

# Wave front sensors at FLASH.

Barbara Keitel

## > 1. Beamline commissioning

- A first implementation as well as long-term observations of diagnostic tools and optics can be facilitated.
- Alignment of focussing mirrors
- Effects of filters and gas attenuator on FEL wave front

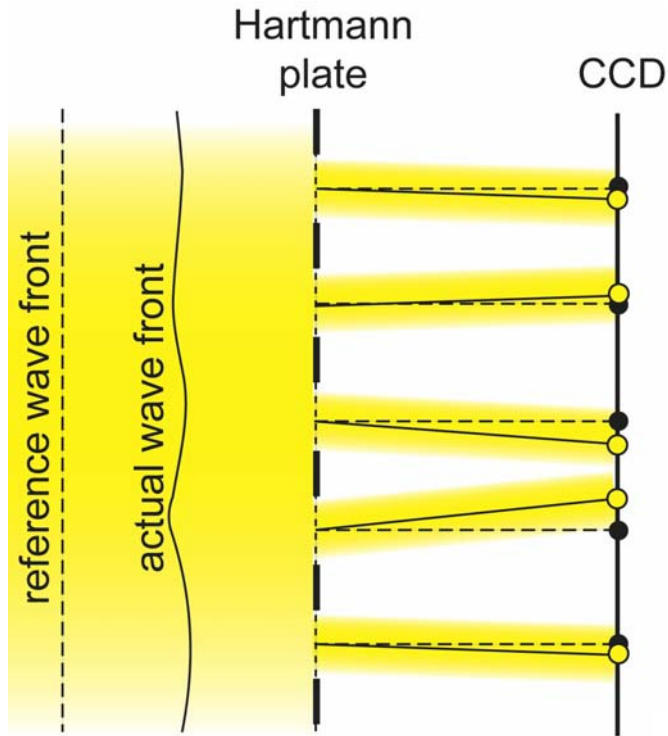
## > 2. FEL characteristics

- The FEL source can be analysed in position, shape and size. The beam position and its stability can be documented.

## > 3. Diagnostic for user experiments

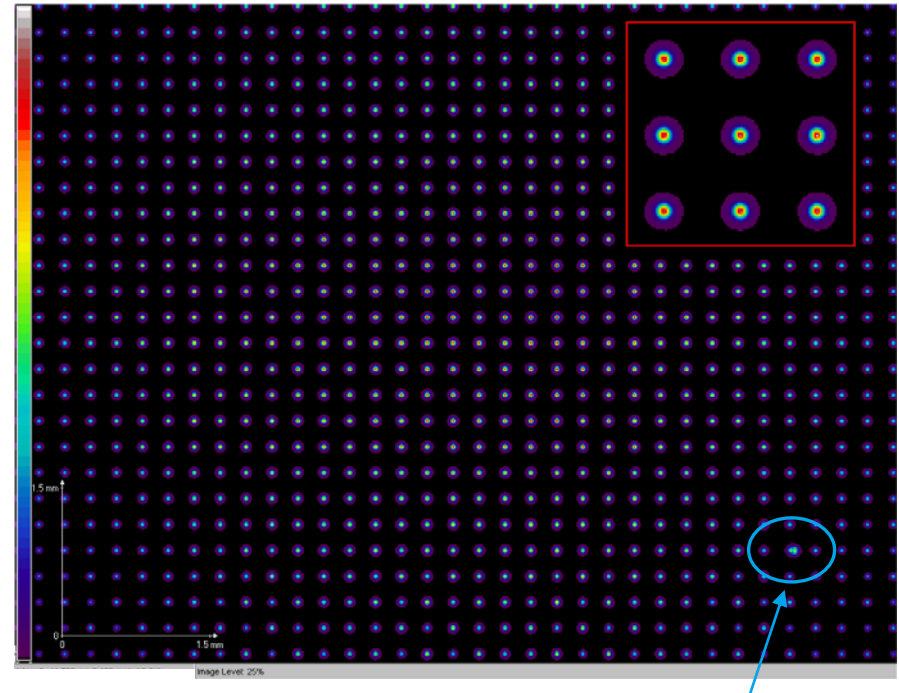
- Focus size and position can be determined online for single shots, if the main experiment is transparent for the FEL beam.

# Wave front sensor principle



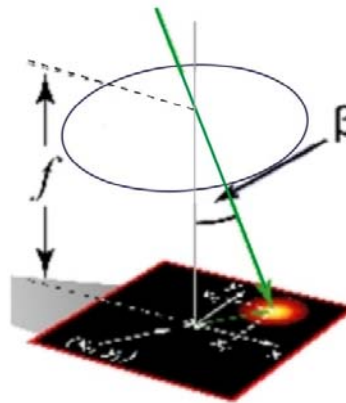
Courtesy of Pascal Mercère, SOLEIL

## Reference spot pattern



Alignment pinhole

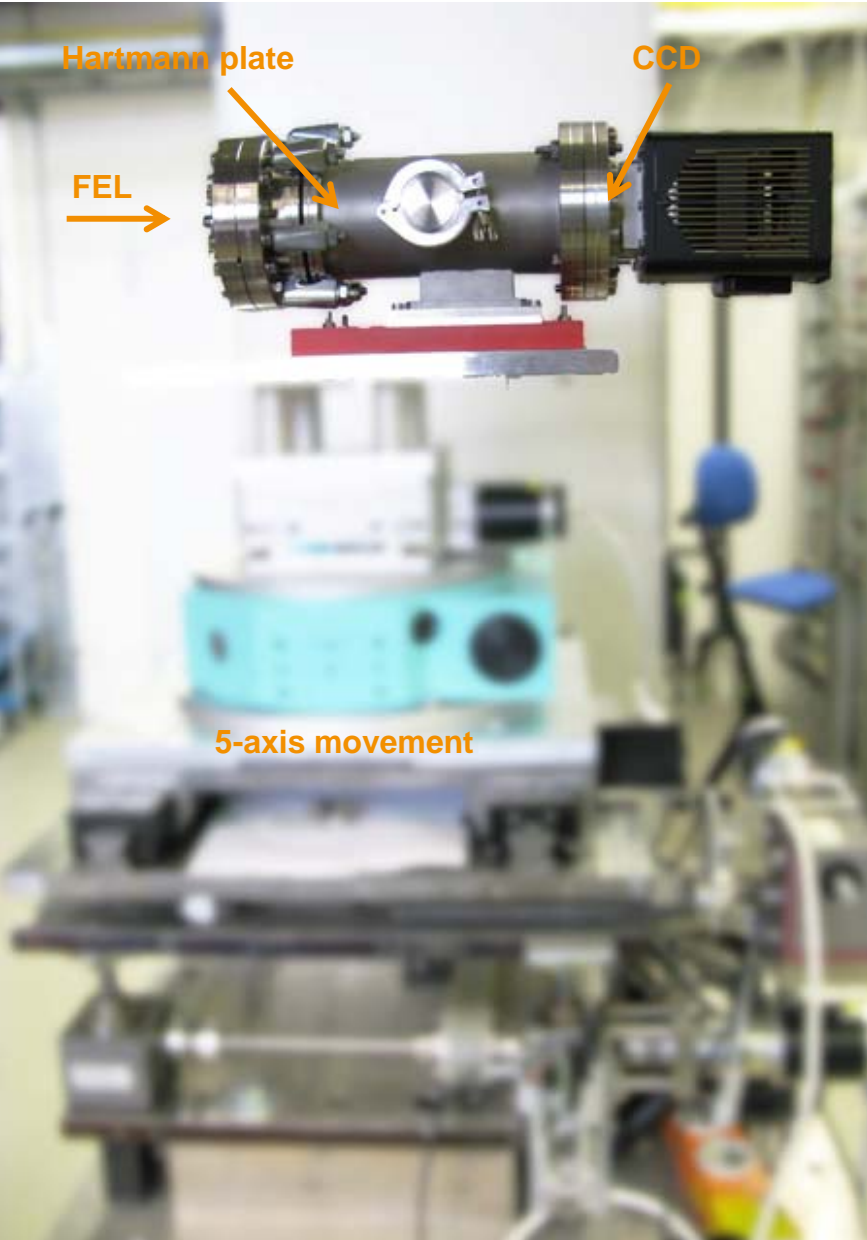
The actual beam is compared to a reference wave (perfect spherical wave)



Intensity and phase information of beam in single shot measurement:

- local intensity: amplitude of each spot
- local slope, WF phase: position of each spot

# The wave front sensor



**Wave front sensor: (10 – 40 nm)**

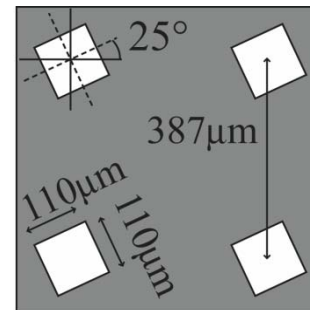
**Hartmann plate:** ~ 80 $\mu$ m Ni plate  
51 x 51 quadratic holes  
tilted by 25° to prevent  
interference of adjacent holes

**CCD:** field of view: 19.5mm x 19.5mm  
1340 x 1300 pixel, 20 $\mu$ m pixel size

**Plate – CCD Chip:** 252mm

**Repeatability (wave front rms):**  $\lambda_{13.4\text{nm}}/100$

Soft- and hardware by Imagine Optic (HASO 3.0)



# Compact Hartmann sensor (first version)

## Wave front sensor (6 – 30nm)

### Hartmann plate:

- 7 $\mu\text{m}$  tantalum foil with circular laser-drilled holes in a squared grid (pitch 320 $\mu\text{m}$ , diameter 65 $\mu\text{m}$ )
- 20 $\mu\text{m}$  Ni foil with electroformed holes in a squared grid (pitch 250 $\mu\text{m}$ , diameter 75 $\mu\text{m}$ )

### CCD (LM165 12bit):

- field of view: 8.25mm x 6.6mm
- 1279 x 1023 pixel, 6.45 $\mu\text{m}$  pixel size,
- chip with phosphorescent coating (Gd<sub>2</sub>O<sub>2</sub>S:Tb, grain size 1-2 $\mu\text{m}$ , central emission wavelength 545nm)

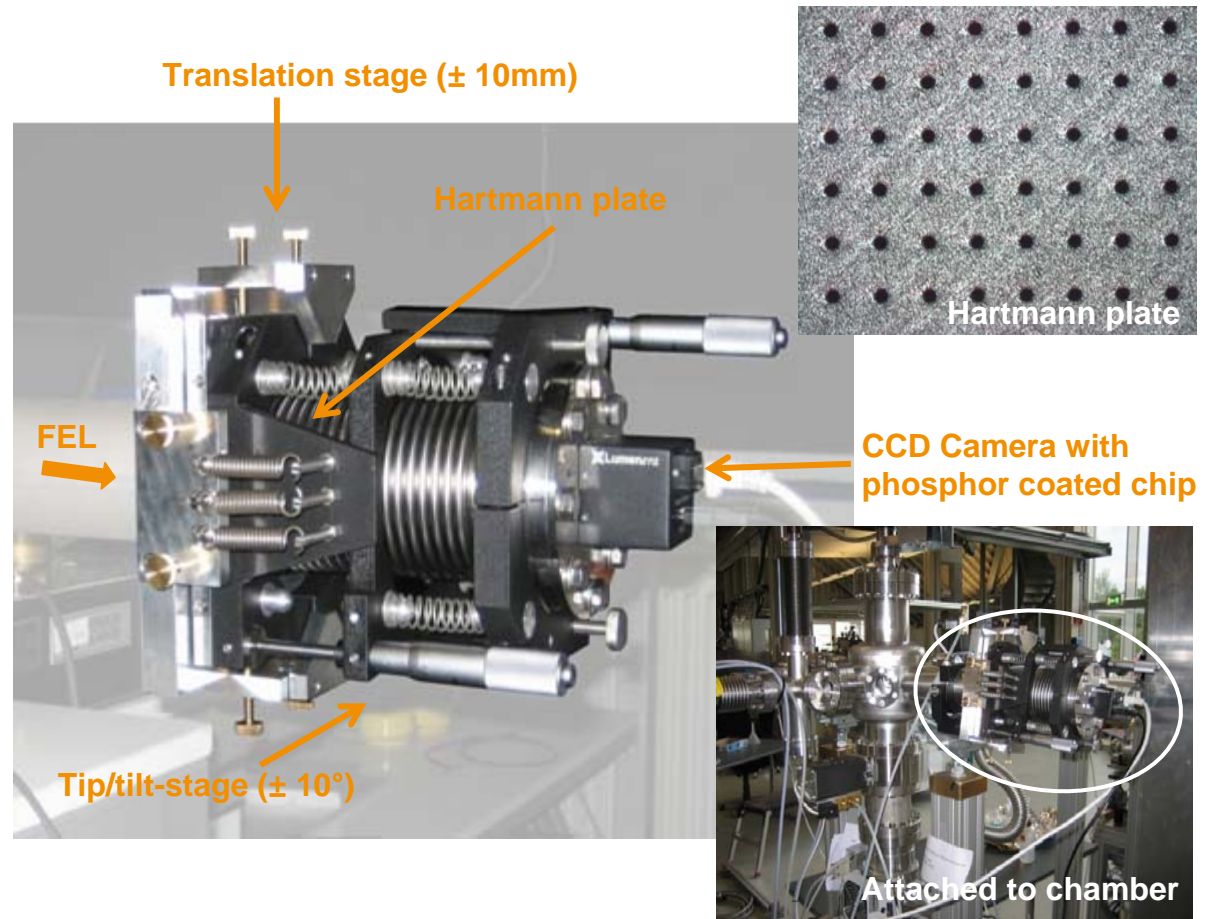
Plate – CCD Chip: 97.08mm

Plate – Flange: 100mm

### Repeatability (wave front rms):

- $\lambda_{13.5\text{nm}}/90$  for tantalum foil

Software by LLG (MrBeam 3.5.0)



Collaboration with Laser-Laboratorium Göttingen e.V. (LLG)

B. Flöter et al., New J. of Phys. 12 (2010), 083015



# Compact Hartmann sensor (improved version)

## Wave front sensor (6 – 30nm)

### Hartmann plate:

20 $\mu$ m Ni foil electroformed holes in a squared grid (pitch 250 $\mu$ m, diameter 75 $\mu$ m)

### CCD (MR285MC 14 bit):

field of view: 8.98mm x 6.71mm (HxV)  
1392 x 1040 pixel, 6.45 $\mu$ m x 6.45 $\mu$ m pixel size,  
chip with phosphorescent coating (Gd<sub>2</sub>O<sub>2</sub>S:Tb,  
grain size 1-2 $\mu$ m, central emission wavelength  
545nm)

Peltier cooling possible

Plate – CCD Chip: 198.251mm

Plate – Flange: 131mm

x/y and tip/tilt stages: motorized

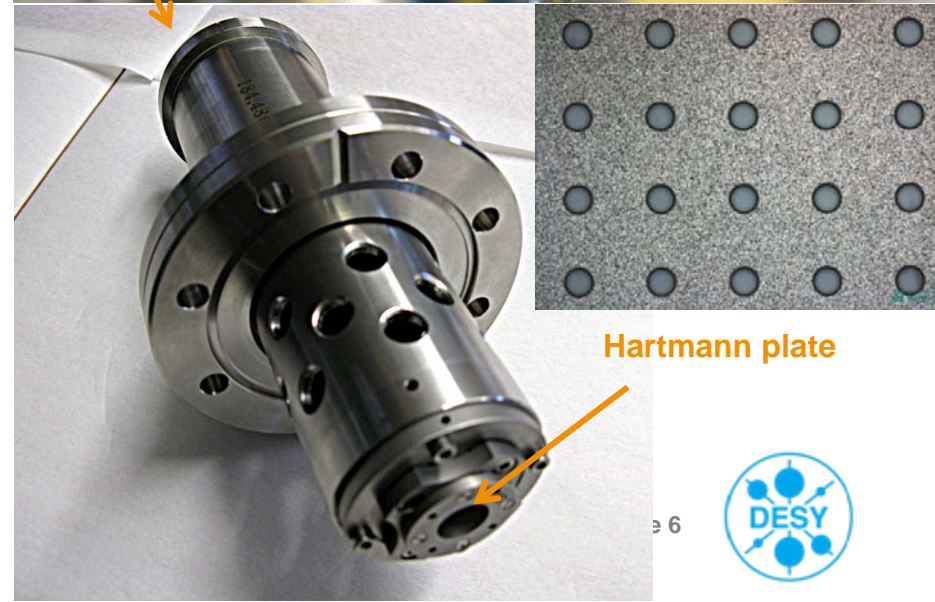
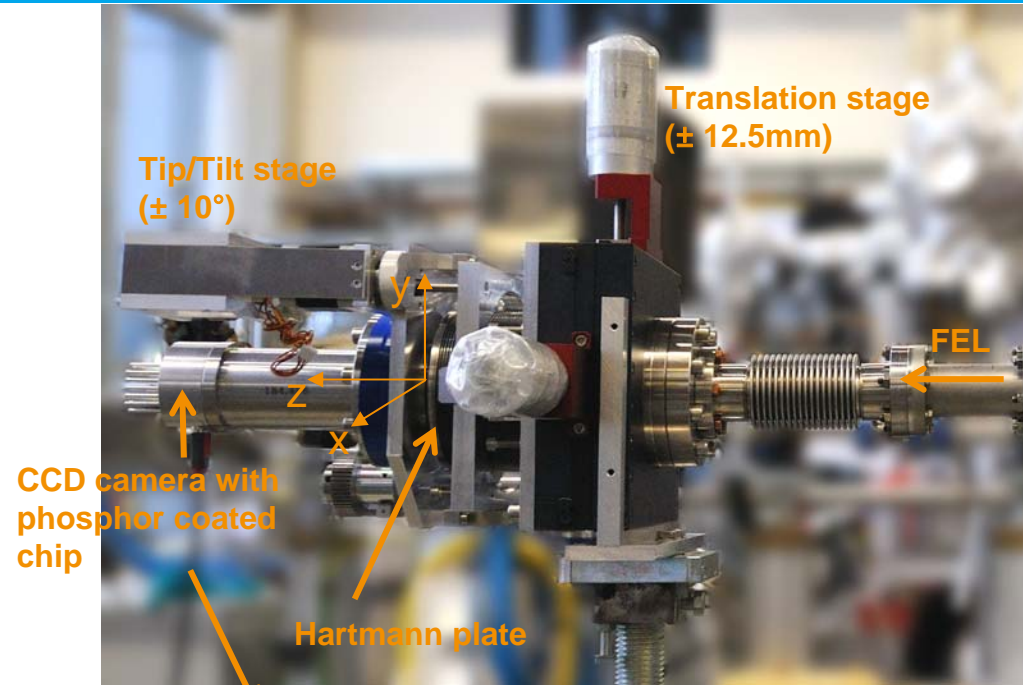
New design: higher mechanical stability

### Repeatability (wave front rms):

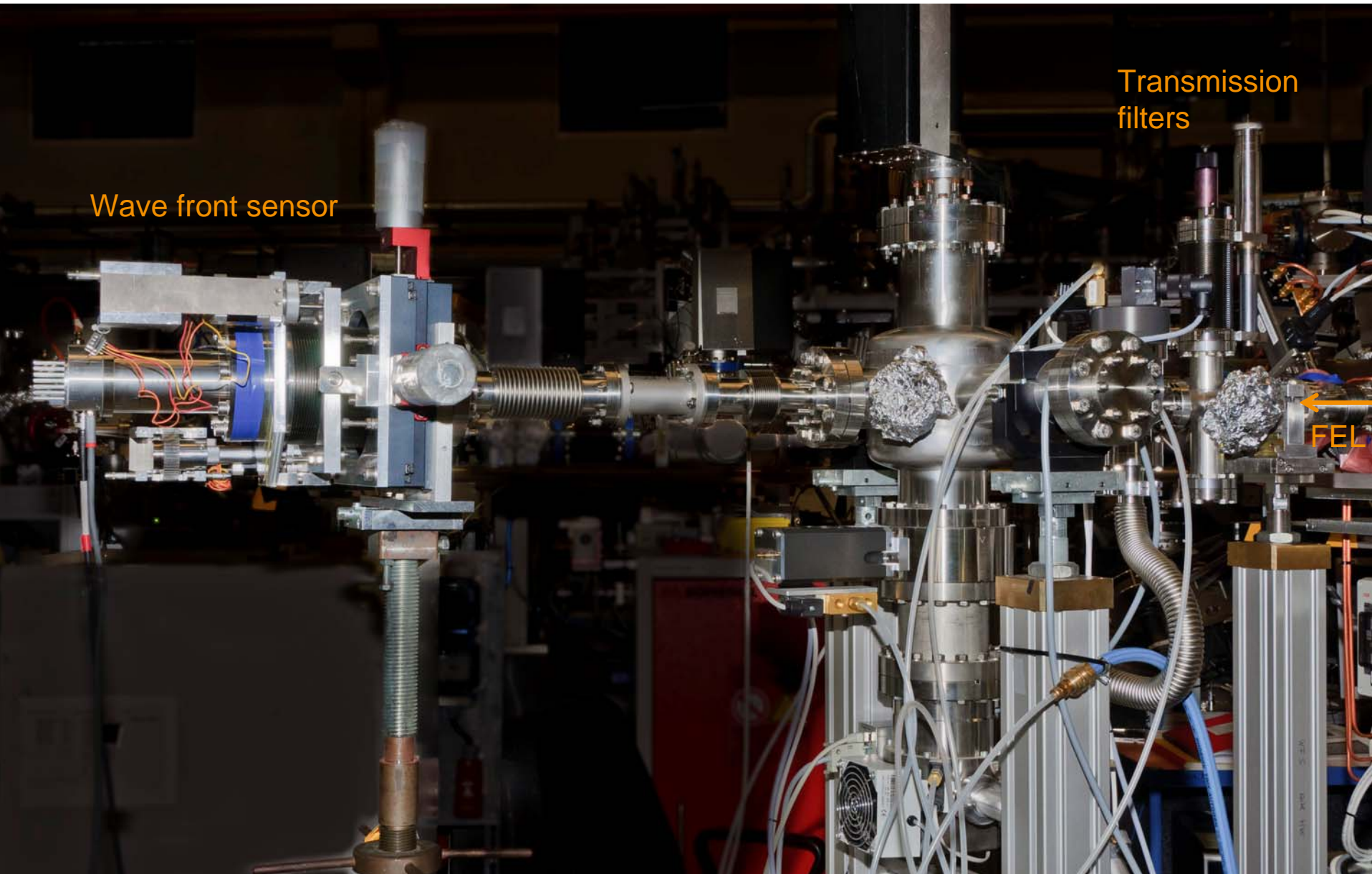
$-\lambda_{13.5\text{nm}}/116$  for Ni foil

Software by LLG (MrBeam 3.5.2)

Collaboration with Laser-Laboratorium Göttingen e.V. (LLG)



# Setup at BL3



Wave front sensor

Transmission filters

FEL

# Settings

- > Single bunch
- > 13.3nm
- > 0.01mbar Xe in attenuator -> attenuation to about  $2\mu\text{J}$  per pulse
- > both 10mm apertures in tunnel
- > no transmission filters used, but checked that
  - 200nm Si filter (Luxél) shows nearly no effect on the wave front
  - 137nm Al (Uni Frankfurt) influences the wave front due to bad filter quality
- > CCD camera triggered by fast shutter



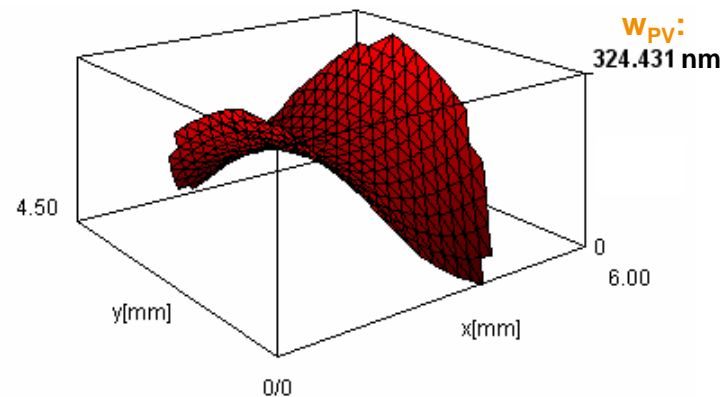


BL3M2 adjustment 29./30.1.11  
C coating on BLOMO

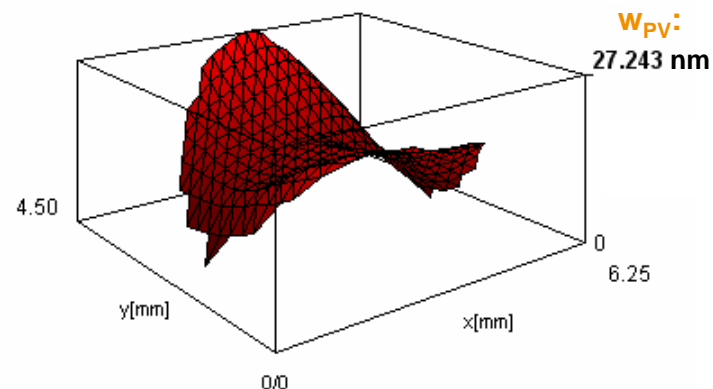


# Starting conditions

# During adjustment

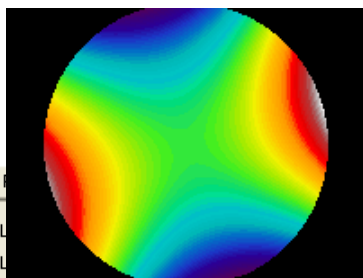


13.3nm  
single bunch  
2 $\mu$ J

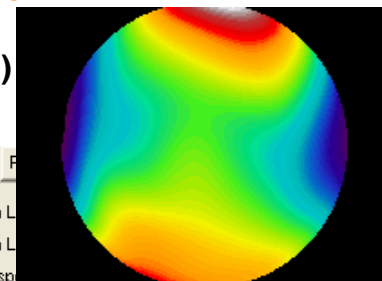


$W_{rms}$ : 4nm @ 13nm  $\rightarrow$   $N/3$

Rotation: 0 mrad  
Yaw: 0 mrad



Rotation: -1mrad (-70000 steps)  
Yaw: 0.65mrad



Wavefront		Beam Parameters		Zernike Aberrations	
Irregularity	0.0003243228	[mm]	Rayleigh L		
Defocus	843.224	[mm]	Rayleigh L		
RMSDeformation	0	[mm]	W. C. Aspect Ratio	0.8398	
General Astigm.	0.2262753				
Strehl	0.0000				
$M^2$	6.5423				
$M^2$ X	24.9349				
$M^2$ Y	24.7418				
DivergenceX	4.1164	[mrad]			
DivergenceY	4.8800	[mrad]			
BeamWidthX	3.6358	[mm]			
BeamWidthY	3.9727	[mm]			
WaistPositionX	-882.8546	[mm]			
WaistPositionY	-813.8692	[mm]			
WaistDifference	-3.0831	[RL]			
WaistDiameterX	0.1079769	[mm]			
WaistDiameterY	0.0903749	[mm]			

Wavefront		Beam Parameters		Zernike Aberrations		Profiles		MTF		Dat	
+	-										
		1000:1	[mm]								
TiltX											
TiltY											
Defocus											
Astigmatism Y <sup>2</sup> -X <sup>2</sup>				0.134							
Astigmatism XY				0.086							
Coma X				0.001							
Coma Y				0.002							
Triangular Coma				0.004							
Quadratic Astigmatism				0.000							
Spher. Aberration				0.001							
5th Spher. Aberration				0.000							

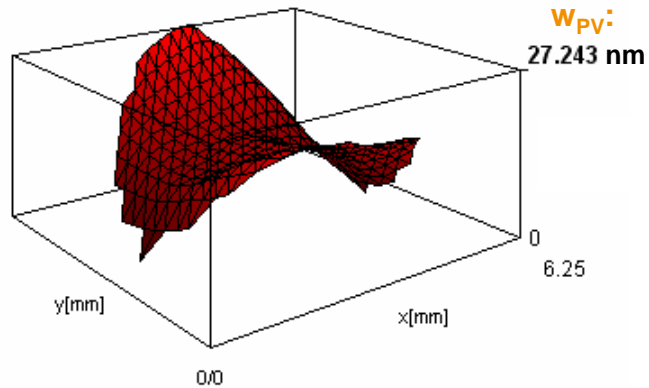
Wavefront		Beam Parameters		Zernike Aberrations		Profiles	
Irregularity	2.722862E-5	[mm]	Rayleigh L				
Defocus	850.0104	[mm]	Rayleigh L				
RMSDeformation	3.966993E-6	[mm]	W. C. Asp				
General Astigm.	0.05463203						
Strehl	0.0412						
$M^2$	3.7809						
$M^2$ X	2.2524						
$M^2$ Y	1.9664						
DivergenceX	4.5649	[mrad]					
DivergenceY	4.7649	[mrad]					
BeamWidthX	3.8648	[mm]					
BeamWidthY	4.0626	[mm]					
WaistPositionX	-846.6342	[mm]					
WaistPositionY	-852.6102	[mm]					
WaistDifference	3.4437	[RL]					
WaistDiameterX	0.0087955	[mm]					
WaistDiameterY	0.0073565	[mm]					

Wavefront		Beam Parameters		Zernike Aberrations		Profiles	
+	-						
		1000:1	[mm]				
TiltX				0.024			
TiltY							
Defocus							
Astigmatism Y <sup>2</sup> -X <sup>2</sup>				0.012			
Astigmatism XY				0.003			
Coma X				0.000			
Coma Y				0.000			
Triangular Coma				0.002			
Quadratic Astigmatism				0.001			
Spher. Aberration				0.001			
5th Spher. Aberration				0.000			

# During adjustment

# Final alignment

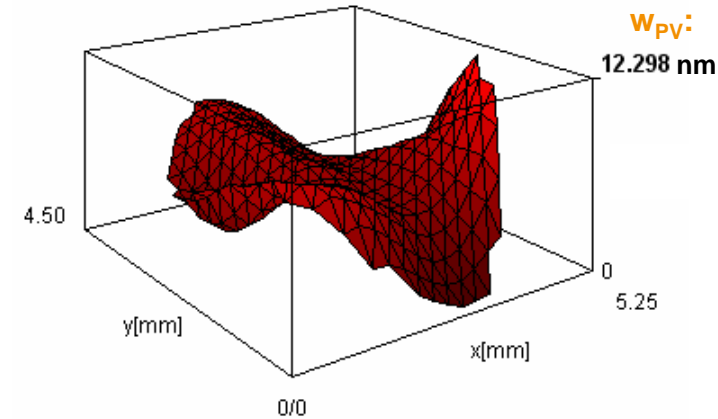


rms: 4nm @ 13nm →  $\lambda/3$

13.3nm  
single bunch  
2μJ

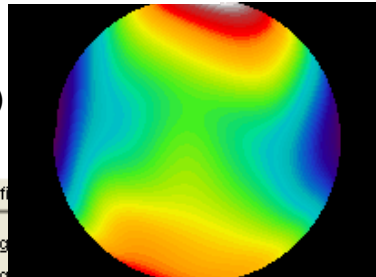
Focus position from  
valve flange: 528.7mm

Focus size to be  
checked

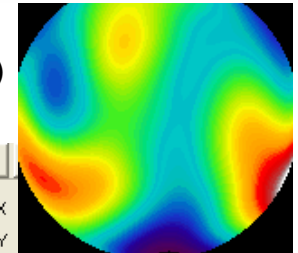


rms: 1.3nm @ 13nm →  $\lambda/10$

Rotation: -1mrad (-70000 steps)  
Yaw: 0.65mrad



Rotation: -0.95mrad (-66000 steps)  
Yaw: 0.65mrad



Wavefront	Beam Parameters	Zernike Aberrations	Profiles
Irregularity	2.722862E-5 [mm]	Rayleigh Length	
Defocus	850.0104 [mm]	Rayleigh Length X	
RMSDeformation	3.966993E-6 [mm]	W. C. Aspect Ratio	0.9564
General Astigm.	0.05463203		
Strehl	0.0412		
M <sup>2</sup> z	3.7809		
M <sup>2</sup> X	2.2524		
M <sup>2</sup> Y	1.9664		
DivergenceX	4.5649 [mrad]		
DivergenceY	4.7649 [mrad]		
BeamWidthX	3.8648 [mm]		
BeamWidthY	4.0626 [mm]		
WaistPositionX	-846.6342 [mm]		
WaistPositionY	-852.6102 [mm]		
WaistDifference	3.4437 [RL]		
WaistDiameterX	0.0087955 [mm]		
WaistDiameterY	0.0073565 [mm]		

Wavefront	Beam Parameters	Zernike Aberrations	Profiles
TiltX	0.024		
TiltY			
Defocus			
Astigmatism Y <sup>2</sup> -X <sup>2</sup>	0.012		
Astigmatism XY	0.003		
Coma X	0.000		
Coma Y	0.000		
Triangular Coma	0.002		
Quadratic Astigmatism	0.001		
Spher. Aberration	0.001		
5th Spher. Aberration	0.000		

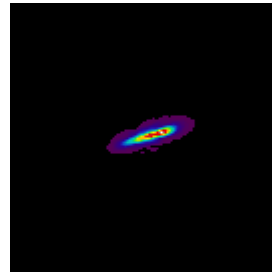
Wavefront	Beam Parameters	Zernike Aberrations	Profiles
Irregularity	1.244393E-5 [mm]	Rayleigh Length X	
Defocus	848.8526 [mm]	Rayleigh Length Y	
RMSDeformation	1.3141E-6 [mm]	W. C. Aspect Ratio	0.8629
General Astigm.	0.02400378		
Strehl	0.7017		
M <sup>2</sup> z	3.3108		
M <sup>2</sup> X	1.9992		
M <sup>2</sup> Y	1.8290		
DivergenceX	3.9330 [mrad]		
DivergenceY	4.5400 [mrad]		
BeamWidthX	3.3389 [mm]		
BeamWidthY	3.8528 [mm]		
WaistPositionX	-848.9389 [mm]		
WaistPositionY	-848.6329 [mm]		
WaistDifference	-0.1575 [RL]		
WaistDiameterX	0.0090610 [mm]		
WaistDiameterY	0.0071810 [mm]		

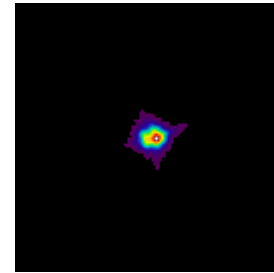
Wavefront	Beam Parameters	Zernike Aberrations	Profiles
TiltX			
TiltY	0.429		
Defocus			
Astigmatism Y <sup>2</sup> -X <sup>2</sup>	0.001		
Astigmatism XY	0.001		
Coma X	0.000		
Coma Y	0		
Triangular Coma	0.003		
Quadratic Astigmatism	0.001		
Spher. Aberration	0		
5th Spher. Aberration	0		

# Simulated beam profiles

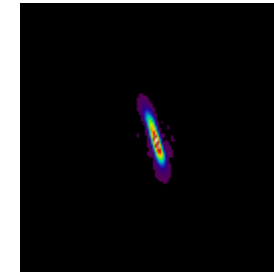
before alignment



-50mm

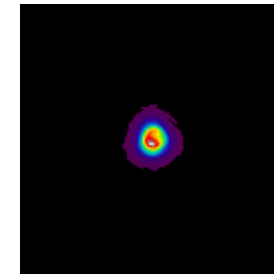
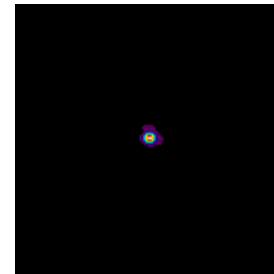
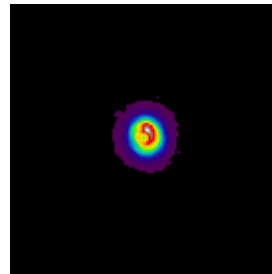


focal plane



+50mm

after alignment



Numerical propagation via Kirchhoff-Fresnel integral



# Conclusions

- > The new compact Hartmann sensor proved to be a valuable diagnostic tool during the beamline commissioning at FLASH.
- > Online diagnostic (wave front, aberration, focus position,...) for single pulses is possible.
- > A high sensitivity and resolution of the Hartmann sensor is required for the high beam quality of the FEL.



# Acknowledgements

Many thanks to:

*B. Flöter, K. Mann, T. Mey, B. Schäfer, Laser-Laboratorium Göttingen e.V.*

*G. Brenner, P. Juranić, S. Kapitzki, H. Kühn, M. Markert, E. Plönjes-Palm,  
K. Tiedtke, Photon Diagnostic at FLASH*

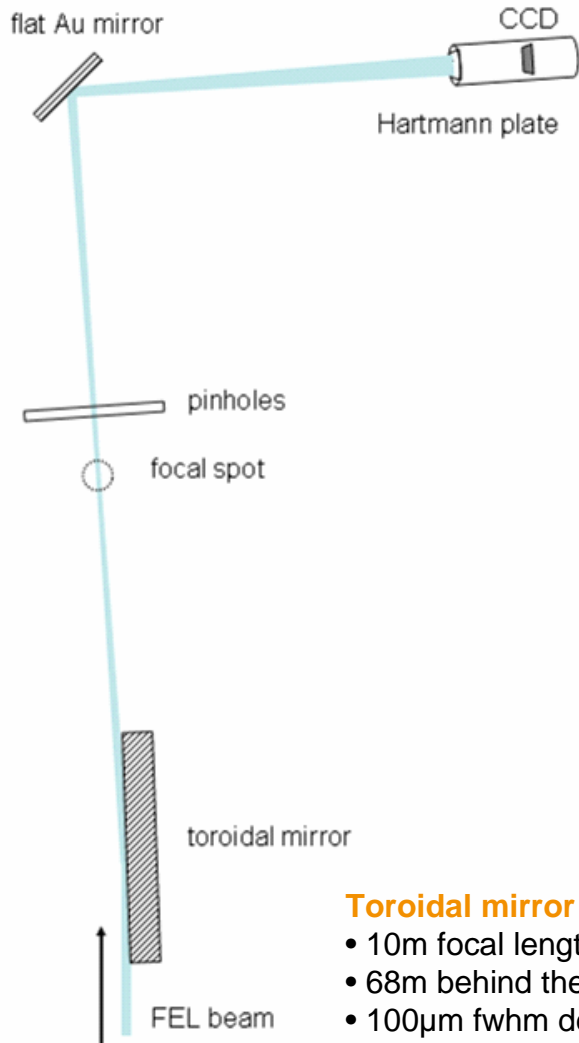
the whole FLASH team



**Thank you.**

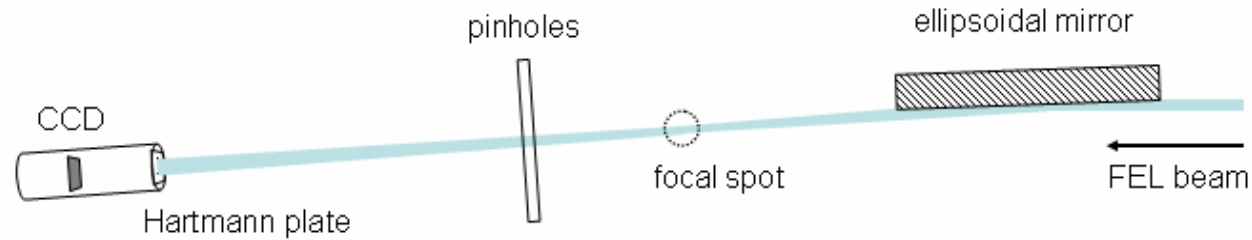


# Experimental setups at FLASH



## Toroidal mirror (BL1)

- 10m focal length
- 68m behind theoretical source
- 100 $\mu$ m fwhm designed spot size



## Ellipsoidal mirror (BL2/BL3)

- 2m focal length
- 73m behind theoretical source
- 20 $\mu$ m fwhm designed spot size

## Distances for compact wave front sensors:

L(mm)	$\lambda=13.5\text{nm}$	$\lambda=20\text{nm}$	$\lambda=30\text{nm}$	$\lambda=40\text{nm}$	$\lambda=50\text{nm}$	$\lambda=60\text{nm}$	$\lambda=65\text{nm}$
d=5 $\mu$ m	3207	2299	1533	1150	920	766	707
d=10 $\mu$ m	6415	4598	3066	2299	1839	1533	1415
d=20 $\mu$ m	13357	9196	6131	4598	3679	3066	2830

Without pinhole: Hartmann plate about 700mm from focal position

L: distance plate-pinhole  
d: diameter pinhole