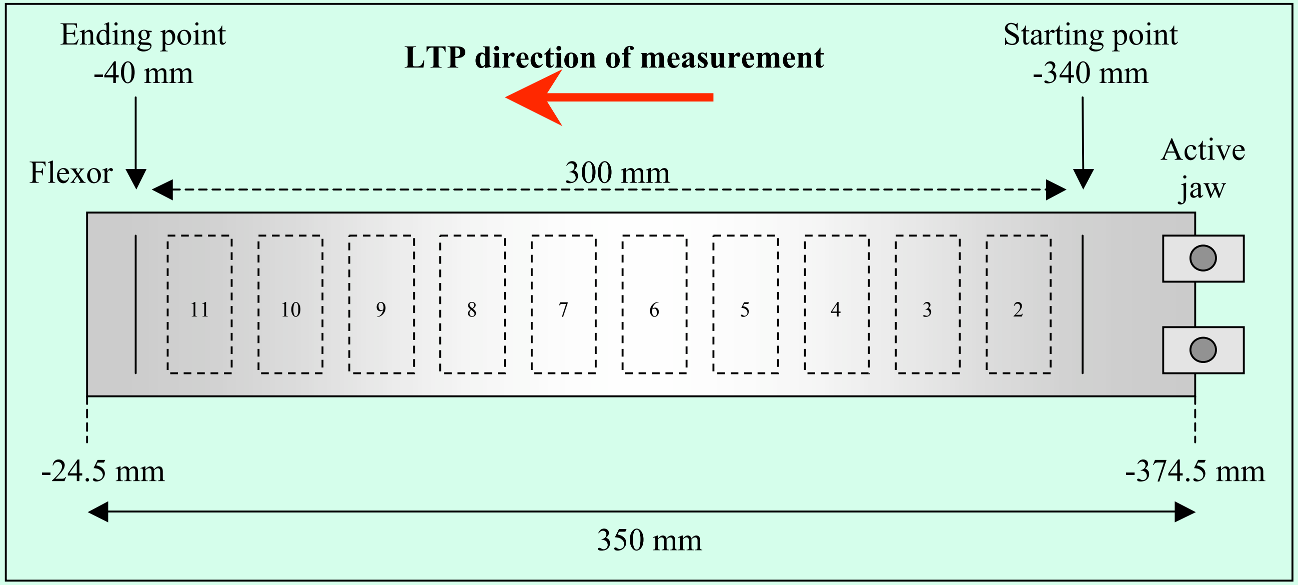


Alignment of the mirror

Twist correction
- interferometer
- LTP

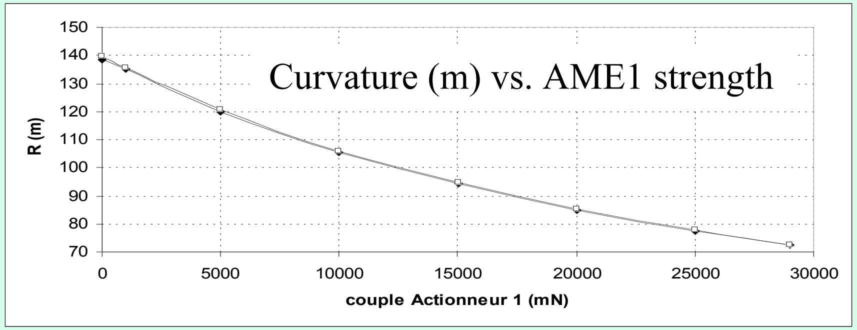


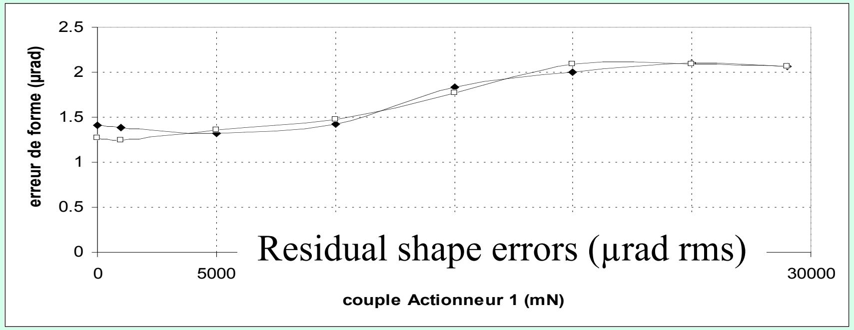
LTP measurements

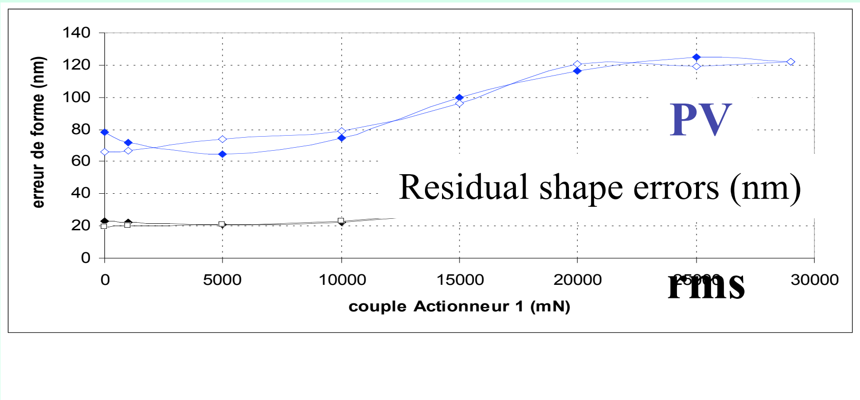


Measurement over 300 mm by 1 mm steps

Curvature actuator : classical x-ray bender



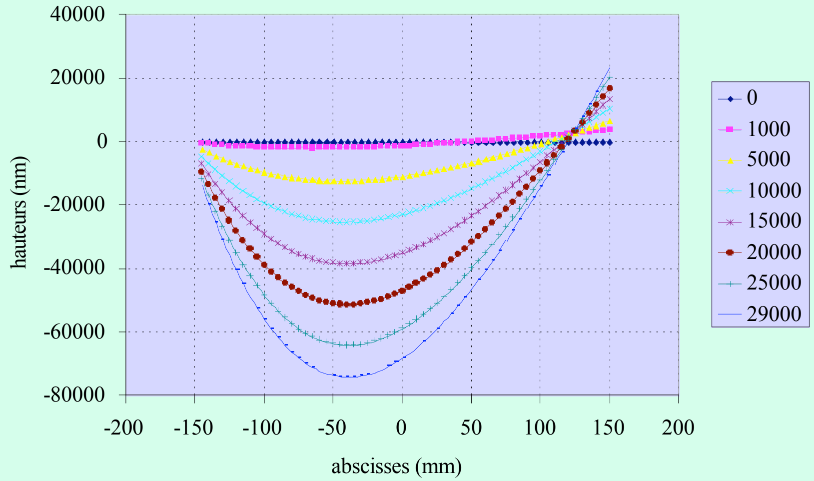


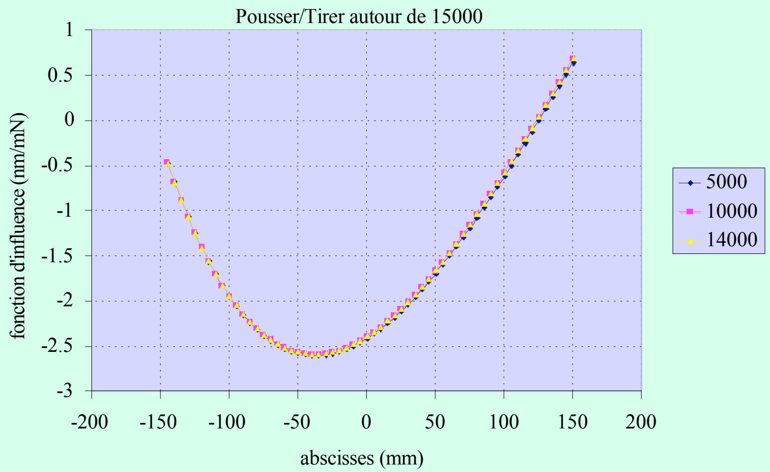


The mirror is pre-curved (R = 140 m)

Curvature dynamic range : 140 to 72 m

Heigth at the center : 80 to 160 µm



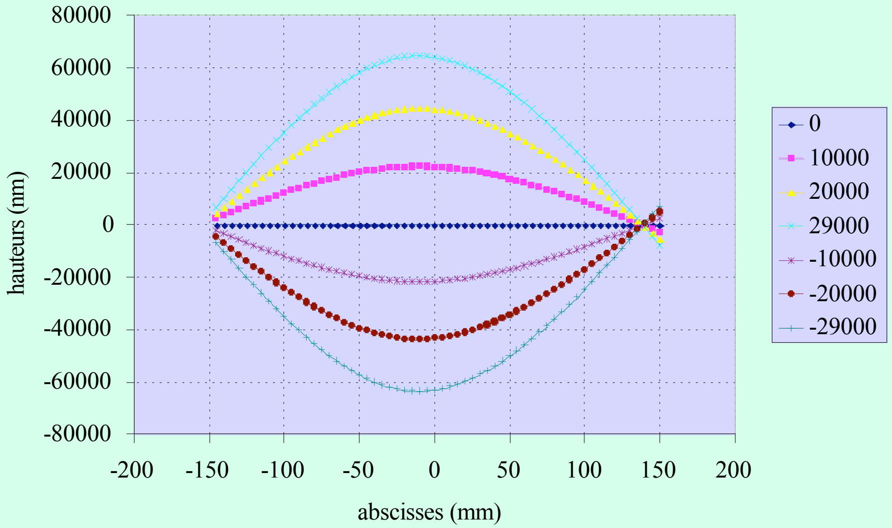


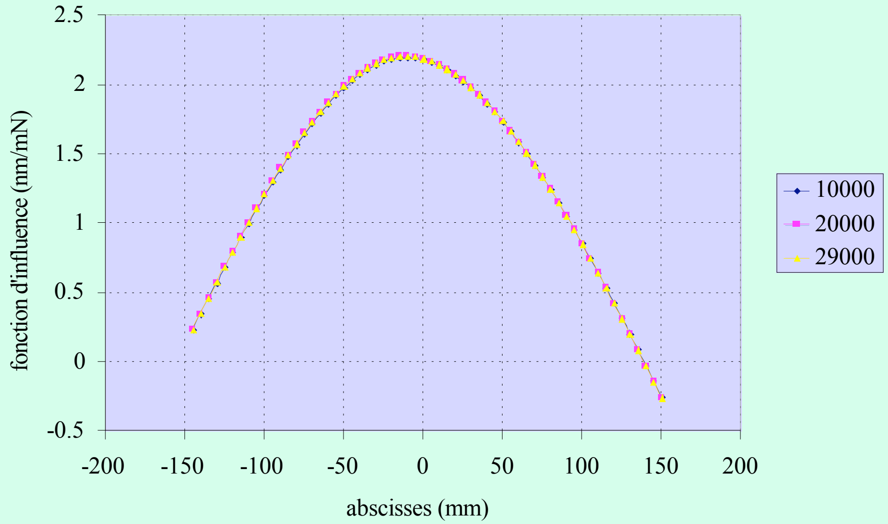
In principle able to go from Flat to 55 m

Shape correction actuators

INFLUENCE FUNCTIONS

→ Case of actuator n°6





We realized successive shape measurements for different strength values of AME6. (the nominal shape of the mirror is subtracted from all measurements).

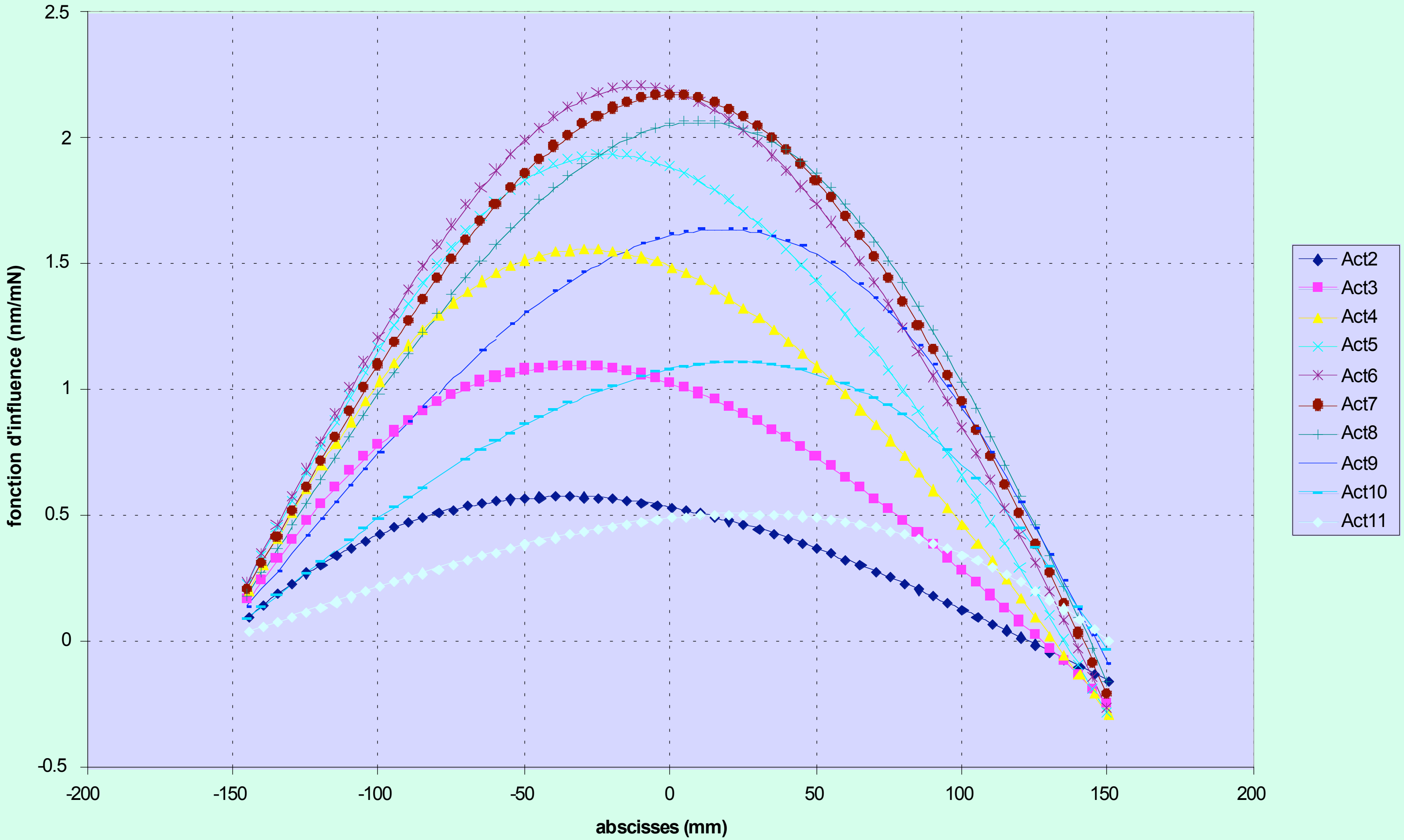
→ Deformation of the mirror surface is symmetric.

The influence function is the same on the whole range of the actuator.

→Demonstrate the linearity of the system (true for all actuators)

Shape correction actuators

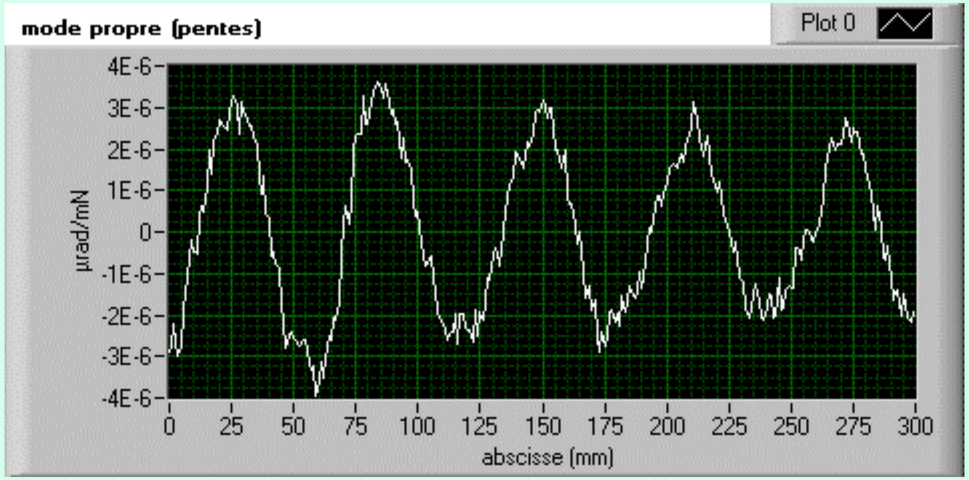
INFLUENCE FUNCTIONS



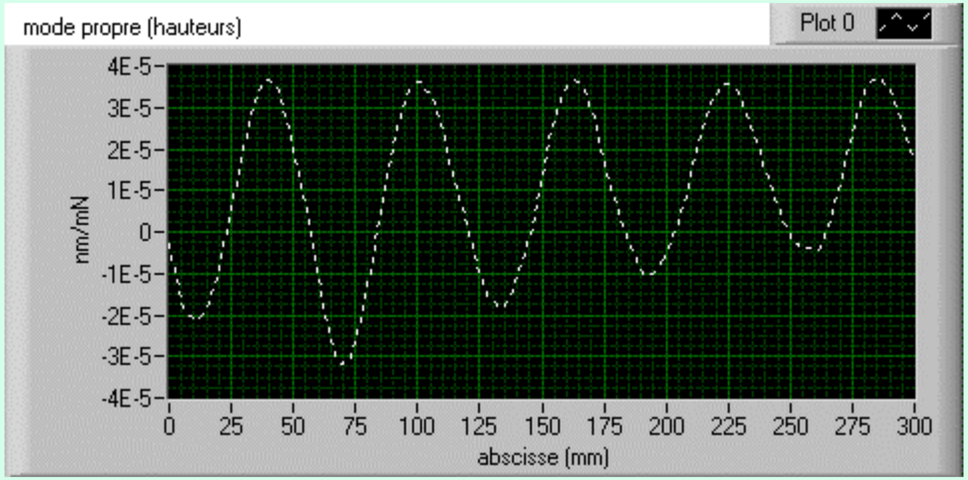
The actuators at the edges of the mirror induce 4 times less deformation of the surface (~0.5 nm/mN) than those in the middle (~2 nm/mN).

Shape correction actuators

EIGEN MODES



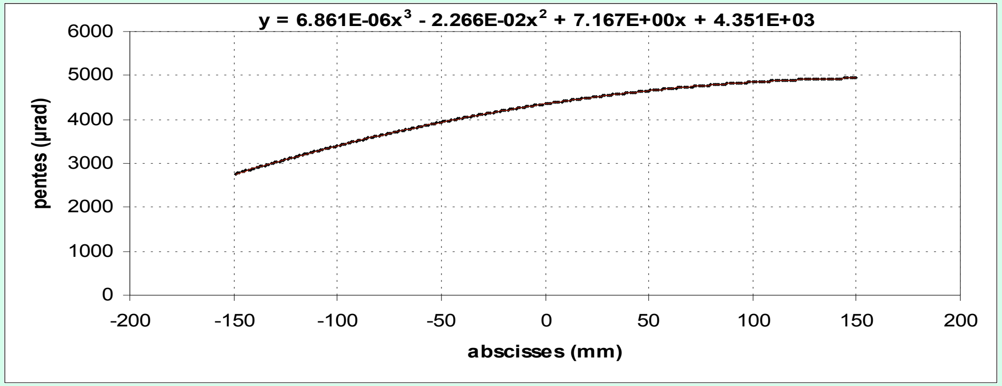
SLOPE



HEIGHT

Imagine Optic — SOLEIL SYNCHROTRON — ISP SYSTEM

Nominal shape measurement (all actuators @ 0)



Curvature actuator @ 0

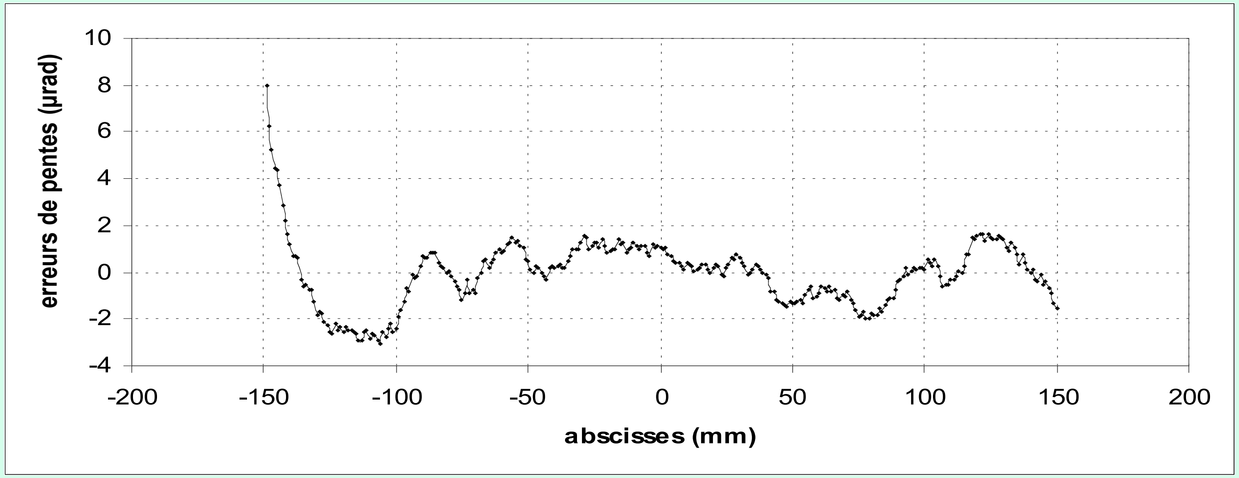
R = 139.519 m

Residual to best elliptical fit

σ = 1.42 µrad rms

h = 24 nm rms

H = 81.6 nm PV



Shape correction using the 10 inside actuators

Target: Best elliptical fit from nominal shape measurement *(strengths between -7N and +6N)*

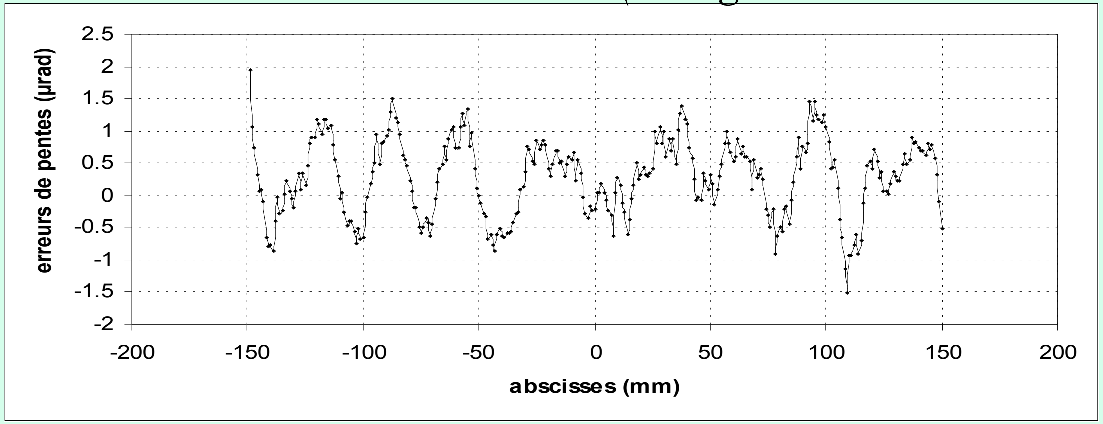
Residual to best elliptical fit

R = 139.6 m

σ = 0.59 µrad rms

h = 3.921 nm rms

H = 16.317 nm PV



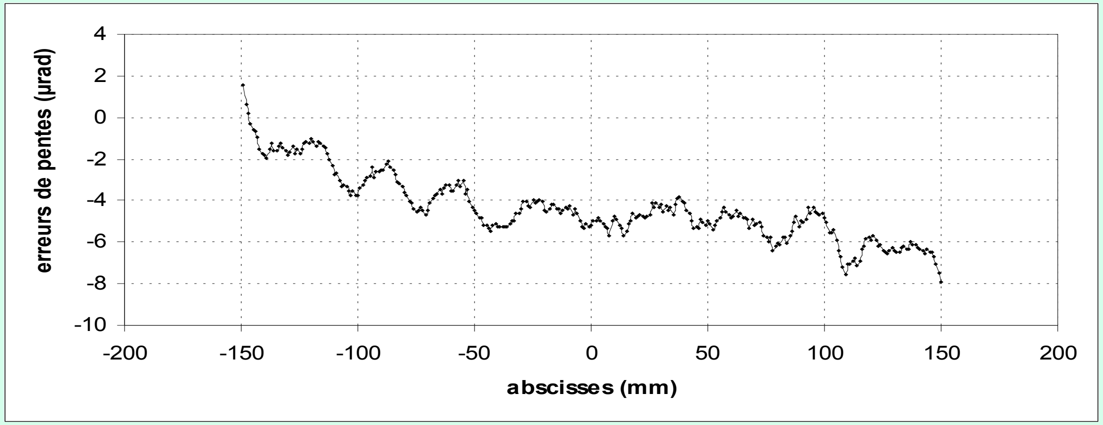
Residual to target

R = 139.519 m

σ = 1.65 µrad rms

h = 389.4 nm rms

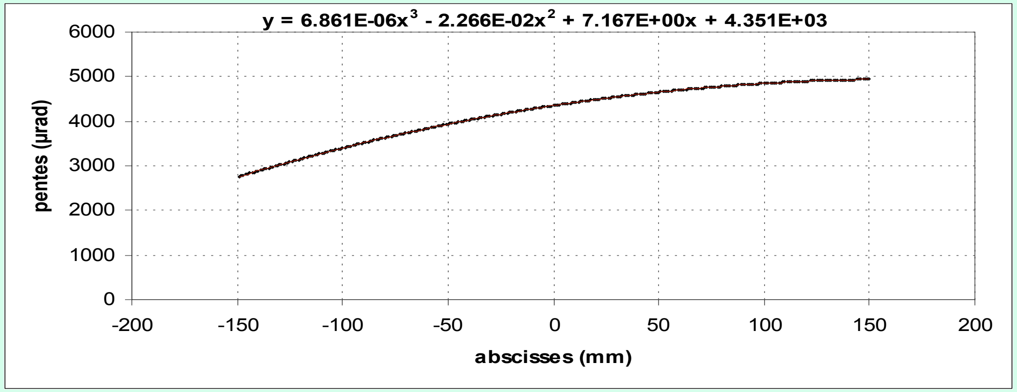
H = 1291.4 nm PV



→ Correction in a single iteration

→ Small drift in final curvature **(can be corrected using AME1)**

Mirror is hold in correction and curved to 100 m



Curvature actuator @ 12N

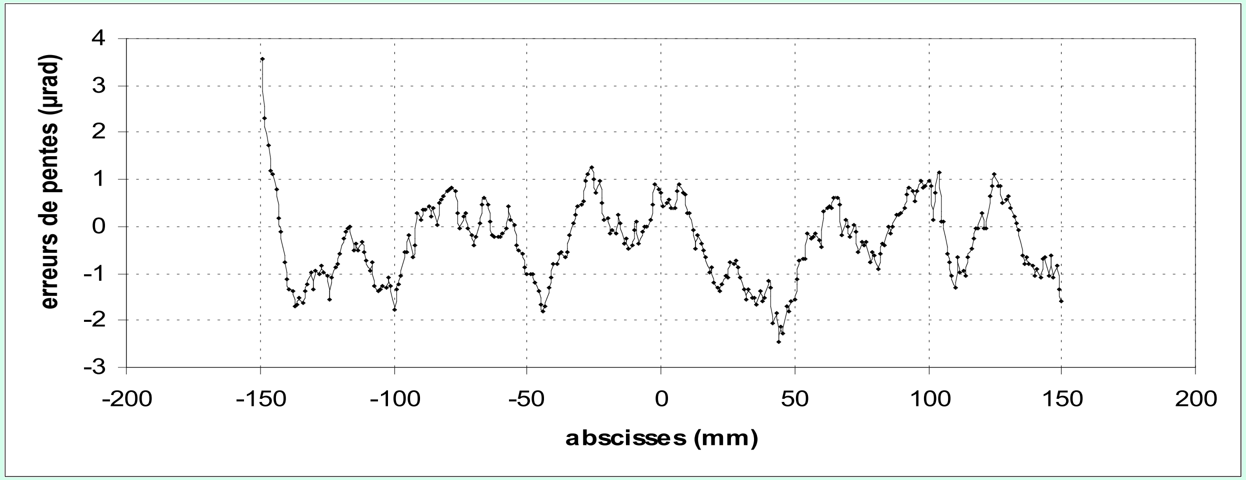
R = 100 m

Residual to best
Elliptical fit

σ = 0.84 µrad rms

h = 9.86 nm rms

H = 39.66 nm PV



Small degradation of the surface shape errors by curving the mirror

Shape correction using the 10 inside actuators

Target: Best elliptical fit from previous shape measurement

(strengths between -10N and +9N)

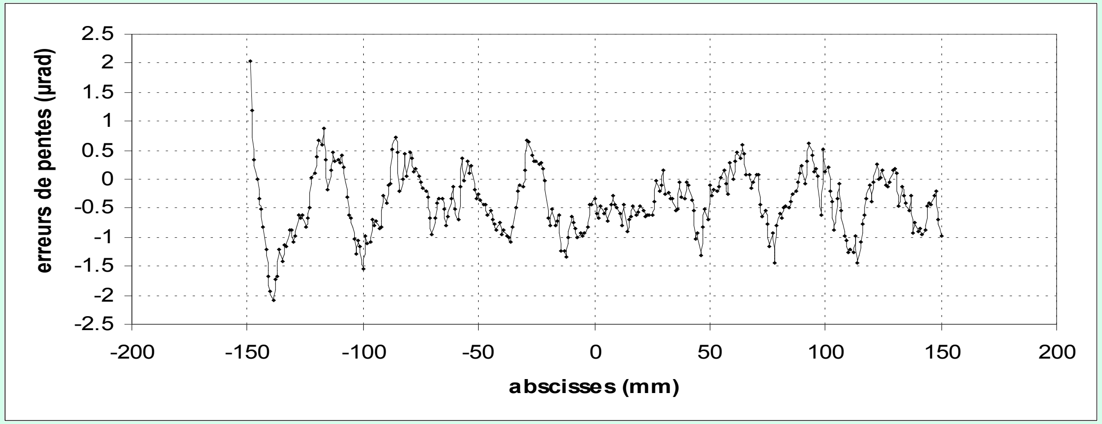
Residual to best elliptical fit

R = 100.32 m

σ = 0.55 µrad rms

h = 3.06 nm rms

H = 15.9 nm PV



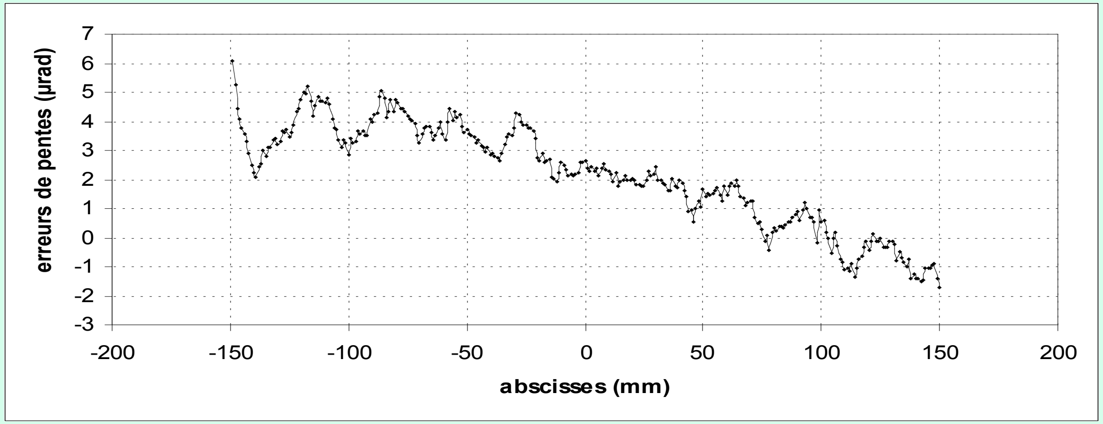
Residual to target

R = 100 m

σ = 1.357 µrad rms

h = 204.4 nm rms

H = 630 nm PV



→ Correction in 2 iterations **using the same interaction matrix**

→ Small drift in curvature

CONCLUSION

- Curvature range from 140 to 72 m **(possible to go from flat to 55 m)**
- The mirror system is **linear**.
- **1 single interaction matrix can be used**.
- Slope errors can be corrected to 0.6 µrad rms, in 1 or 2 iterations.
- Small drift on curvature respect to the target ellipse.

- Upgrades:

Use of AME1 to correct the drift in curvature: 2 steps correction

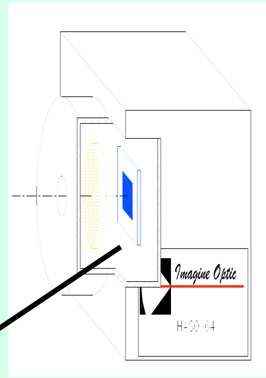
1- Curvature adjustement (use of AME1)

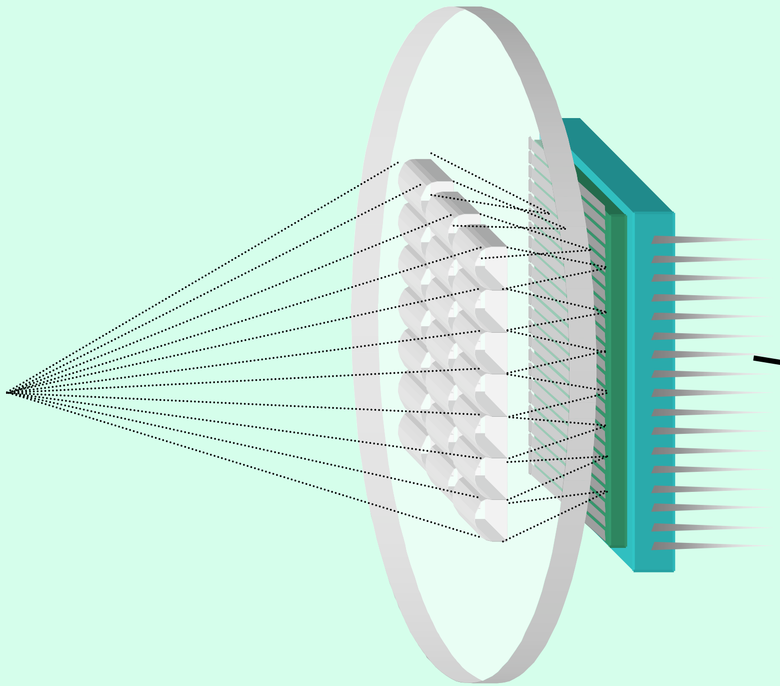
2- Residual shape errors correction (use of the 10 inside actuators)

- Coupling with a hard X-ray Hartmann wavefront sensor and closed loop experiment on synchrotron radiation beamlines (end of 2008).

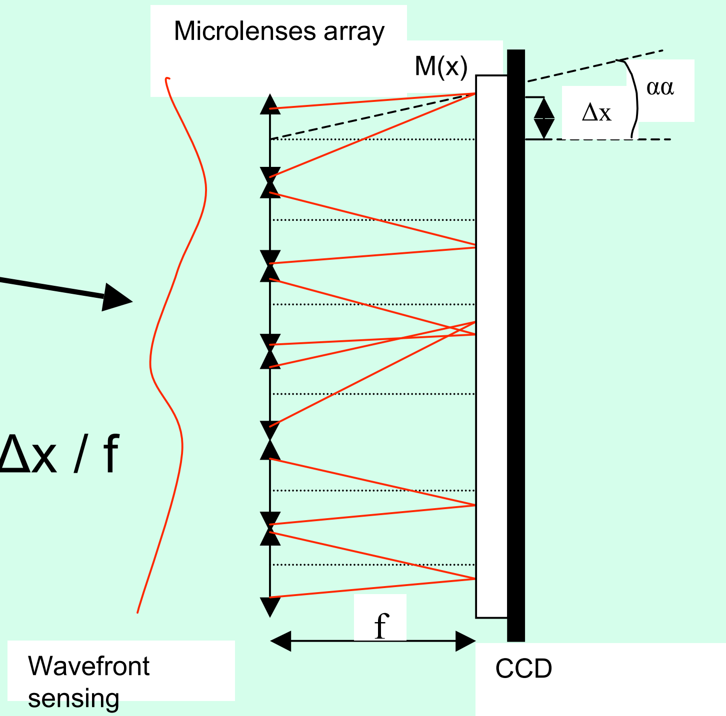
3rd Part Wavefront sensor

Principle of Shack Hartmann wavefront sensor

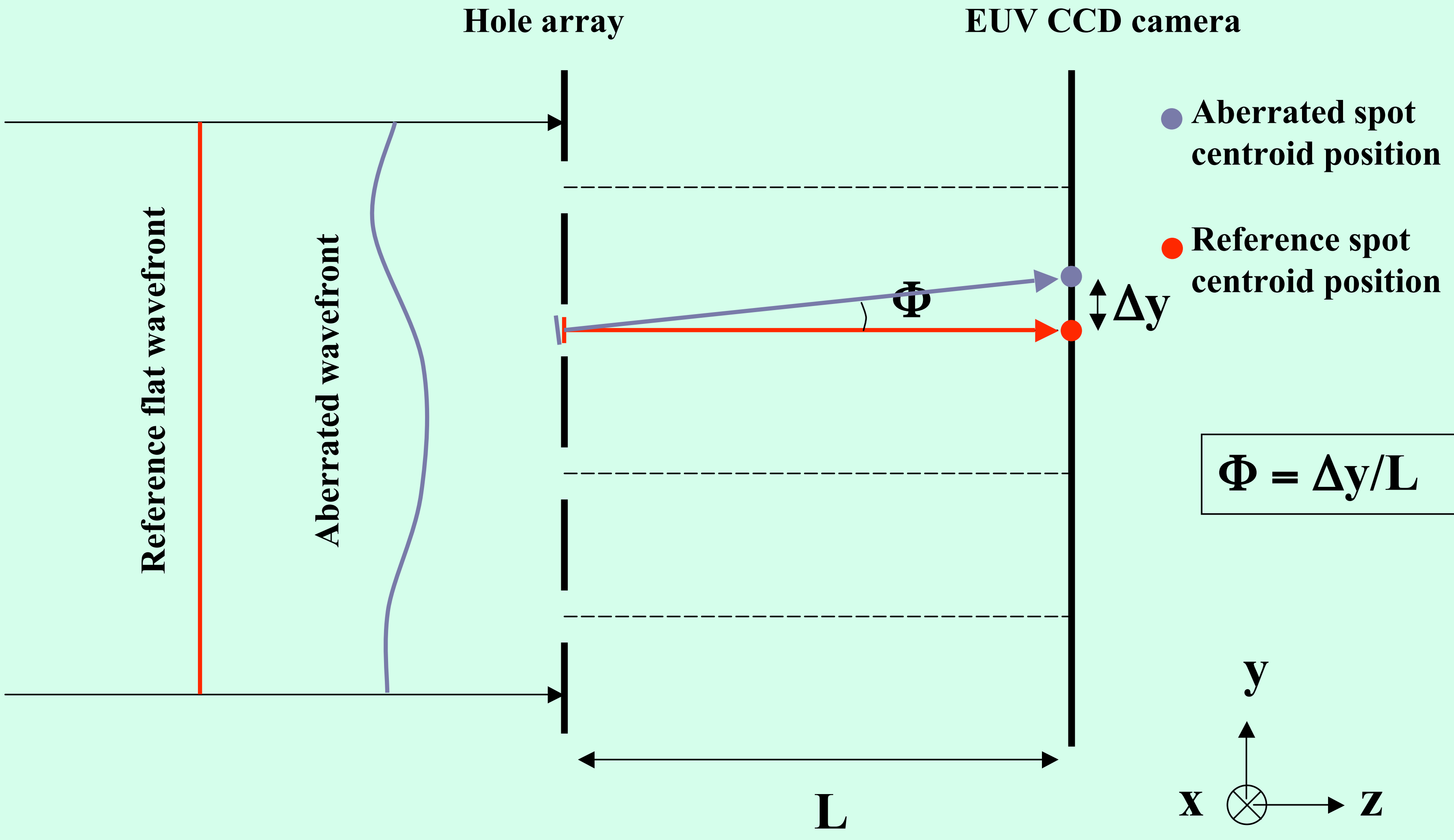




$$\tan(\alpha)=\Delta x / f$$



Principle of Hartmann wavefront sensor

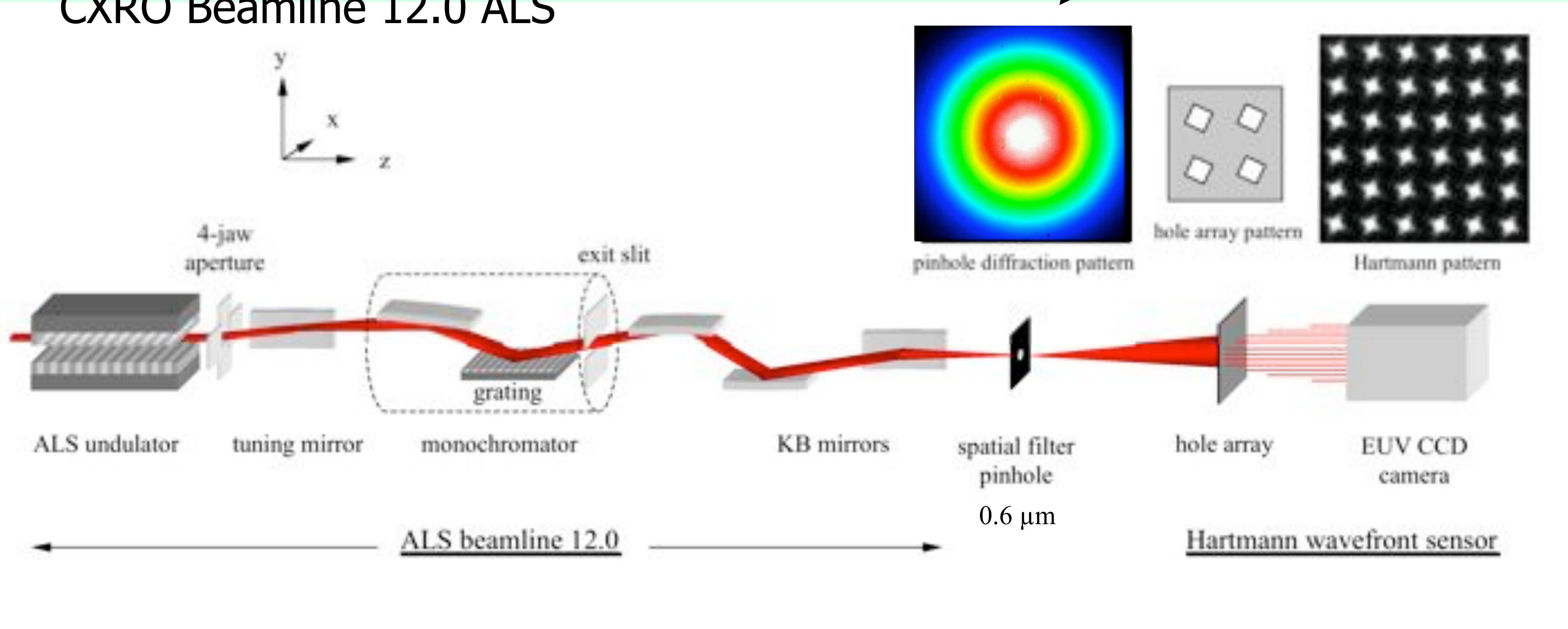


$$\Phi = \Delta y / L$$

Hartmann wavefront sensor
1st TEST

Perfect diffracted wavefront

CXRO Beamline 12.0 ALS



Hartmann wave-front measurement at 13.4 nm with λ EUV 120

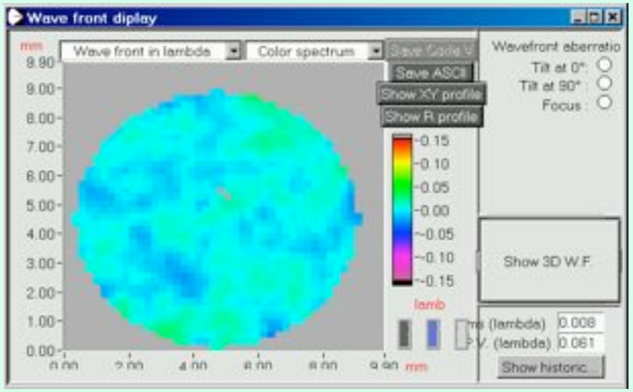
Optics Letters, Vol. 28 Issue 17 Page 1534 (September 2003)

P. Mercère, P. Zeitoun, Mourad Idir, S. Le Pape, D. Douillet, X. Levecq, G. Dovillaire, S. Bucourt, K.A. Goldberg, P. Naulleau, S. Rekawa

EUV Calibration

Reproducibility

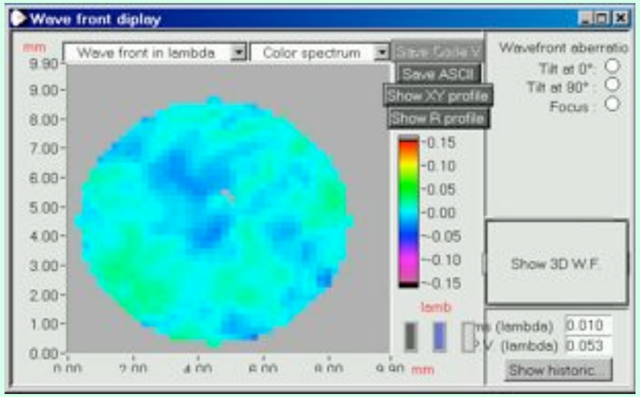
0.6µm pinhole



λ_{EUV}/125 rms , λ_{EUV}/16 PV
0.1 nm rms, 0.8 nm PV

Sensibility – Precision

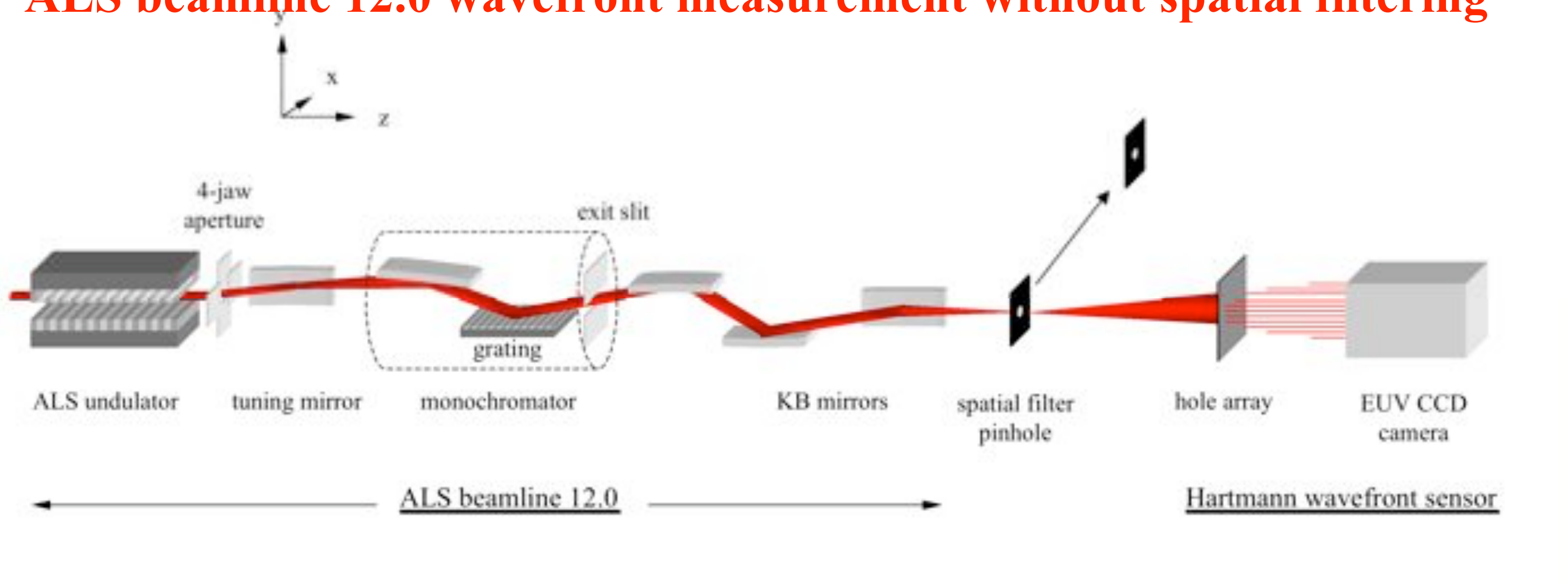
0.6µm pinhole
1.86 µm in the X direction

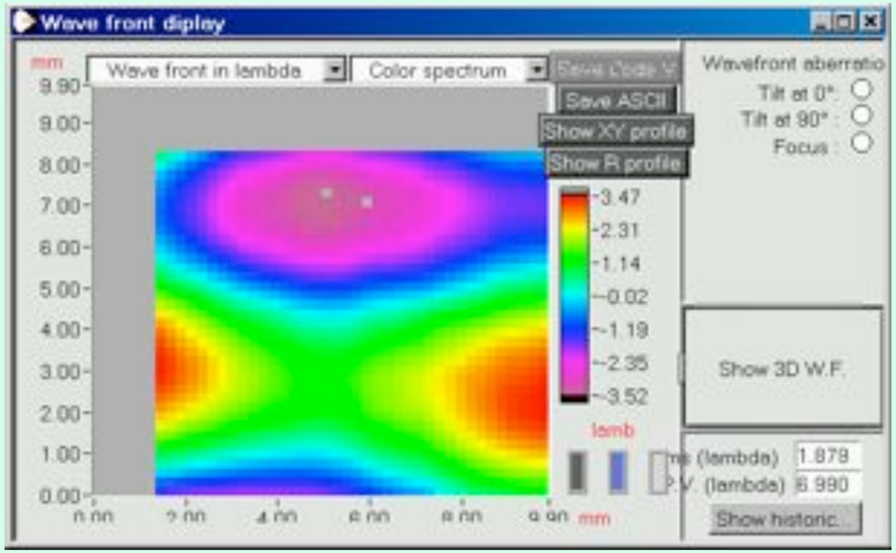


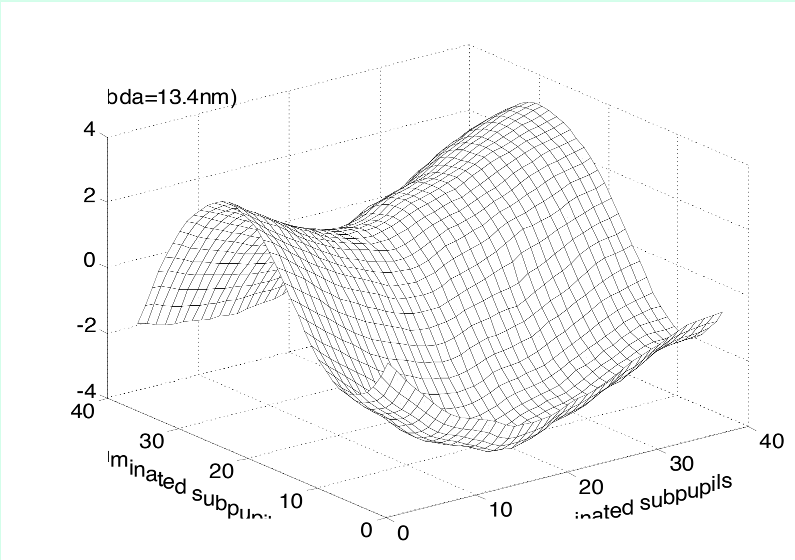
λ_{EUV}/100 rms , λ_{EUV}/19 PV
0.13 nm rms, 0.8 nm PV

- Wavefront precision ~ λ/100 rms (0.1 nm rms)
- Tilt Precision ~ 0.02 µrad rms
- Focal distance precision ~ 1. 10^{-5} m $^{-1}$ rms

ALS beamline 12.0 wavefront measurement without spatial filtering

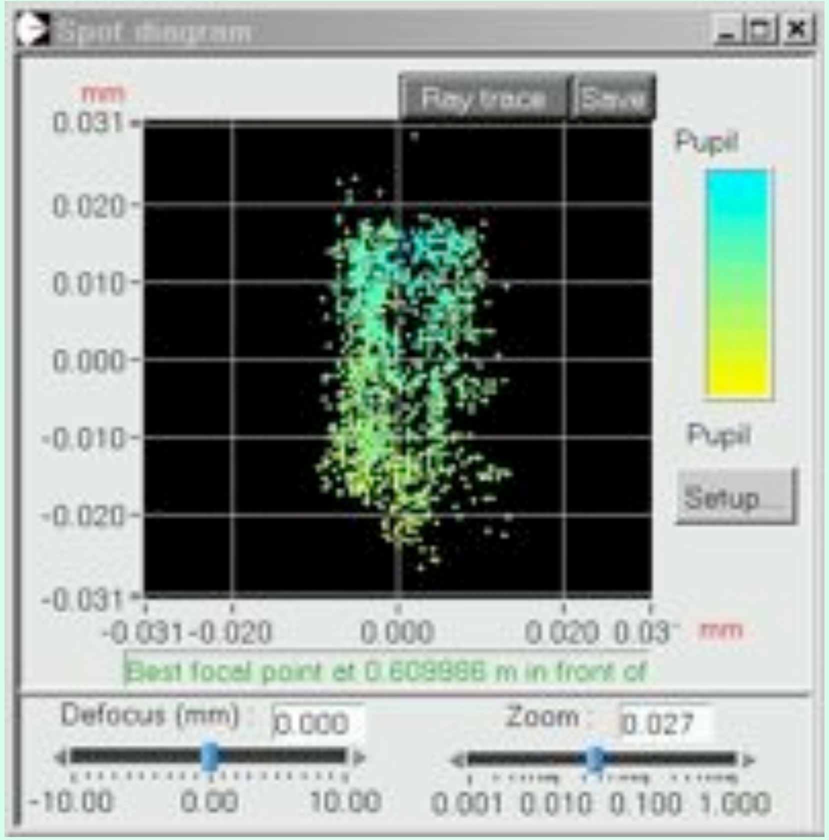




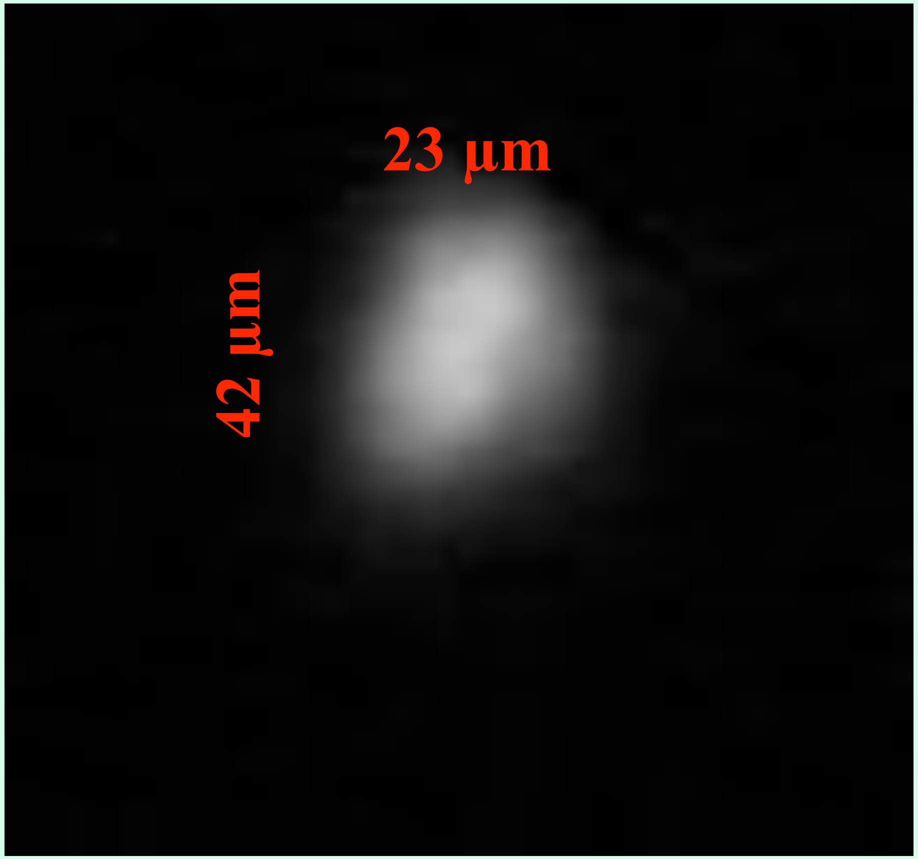


KB optimization

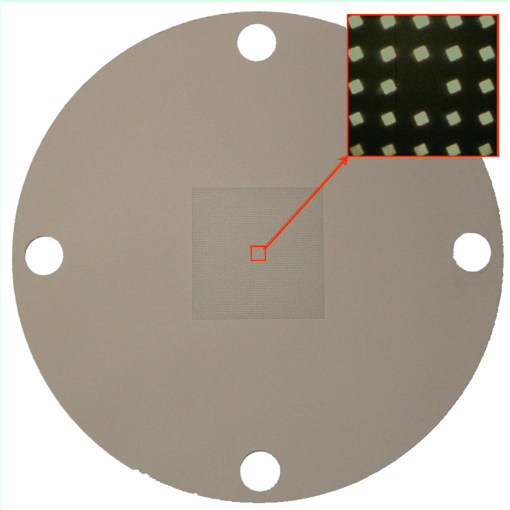
Ray tracing calculated with Hartmann sensor software based on phase measurement

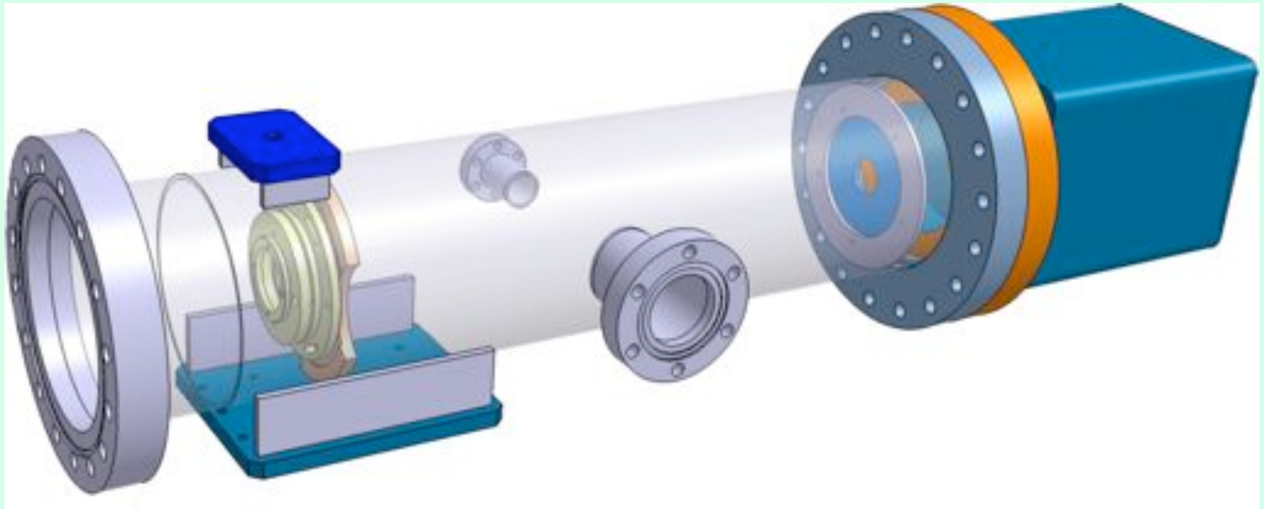


Measured spot size (YAG crystal+µscope objective)

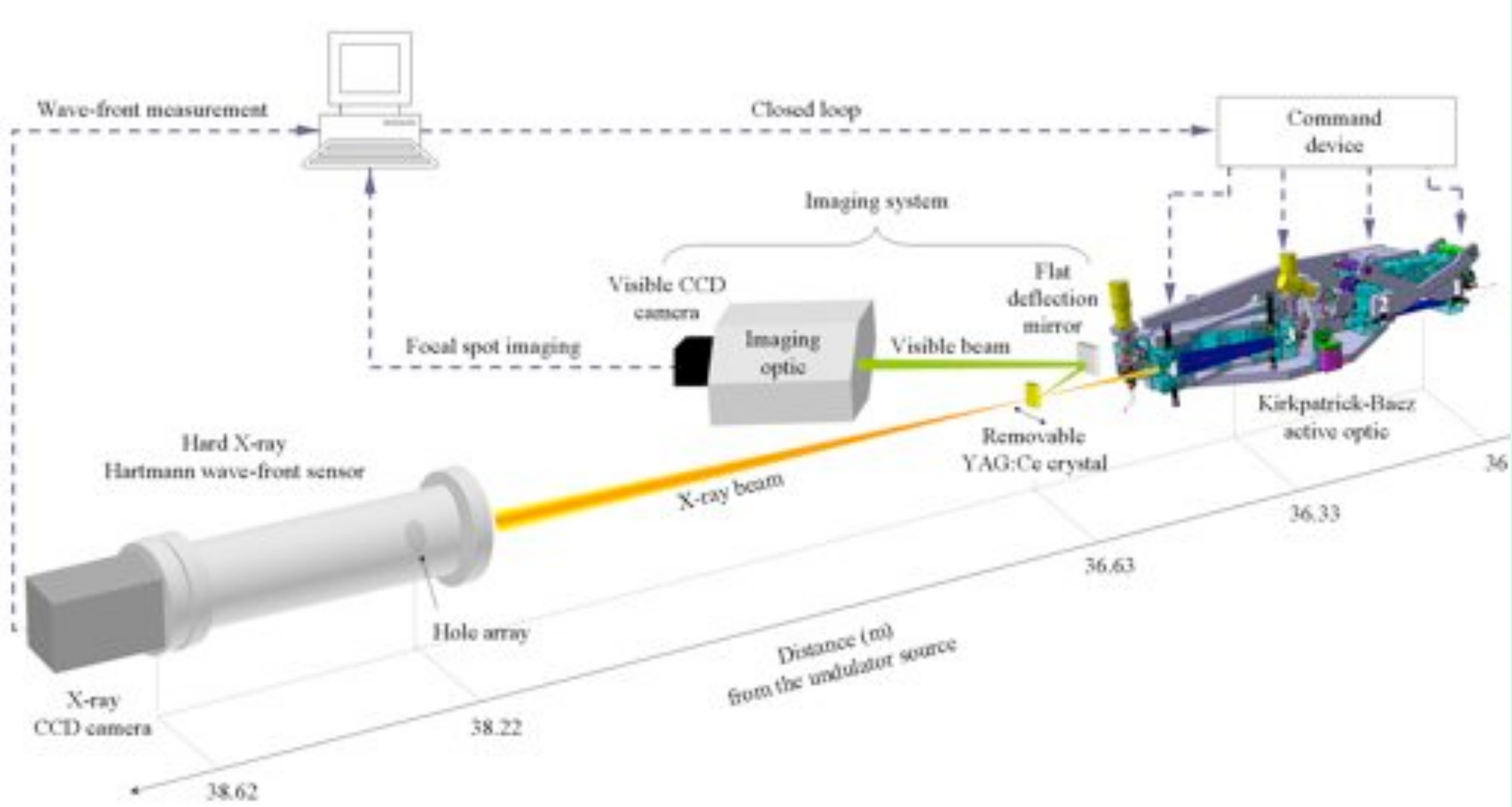


SLS LUCIA wavefront system
Generation II



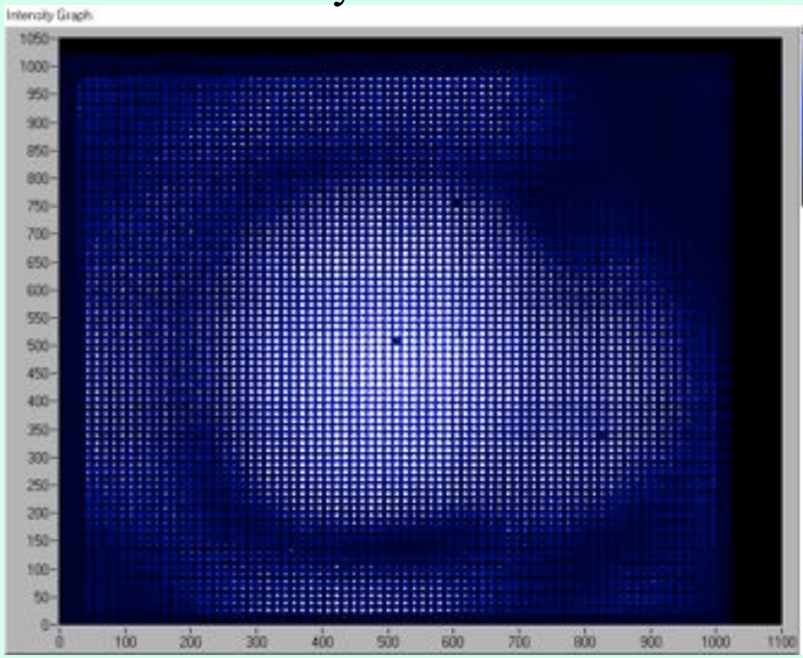


Hartmann Wavefront measurement and correction

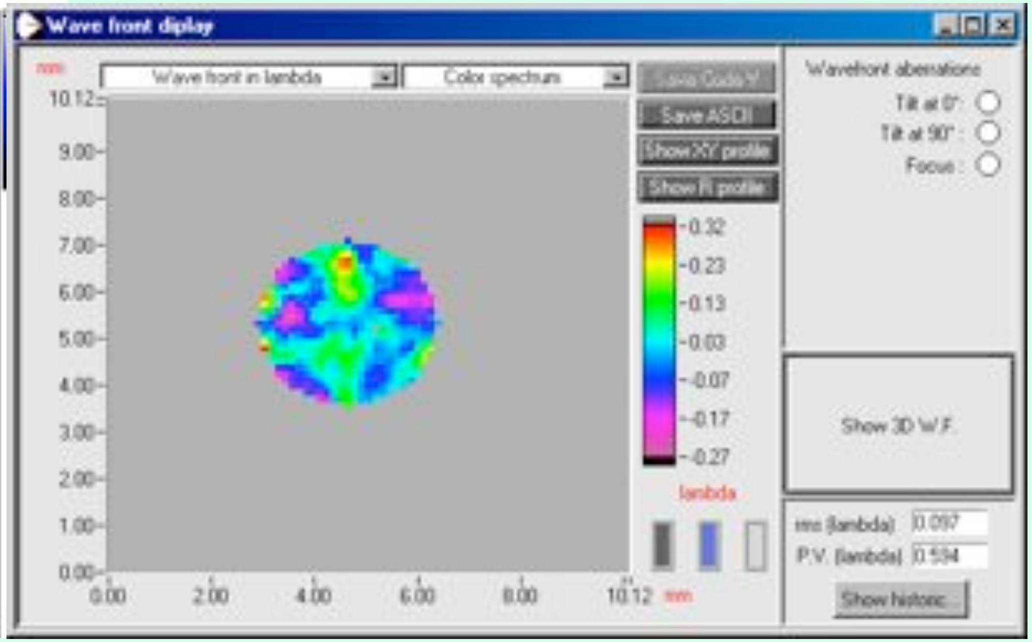


Calibration of the sensor on a spatially filtered reference beam at 700 eV

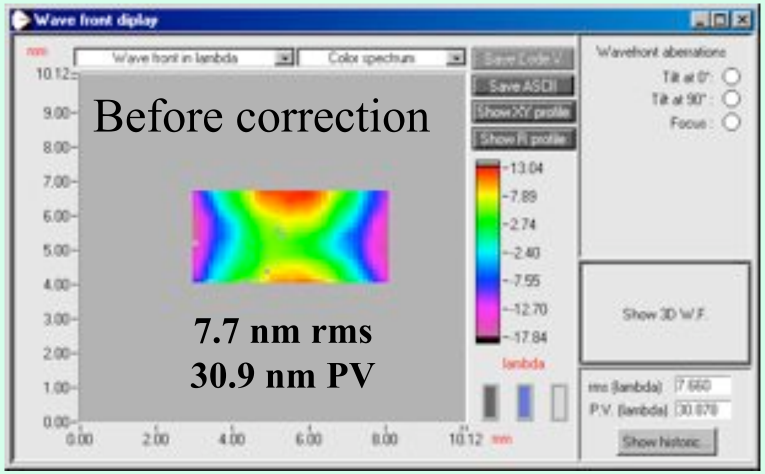
1-µm pinhole diffracted wave
seen by the sensor

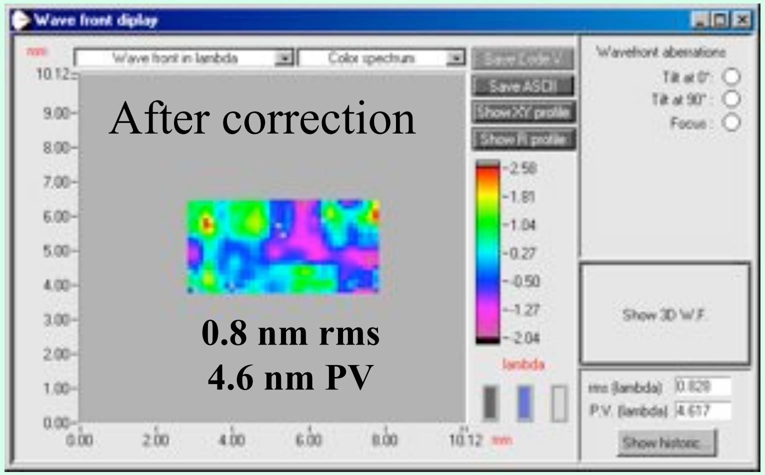


Absolute wavefront measurement after calibration

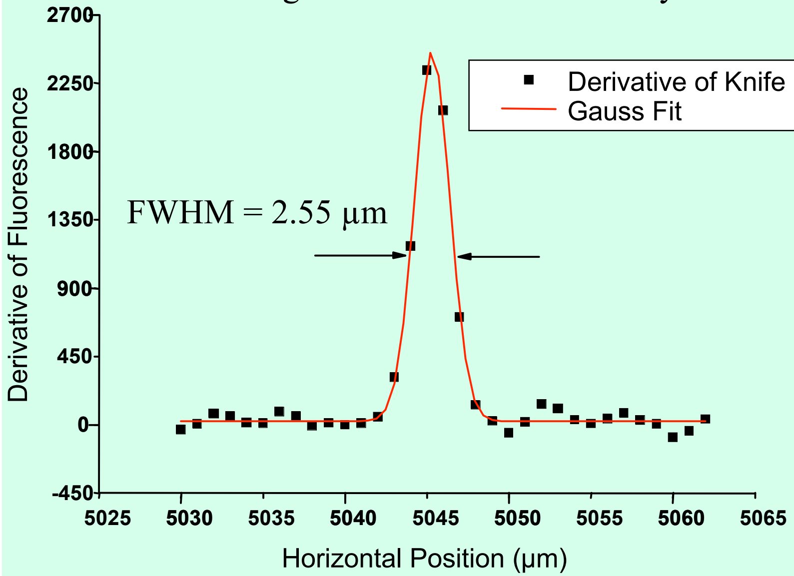


Closed loop correction at 3.64 keV

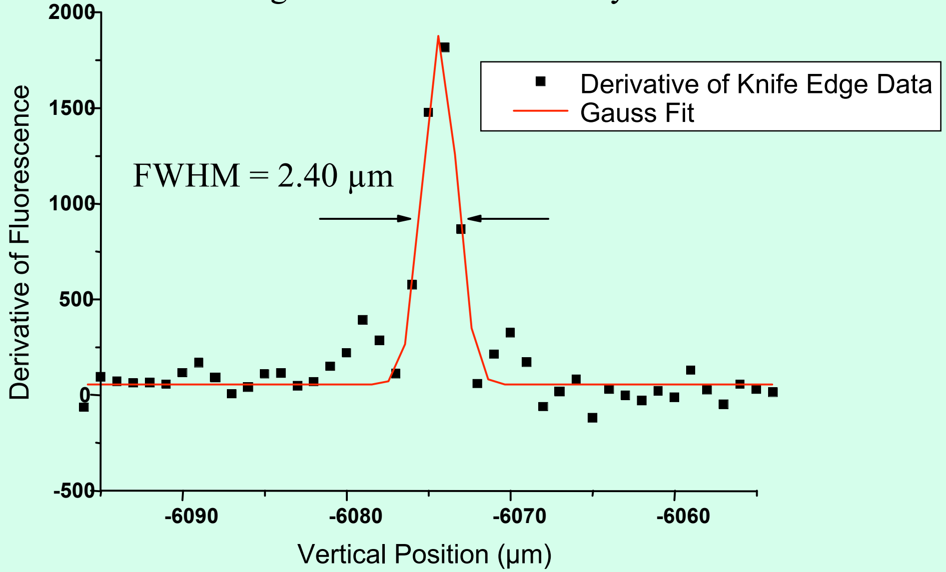




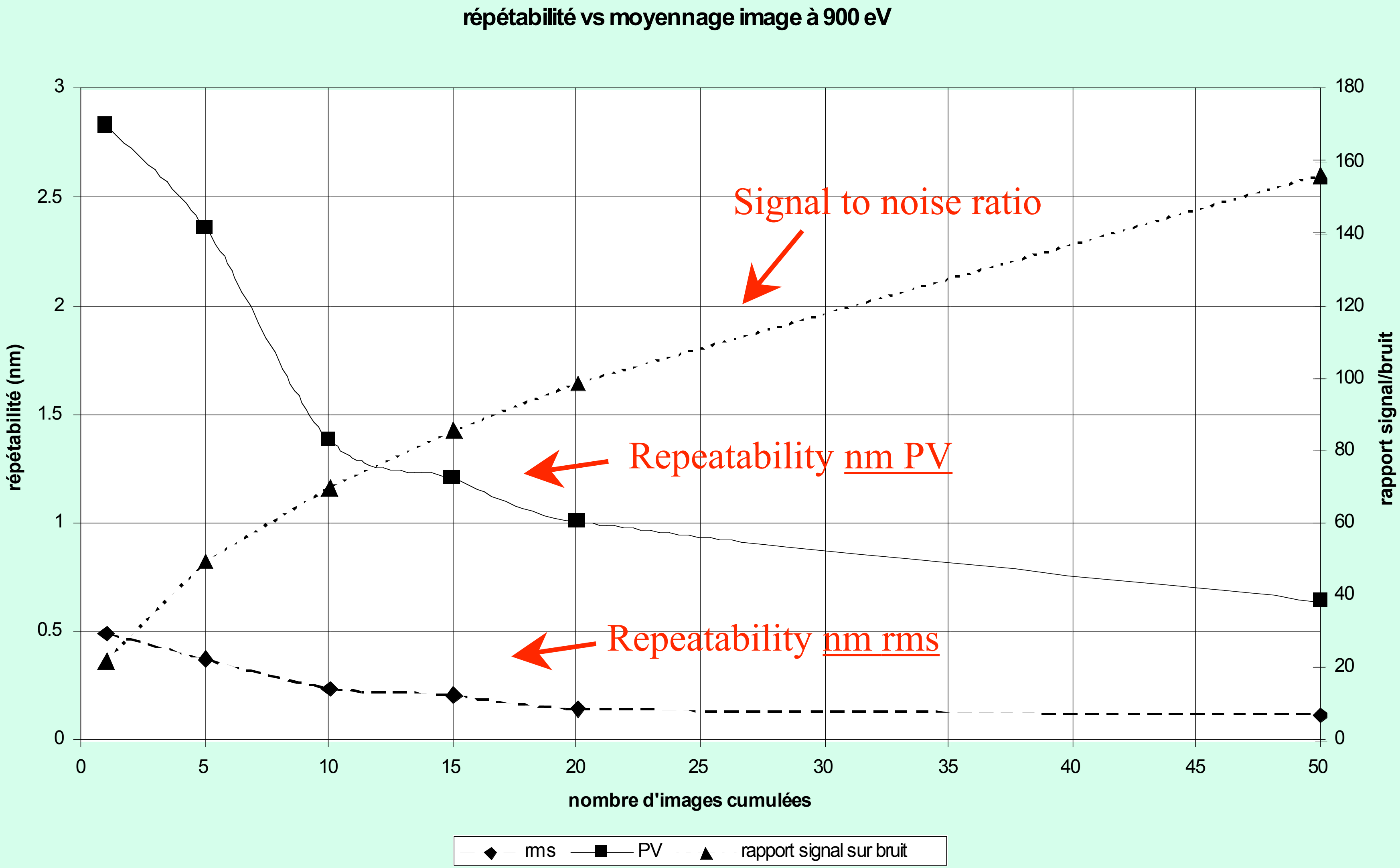
Knife Edge Scan of Horizontal X-ray beam at LUCIA



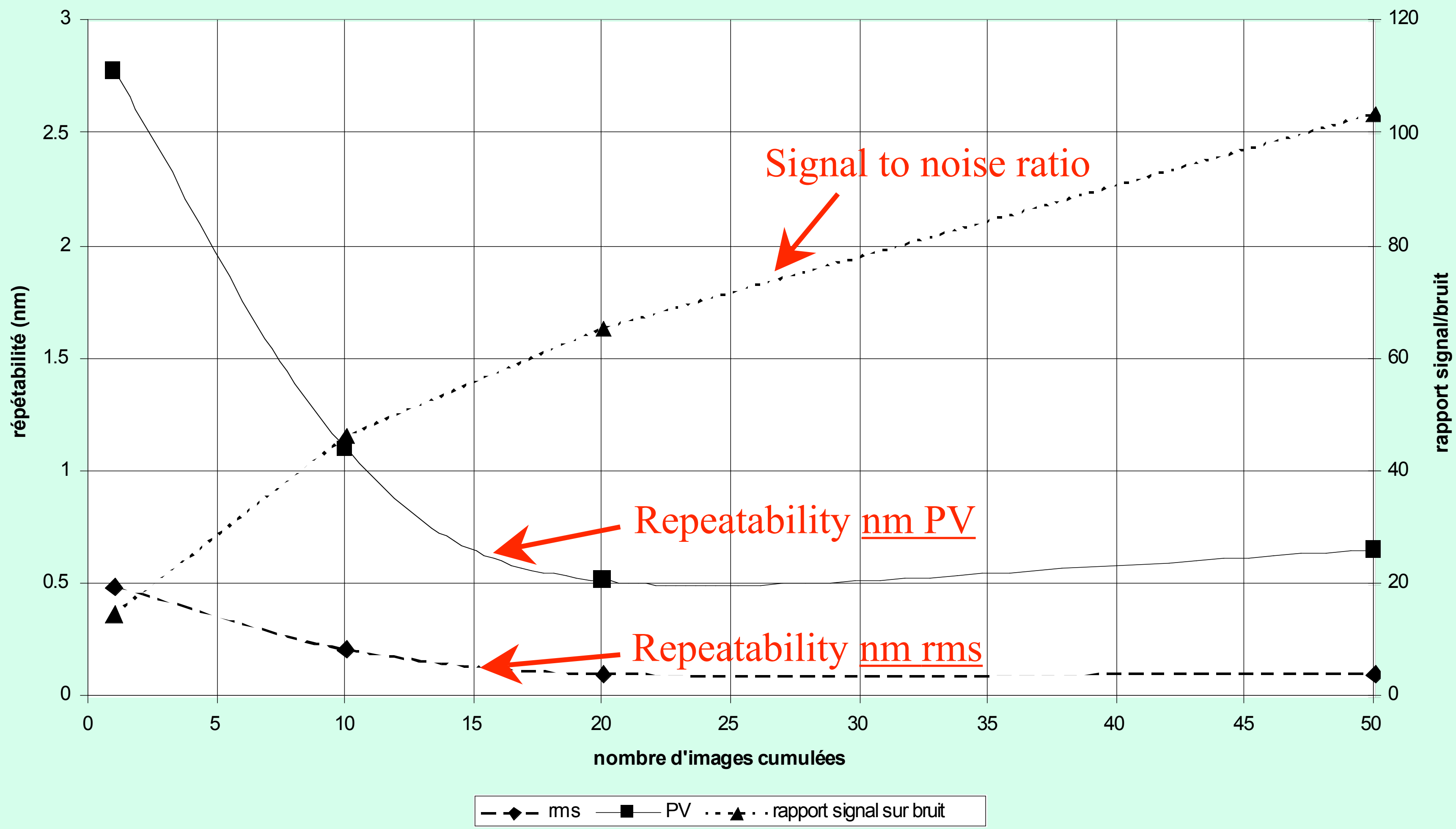
Knife Edge Scan of Vertical X-ray beam at LUCIA



Accuracy of the sensor is limited by shot noise.
But signal to noise ratio can be improved by accumulation of several images :

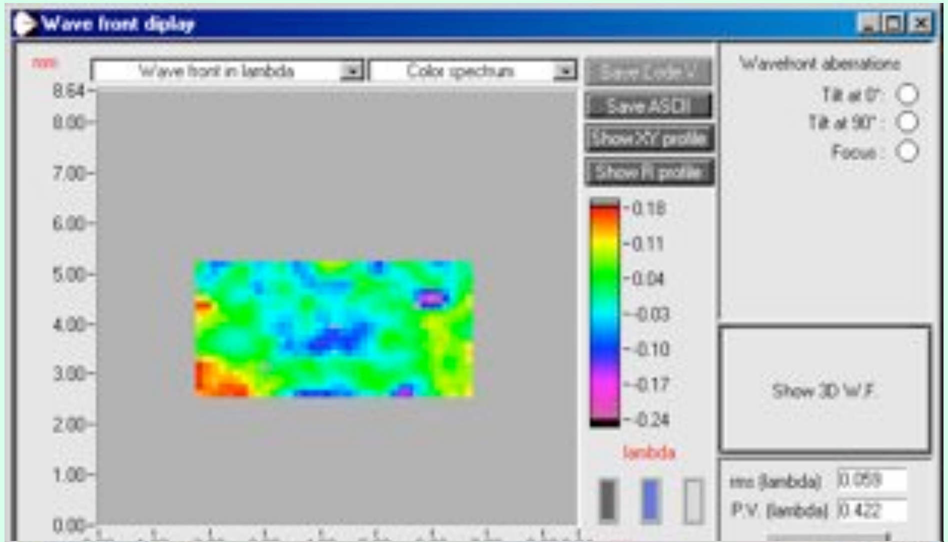


répétabilité vs moyennage image à 2100 eV

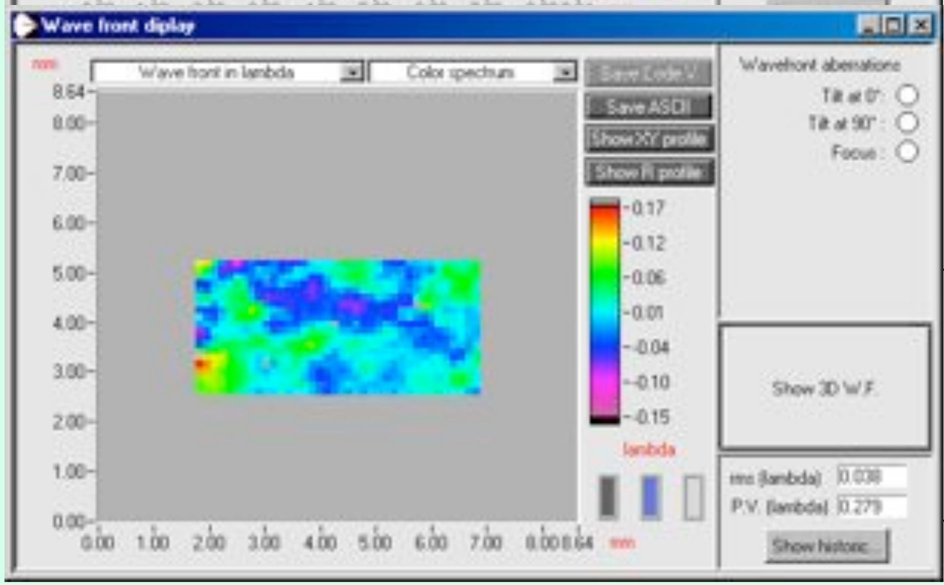


➤ Possible IMPROVEMENTS

Use of a high readout rate (30 Hz) Hamamatsu CCD camera

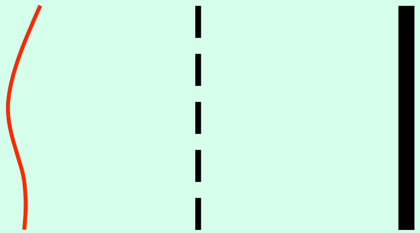


Accumulation of 100 images : 3 s
Repeatability : 0.06 nm rms
0.42 nm PV

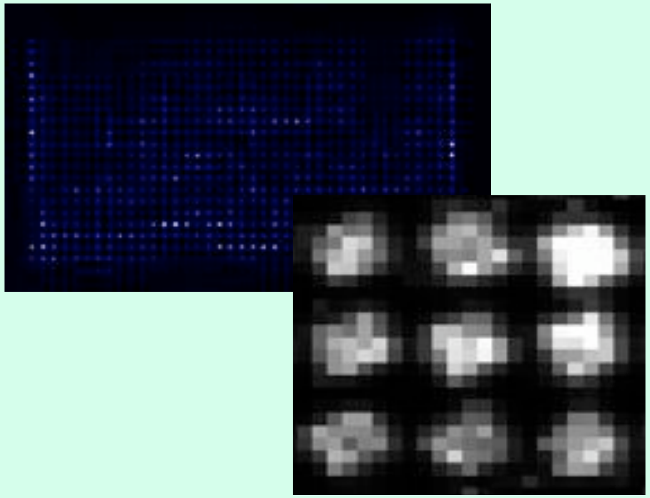


Accumulation of 500 images : 15 s
Repeatability : 0.038 nm rms
0.28 nm PV

Direct detection



1000x1000 pixels of 8µm
Grid pitch of 57 µm
Distance grid / CCD of 100mm



<u>Problems :</u>

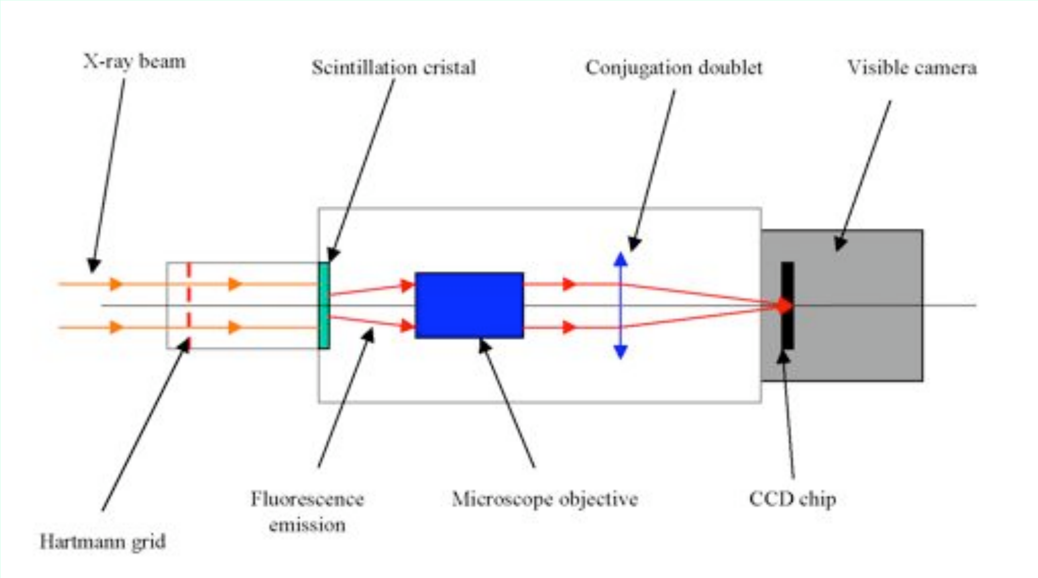
The shot noise limits the sensor sensitivity

The CCD is slowly « destroyed » by hard Xrays

The direct detection sensor is adapted to soft Xrays

Hartmann wavefront sensors for Xray beams

Indirect detection : adapted for hard Xrays

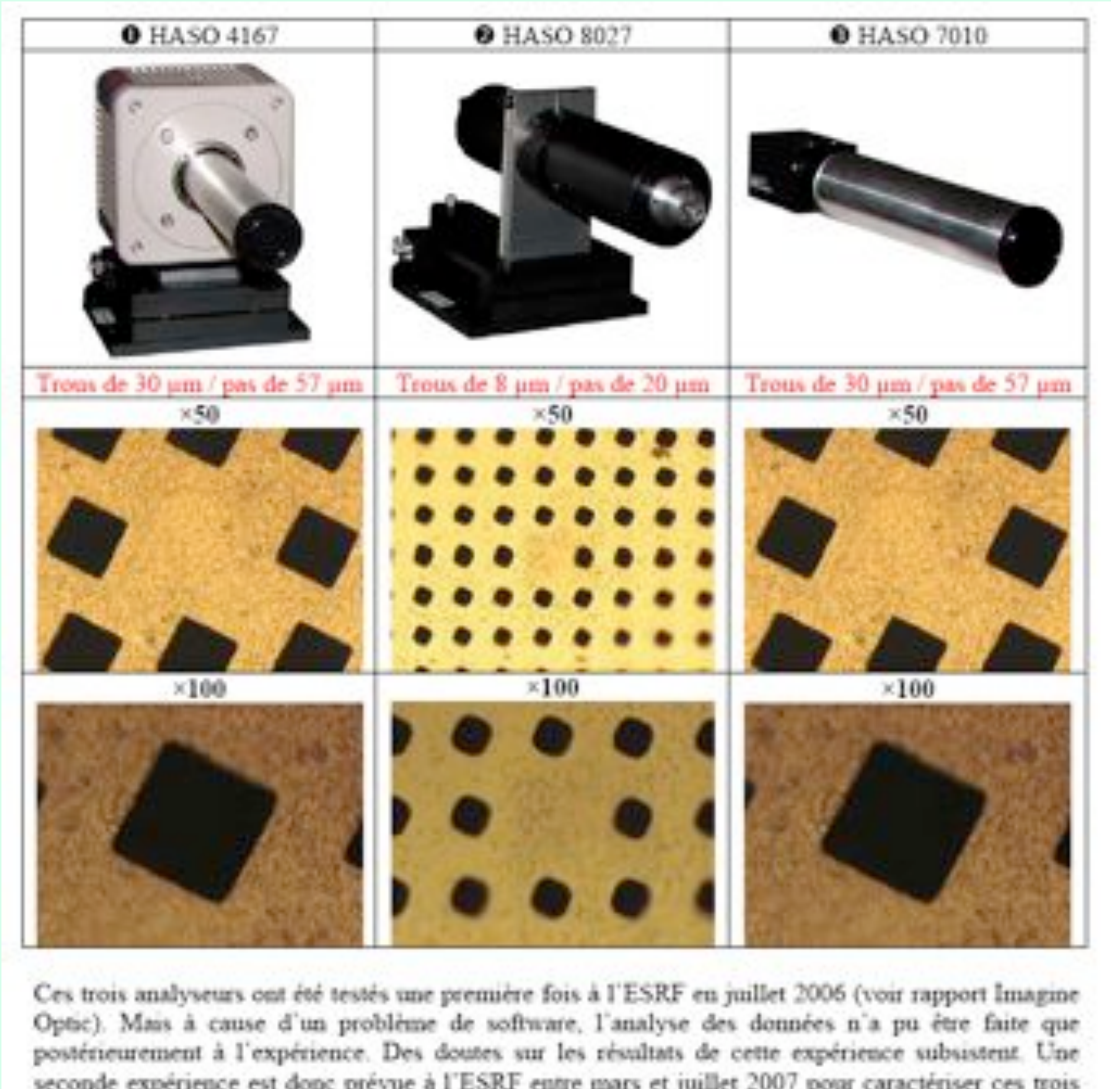


640x480 pixels of 7.4µm
Visible magnification x4.5
Grid pitch of 20 µm
Distance grid / YAG of 14mm

Sensor sensitivity : 0.023 nm rms
Sensor accuracy : 0.25 nm rms

limited by the calibration process

The X-ray Hartmann wave-front sensor for in situ alignment



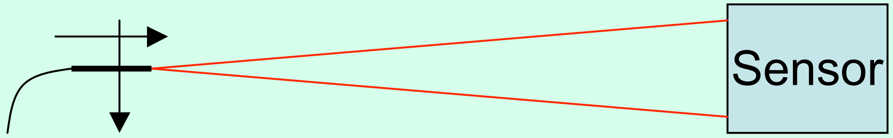
❶ HASO 4167	❷ HASO 8027	❸ HASO 7010
Trous de 30 µm / pas de 57 µm	Trous de 8 µm / pas de 20 µm	Trous de 30 µm / pas de 57 µm
×50	×50	×50
×100	×100	×100

Ces trois analyseurs ont été testés une première fois à l'ESRF en juillet 2006 (voir rapport Imagine Optic). Mais à cause d'un problème de software, l'analyse des données n'a pu être faite que postérieurement à l'expérience. Des doutes sur les résultats de cette expérience subsistent. Une seconde expérience est donc prévue à l'ESRF entre mars et juillet 2007 pour caractériser ces trois

Hartmann wavefront sensors for Xray beams

Calibration process :

For visible wavefront sensors



Source on translation stages
Single mode fiber : no aberration
Measured tilts and curvature must fit the real movement of the source

For XRays wavefront sensors

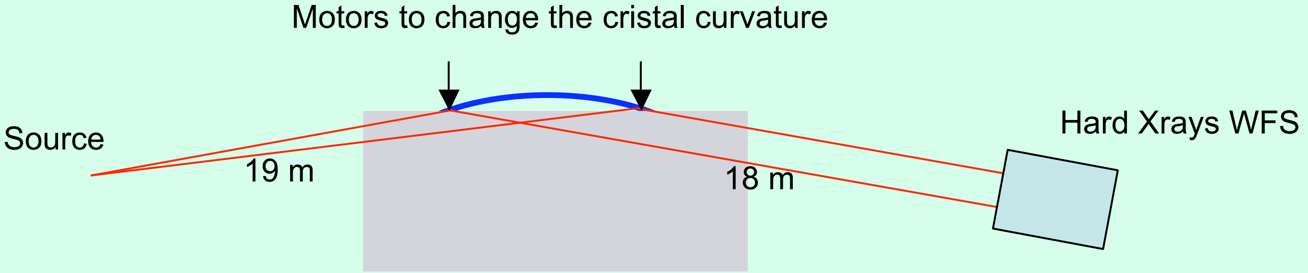
1/ We use a visible source, the Talbot diffraction effect gives us a calculable image to adjust the main parameters of the calibration

2/ « at wavelength » on the most possible « aberration free » beam, some measurements are done to finalize the calibration

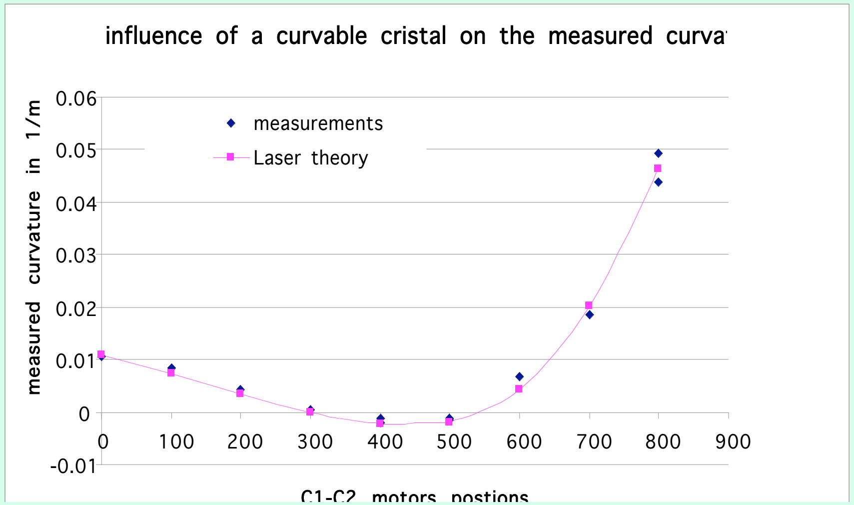
> ***Soft Xrays*** *: A small pinhole is set in the beam to diffract a pure diverging beam.*
> ***Hard Xrays*** *: Some small areas of the beam are used for different positions of the sensor relatively to the beam. These measurements are averaged.*

Hartmann wavefront sensors for Xray beams

Hard Xrays : measurement of the influence of a curvable cristal on CRISTAL beam line at SOLEIL at ***10.6 keV***



We plotted the curvature measured by the sensor (in dioptries) in function of the position of the motors. The fit is obtained by using the laser propagation theory.



- Xrays beams can be modelized by the propagation of a gaussian beam in vaccum.
- Even at this short wavelength, the effect of diffraction must be taken into account.
- The Xrays source can be considered as a « Waist »

Conclusion

- **Hartman based Wavefront sensor are available from VUV to hard X-ray (Imagine Optic)**
- **Small actuator design on specs are available (ISP System)**
- **A full adaptive optics solution is available (Wavefront sensor + mirror on specifications) are avalabile (Imagine Optic)**

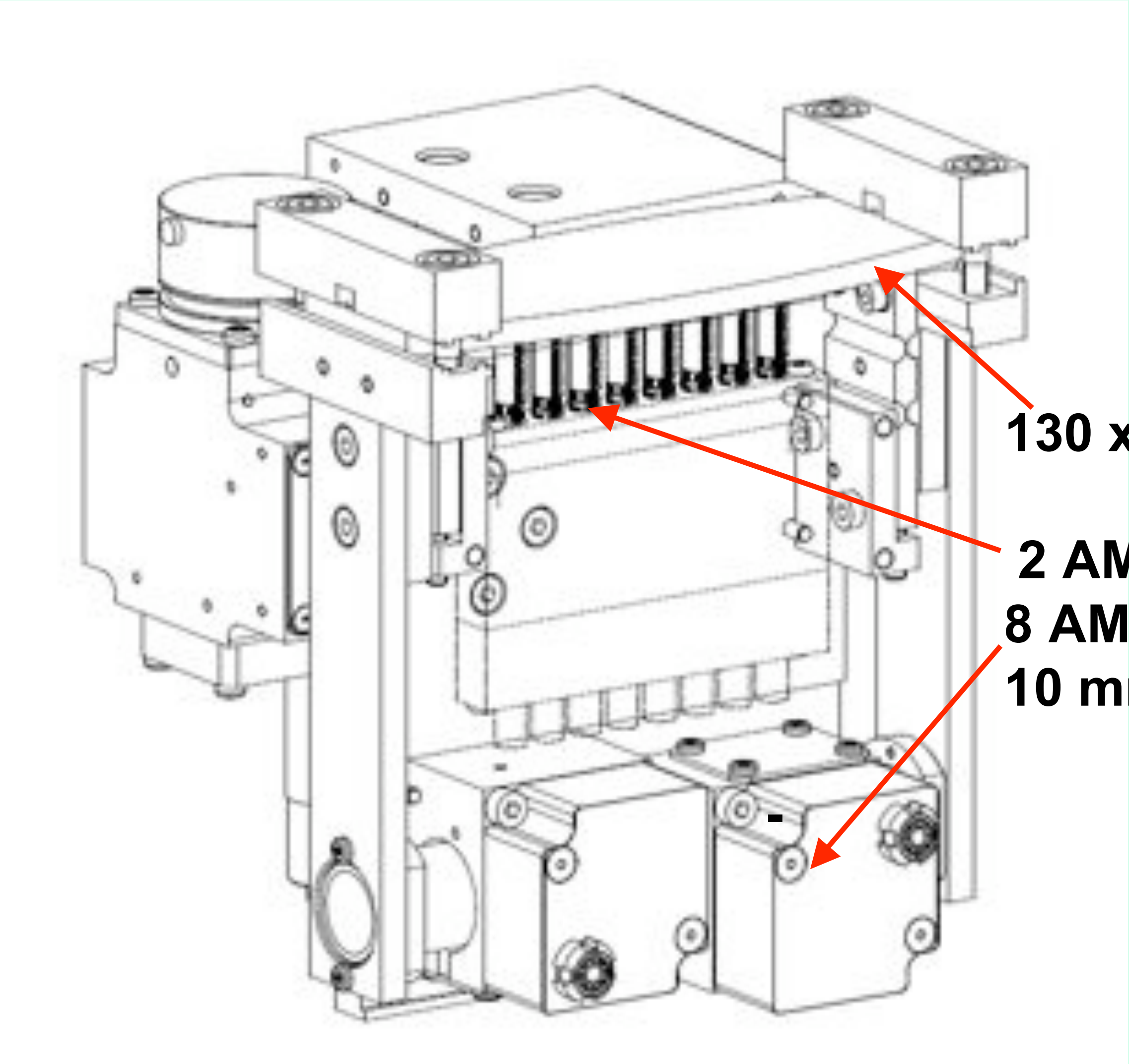
More to do

Test on a beamline the full system

SOLEIL and DIAMOND end of November

1. Development of KB mirrors with mirror cooling fixture for more powerful X-ray beams (MARX2)
2. Smaller mirror possible →

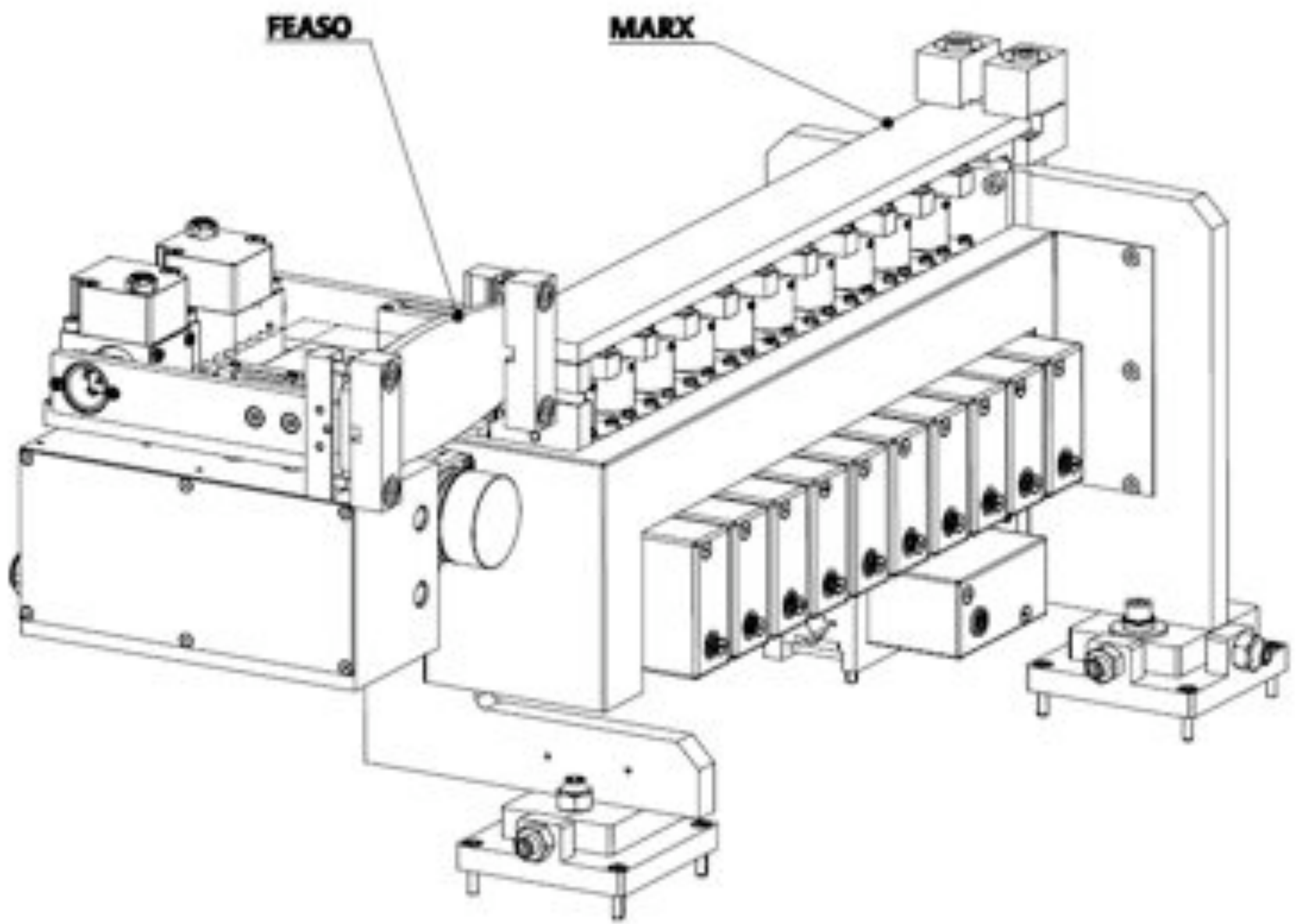
Mini MARX



130 x 40mm (torpédo shape)

2 AME40 (+40N) for curvature
8 AME3 (+/-3N) for small correction
10 mm distance

Minimum radius 23 m


FEASO
MARX

THANKS TO THE MARX PROJECT TEAM

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  - Mourad IDIR
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  - Thierry MORENO
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  - Guillaume DOVILLAIRE
  - Johan FLORIOT
- ***ISP SYSTEM***
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  - Lionnel ESCOLANO
  - Nicolas NIVELET
  - Benjamin SAUX

Thank you for your attention