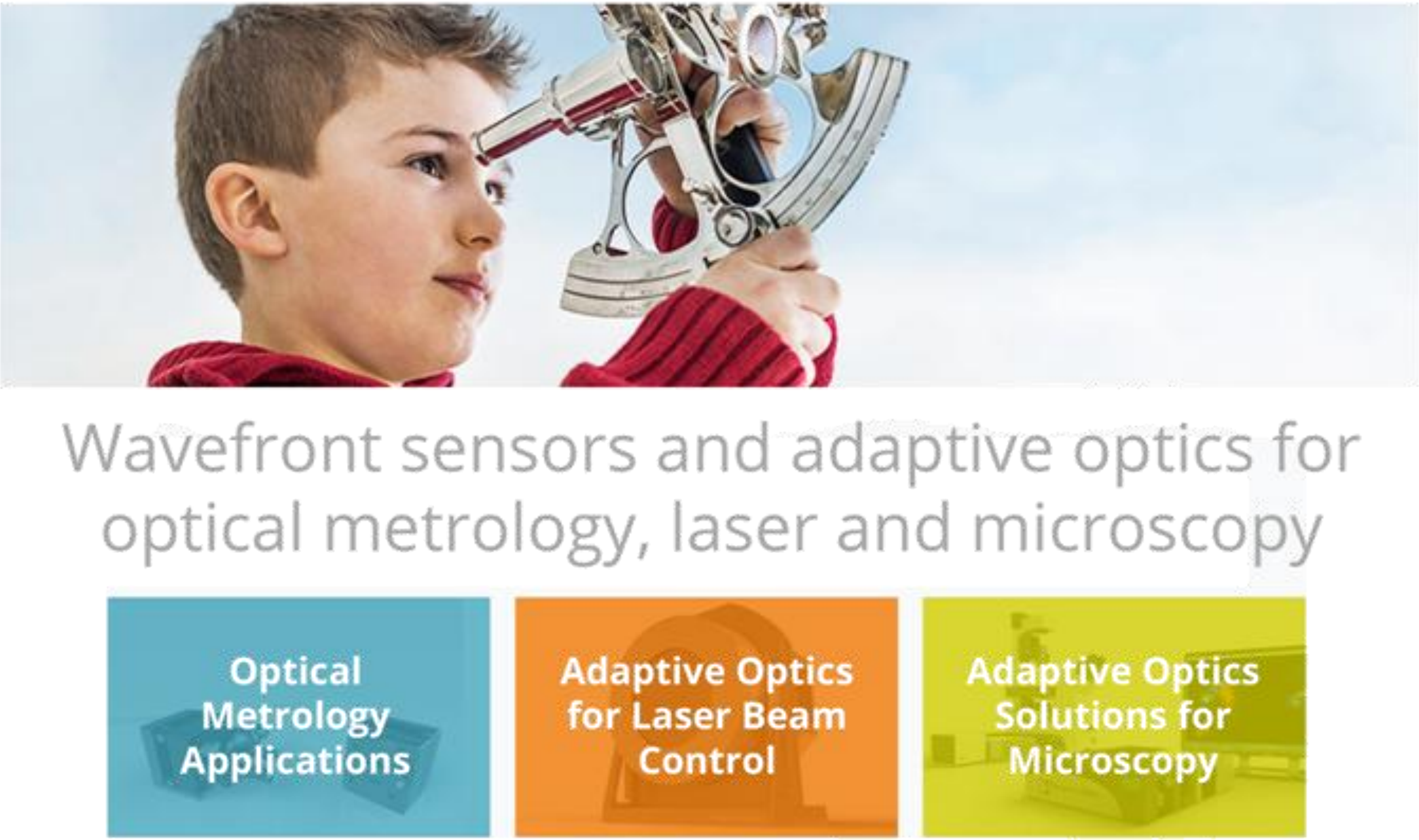
Hartmann wavefront sensing
Beamline alignment

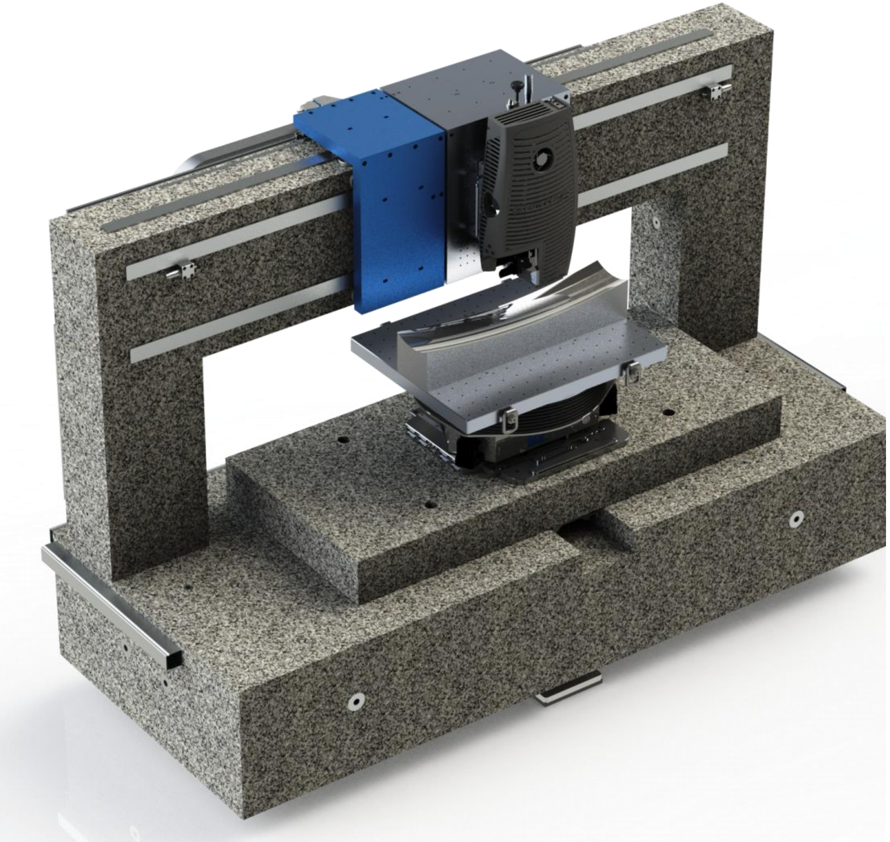
Guillaume Dovillaire



Wavefront sensors and adaptive optics for optical metrology, laser and microscopy

Metrology : Off-line metrology

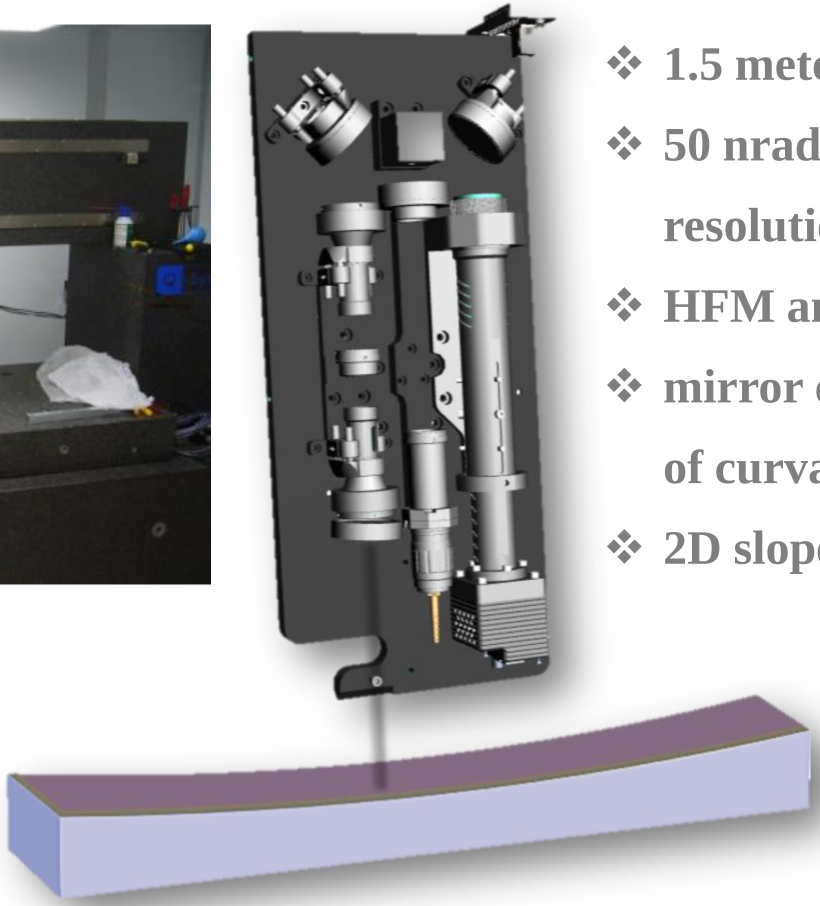
EUREKA Eurostar project



SHARPeR
EUROSTARS PROJECT

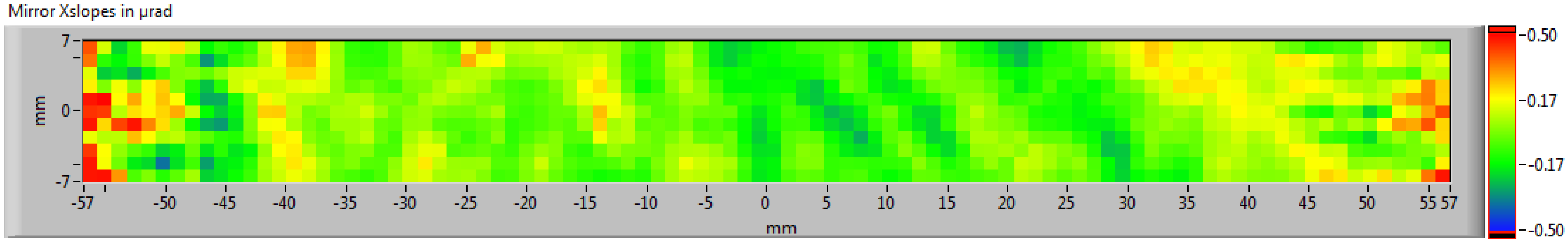
Off-line metrology

Optical head at BNL

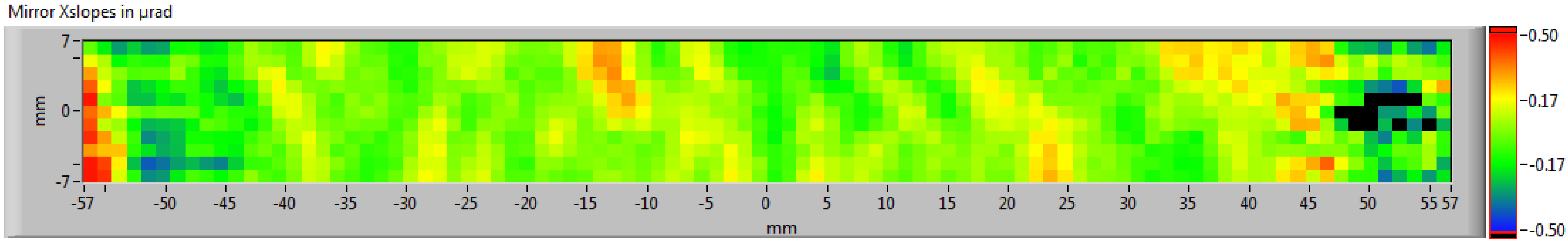


- 1.5 meter long mirrors
- 50 nrad rms accuracy / 1.2mm resolution
- HFM and VFM configuration
- mirror down to 1.5m of radius of curvature
- 2D slopes maps, height

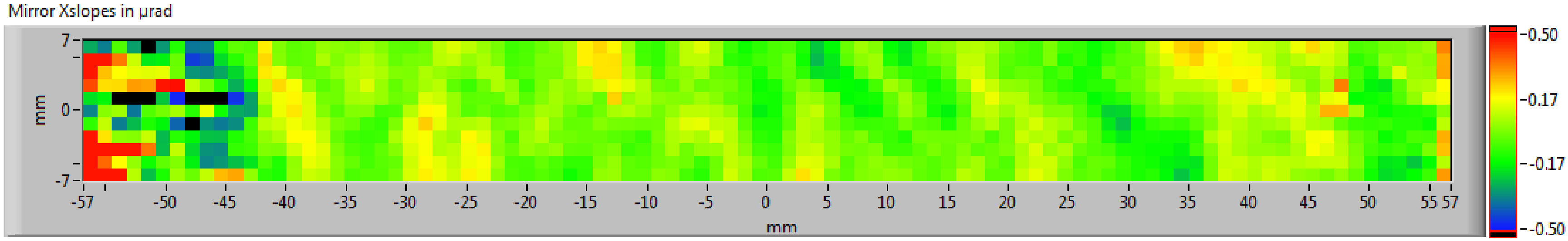
Flat mirror characterization



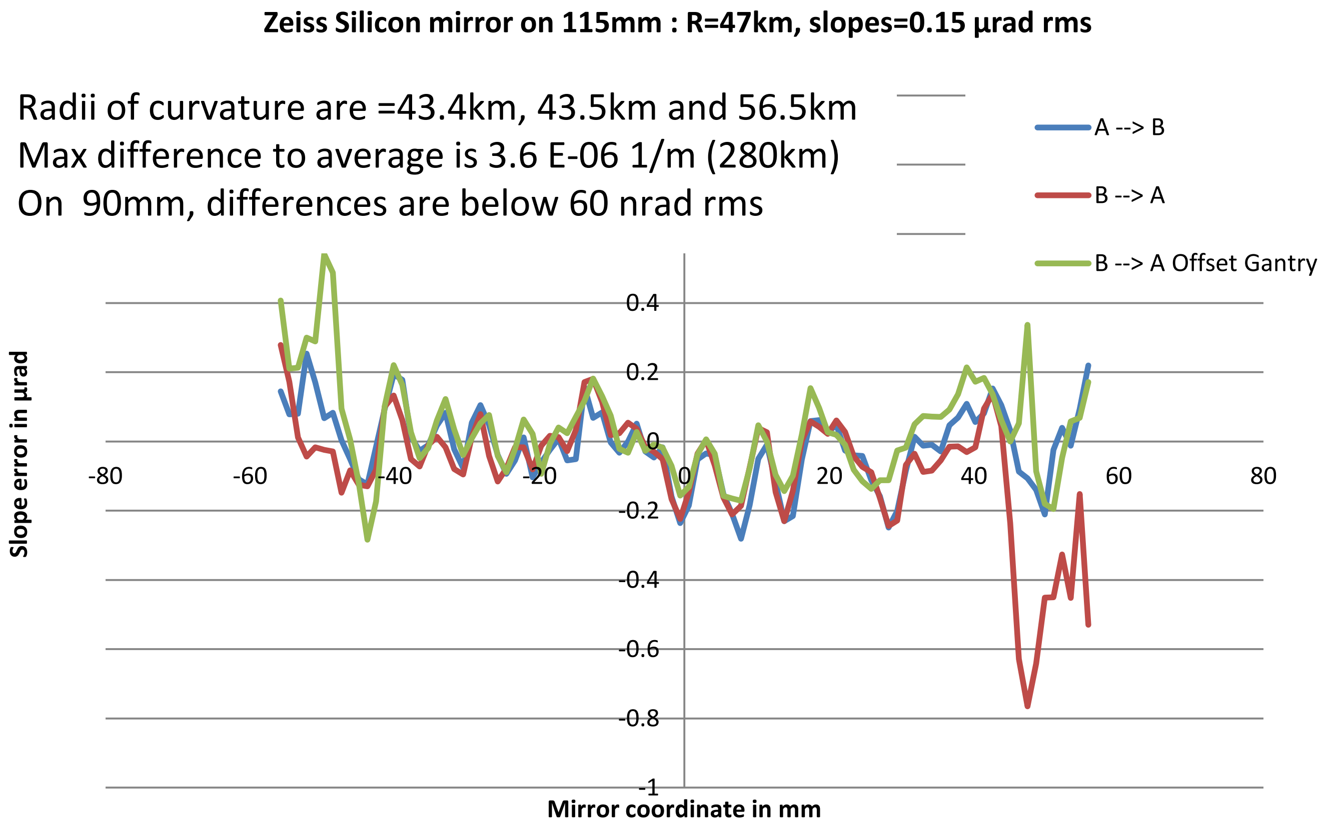
Mirror flipped and data flipped



Mirror shifted



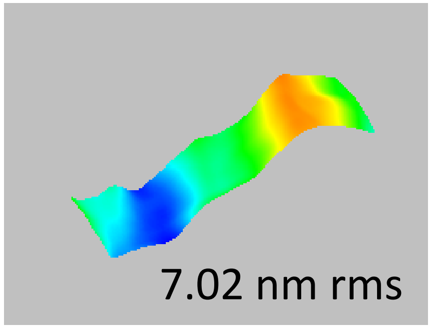
Flat mirror characterization

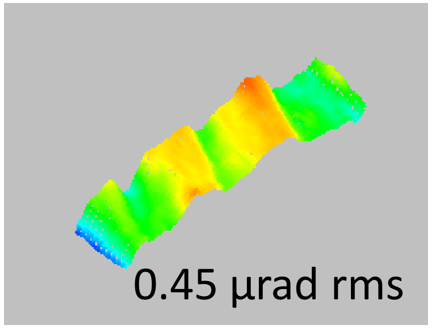


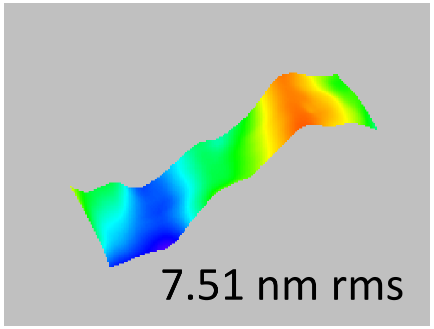
Toroidal mirror characterization

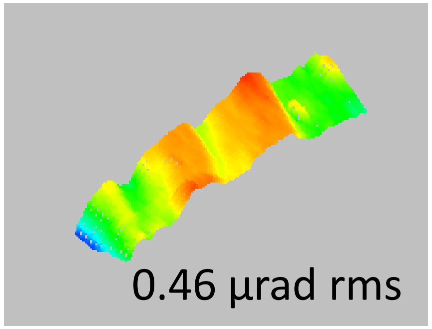
From A to B

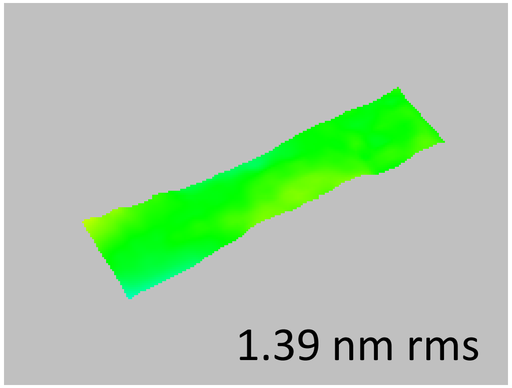
From B to A and data flipped

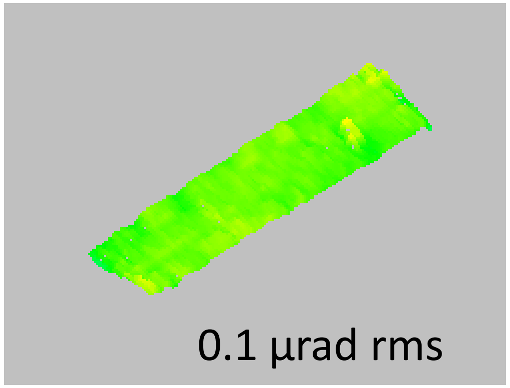

7.02 nm rms


0.45 µrad rms


7.51 nm rms


0.46 µrad rms

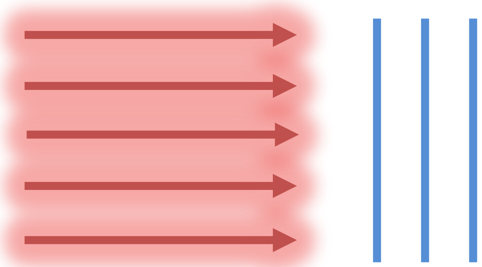

1.39 nm rms


0.1 µrad rms

EUV wavefront sensors
The Hartmann sensor

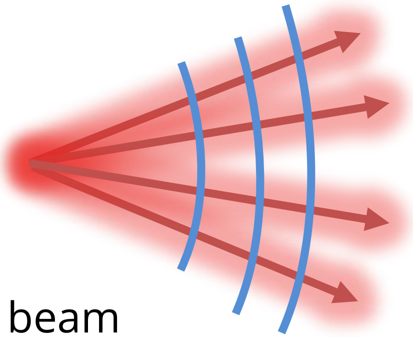
The wavefront

Geometrical approach: surface orthogonal to all rays



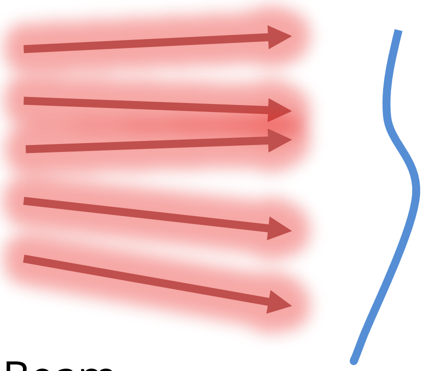
Collimated beam

Flat wavefront
No aberration



Diverging beam

Spherical wavefront
No aberration



Beam

Distorted wavefront
Some aberrations

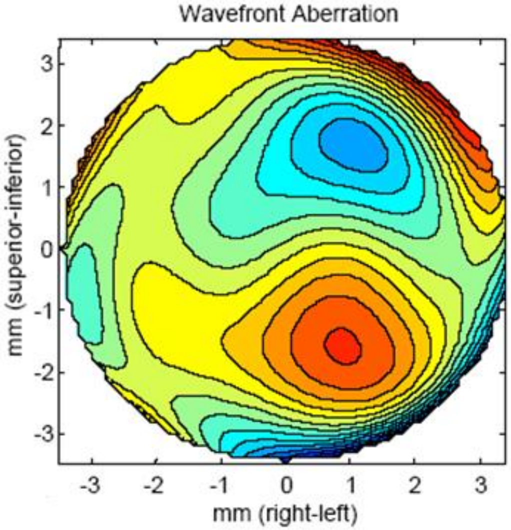
The wavefront

Diffraction approach: surface defined by phase = constant

$$U(\vec{r}) = a(\vec{r}).e^{i\varphi(\vec{r})} \longrightarrow \varphi(\vec{r}) = \frac{2\pi\delta(\vec{r})}{\lambda}$$

Amplitude

Phase

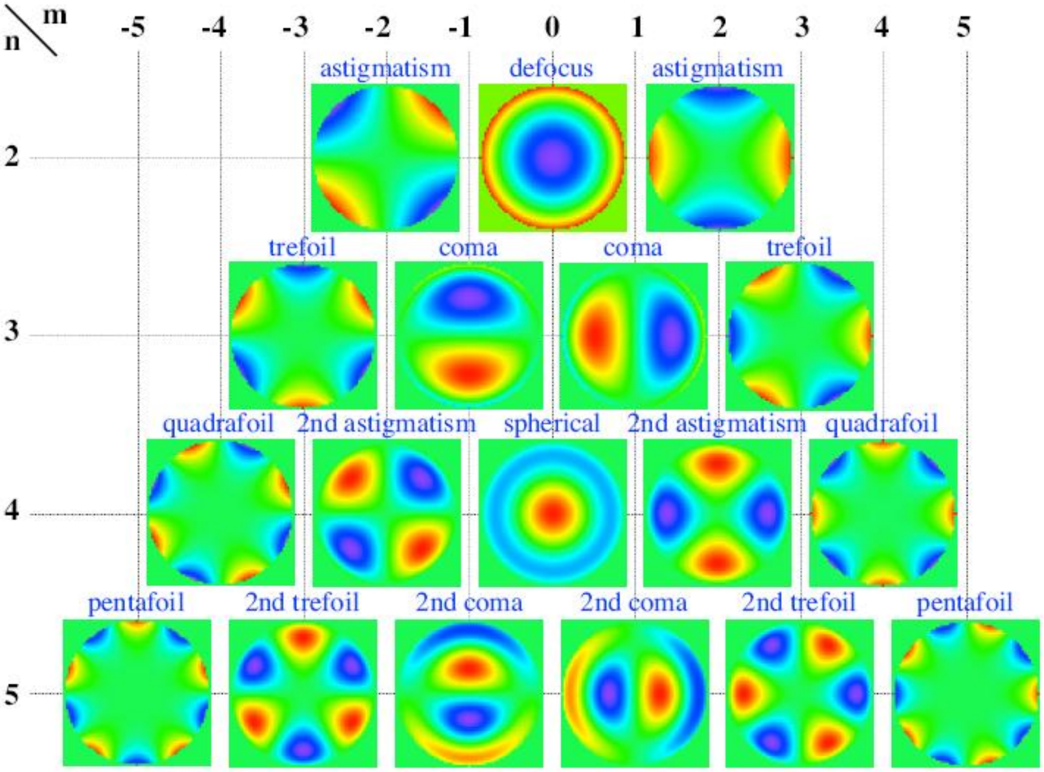


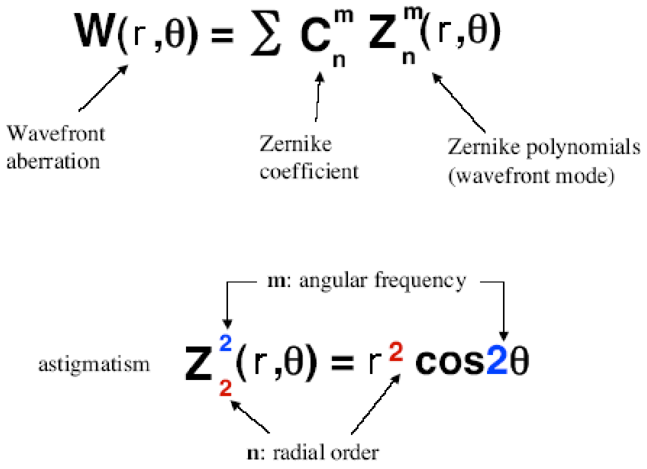
φ In radian

δ In micron

$\frac{\delta}{\lambda}$ In wave

The wavefront : The Zernike base





$$W(r,\theta) = \sum C_n^m Z_n^m(r,\theta)$$

Wavefront aberration

Zernike coefficient

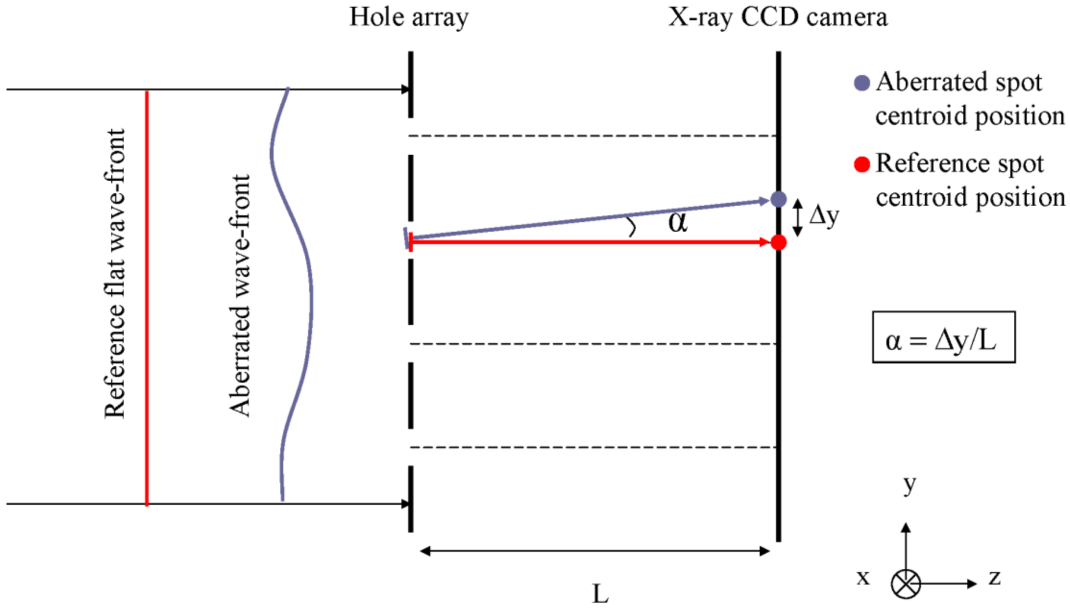
Zernike polynomials (wavefront mode)

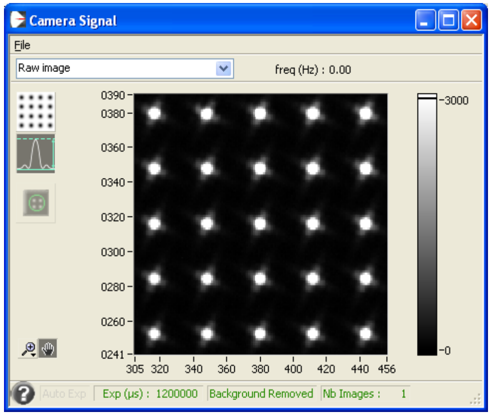
m: angular frequency

astigmatism $Z_2^2(r,\theta) = r^2 \cos 2\theta$

n: radial order

Hartmann wavefront sensors





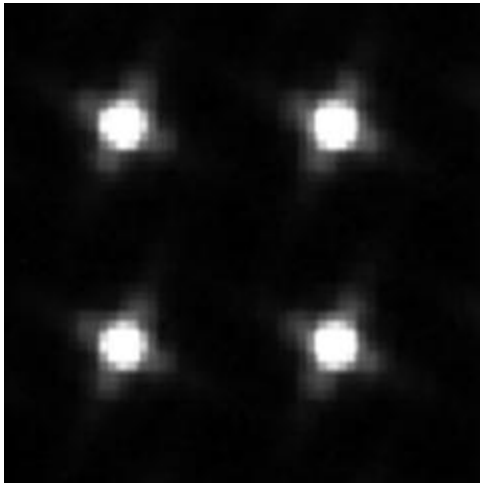
Raw image

freq (Hz) : 0.00

Exp (µs) : 1200000

Background Removed

Nb Images : 1

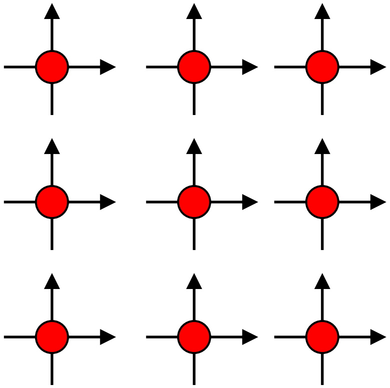


Holes are small enough to create diffraction on the CCD

Holes pitch is large enough to avoid crosstalk

Hartmann wavefront sensors : slopes integration

How calculating the wavefront knowing the slopes ?



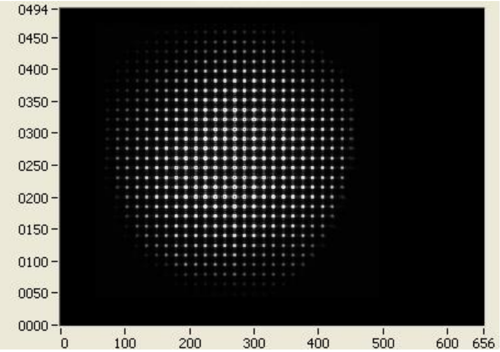
Wave-front estimation from wave-front slope measurements
W.H. Southwell, JOSA Vol70, No 8, Août 1980

$$\frac{S^{x}_{i+1,j}+S^{x}_{i,j}}{2}=\frac{\Phi^{x}_{i+1,j}-\Phi^{x}_{i,j}}{Pitch_{hole}}$$

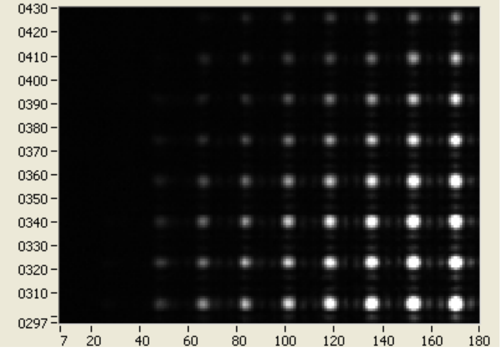
« Successive Over relaxation method »

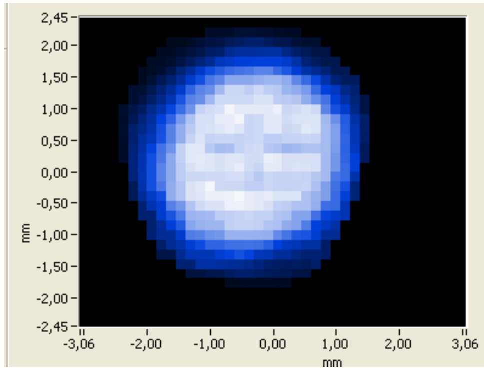
$$\Phi^{(m+1)}_{j,k}=\Phi^{(m)}_{j,k}+\omega Err(\Phi^{(m)}_{j,k},P_{j,k})$$

Hartmann wavefront sensors



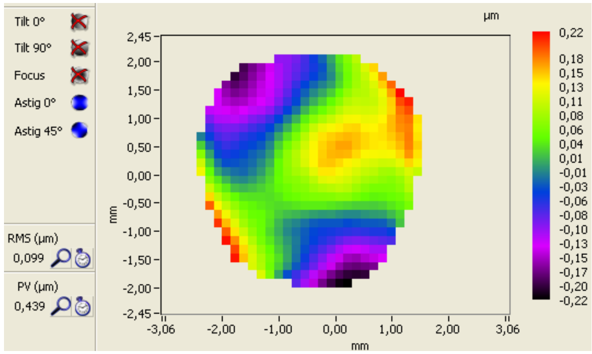
Raw signal on the CCD sensor





Measured intensity profile

$$U(\vec{r})=a(\vec{r}).e^{i\varphi(\vec{r})}$$



RMS (µm) 0,099

PV (µm) 0,439

Measured wavefront

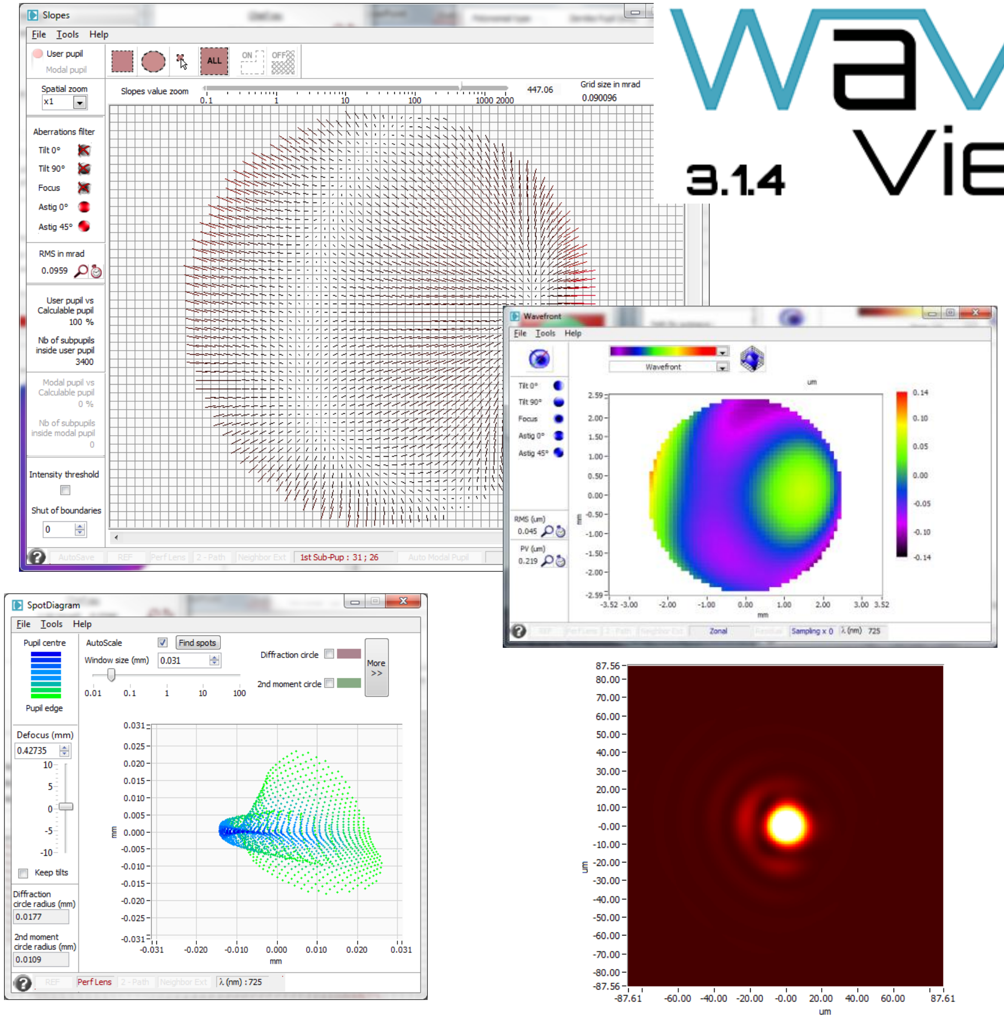
imagine optic™

HASO EUV

HASO
EUV

4 to 40nm
λ/75 rms accuracy
72x72 holes

WaveView 3.14



RMS in mrad: 0.0959

User pupil vs Calculable pupil: 100 %

Nb of subpupils inside user pupil: 3400

Modal pupil vs Calculable pupil: 0 %

Nb of subpupils inside modal pupil: 0

RMS (um): 0.045

PV (um): 0.219

Sampling x 0

λ (nm): 725

Window size (mm): 0.031

Defocus (mm): 0.42735

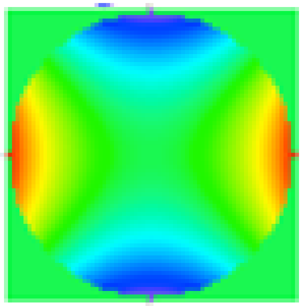
Diffraction circle radius (mm): 0.0177

2nd moment circle radius (mm): 0.0109

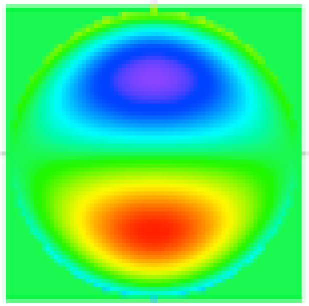
λ (nm) : 725

Beam lines alignment

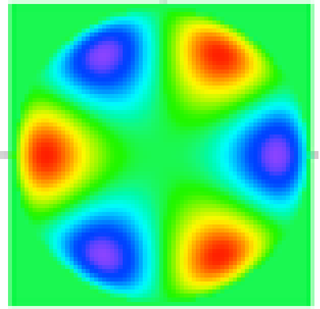
Idea 1 : I understand the wave front I measure



Astigmatism
The benders of my KB do not focus in the same plane



Coma
One of my KB bender is not optimized
My ellipsoid is not aligned

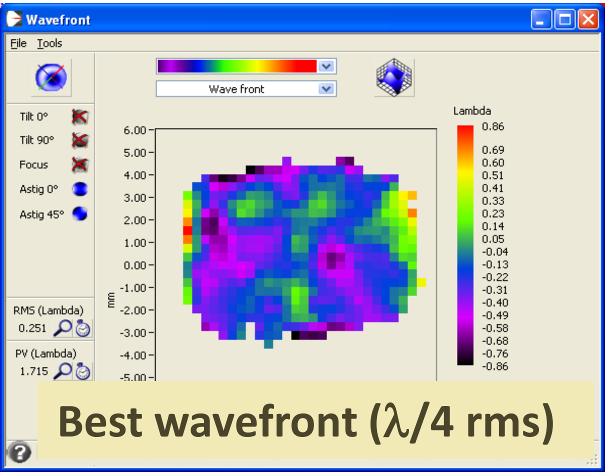


Something
I don’t know…

At-λ alignement of a Kirkpatrick-Baez optics

FERMI : KB alignement at 32nm

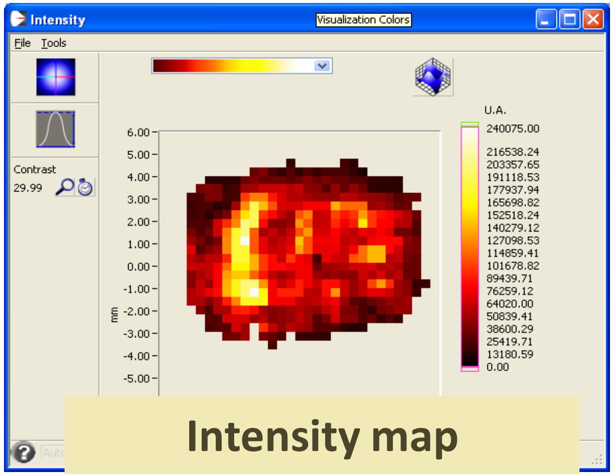
FERMI : Giovanni de Ninno, Lorenzo Raimondi, LOA : Philippe Zeitoun



RMS (Lambda) 0.251

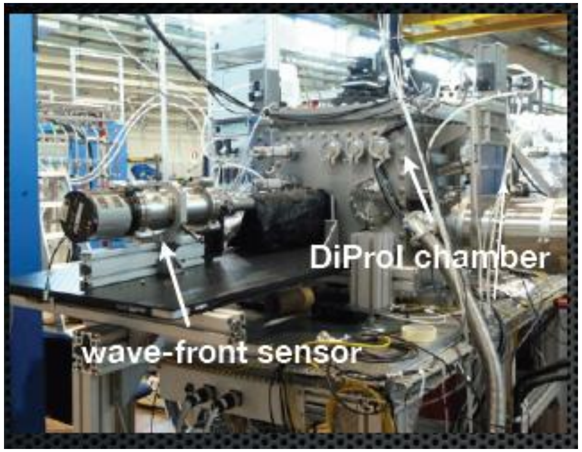
PV (Lambda) 1.715

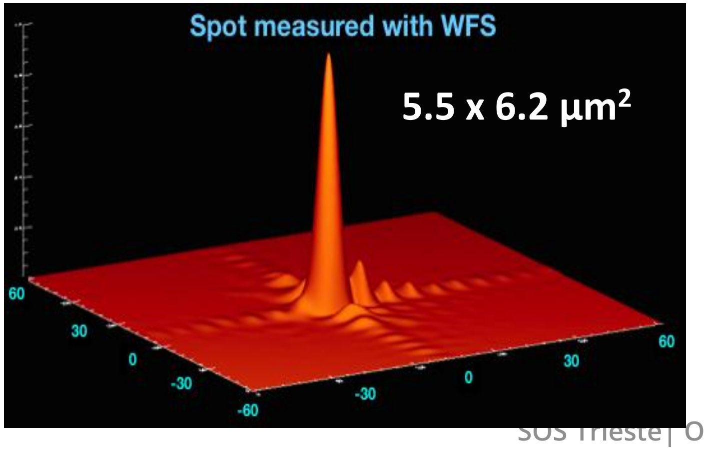
Best wavefront (λ/4 rms)



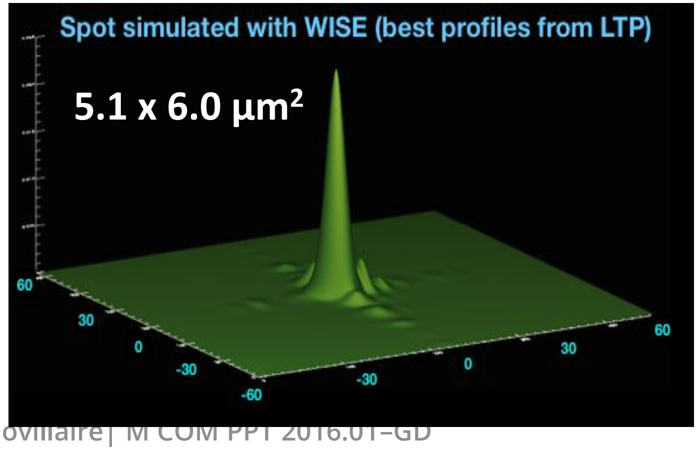
Contrast 29.99

Intensity map





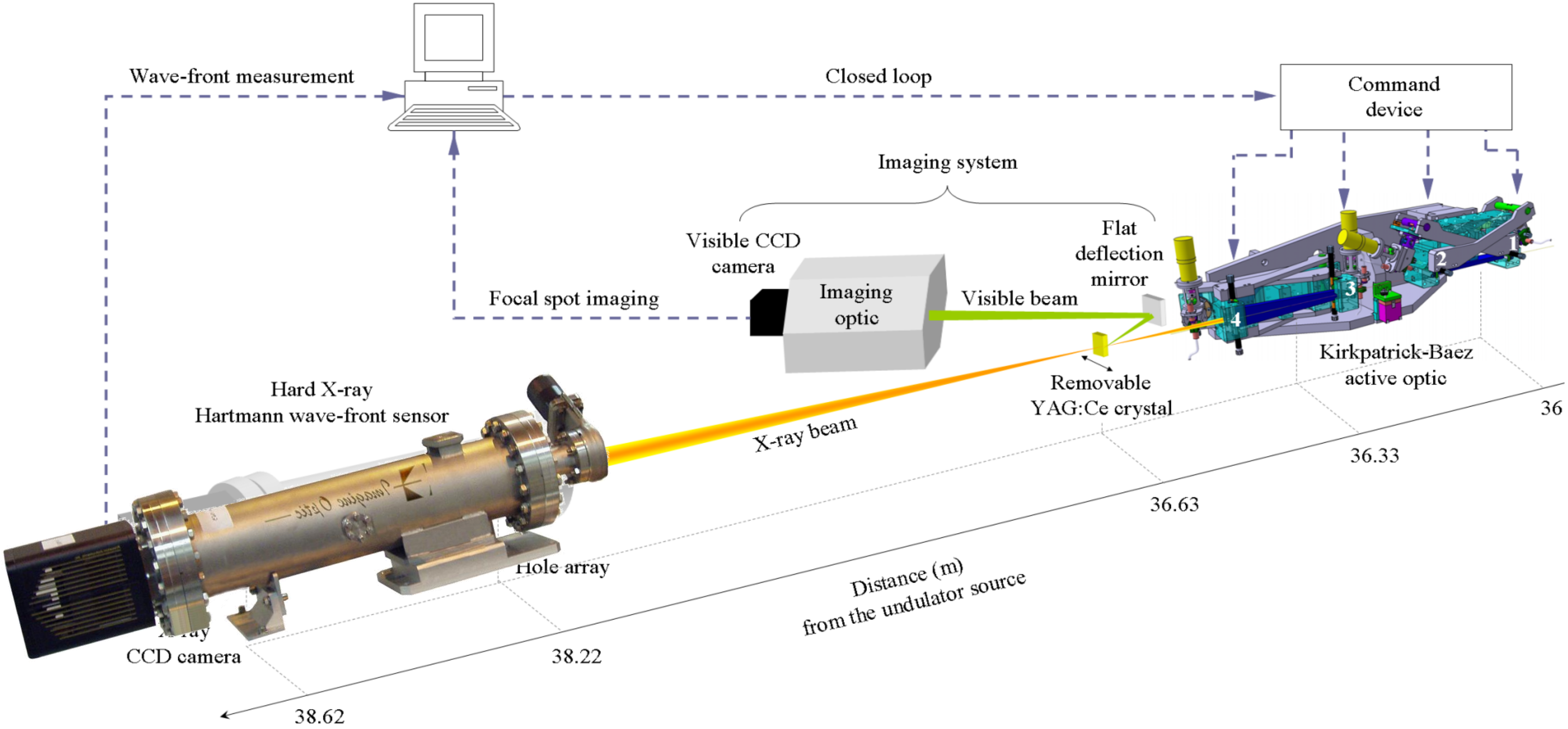
D.L.:
4.1 x 5.9 µm²



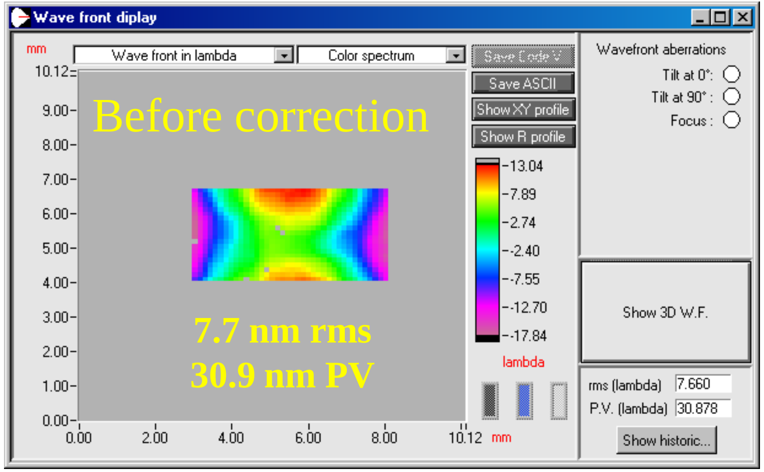
Idea 2 : I want an automatic alignement

SLS : automatic control of a KB at 3.5 keV

SOLEIL : Mourad Idir – Pascal Mercère – Pierre Lagarde



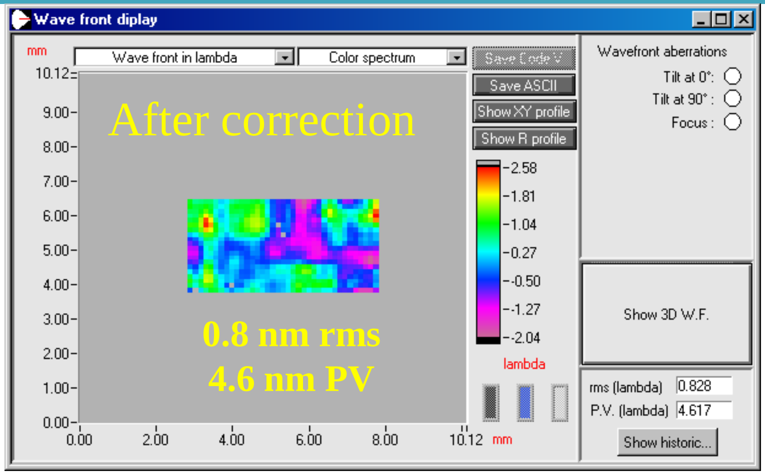
Wavefront correction in the tender X-Rays



Before correction

7.7 nm rms
30.9 nm PV

rms (lambda) 7.660
P.V. (lambda) 30.878

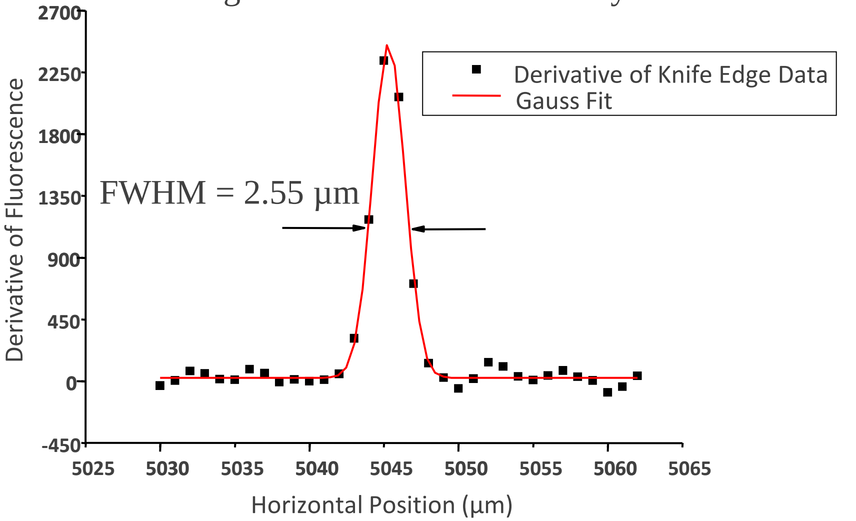


After correction

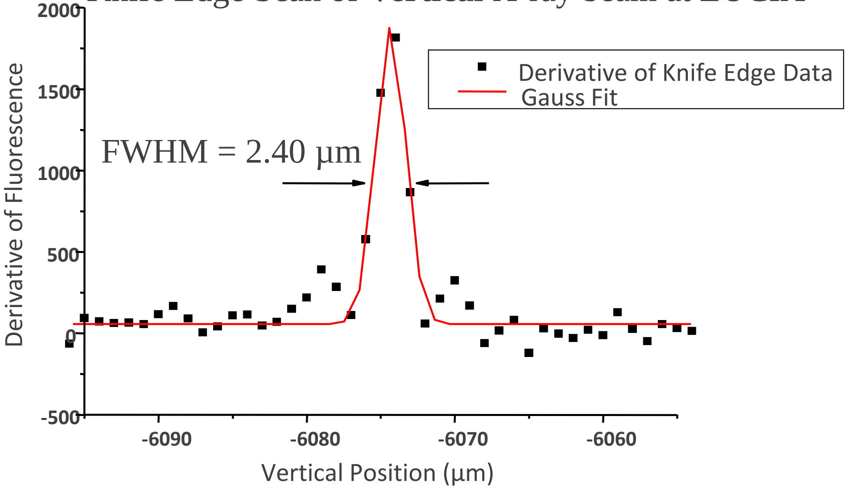
0.8 nm rms
4.6 nm PV

rms (lambda) 0.828
P.V. (lambda) 4.617

Knife Edge Scan of **Horizontal** X-ray beam at LUCIA

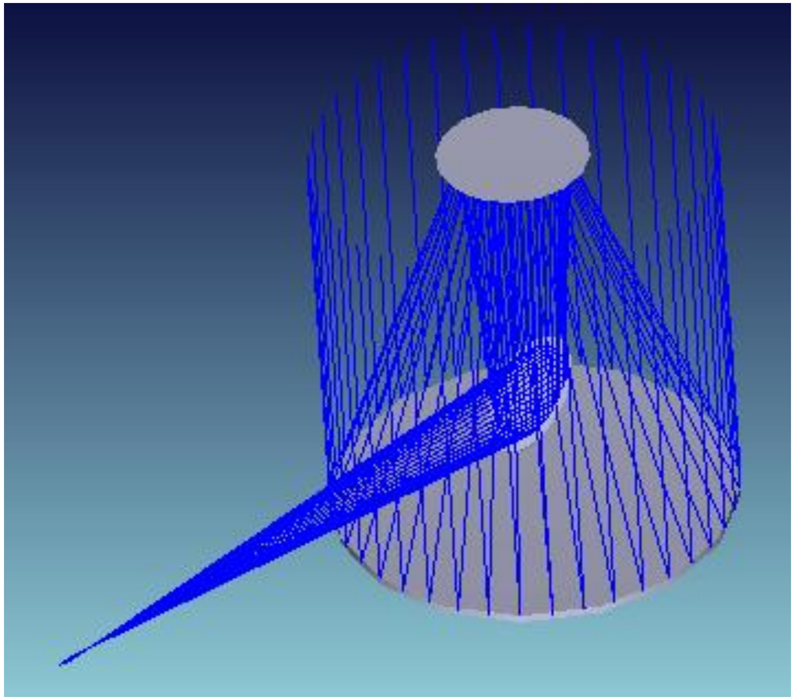


Knife Edge Scan of **Vertical** X-ray beam at LUCIA



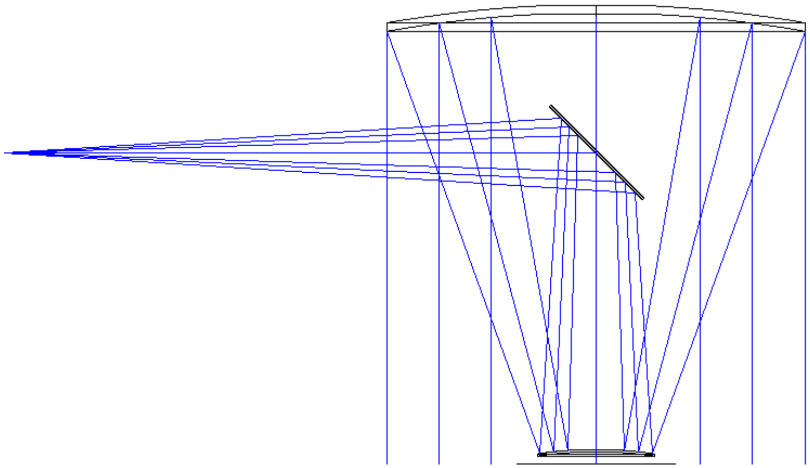
Idea 3:
Coupling wavefront measurements and optics simulation software

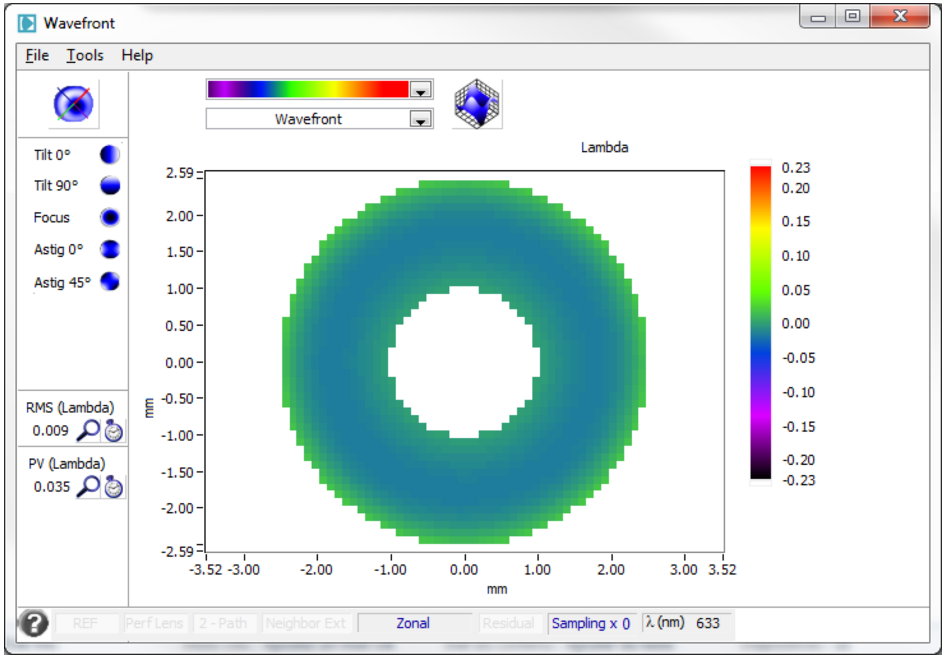
Example in visible : telescope alignment



Tzec Maun Foundation
1m diameter telescope
Modified Cassegrain type

The simulation tool: Zemax





RMS (Lambda) 0.009

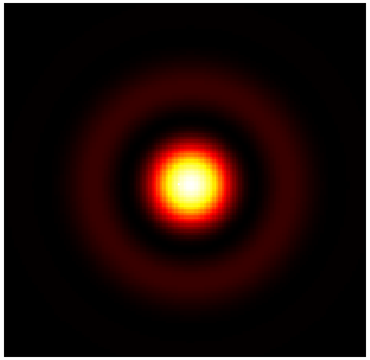
PV (Lambda) 0.035

Sampling x 0

λ (nm) 633

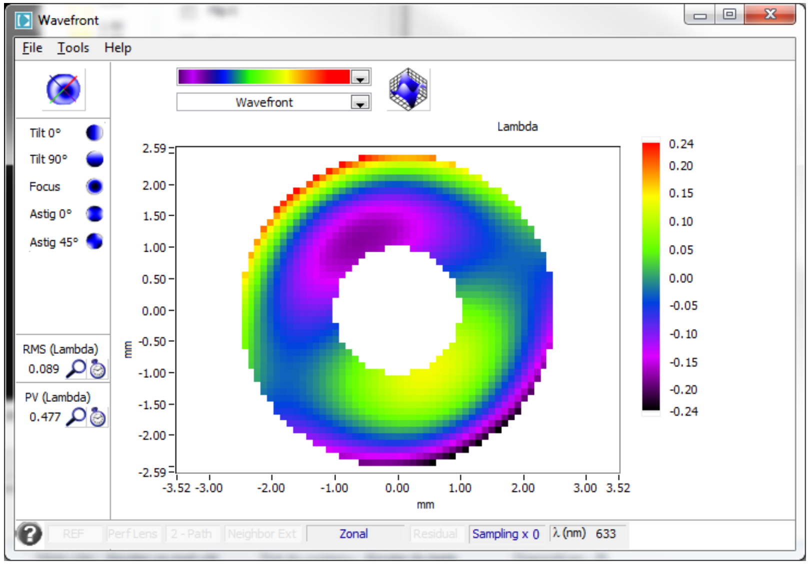
Expected performances

λ/100 rms WFE
Diffraction limited PSF



The measurment tool : HASO4 BB

HASO4 BROADBAND



RMS (Lambda) 0.089

PV (Lambda) 0.477

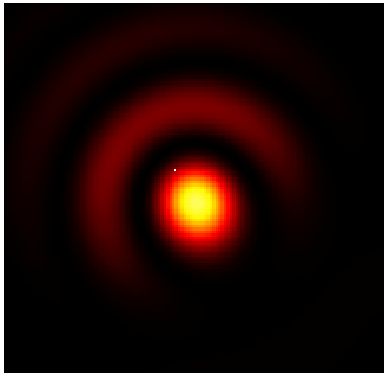
Zonal

Sampling x 0

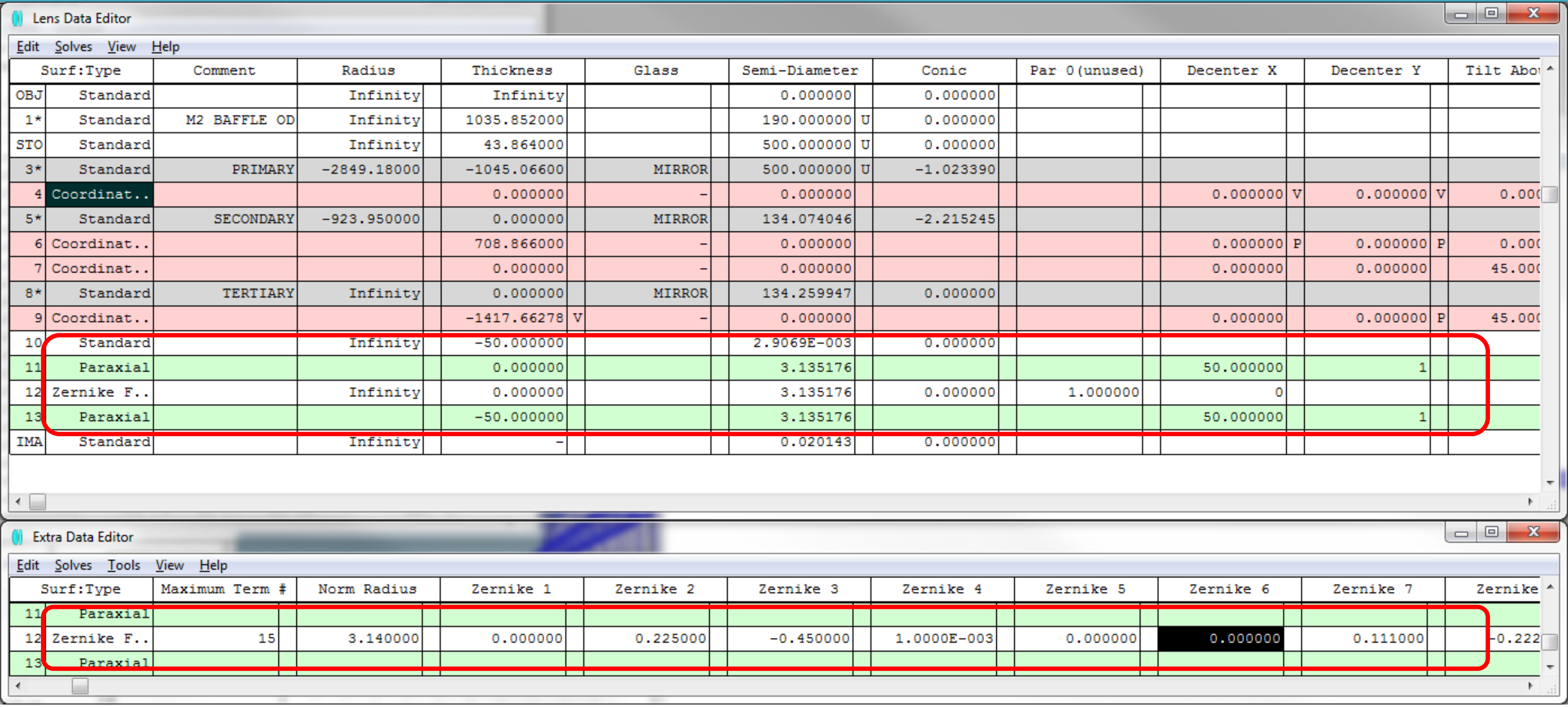
λ (nm) 633

Measured performances

λ/10 rms WFE
The coma aberration reduces the images contrast



The measurement is set in the model



Lens Data Editor

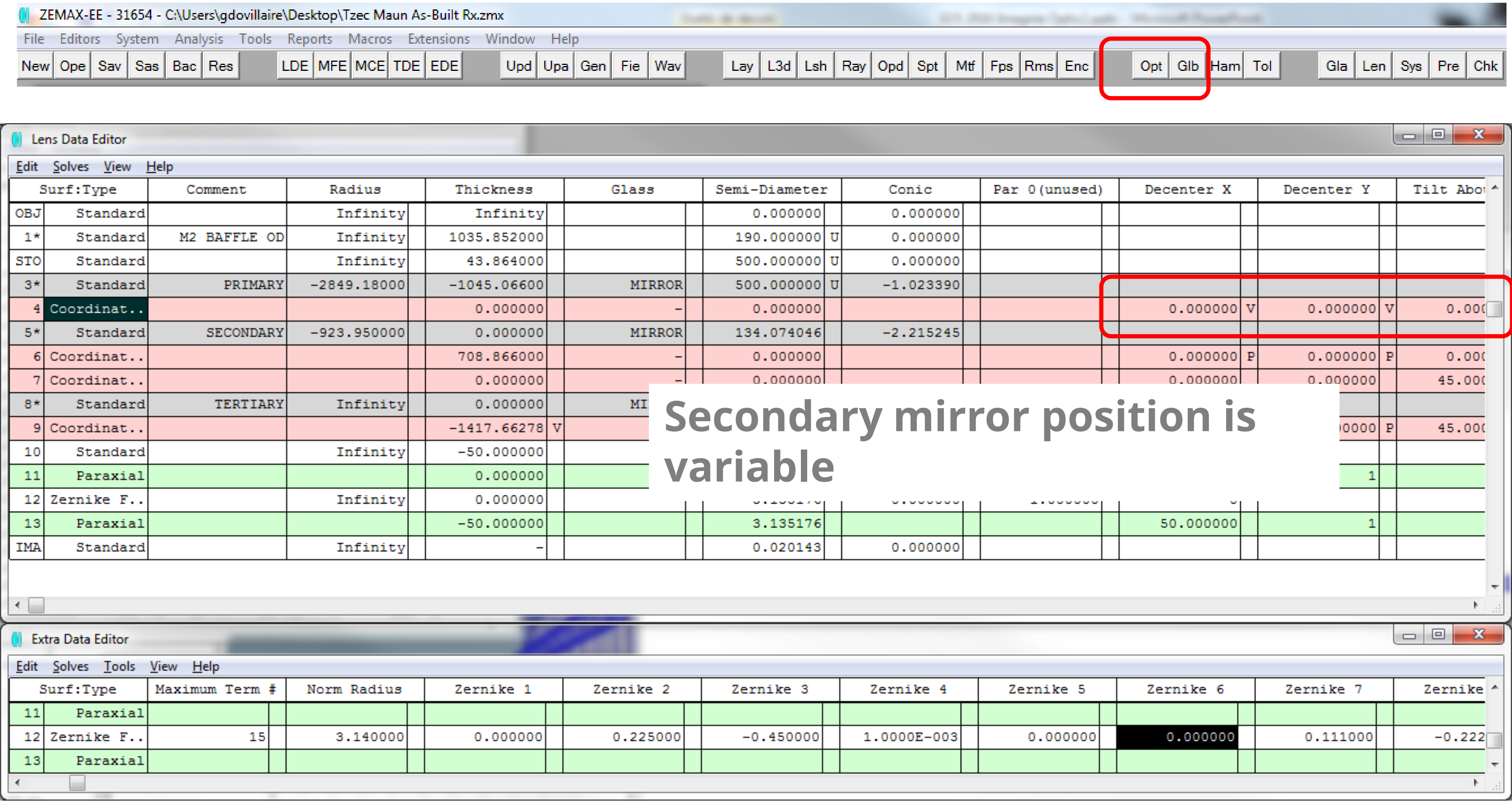
Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Decenter X	Decenter Y	Tilt Abo
OBJ	Standard		Infinity	Infinity		0.000000	0.000000				
1*	Standard	M2 BAFFLE OD	Infinity	1035.852000		190.000000 U	0.000000				
STO	Standard		Infinity	43.864000		500.000000 U	0.000000				
3*	Standard	PRIMARY	-2849.18000	-1045.06600	MIRROR	500.000000 U	-1.023390				
4	Coordinat..			0.000000	-	0.000000			0.000000 V	0.000000 V	0.00
5*	Standard	SECONDARY	-923.950000	0.000000	MIRROR	134.074046	-2.215245				
6	Coordinat..			708.866000	-	0.000000			0.000000 P	0.000000 P	0.00
7	Coordinat..			0.000000	-	0.000000			0.000000	0.000000	45.00
8*	Standard	TERTIARY	Infinity	0.000000	MIRROR	134.259947	0.000000				
9	Coordinat..			-1417.66278 V	-	0.000000			0.000000	0.000000 P	45.00
10	Standard		Infinity	-50.000000		2.9069E-003	0.000000				
11	Paraxial			0.000000		3.135176			50.000000	1	
12	Zernike F..		Infinity	0.000000		3.135176	0.000000	1.000000	0		
13	Paraxial			-50.000000		3.135176			50.000000	1	
IMA	Standard		Infinity	-		0.020143	0.000000				

Extra Data Editor

Surf:Type		Maximum Term #	Norm Radius	Zernike 1	Zernike 2	Zernike 3	Zernike 4	Zernike 5	Zernike 6	Zernike 7	Zernike
11	Paraxial										
12	Zernike F..	15	3.140000	0.000000	0.225000	-0.450000	1.0000E-003	0.000000	0.000000	0.111000	-0.222
13	Paraxial										

The wavefront aberrations are defined by the Zernike coefficients and included in the simulation software

The optimization process



Lens Data Editor

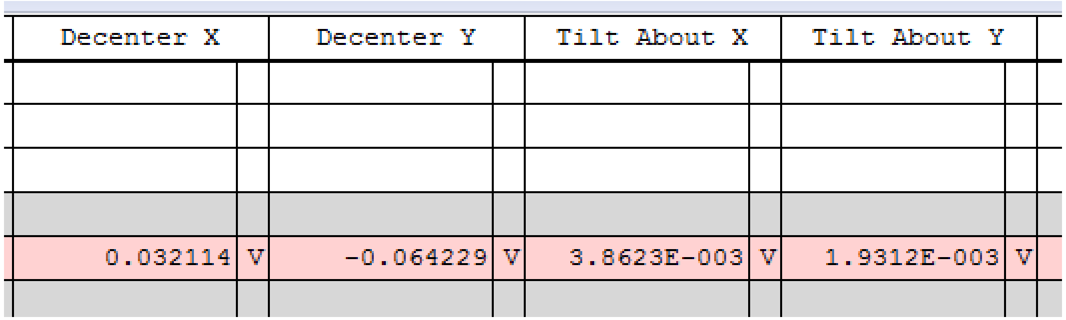
Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Decenter X	Decenter Y	Tilt Abo
OBJ	Standard		Infinity	Infinity		0.000000	0.000000				
1*	Standard	M2 BAFFLE OD	Infinity	1035.852000		190.000000 U	0.000000				
STO	Standard		Infinity	43.864000		500.000000 U	0.000000				
3*	Standard	PRIMARY	-2849.18000	-1045.06600	MIRROR	500.000000 U	-1.023390				
4	Coordinat..			0.000000	-	0.000000			0.000000 V	0.000000 V	0.00
5*	Standard	SECONDARY	-923.950000	0.000000	MIRROR	134.074046	-2.215245				
6	Coordinat..			708.866000	-	0.000000			0.000000 P	0.000000 P	0.00
7	Coordinat..			0.000000	-	0.000000			0.000000	0.000000	45.00
8*	Standard	TERTIARY	Infinity	0.000000	MI						
9	Coordinat..			-1417.66278 V						0000 P	45.00
10	Standard		Infinity	-50.000000							
11	Paraxial			0.000000						1	
12	Zernike F..		Infinity	0.000000							
13	Paraxial			-50.000000		3.135176			50.000000	1	
IMA	Standard		Infinity	-		0.020143	0.000000				

Extra Data Editor

Surf:Type		Maximum Term #	Norm Radius	Zernike 1	Zernike 2	Zernike 3	Zernike 4	Zernike 5	Zernike 6	Zernike 7	Zernike
11	Paraxial										
12	Zernike F..	15	3.140000	0.000000	0.225000	-0.450000	1.0000E-003	0.000000	0.000000	0.111000	-0.222
13	Paraxial										

Secondary mirror position is variable

The result

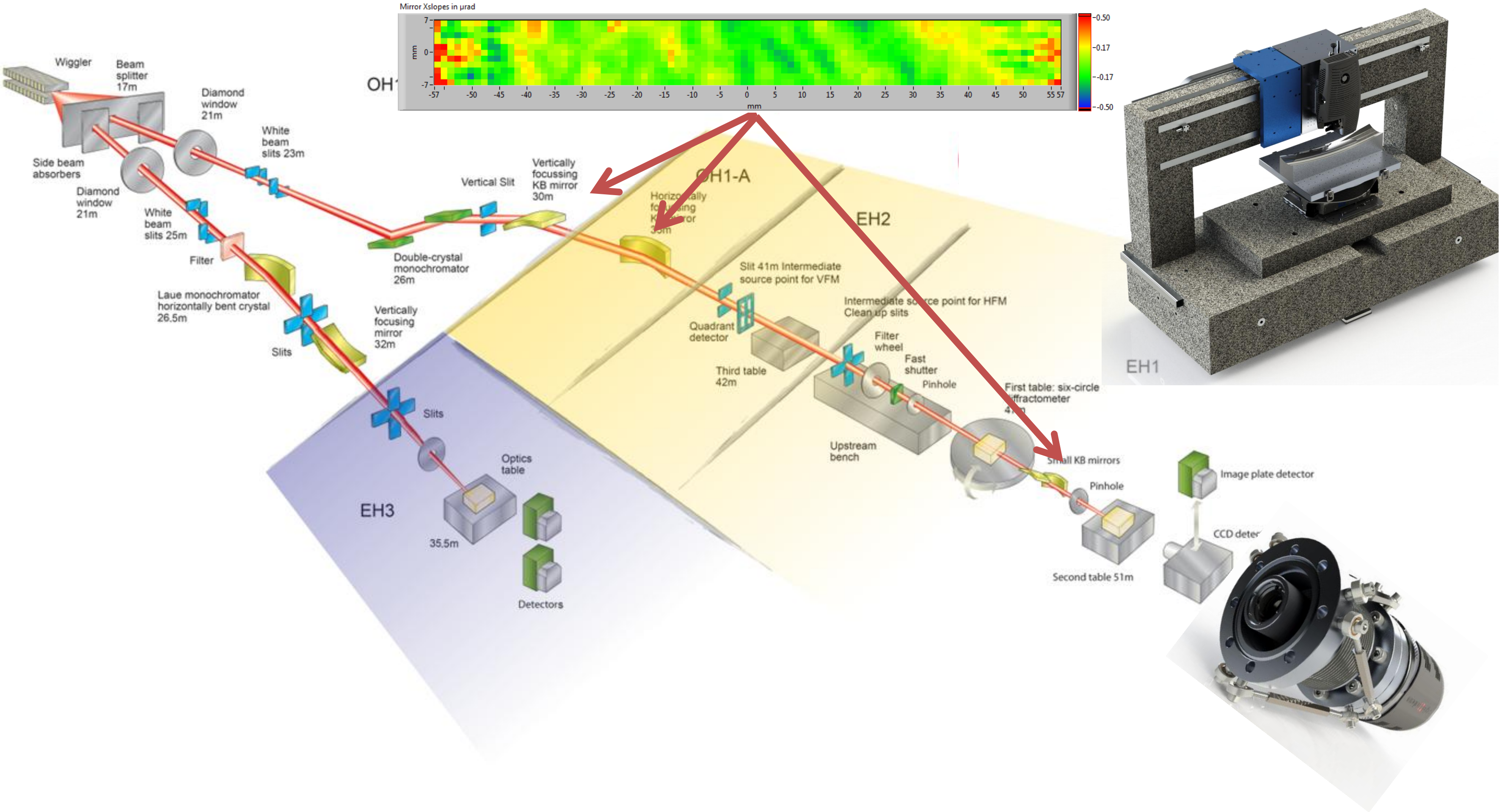


Decenter X		Decenter Y		Tilt About X		Tilt About Y	
0.032114	V	-0.064229	V	3.8623E-003	V	1.9312E-003	V

The secondary mirror must be shifted and tilted to remove the measured aberration.

Just grab the screwdriver…

Conclusion


Mirror Xslopes in µrad
mm
7
0
-7
-57 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55 57
mm
-0.50
-0.17
--0.17
--0.50
Wiggler
Beam splitter 17m
Diamond window 21m
White beam slits 23m
Side beam absorbers
Diamond window 21m
White beam slits 25m
Filter
Laue monochromator horizontally bent crystal 26.5m
Slits
Vertically focusing mirror 32m
Vertical Slit
Vertically focussing KB mirror 30m
Double-crystal monochromator 26m
OH1
OH1-A
Horizontally focusing KB mirror 35m
EH2
Slit 41m Intermediate source point for VFM
Intermediate source point for HFM Clean up slits
Quadrant detector
Third table 42m
Filter wheel
Fast shutter
Pinhole
First table: six-circle diffractometer 47m
Upstream bench
Small KB mirrors
Pinhole
Image plate detector
CCD deter
Second table 51m
EH1
Slits
Optics table
EH3
35.5m
Detectors

Thank You