

Characterizing and correcting aberrations in an optical system

BARBIERI Pierre-Armand & MARTY-BAZAN Jeanne

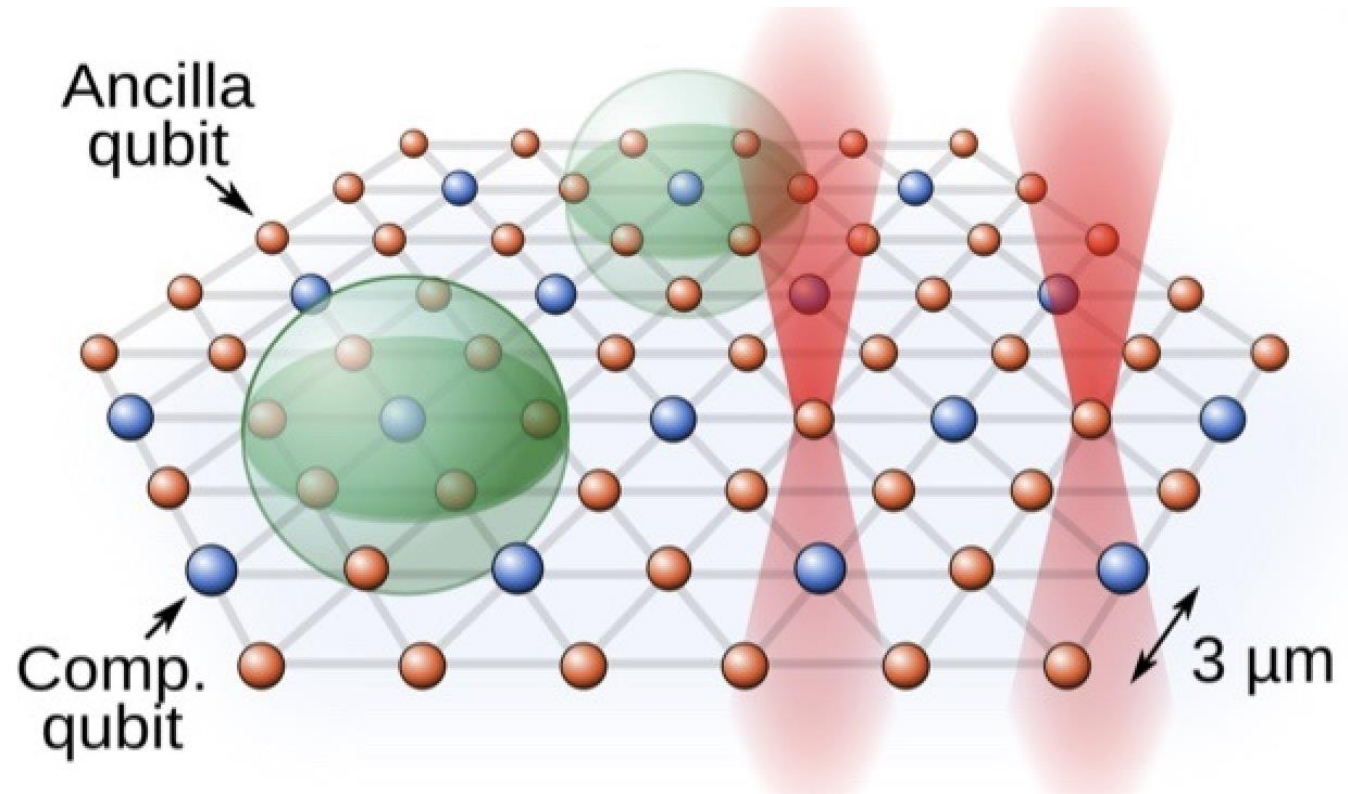
Supervised by BIENAIME Tom & WHITLOCK Shannon



Centre Européen de Sciences Quantiques

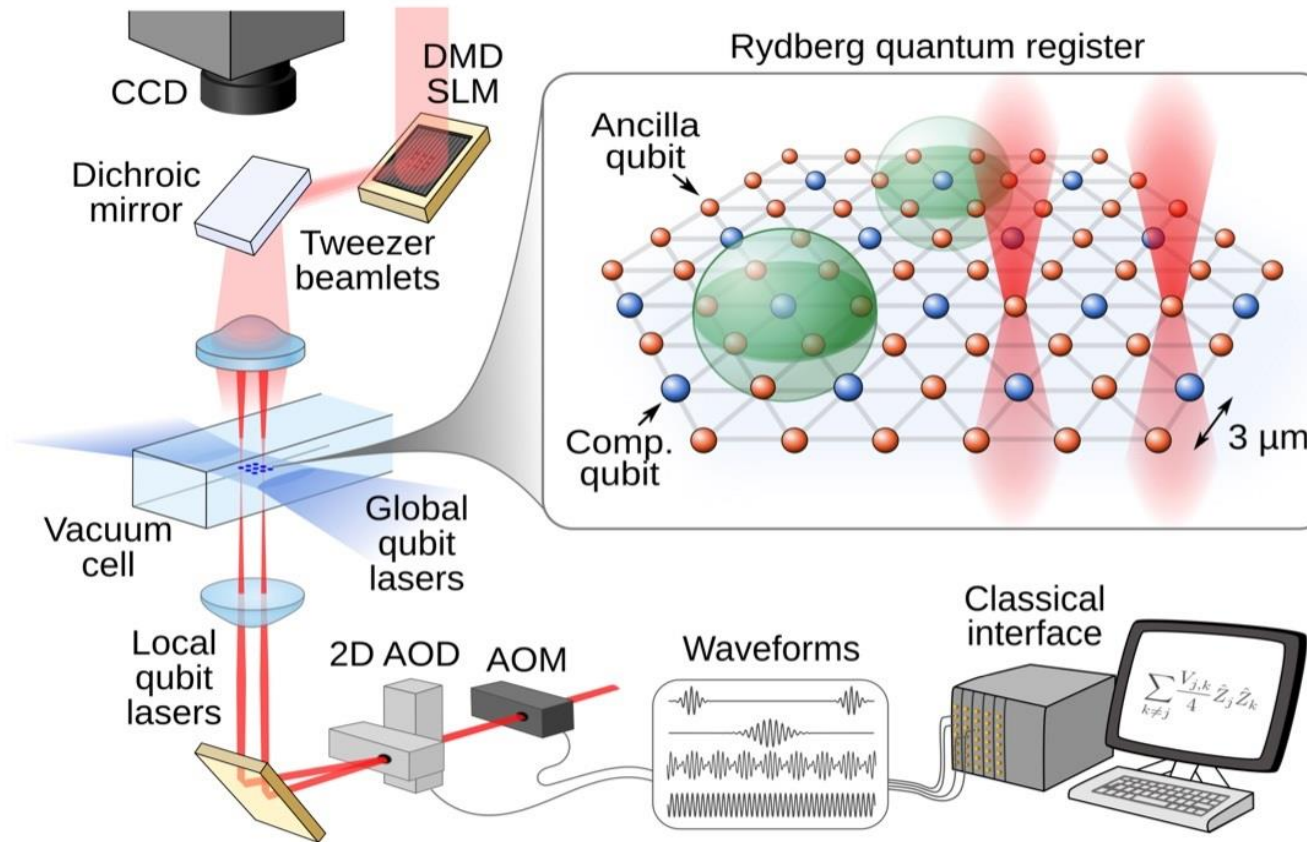


Quantum simulator



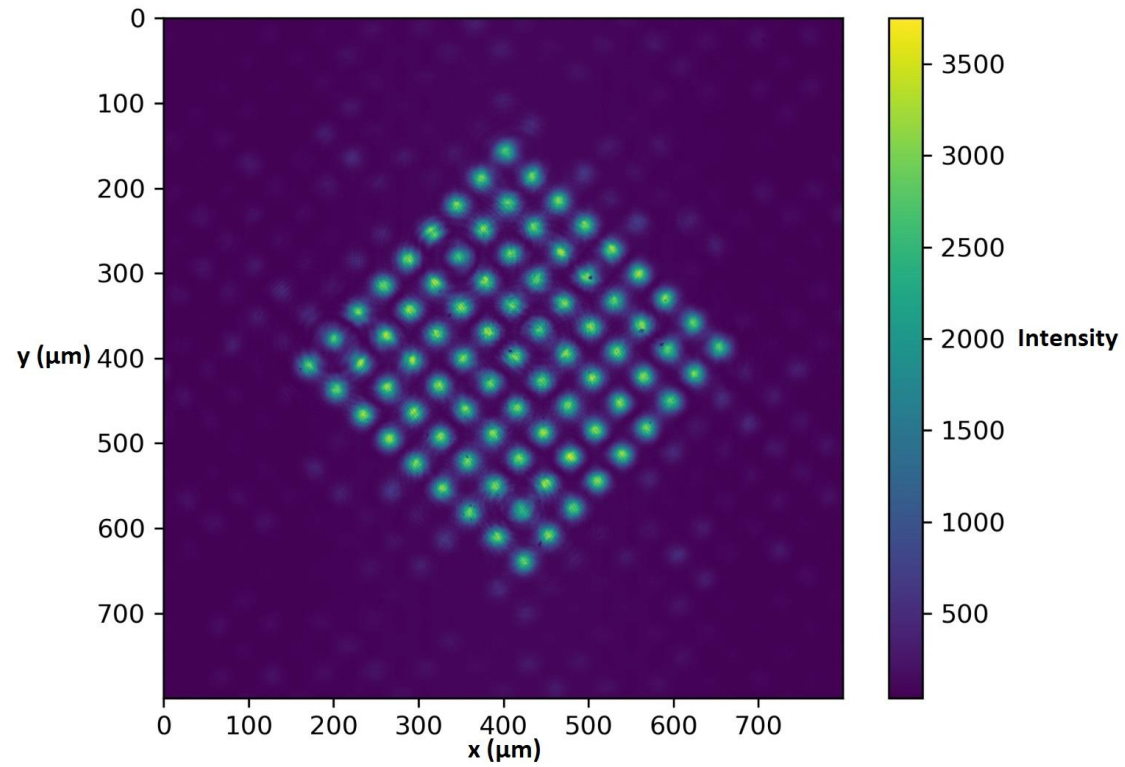
Whitlock, Shannon. "Quantum simulation and computing with Rydberg-interacting qubits." (2021).

Optical setup



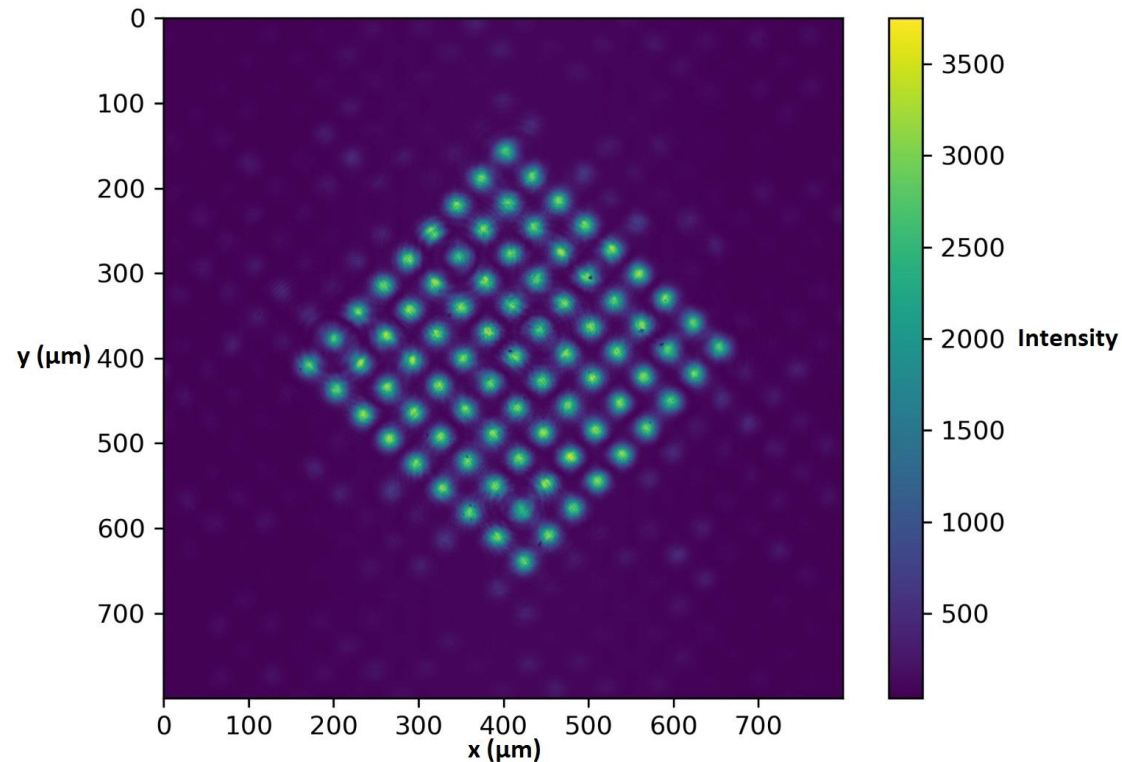
Whitlock, Shannon. "Quantum simulation and computing with Rydberg-interacting qubits." (2021).

Problem : optical aberrations

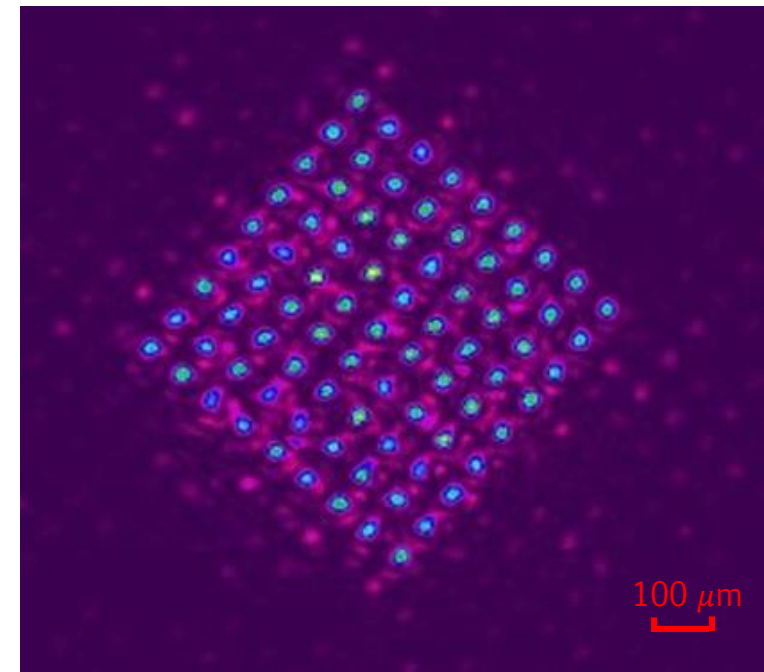


Before the vacuum chamber

Problem : optical aberrations



Before the vacuum chamber

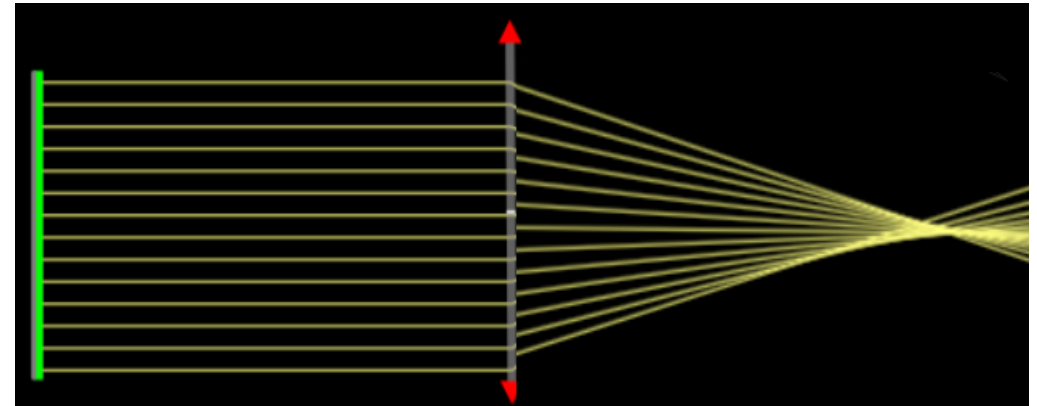
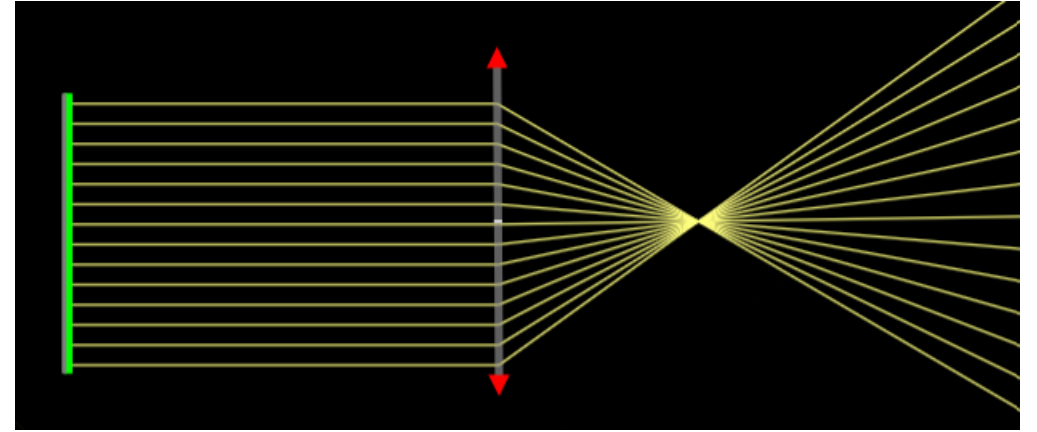


After the vacuum chamber

What is an aberration?

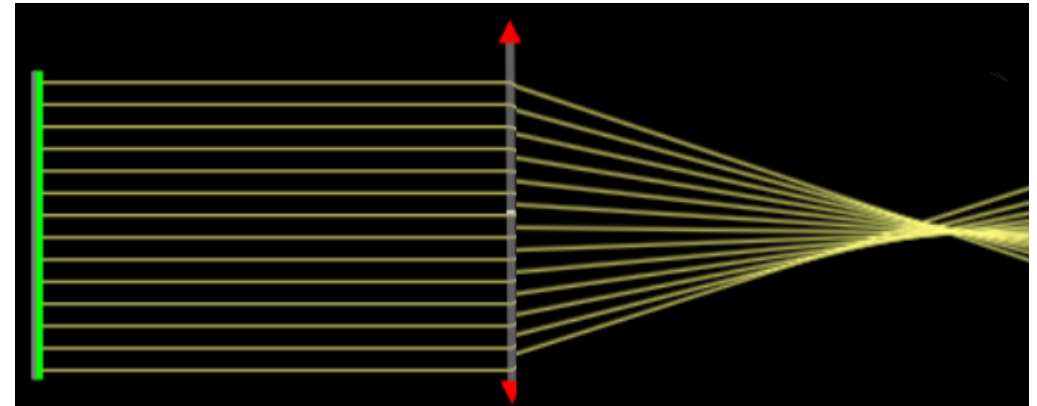
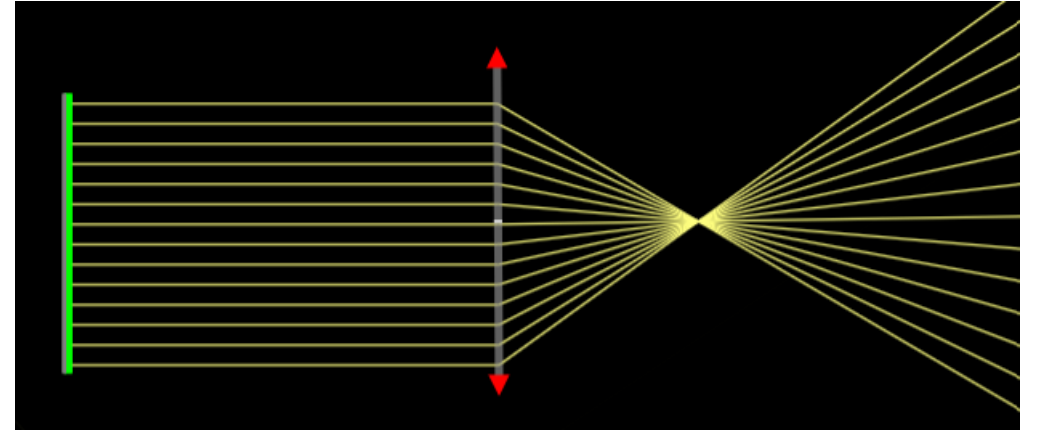
What is an aberration?

- ▶ Light is not focused to a point



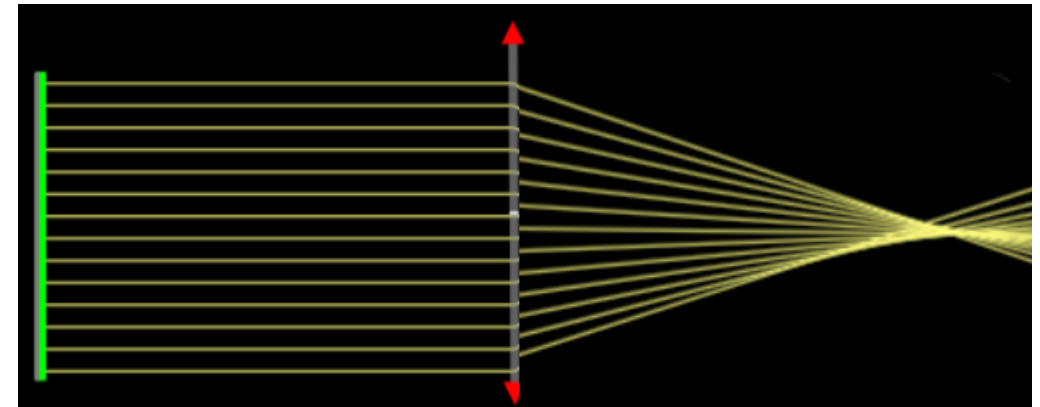
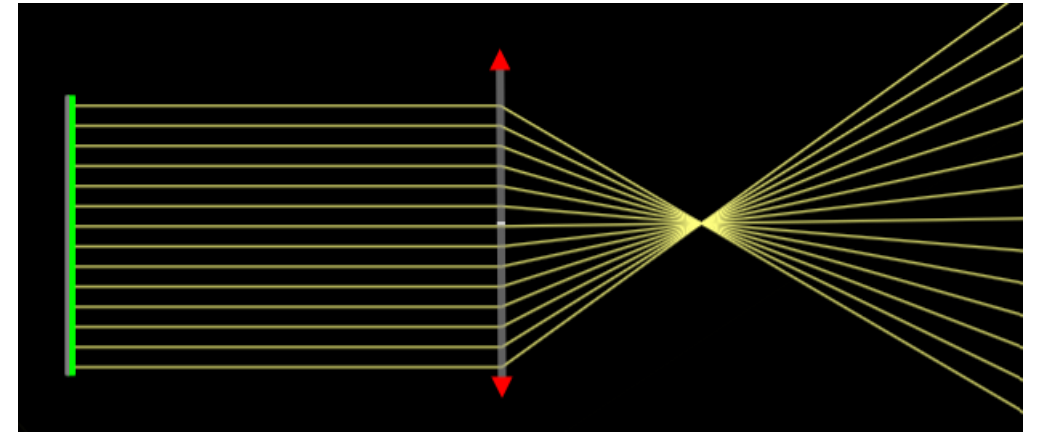
What is an aberration?

- ▶ Light is not focused to a point
- ▶ Aberrations can be introduced by lenses



What is an aberration?

- ▶ Light is not focused to a point
- ▶ Aberrations can be introduced by lenses



Zernike polynomials

Zernike polynomials

$$Z_j(\rho, \theta) = Z_n^m(\rho, \theta) \\ = \begin{cases} \sqrt{2(n+1)}R_n^m(\rho) \cos m\theta, & m \neq 0, j \text{ is even,} \\ \sqrt{2(n+1)}R_n^m(\rho) \sin m\theta, & m \neq 0, j \text{ is odd,} \\ \sqrt{(n+1)}R_n^m(\rho), & m = 0, \end{cases}$$

$$n = \left\lfloor \left(\sqrt{2j-1} + 0.5 \right) - 1 \right\rfloor, \\ m = \begin{cases} 2 \times \left\lfloor \frac{2j+1-n(n+1)}{4} \right\rfloor, & n \text{ is even,} \\ 2 \times \left\lfloor \frac{2(j+1)-n(n+1)}{4} \right\rfloor - 1, & n \text{ is odd,} \end{cases}$$

$$R_n^m(\rho) = \sum_{s=0}^{(n-m)/2} \frac{(-1)^s (n-s)!}{s! \left(\frac{n+m}{2} - s\right)! \left(\frac{n-m}{2} - s\right)!} \rho^{n-2s}.$$

Mathematical properties that are interesting

Mathematical properties that are interesting

- ▶ Orthogonal, so the coefficients of the expansion are totally independent

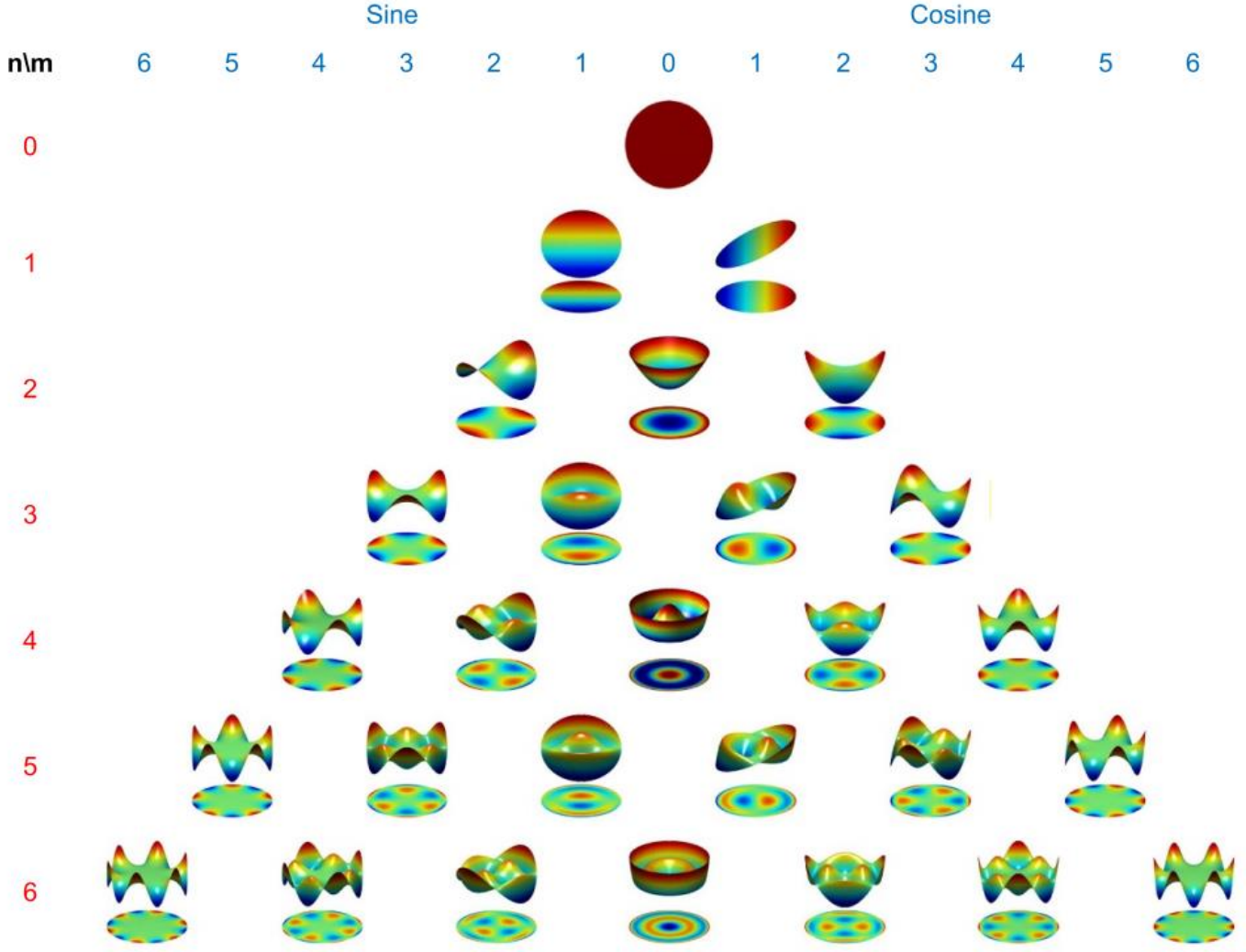
Mathematical properties that are interesting

- ▶ Orthogonal, so the coefficients of the expansion are totally independent
- ▶ Recurrence relations that allow for optimized calculations

Mathematical properties that are interesting

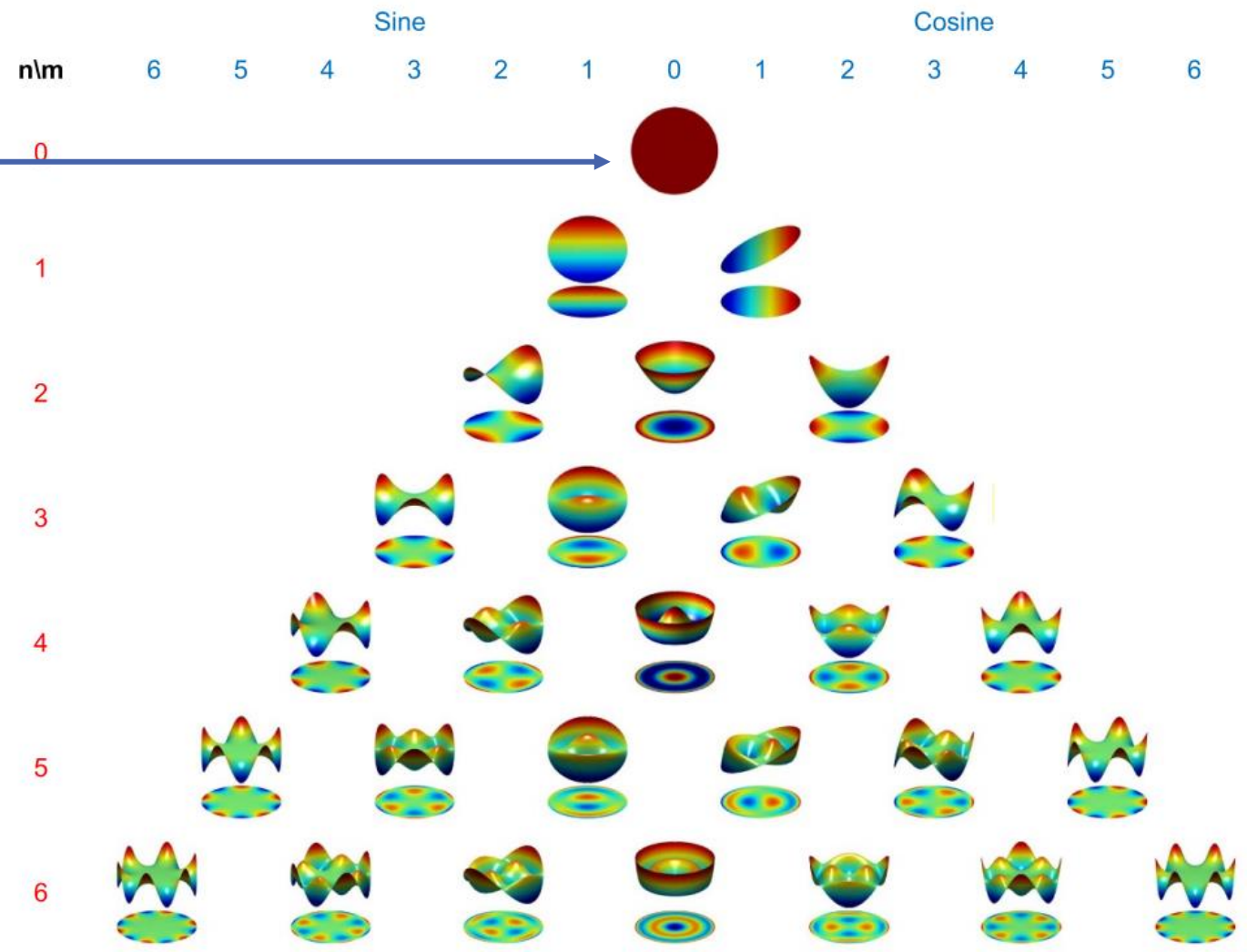
- ▶ Orthogonal, so the coefficients of the expansion are totally independent
- ▶ Recurrence relations that allow for optimized calculations
- ▶ Good corresponding with classical aberrations: astigmatism, coma, spherical aberration

Usual aberrations

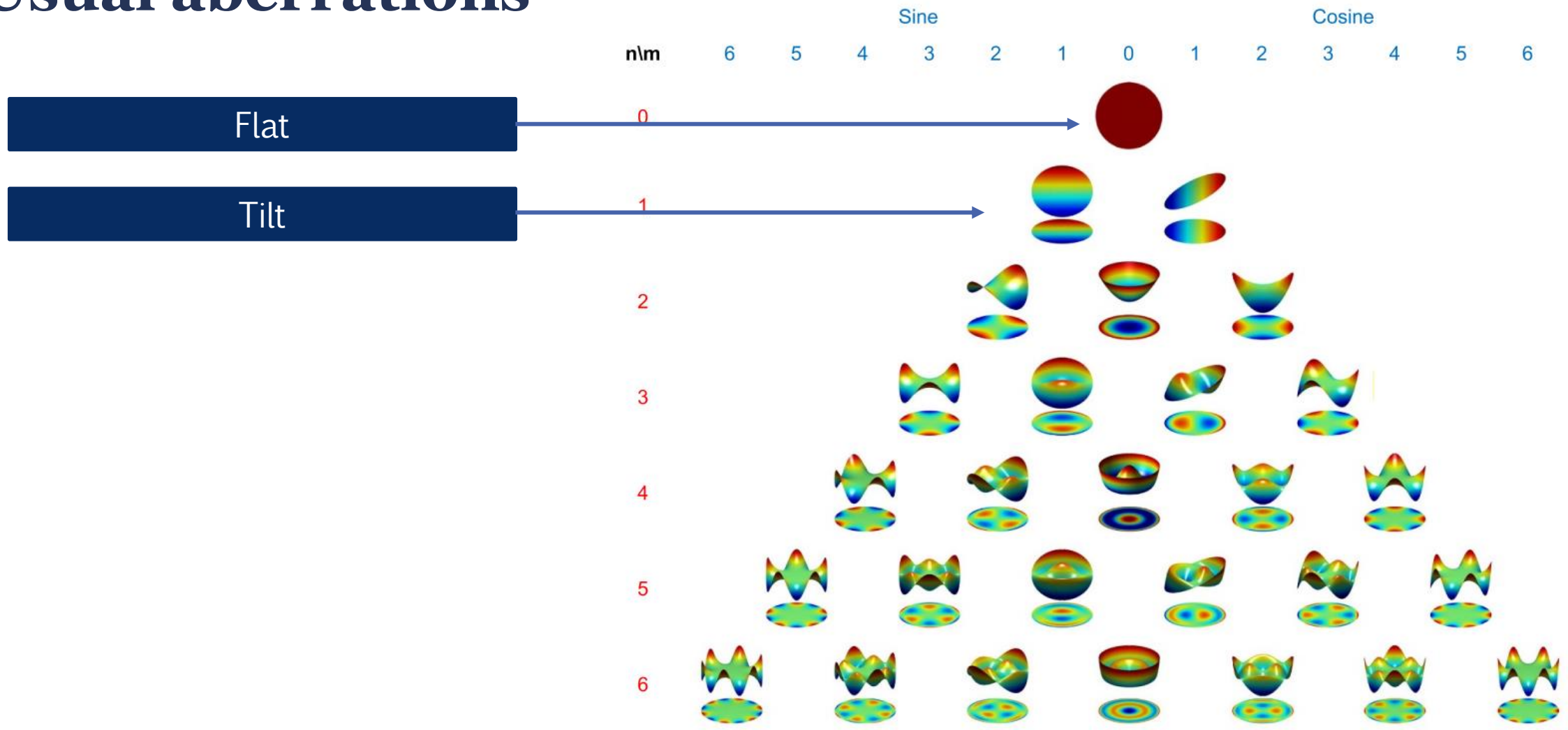


Usual aberrations

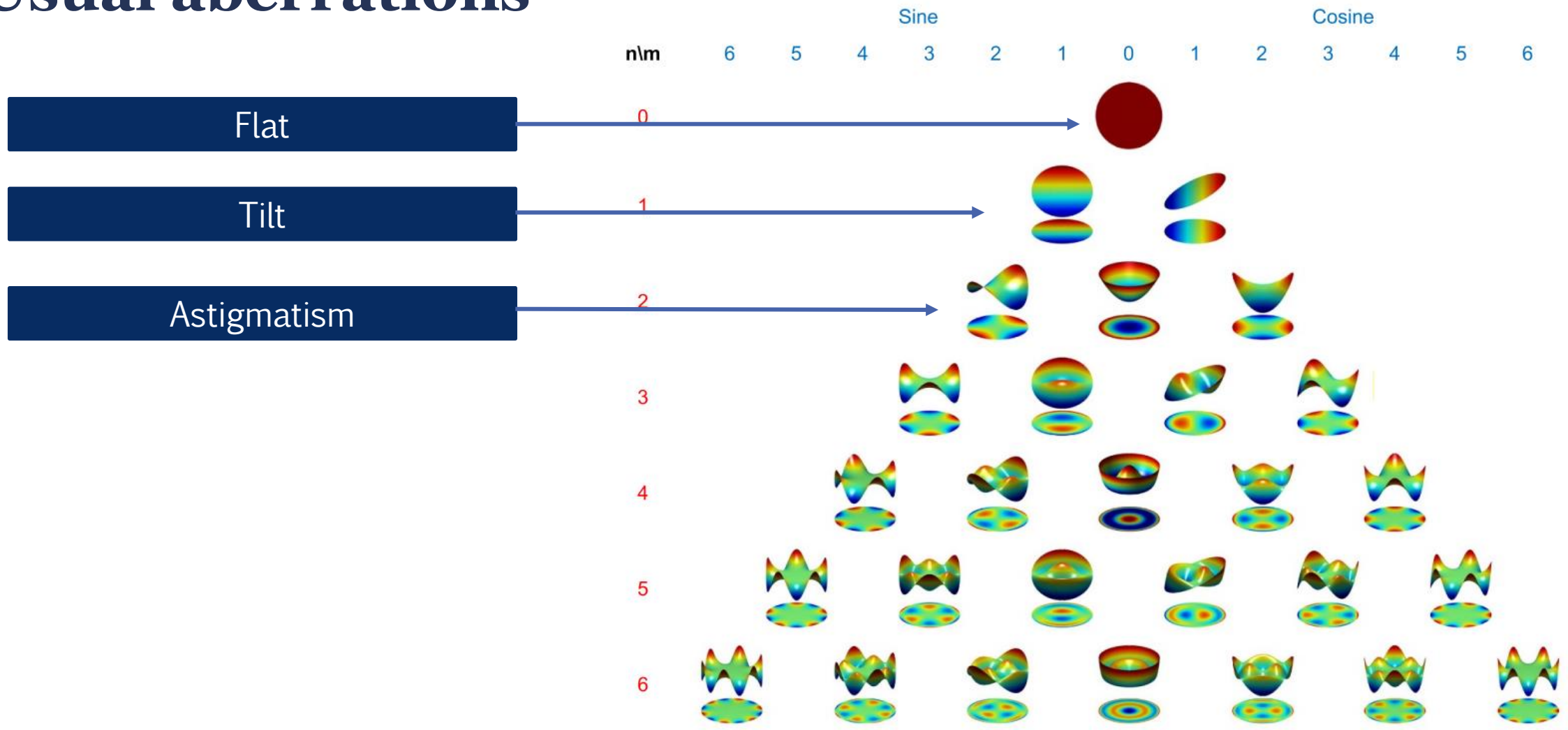
Flat



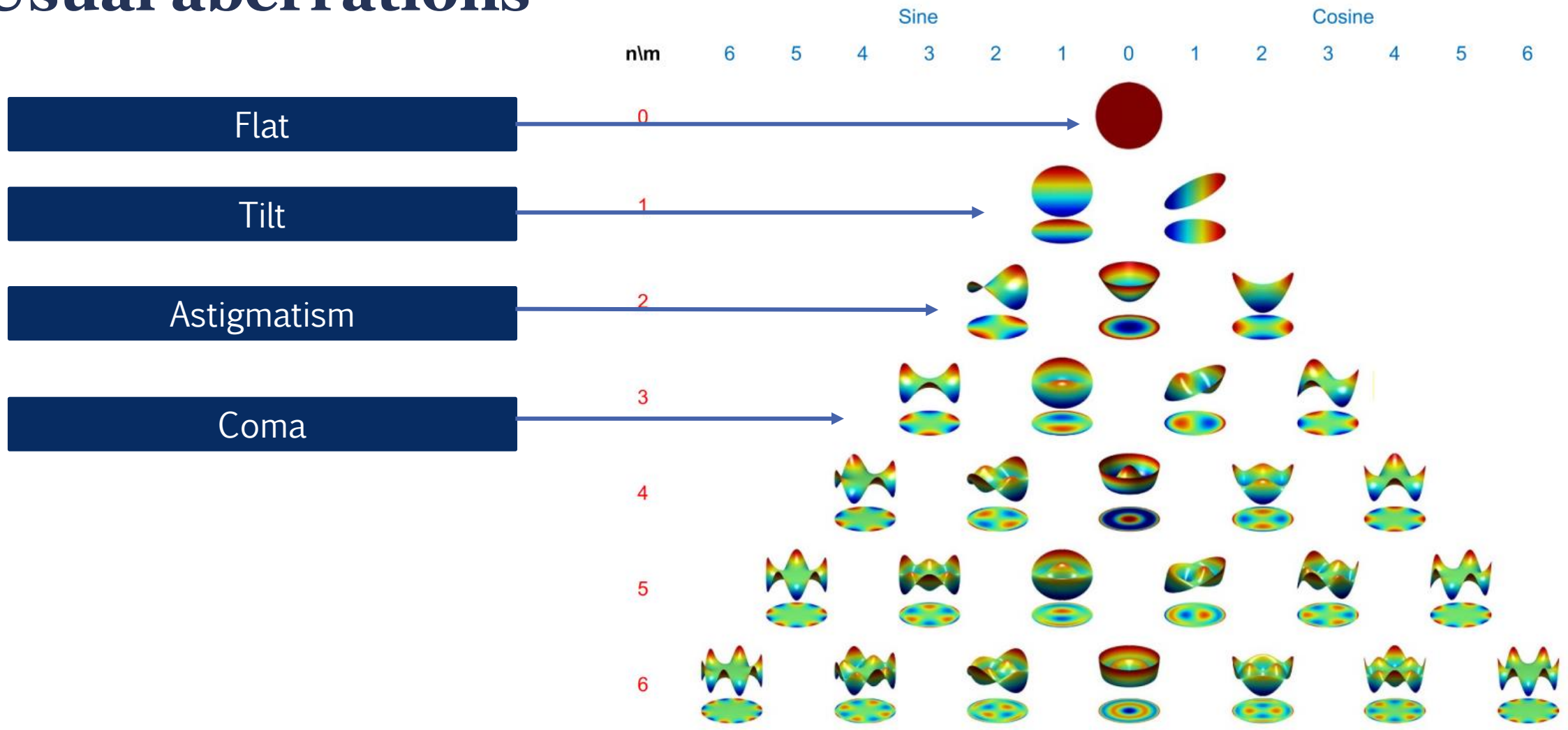
Usual aberrations



Usual aberrations

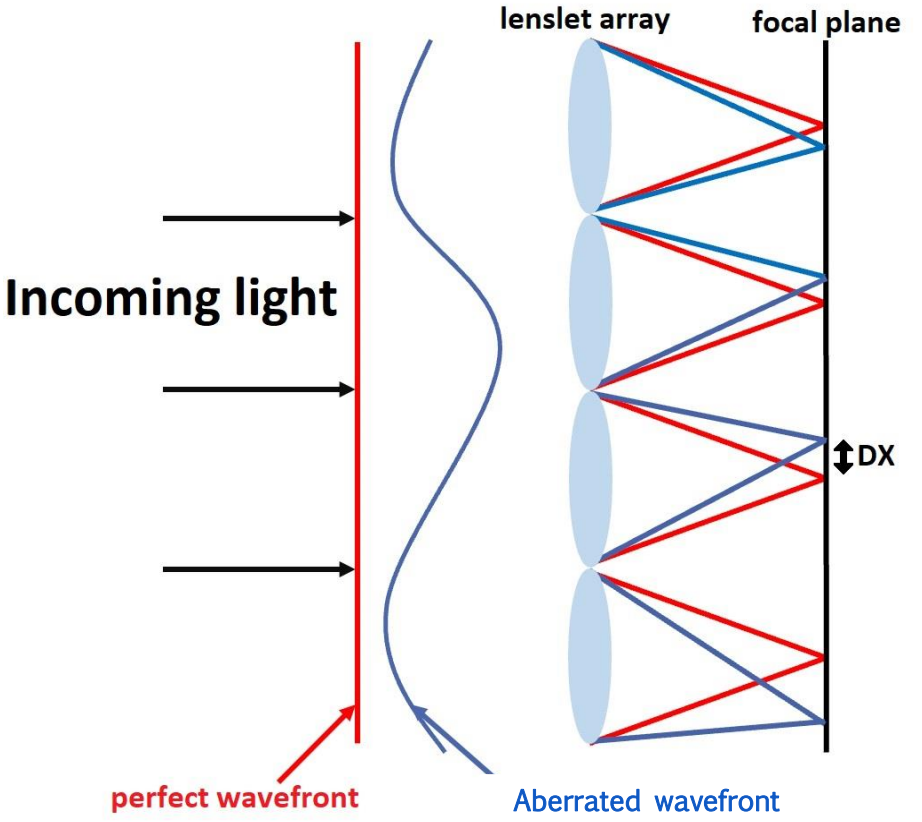


Usual aberrations



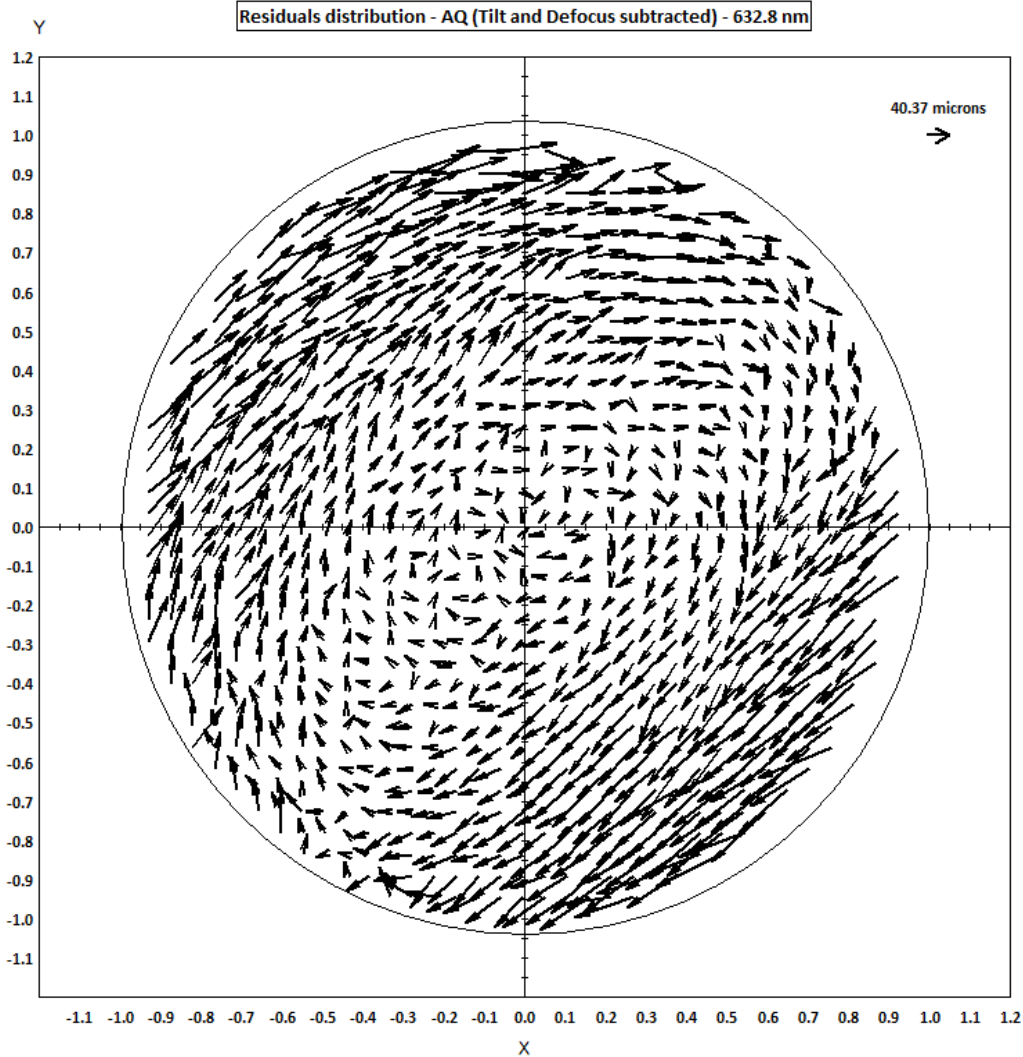
How does it work in practice ?

How does it work in practice ?

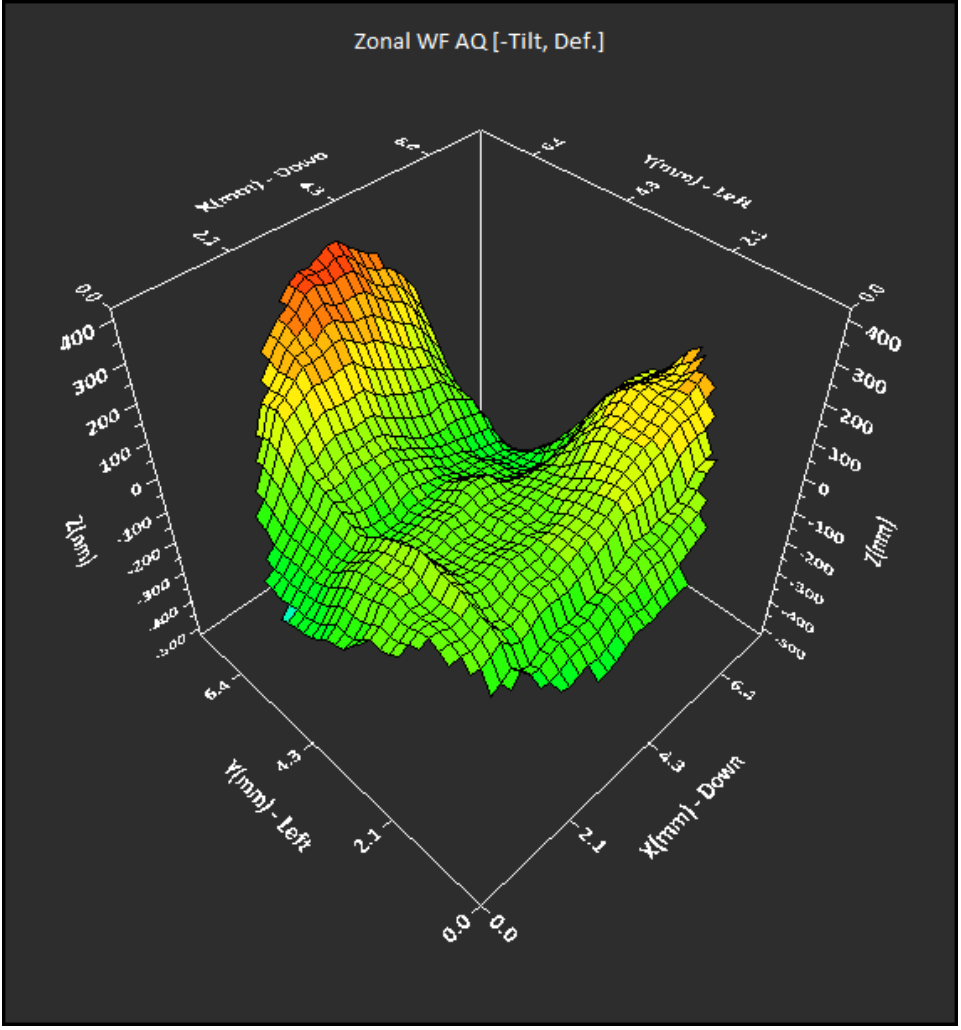
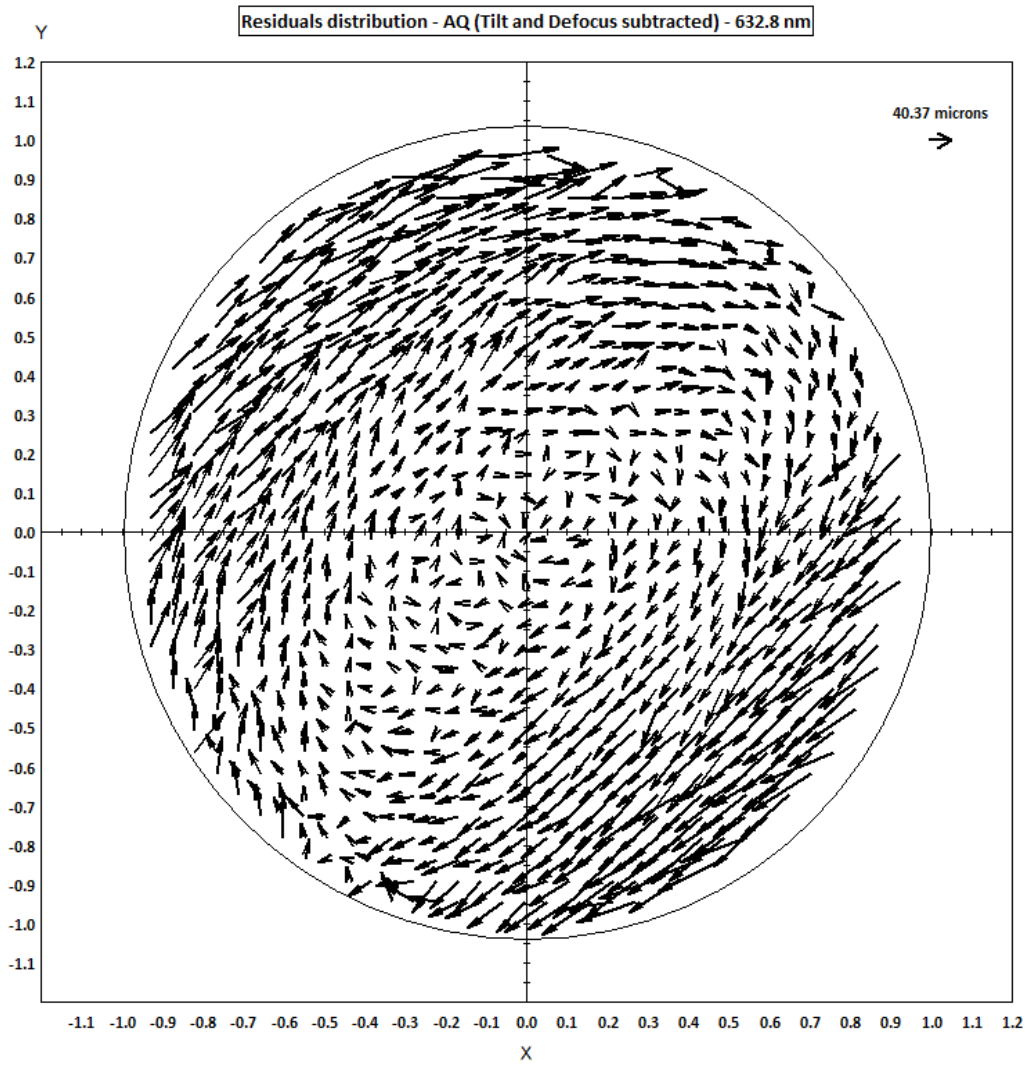


Shack-Hartmann wavefront sensor

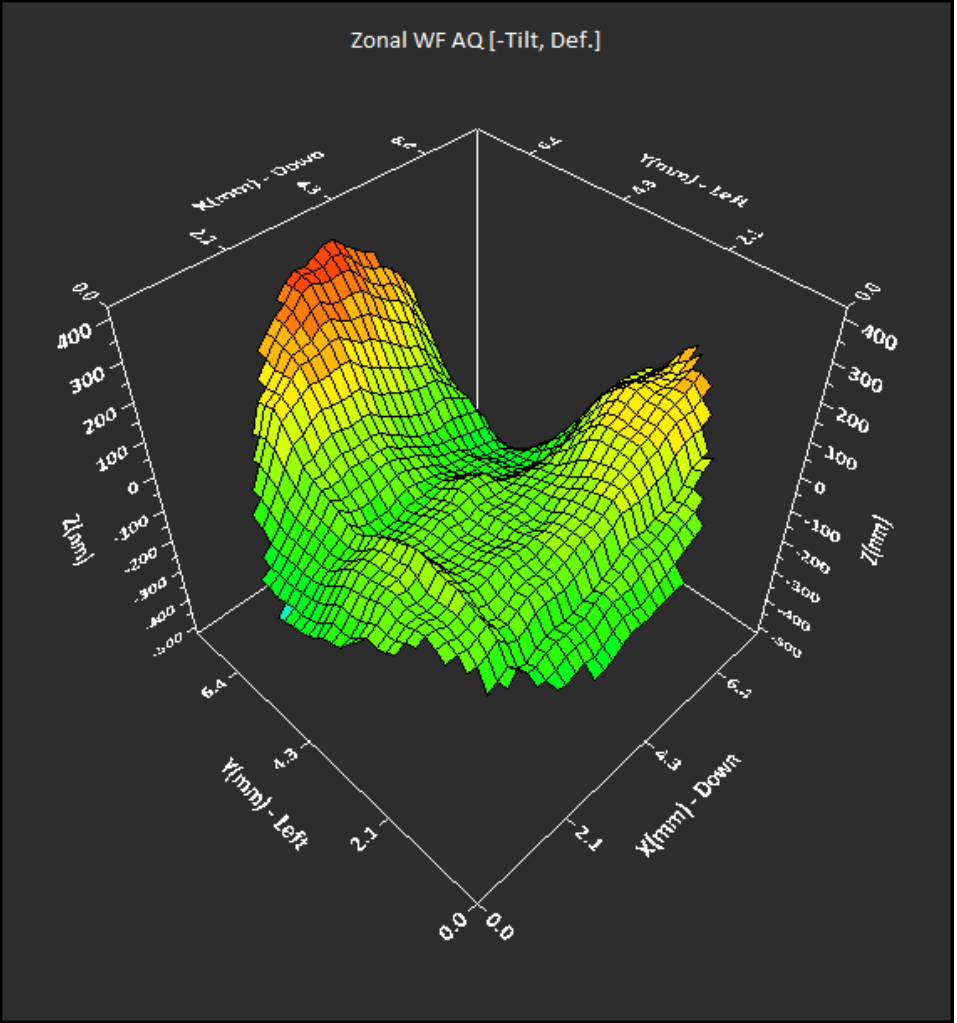
How does it work in practice ?



How does it work in practice ?



How does it work in practice ?



Standard Zernike coefficients - Noll notation

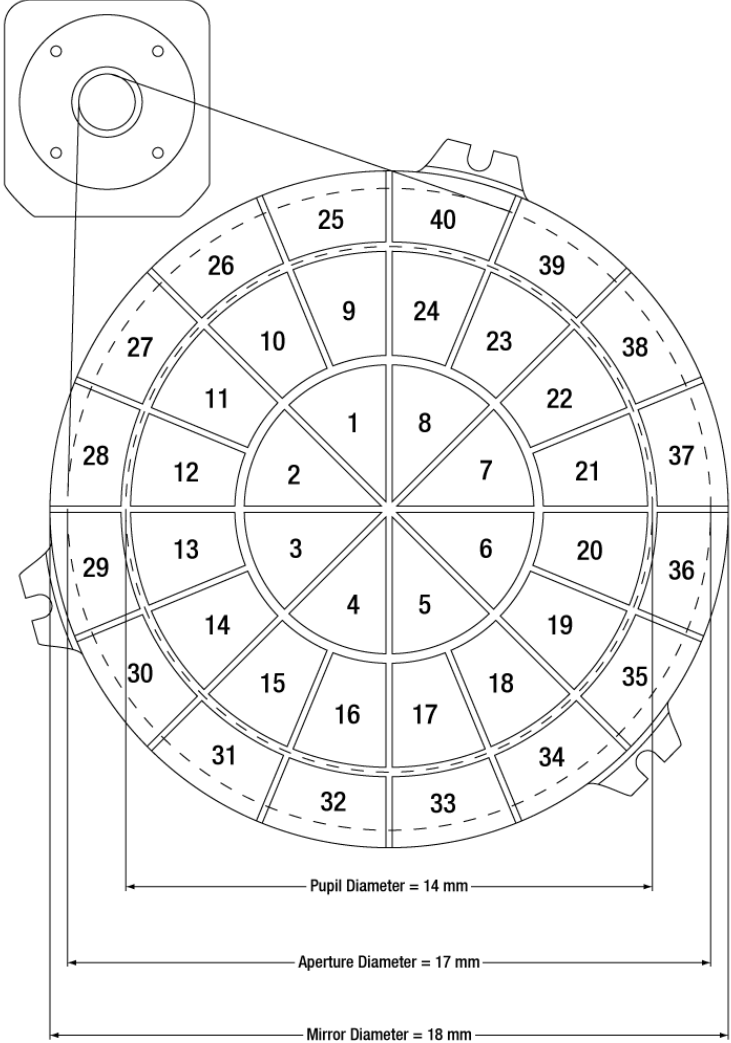
Aber	m n	Z	Z_e(nm)	Z	Z_o(nm)	C(nm)	D(um)
Tilt	1 1	Z2	-414.5	Z3	-298.8	511.0	23.96
Defocus	0 2	Z4		--		-90.1	-29.25
Ast3	2 2	Z6	6.1	Z5	-43.9	44.3	10.18
Coma3	1 3	Z8	27.3	Z7	-14.3	30.8	18.36
TComa	3 3	Z10	-26.3	Z9	88.6	92.4	36.75
SA3	0 4	--		Z11		-37.7	-23.71
Ast5	2 4	Z12	-15.4	Z13	12.1	19.6	--
QAst	4 4	Z14	-13.3	Z15	-13.9	19.3	11.43
Coma5	1 5	Z16	7.4	Z17	16.8	18.3	--
TComa5	3 5	Z18	-3.2	Z19	-5.7	6.6	--

How to correct optical aberrations ?

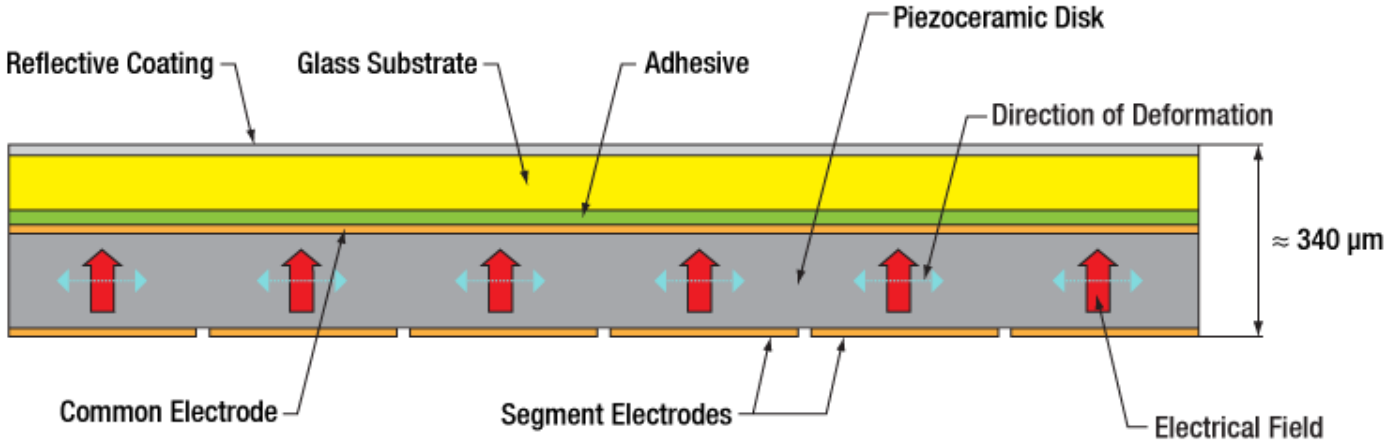
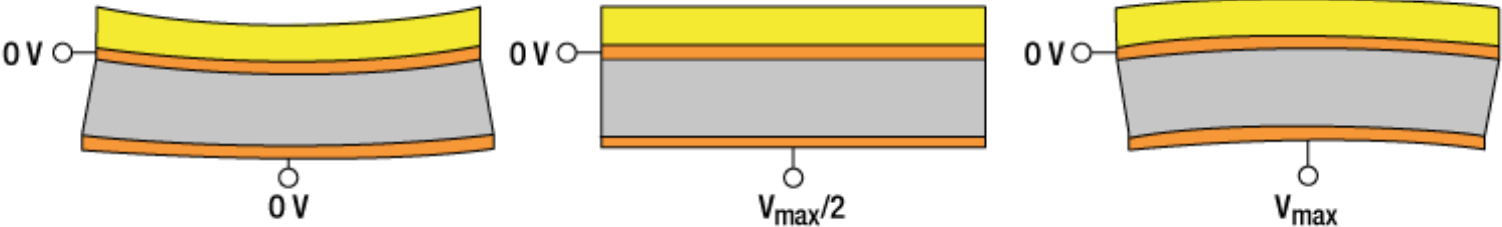
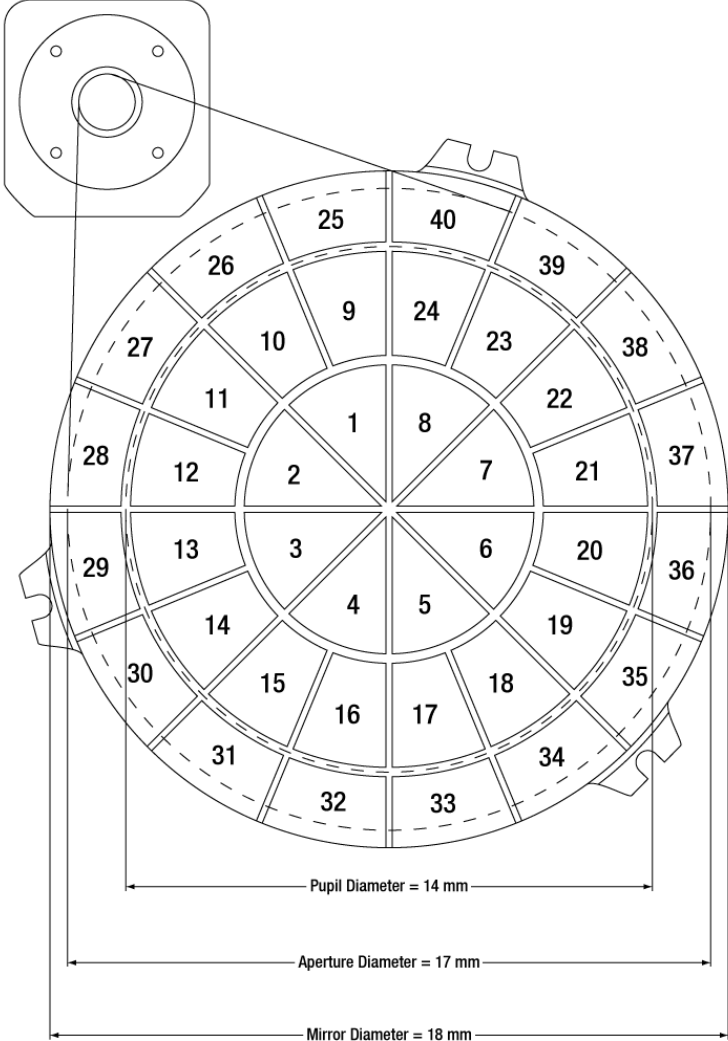
How to correct optical aberrations ?



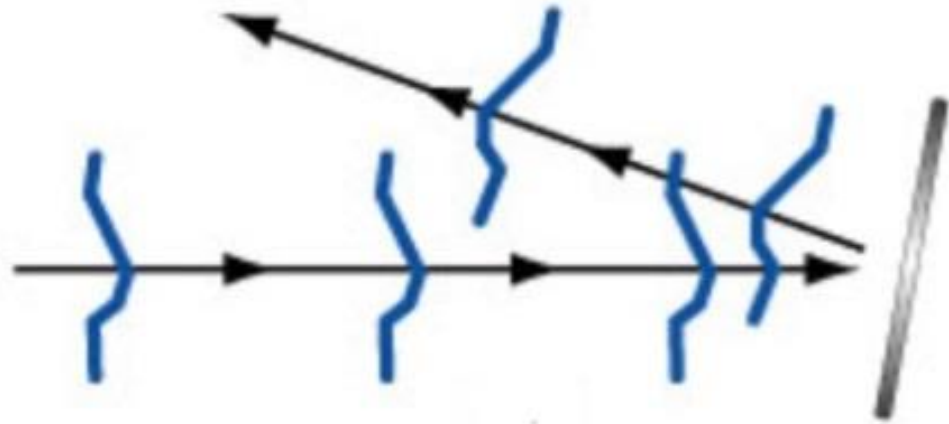
The deformable mirror



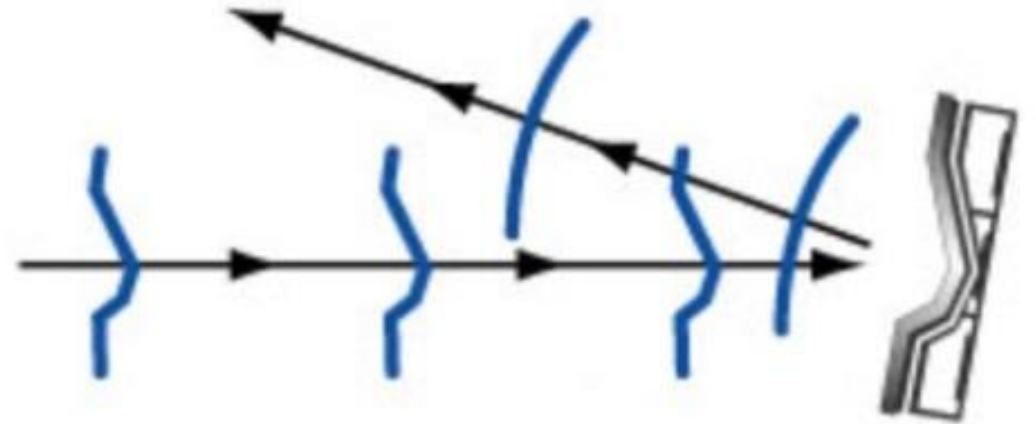
The deformable mirror



Aberration correction



Regular mirror



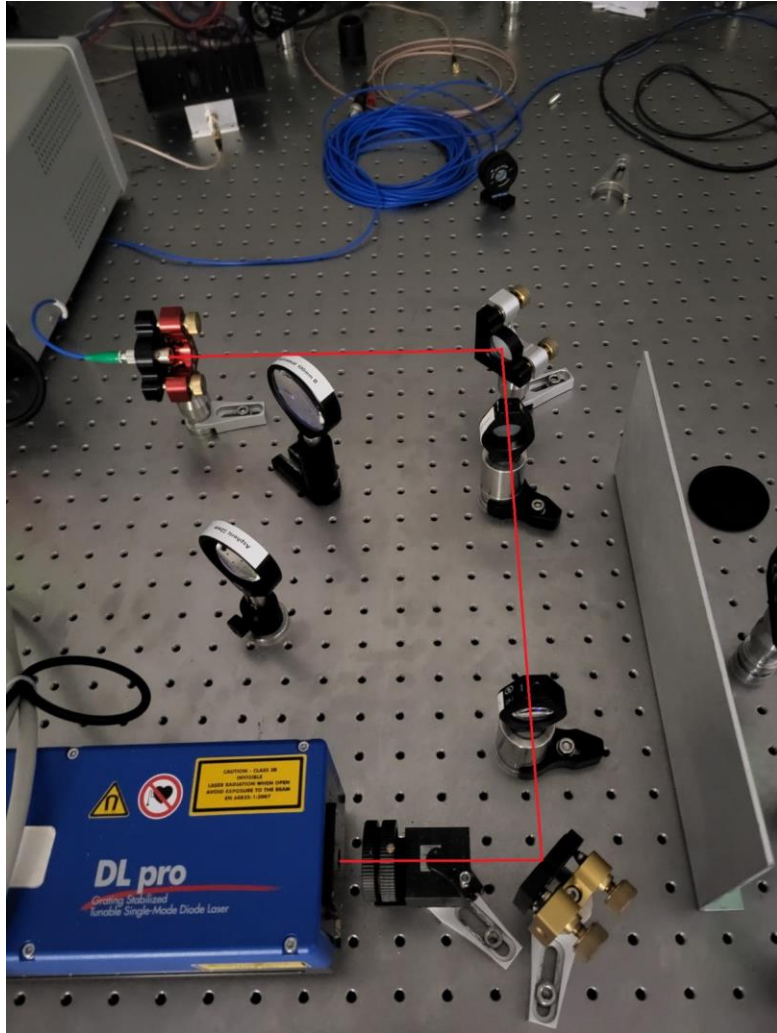
Deformable mirror

Aberration correction

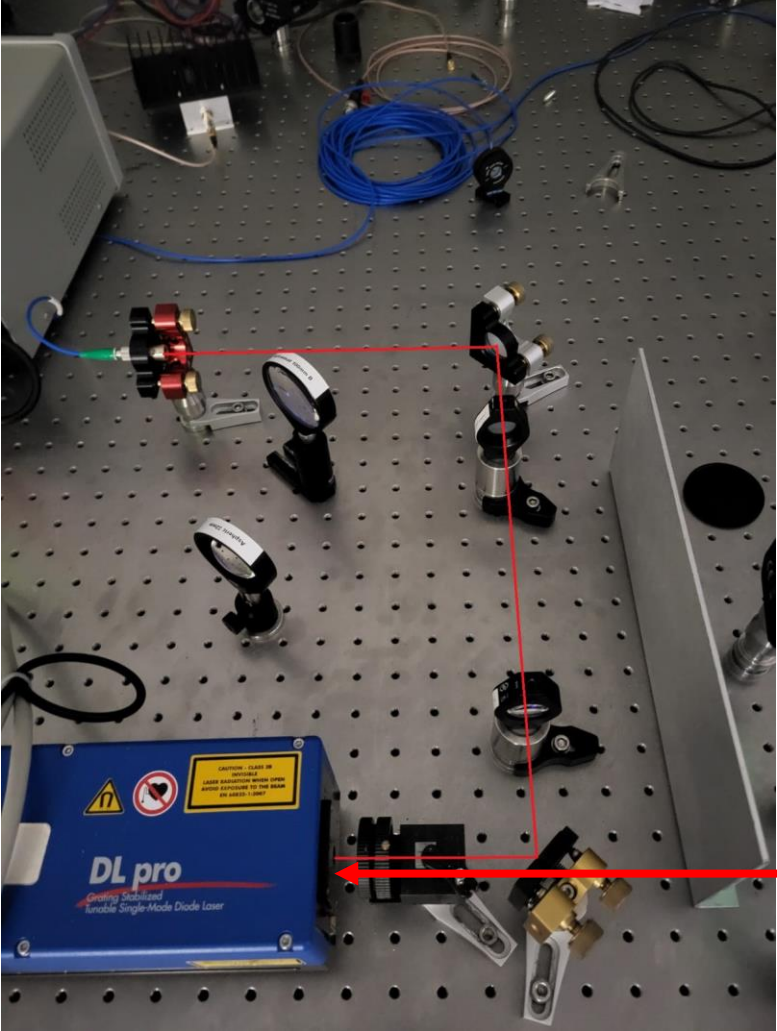
The screenshot displays the Thorlabs software interface for aberration correction. The main window is divided into several sections:

- Status Window:** Shows camera status (Camera on), normalized pupil (Norm. Pupil), and exposure settings (Live, Time: 2.82 msec, Auto, Histogram).
- SH Image:** A large grayscale image showing the wavefront profile. Below it, a "Take Test" button is visible.
- 3D of Wavefront:** A 3D visualization of the wavefront, currently zoomed in.
- Zernike Polynomial:** A list of Zernike modes with their corresponding coefficients. The modes listed are:
 - Amplitude: 0.00
 - Angle: 0.00
 - Z4 Ast45: 0.00
 - Z5 Def: 0.00
 - Z6 Ast0: 0.00
 - Z7 TreY: 0.00
 - Z8 ComX: 0.00
 - Z9 ComY: 0.00
 - Z10 TreX: 0.00
 - Z11 TetY: 0.00
 - Z12 SAstY: 0.00
 - Z13 SAB3: 0.00
 - Z14 SAstX: 0.00
 - Z15 TetX: 0.00
- Zernike Plot:** A circular plot showing the Zernike modes, with a color scale on the right ranging from 0 to 300.

Injection in the optical fiber

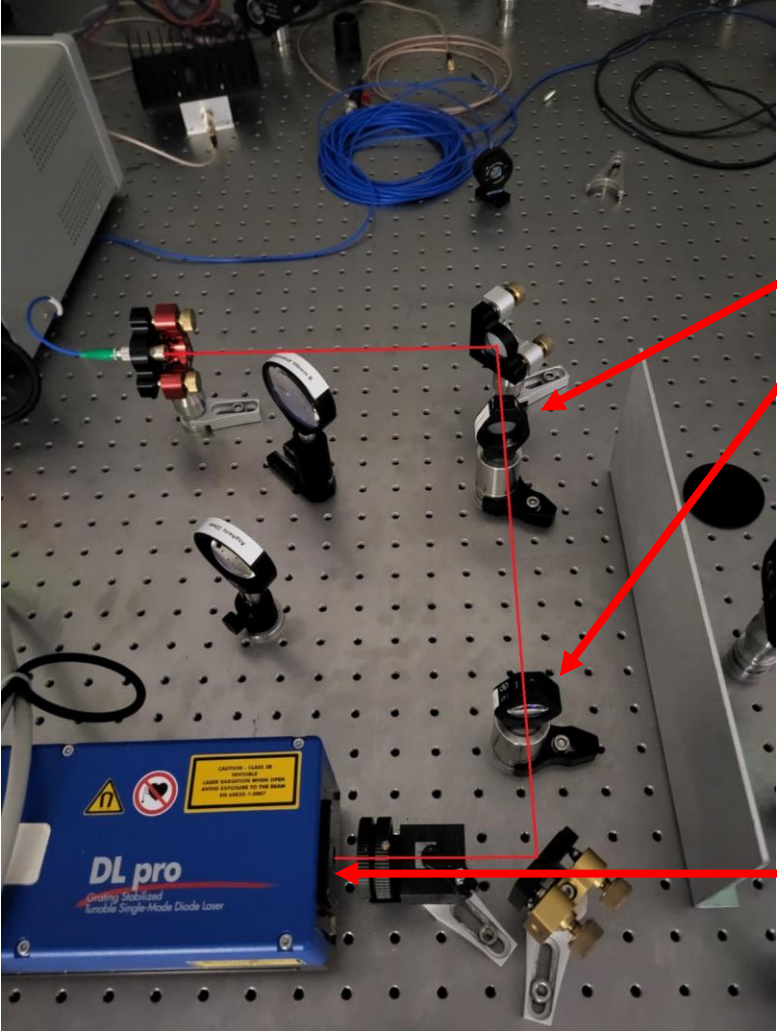


Injection in the optical fiber

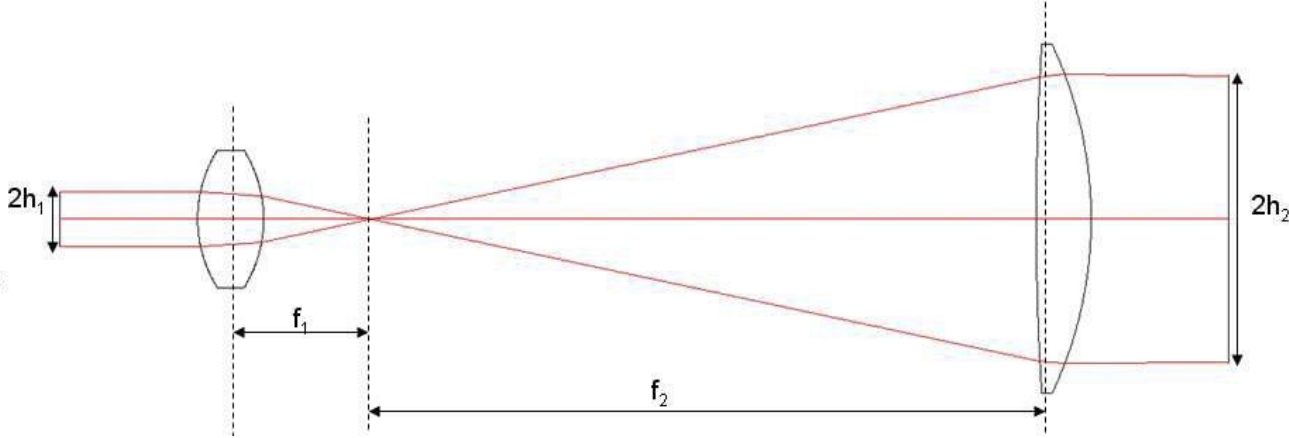


Laser

Injection in the optical fiber

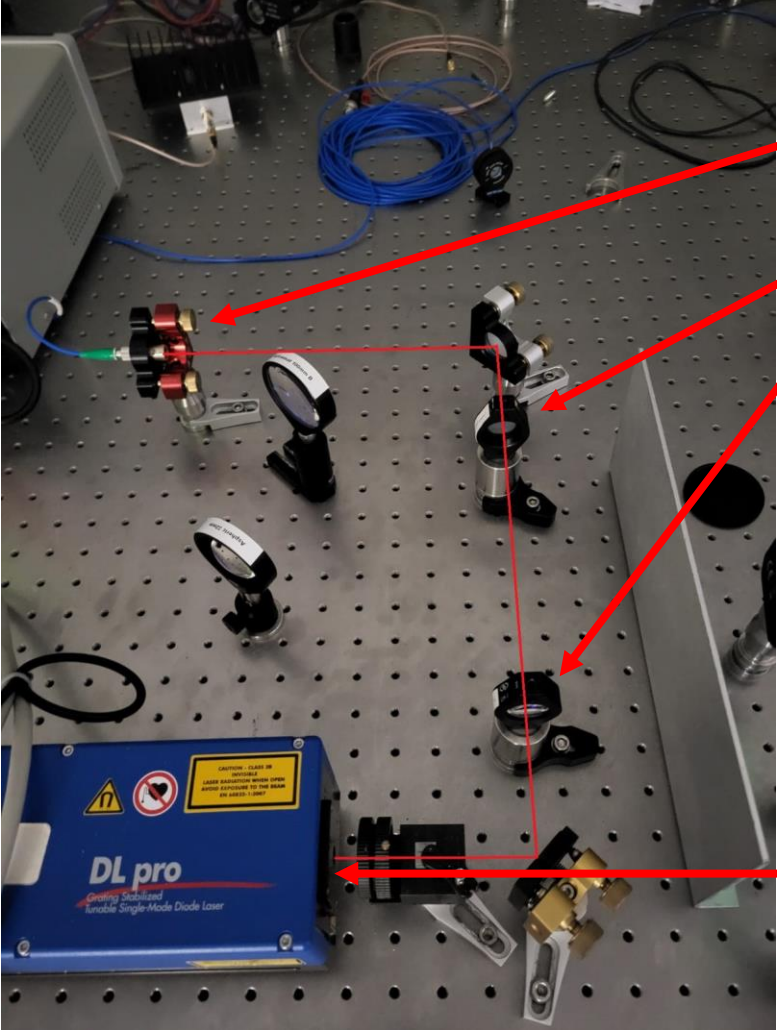


Beam expander group



Laser

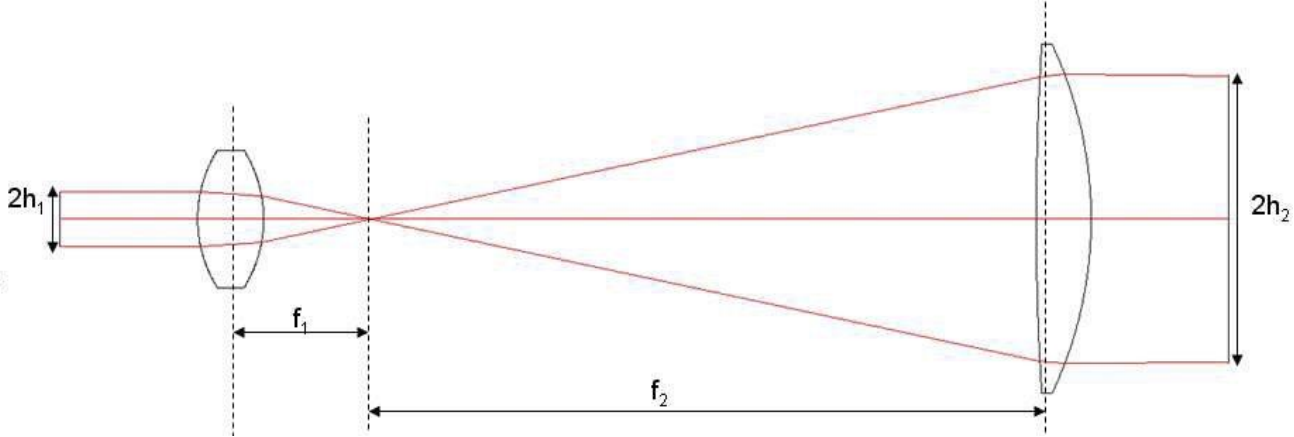
Injection in the optical fiber



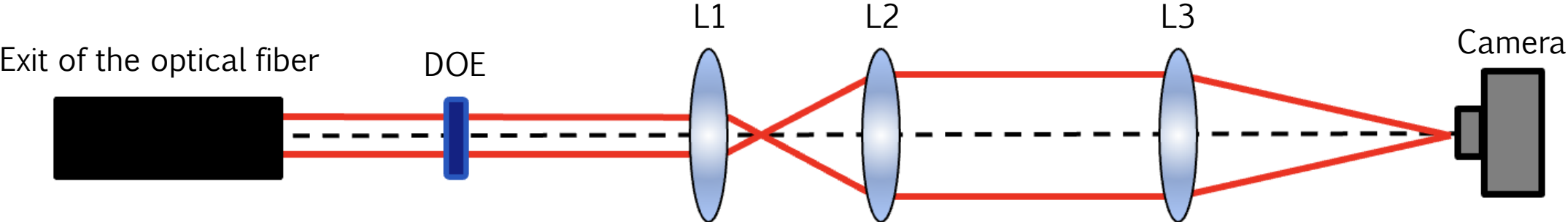
Start of the optical fiber

Beam expander group

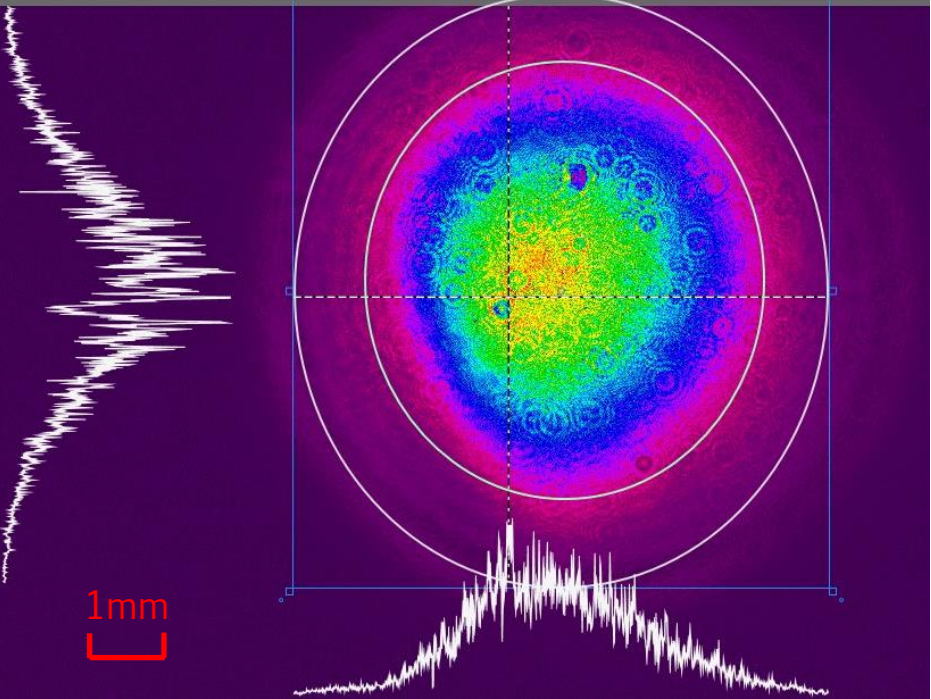
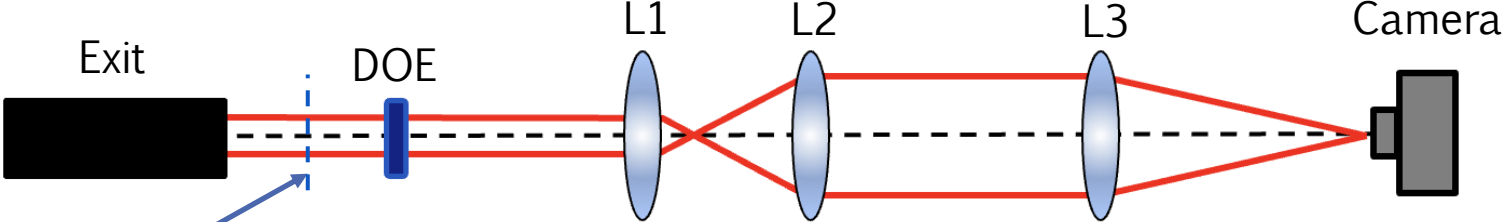
Laser



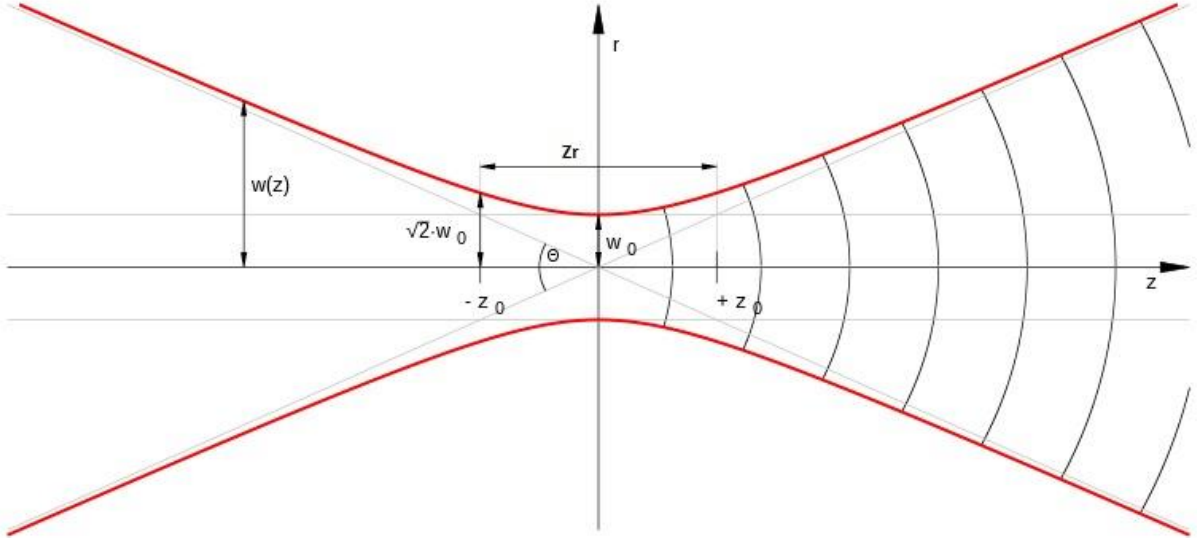
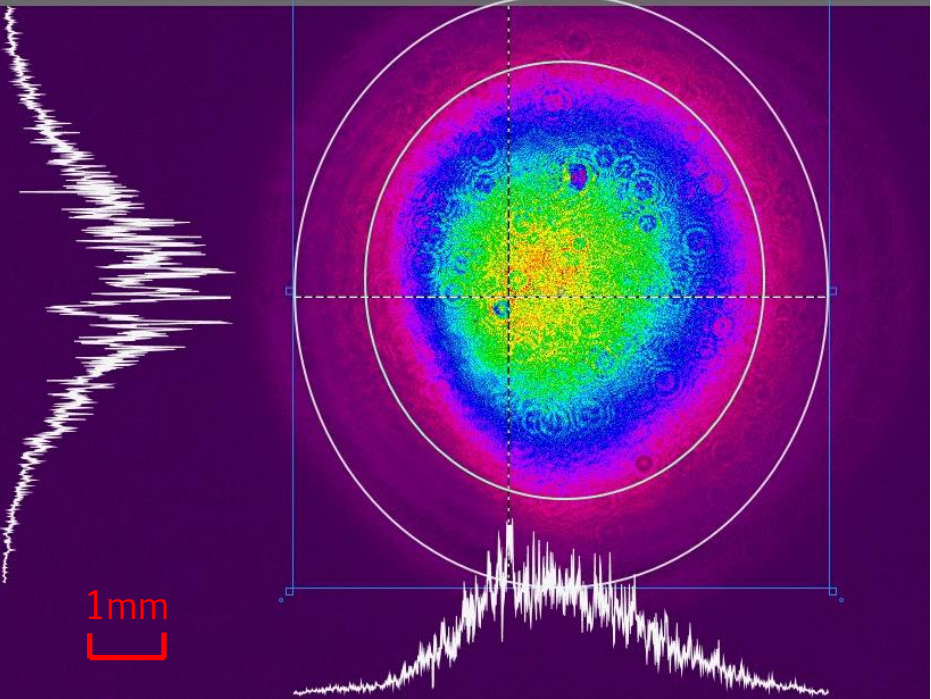
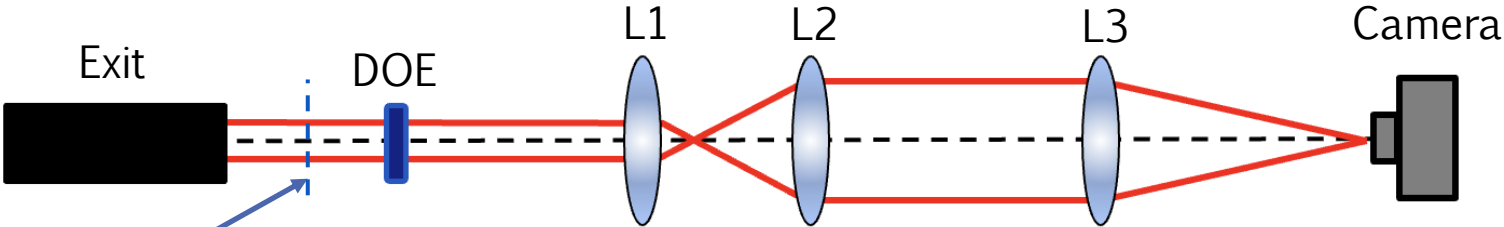
Imaging setup



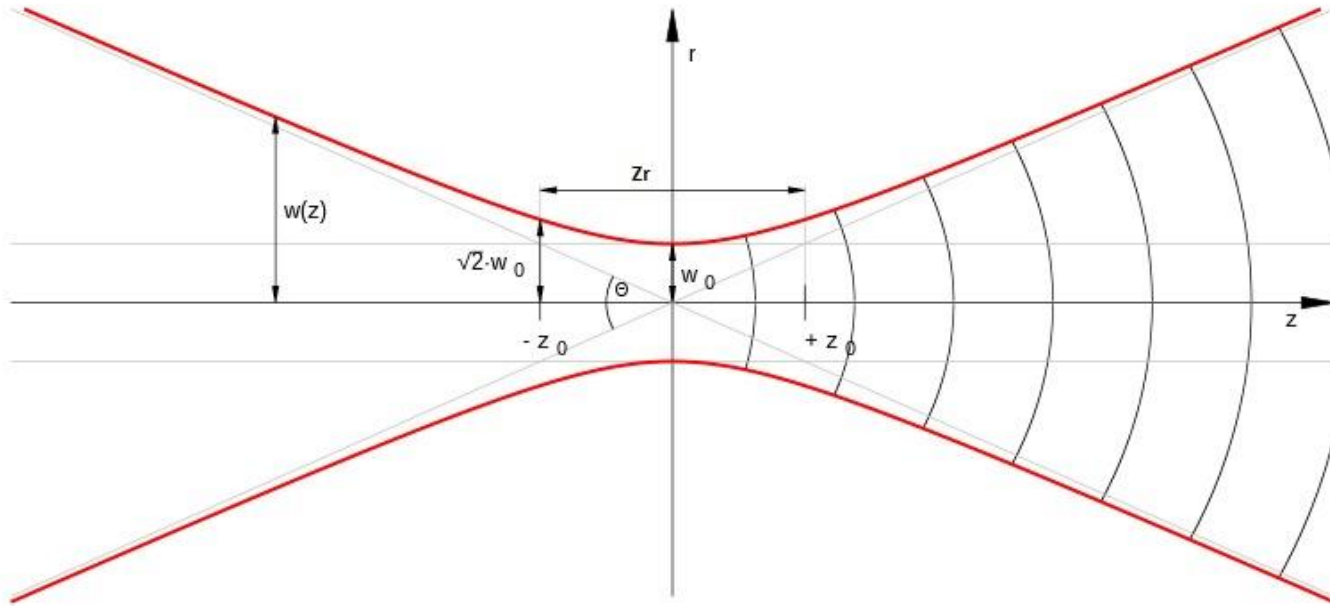
Imaging setup



Imaging setup



Wavefront of the laser beam



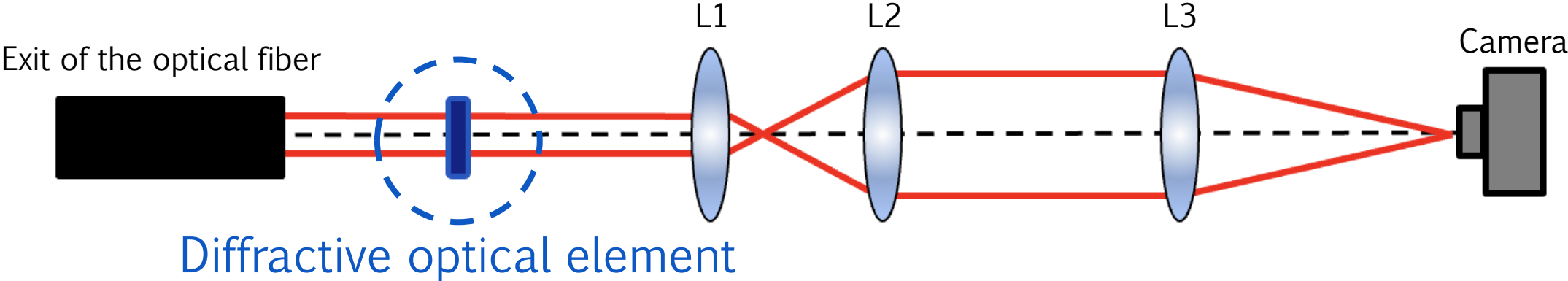
$$z_R = \frac{\pi w_0^2}{\lambda} = \frac{1}{2} k w_0^2$$

Rayleigh length

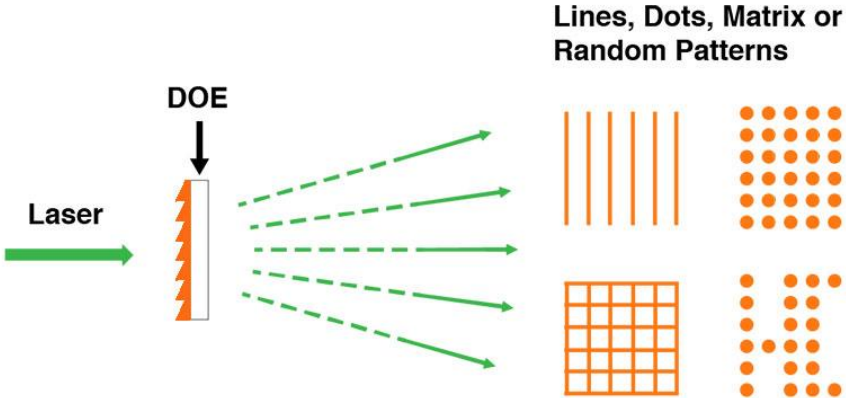
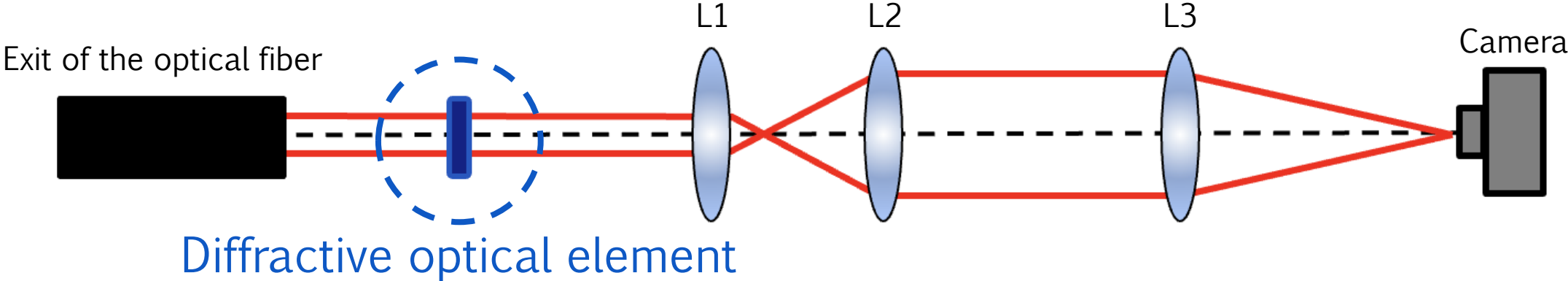
$$\frac{1}{R(z)} = \frac{z}{z^2 + z_R^2}$$

Curvature of the wavefront

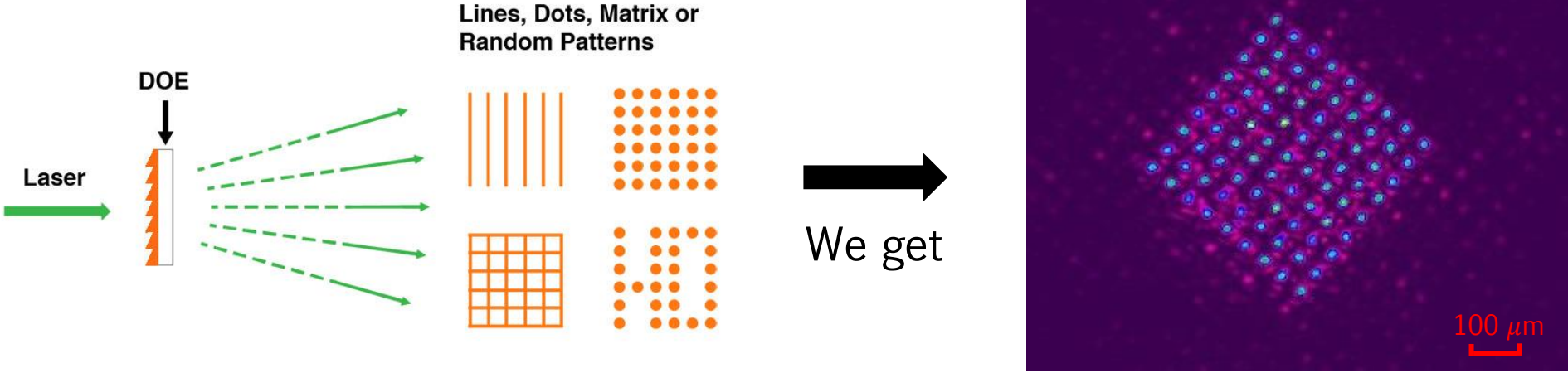
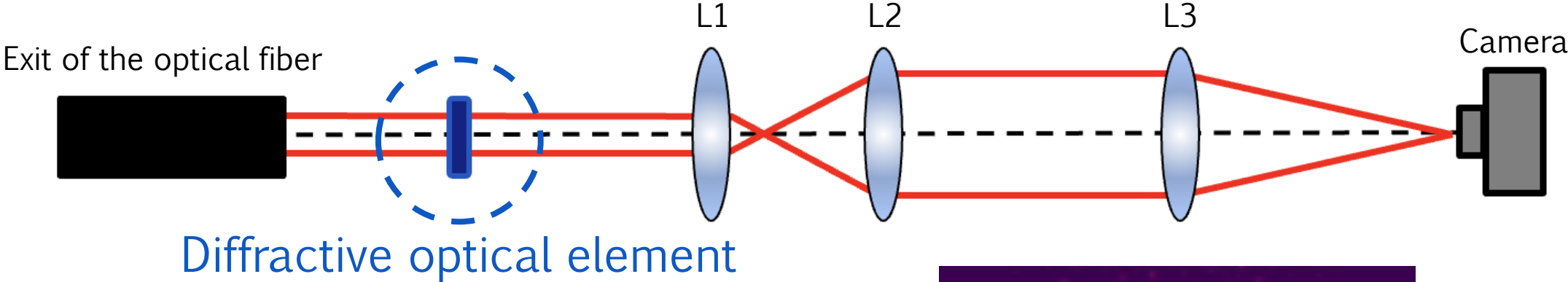
Imaging setup



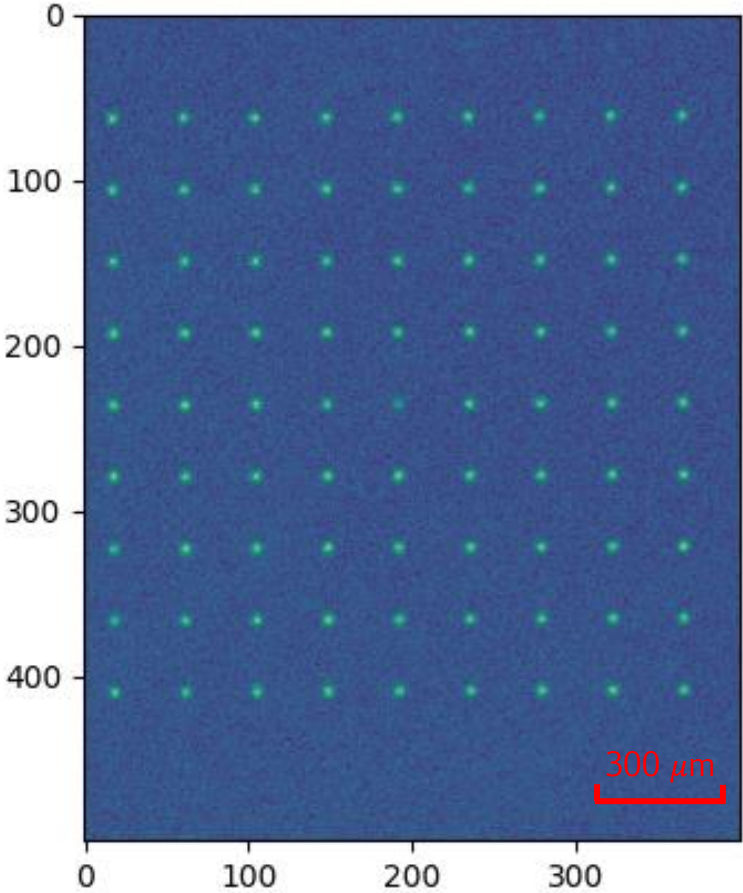
Imaging setup



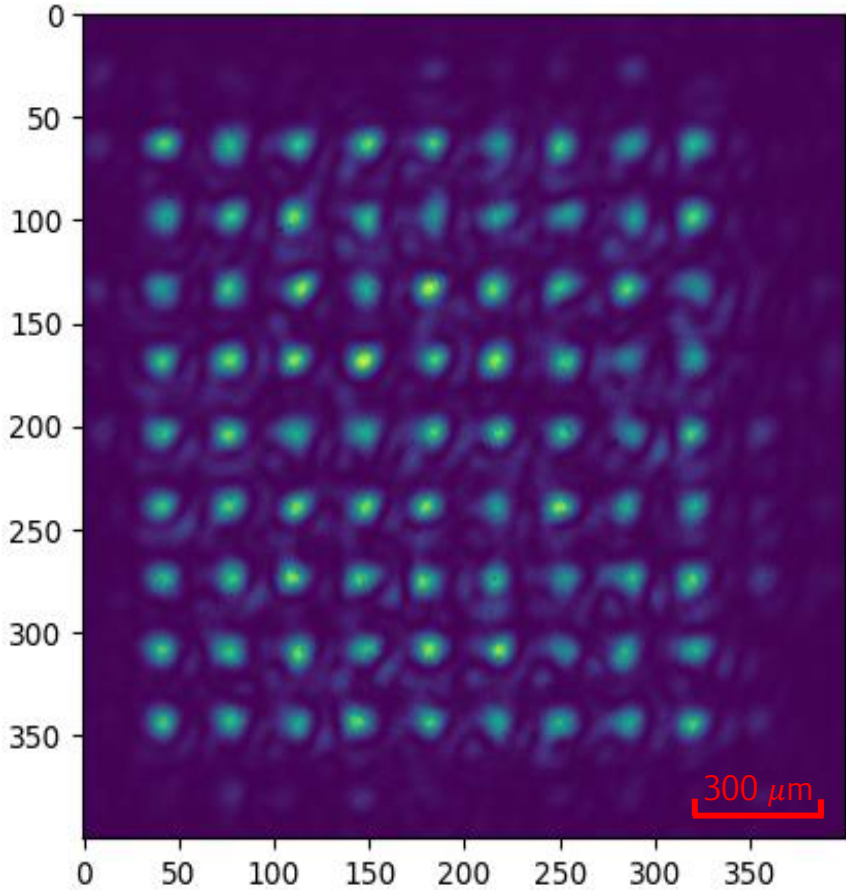
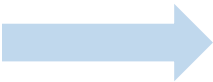
Imaging setup



Imaging the beam



Beam before the imaging system



Beam after the imaging system

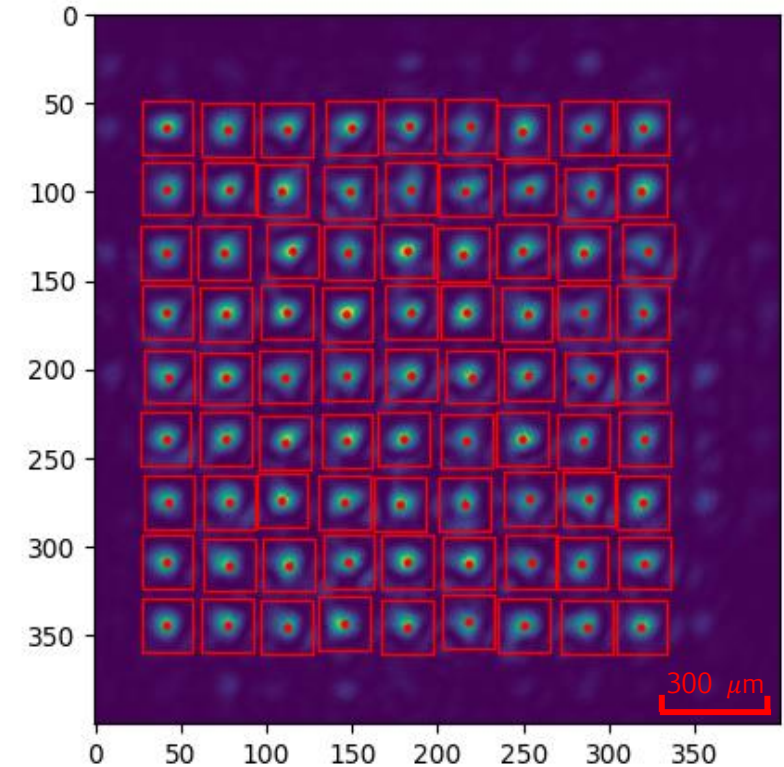
Characterization of the aberration

Step 1: Defining the regions of interest

- Finding the peaks of intensity and defining regions of interest (ROI) around them

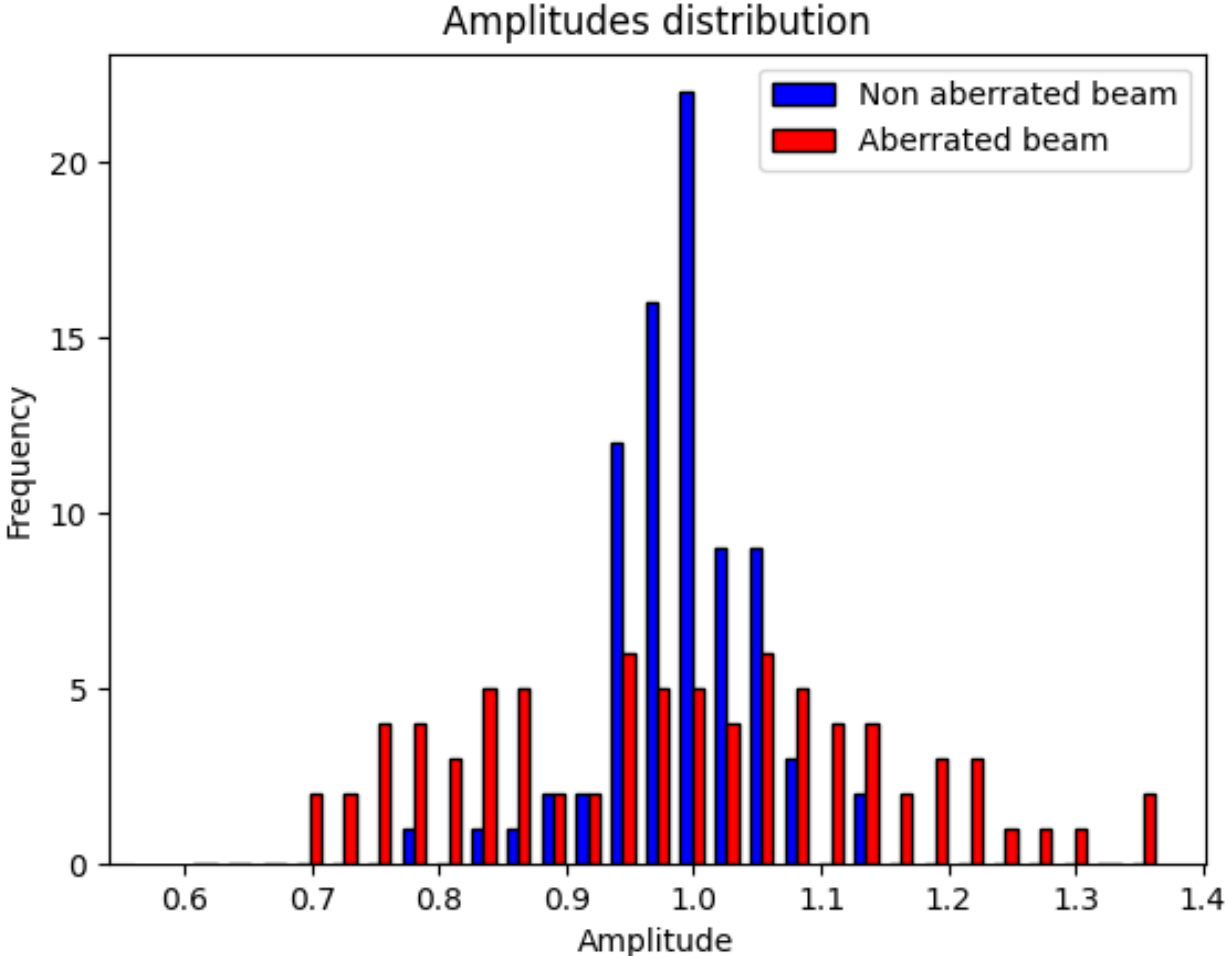
Step 2: Gaussian fit

- Gaussian fit for each dot to extract the amplitude and the waists

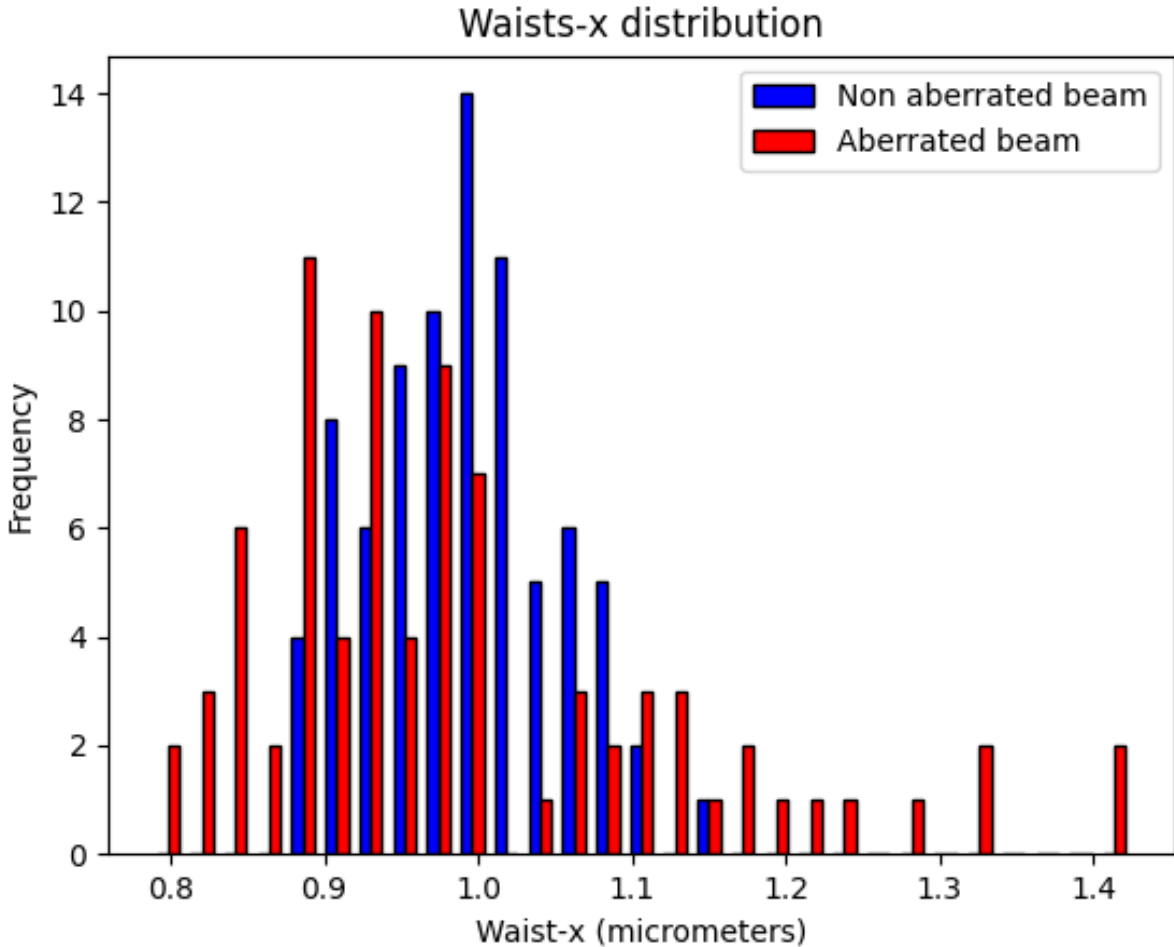


Aberrated image with ROI

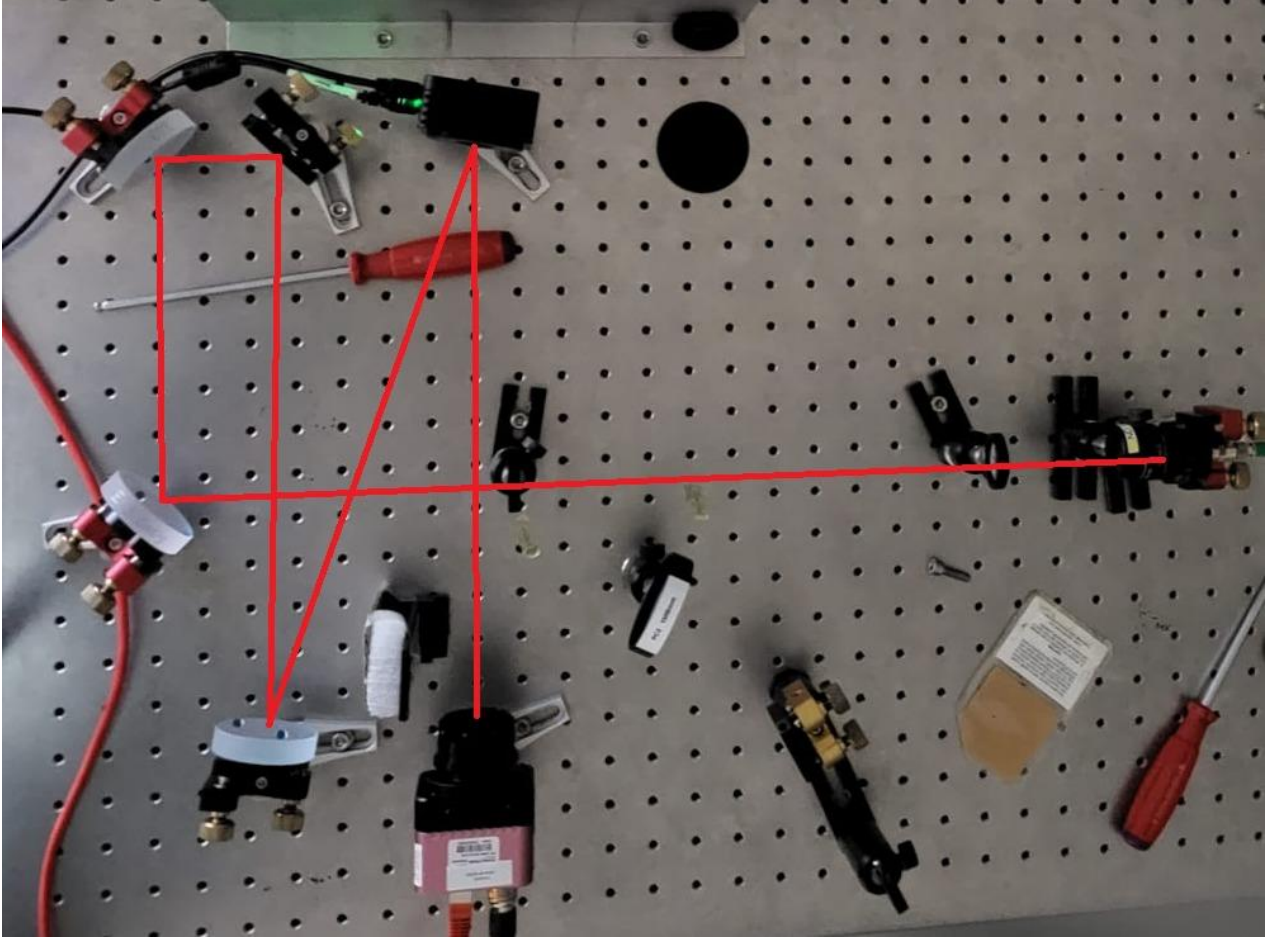
Characterization of the aberration



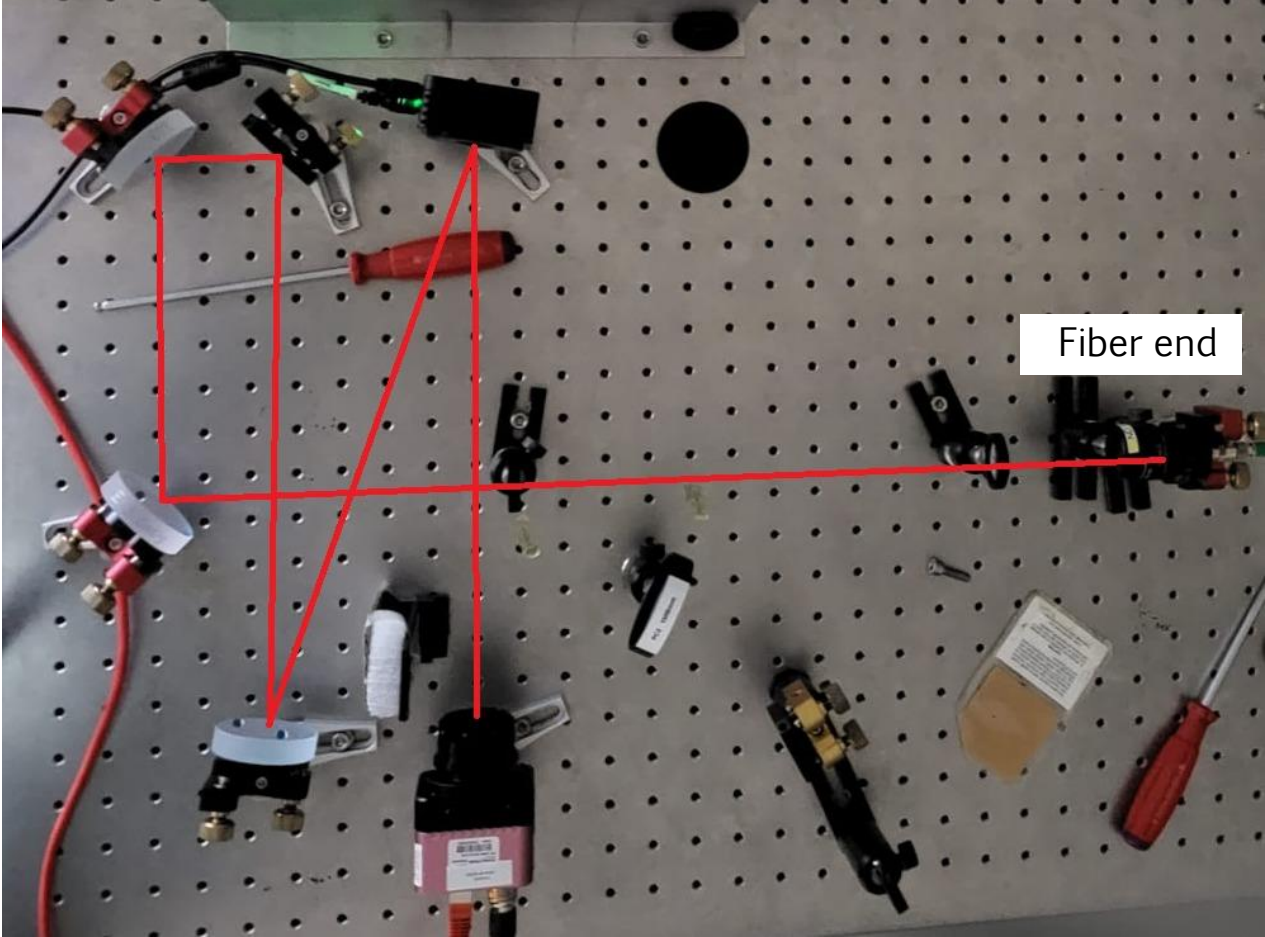
Characterization of the aberration



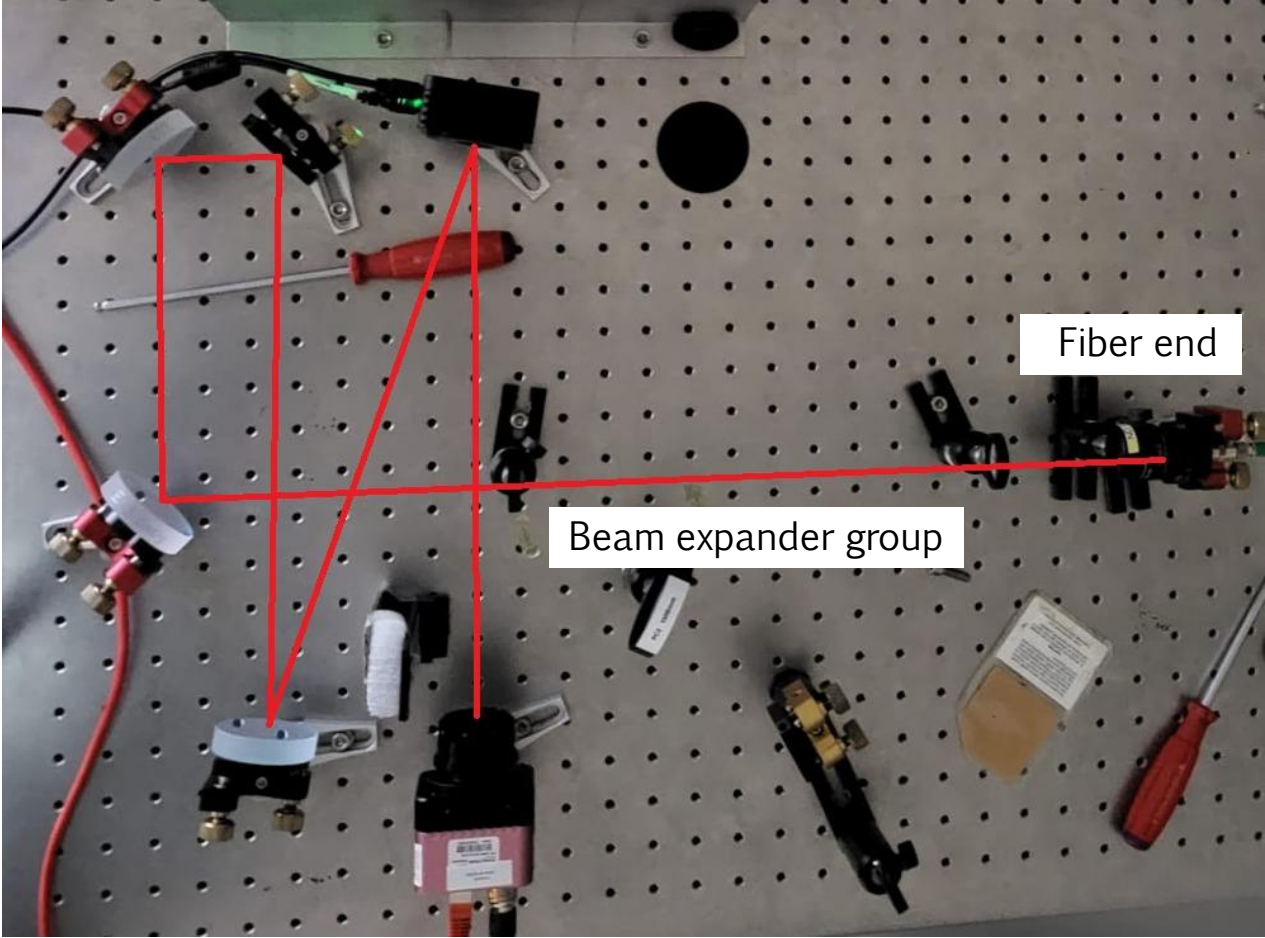
Correction setup



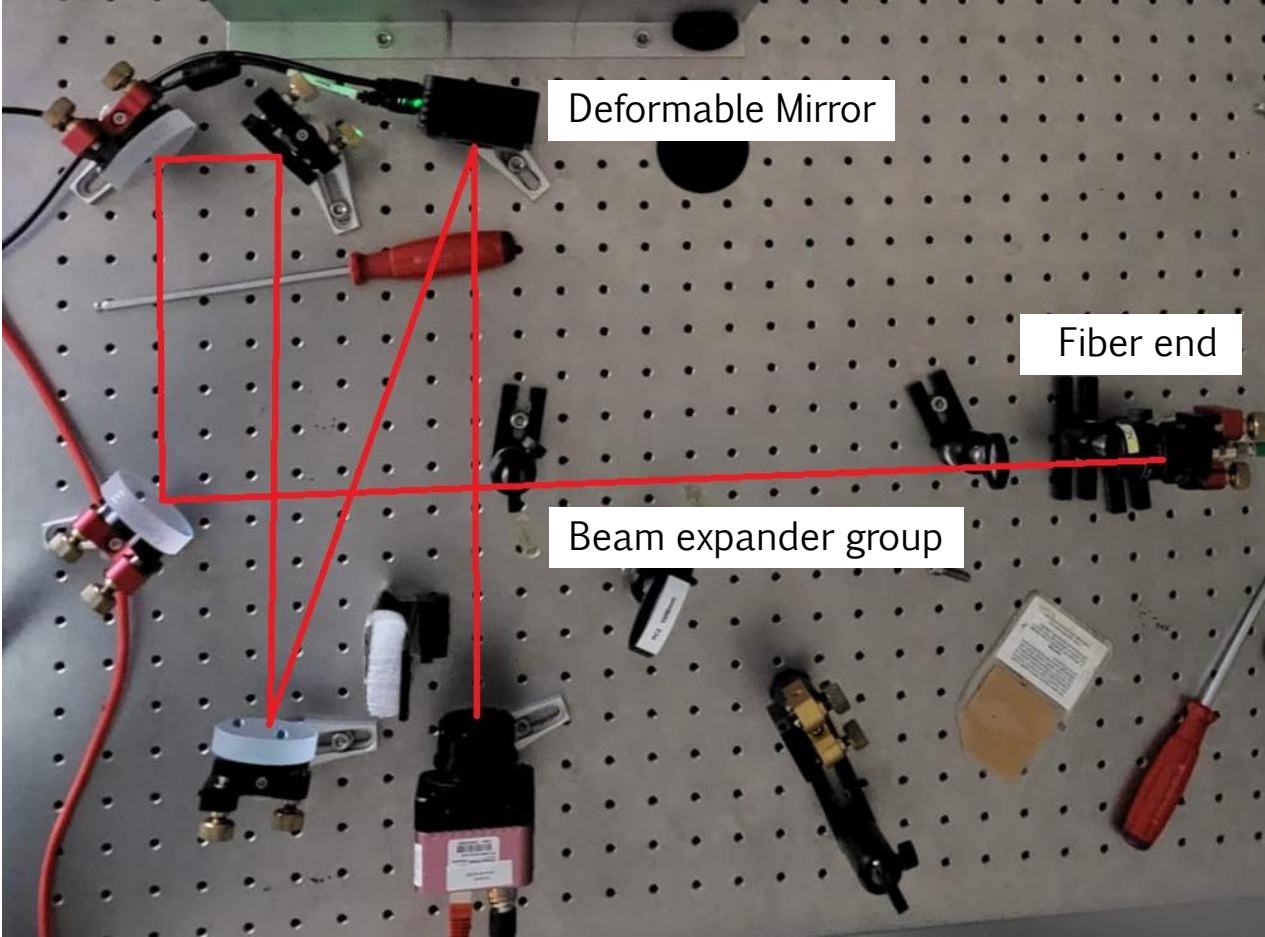
Correction setup



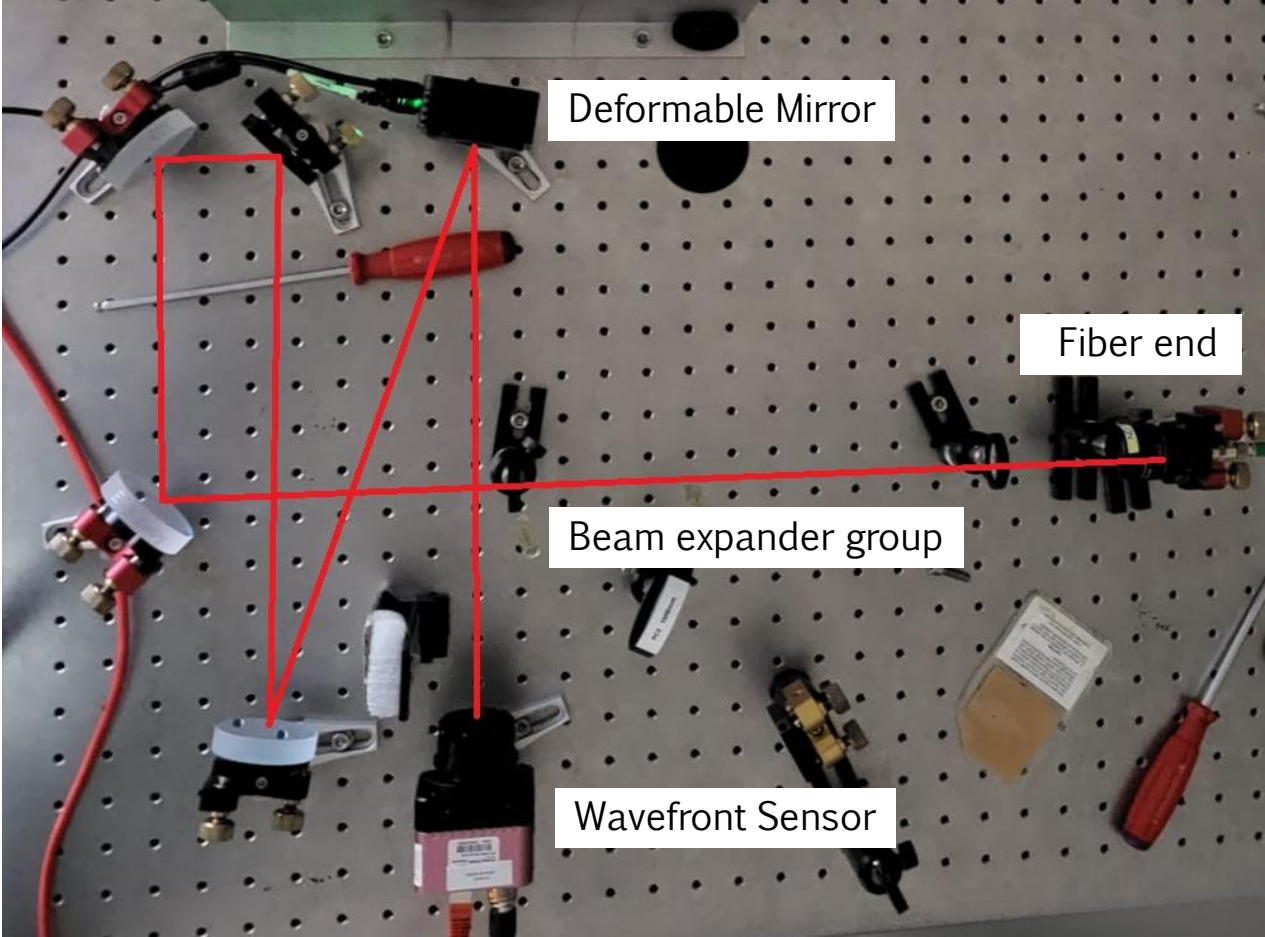
Correction setup



Correction setup



Correction setup



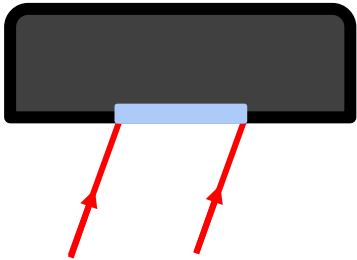
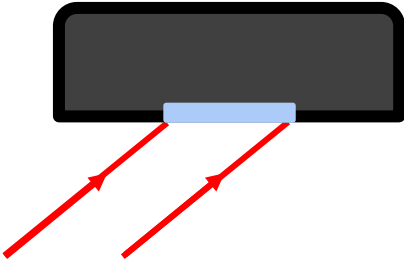
Angle of incidence on the DM

Big angle

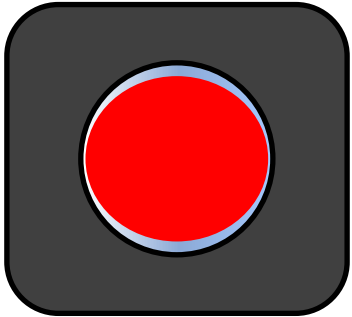
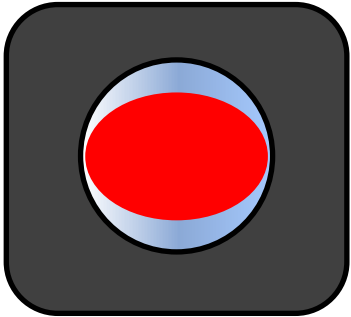
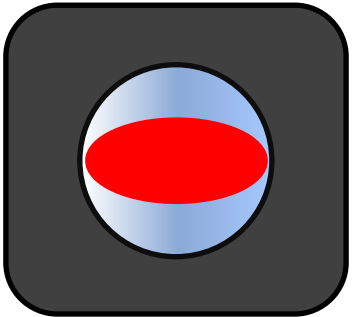
Medium angle

Small angle

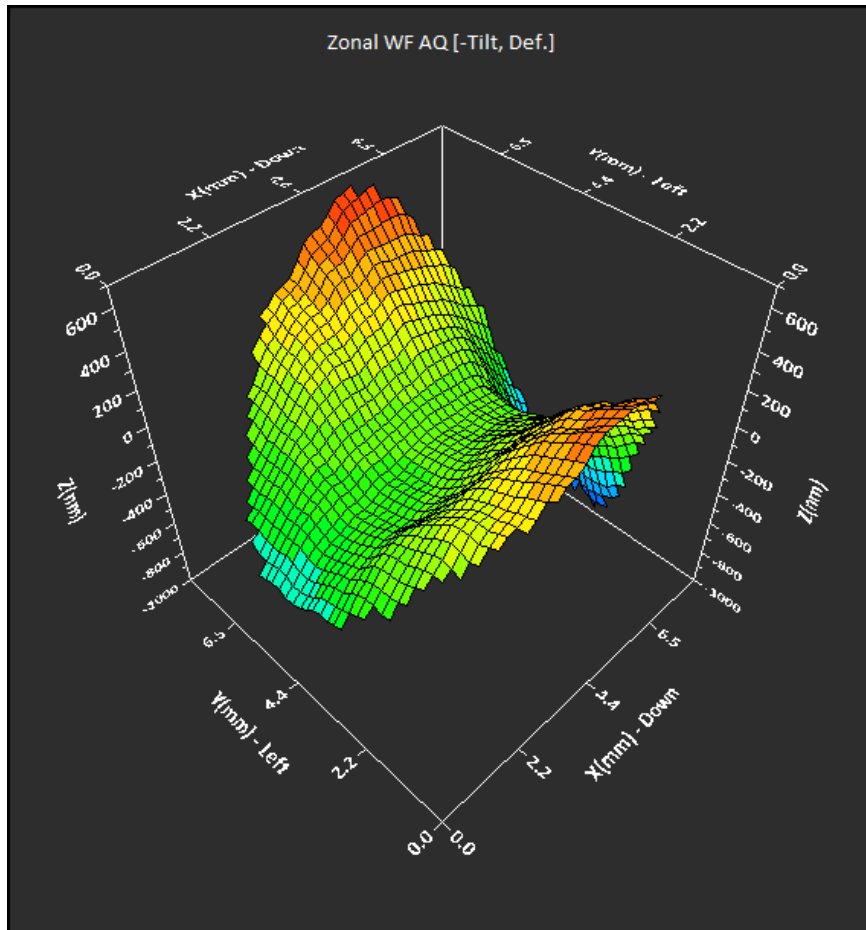
Top view



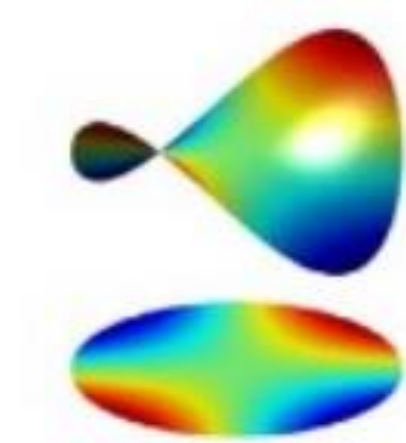
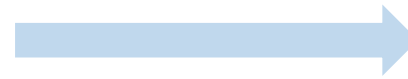
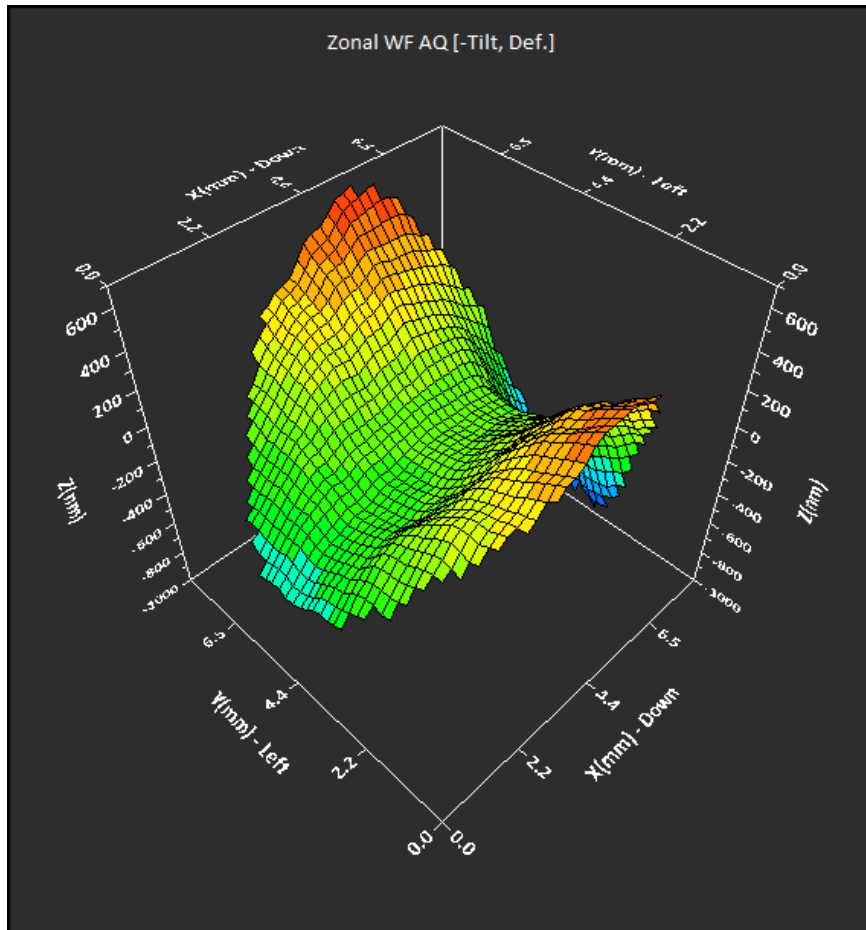
Front view



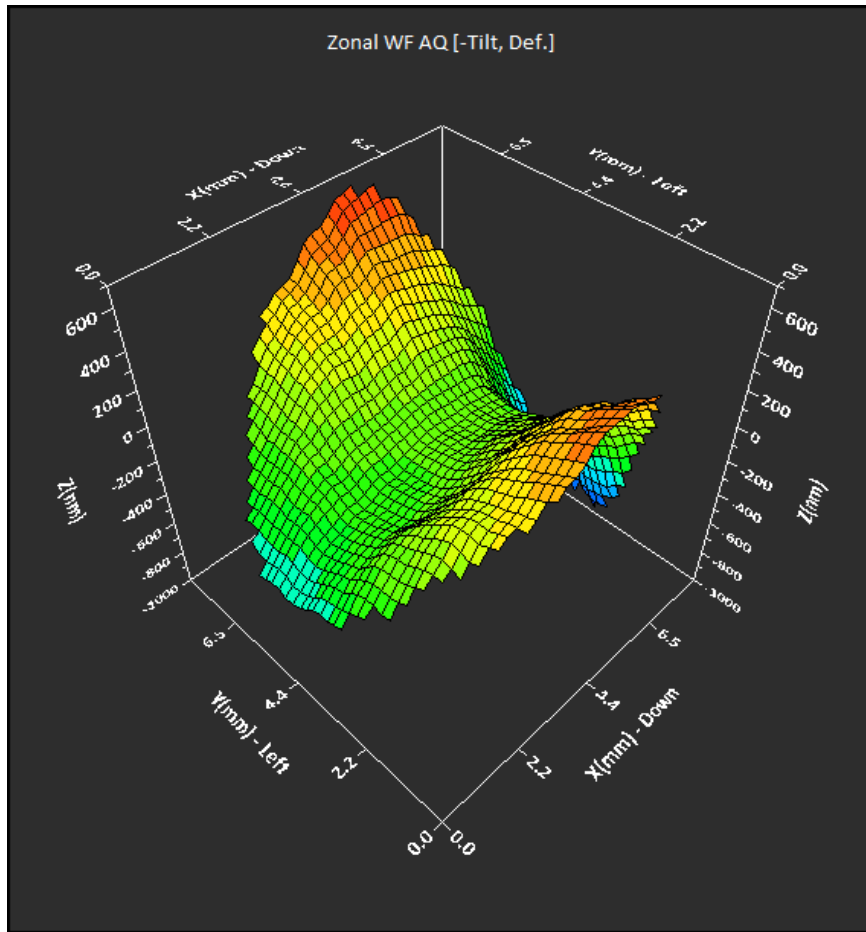
Correcting a specific aberration



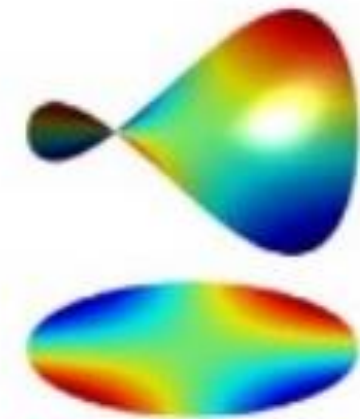
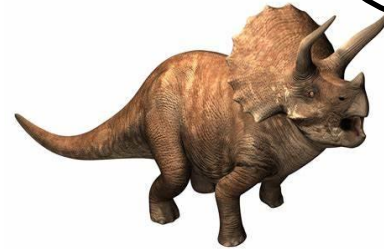
Correcting a specific aberration



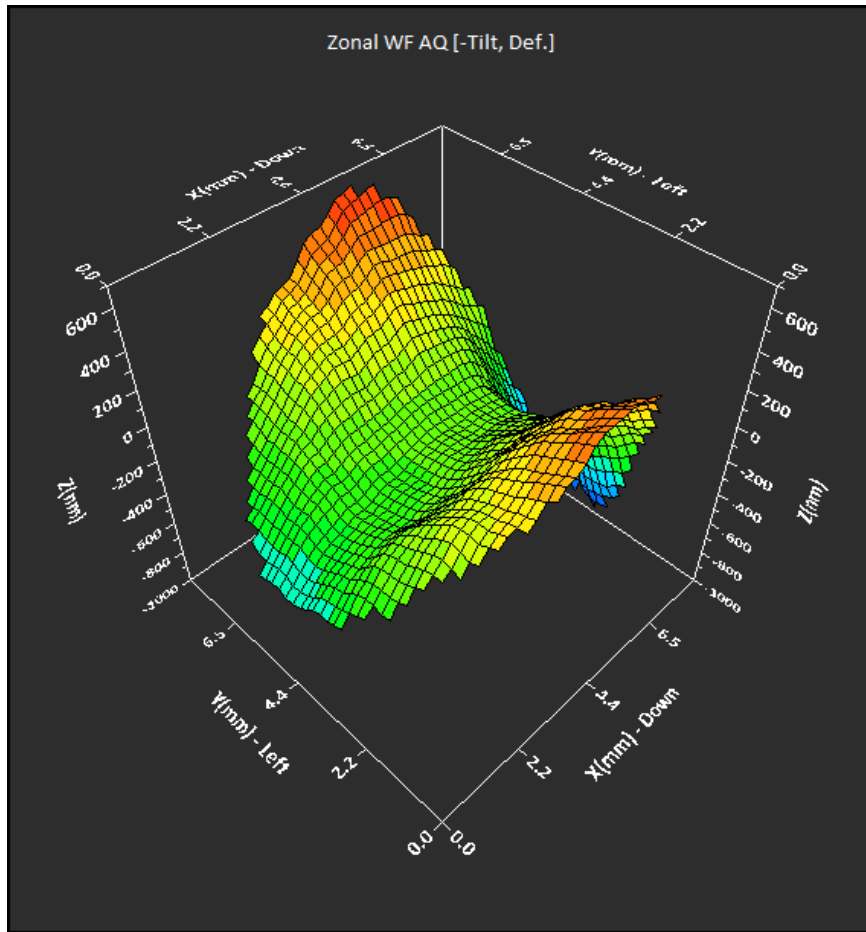
Correcting a specific aberration



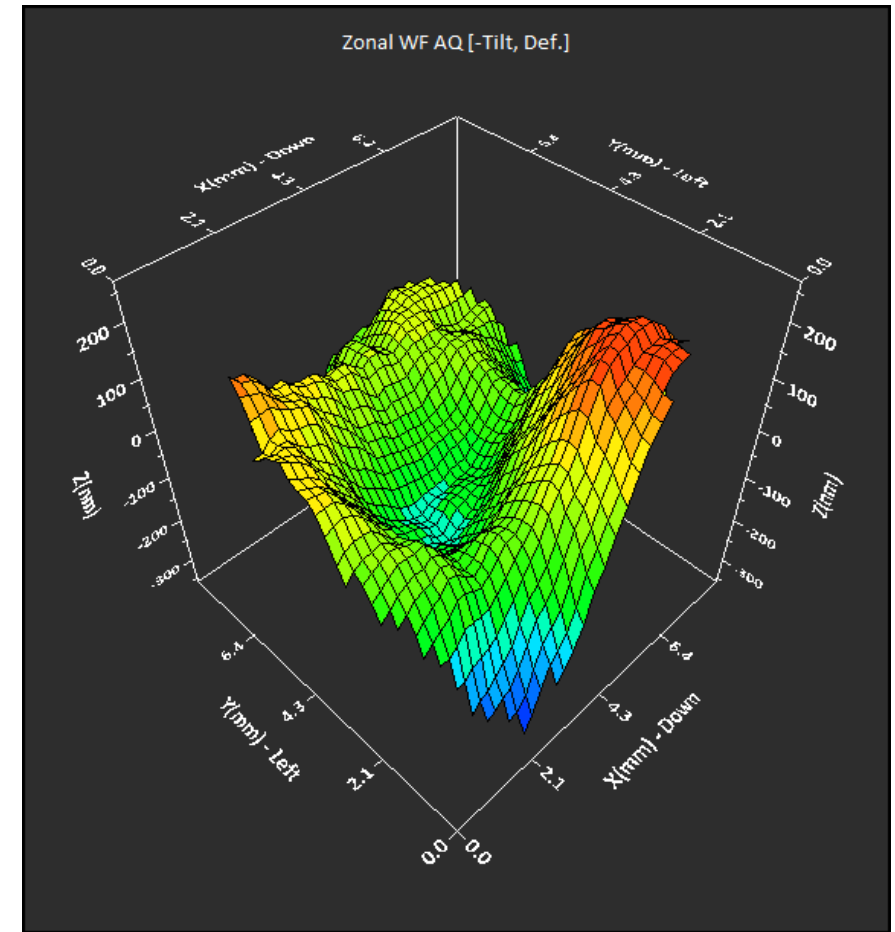
It looks like astigmatism!



Correcting a specific aberration



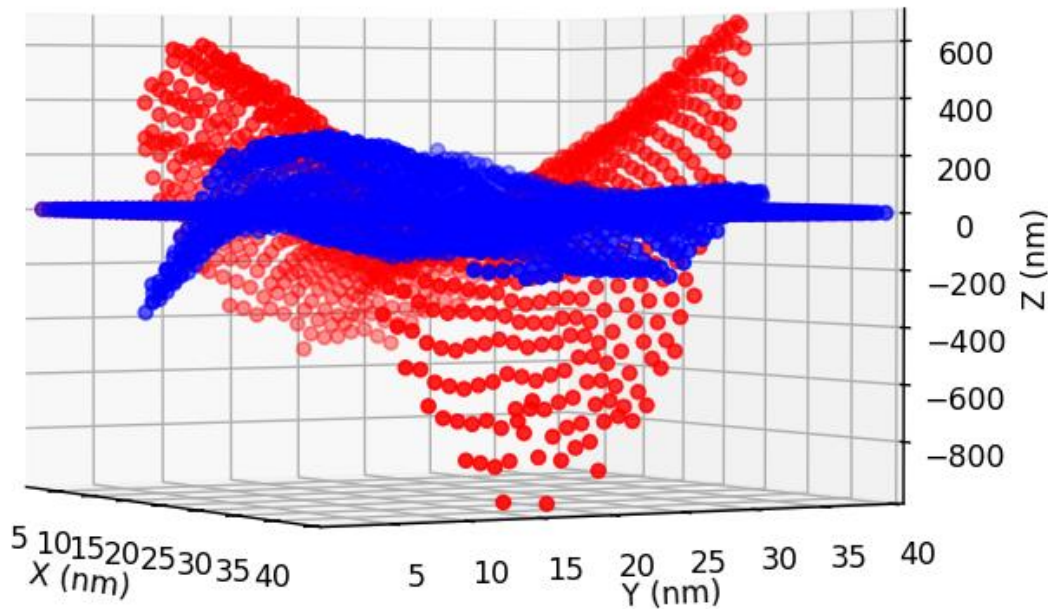
After correction



Correcting a specific aberration

Superposition of the plane wavefront and the aberrated one

- Flat wavefront
- Wavefront with astigmatism

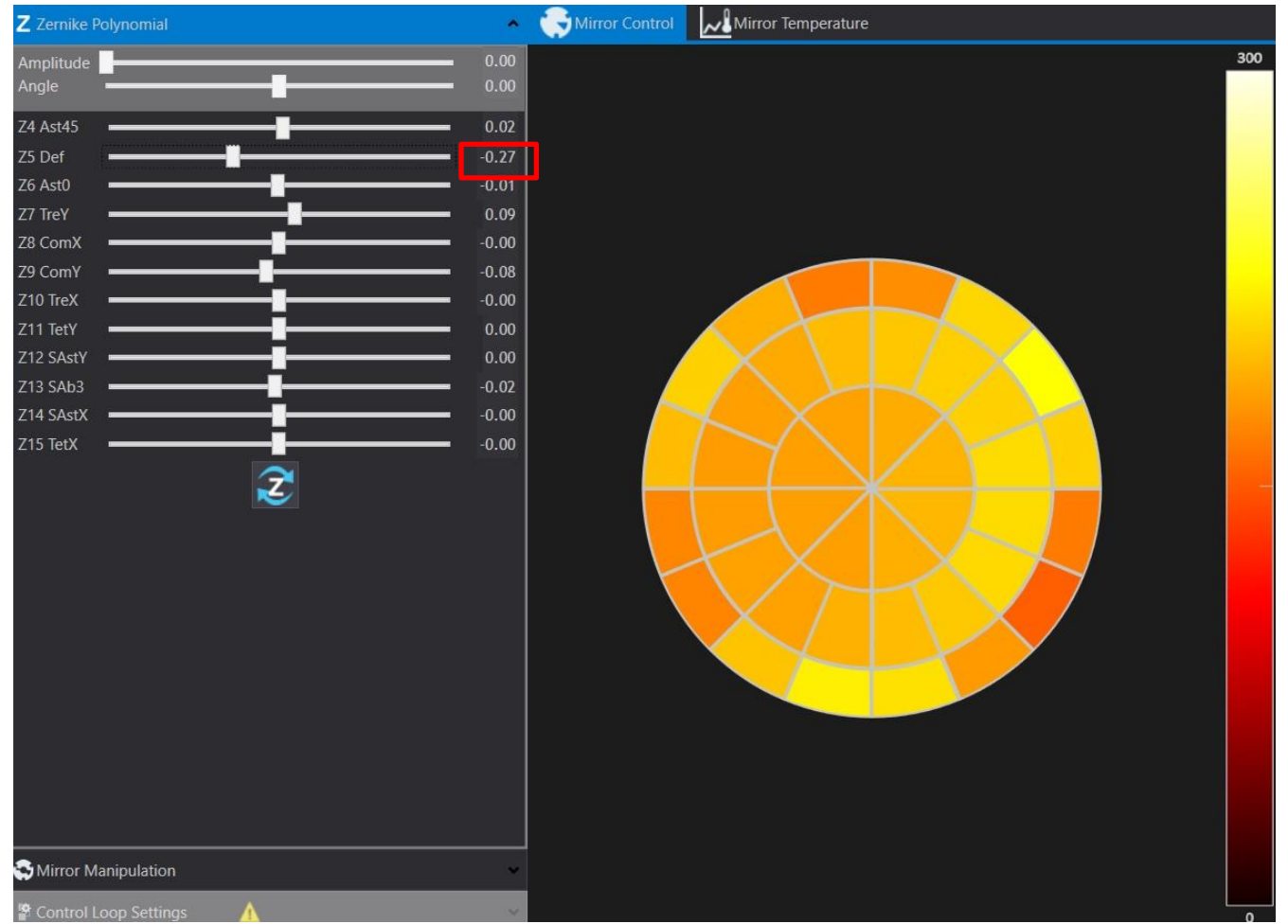
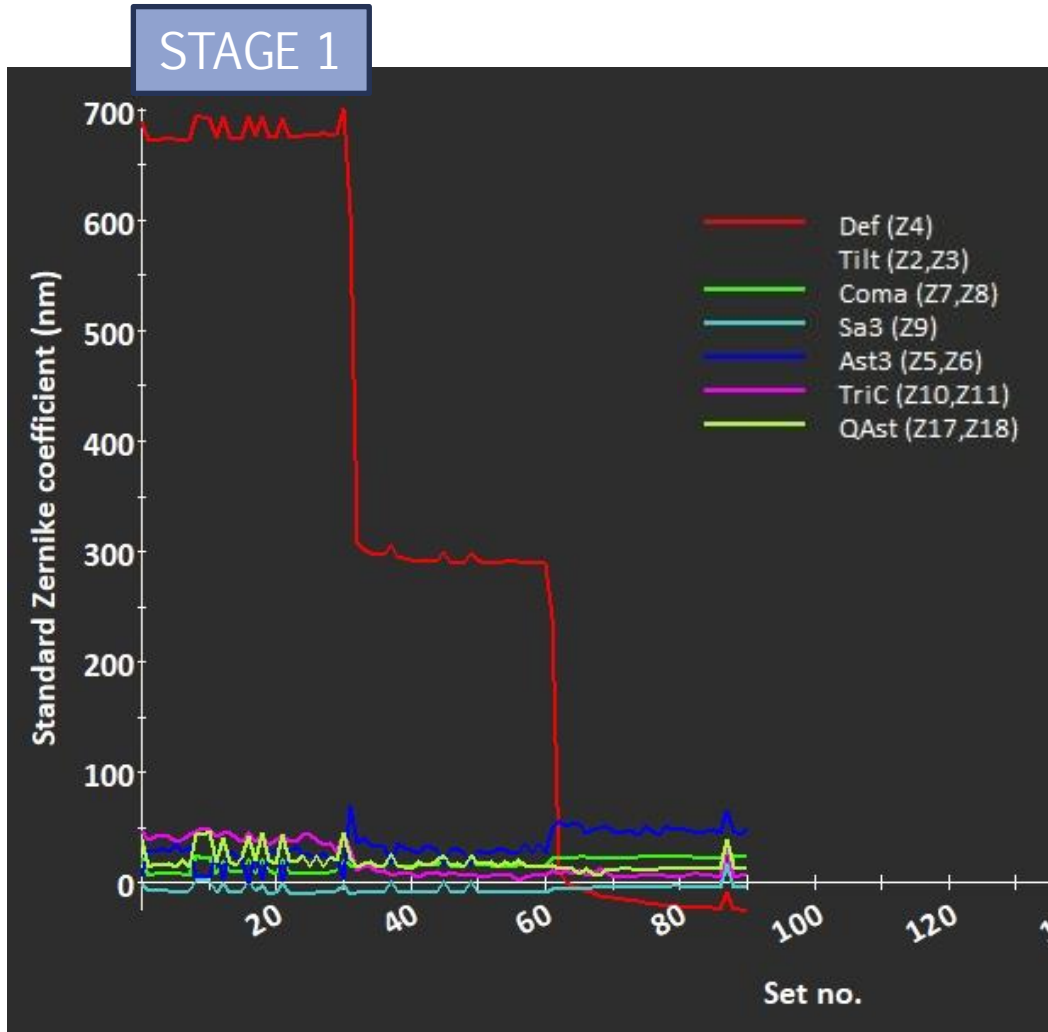


Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	765.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	310.9
Coma3	1 3	Z8	17.8

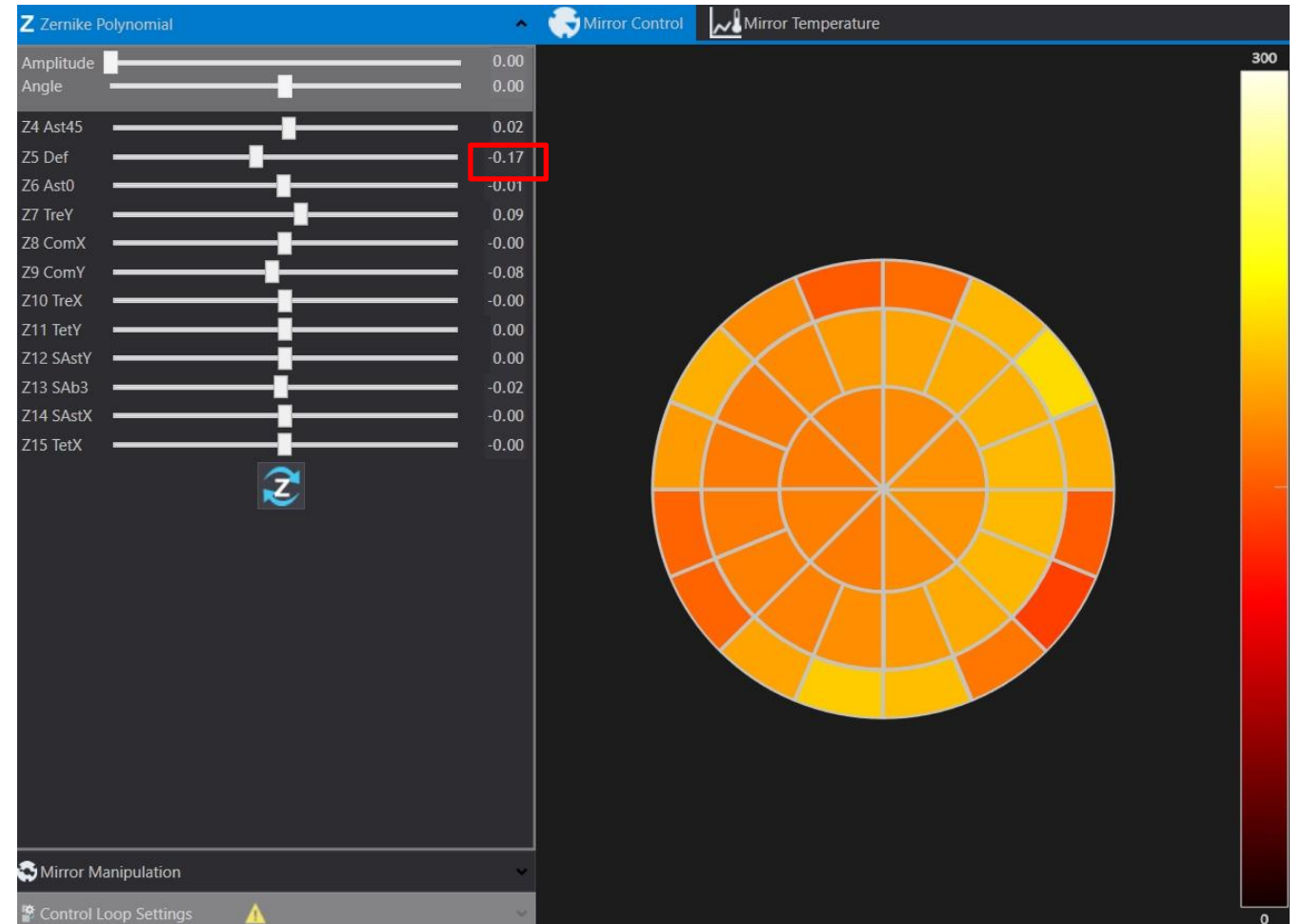
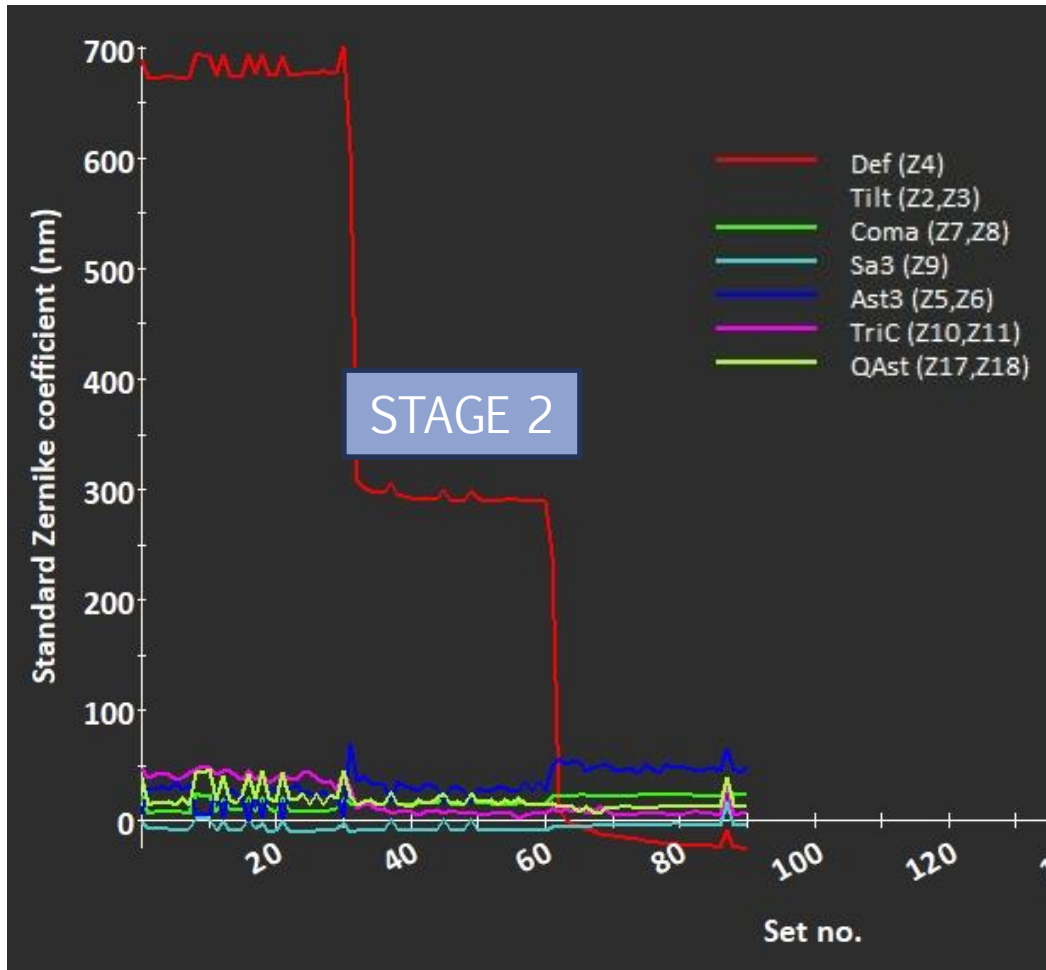


Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	-414.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	6.1
Coma3	1 3	Z8	27.3

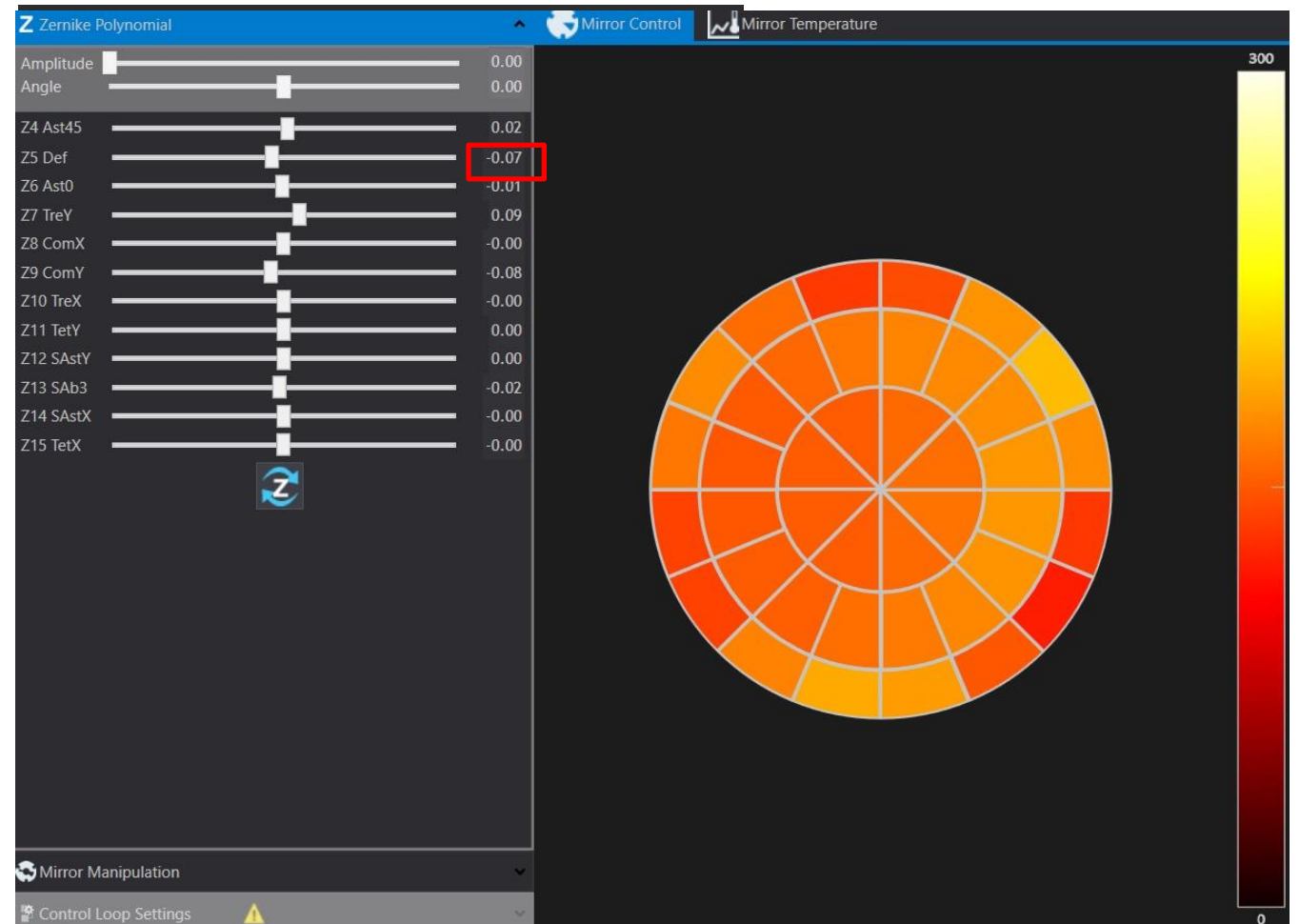
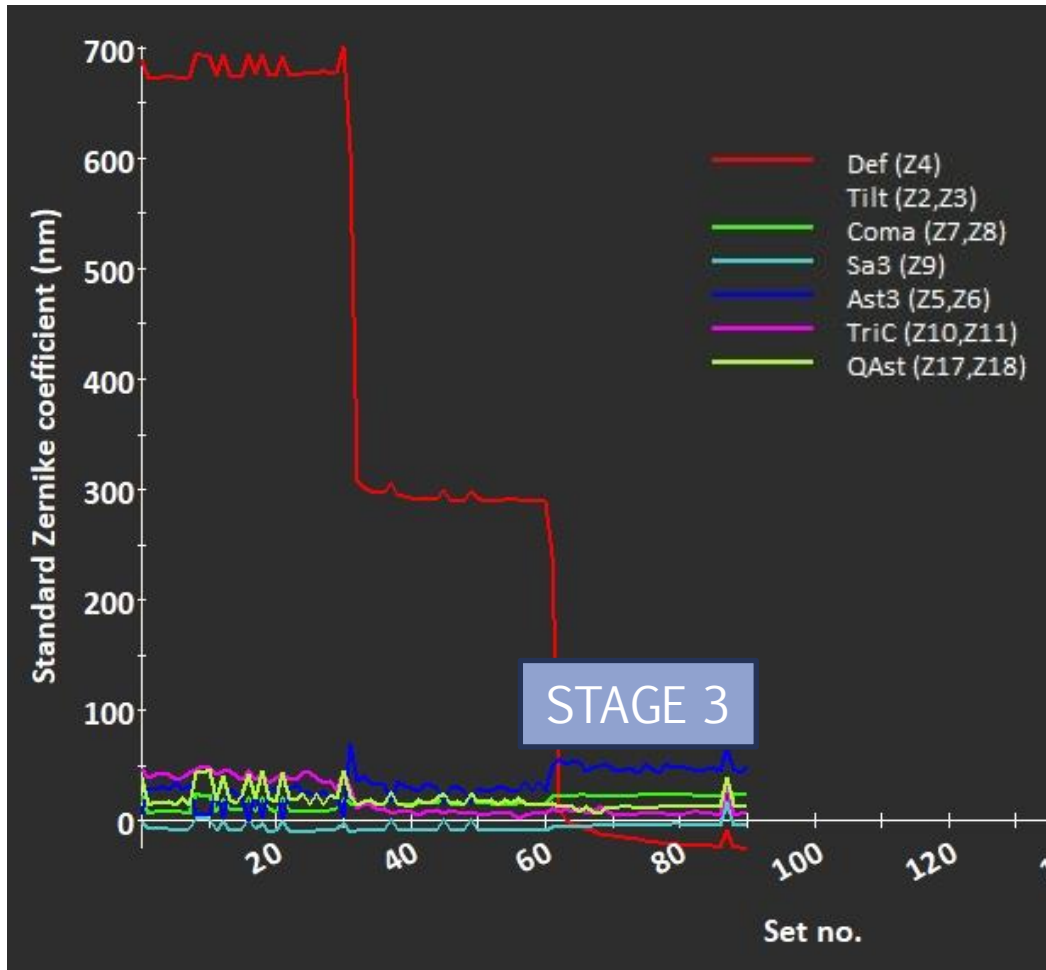
Another correction: defocus



Another correction: defocus



Another correction: defocus



Problem with Zernike coefficients



Problem with Zernike coefficients

- ▶ Mismatching due to different Zernike conventions



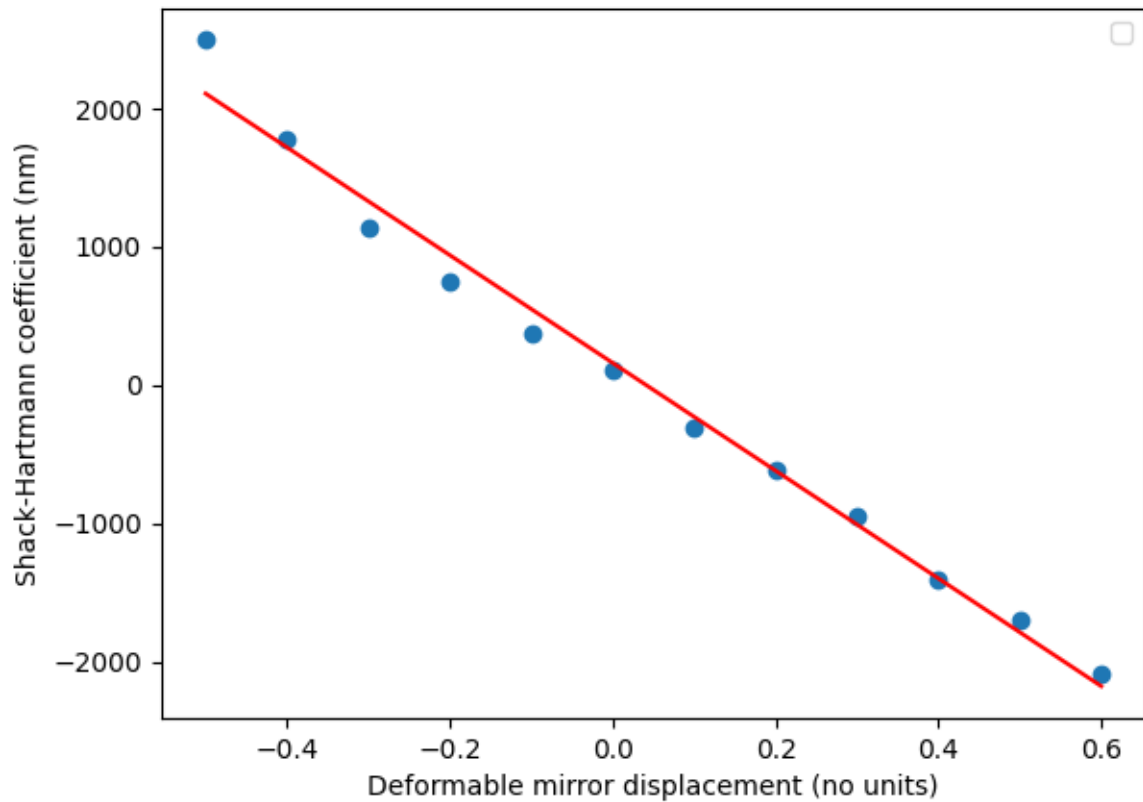
A link had to be established between the coefficients of the SH and those of the DM

- ▶ Mismatching linked to the aberrations themselves

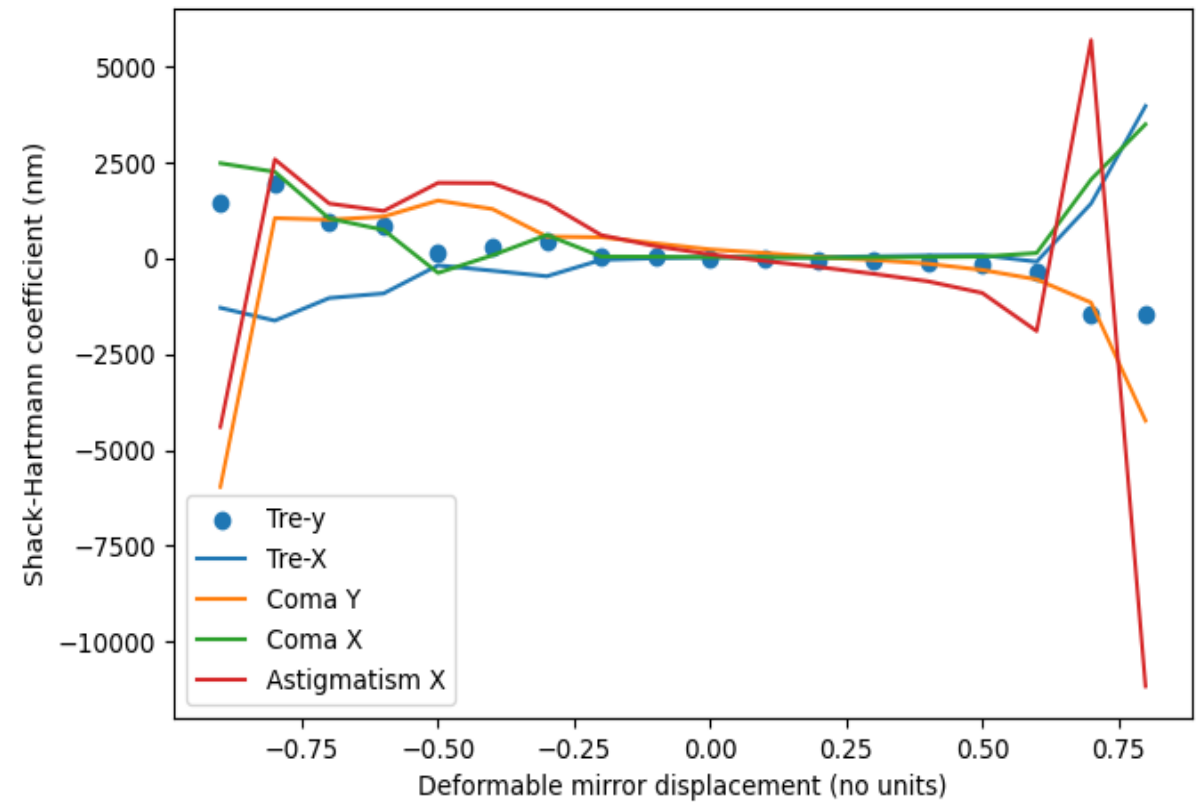
No linearity between the applied coefficient on the DM and the response seen by the SH

Problem with Zernike coefficients

Link between the SH and the DM for astigmatism

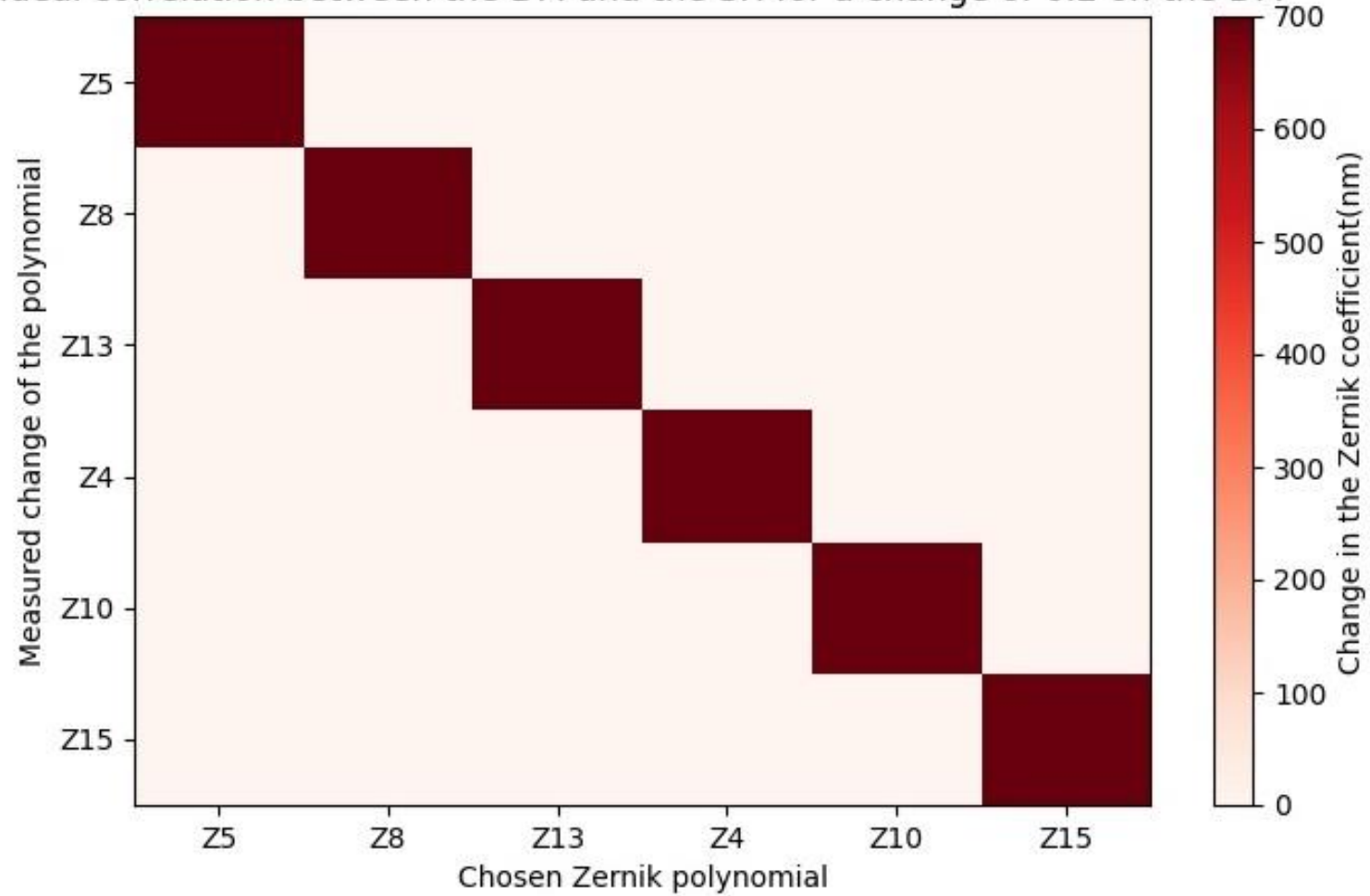


Link between the SH and the DM for several aberrations

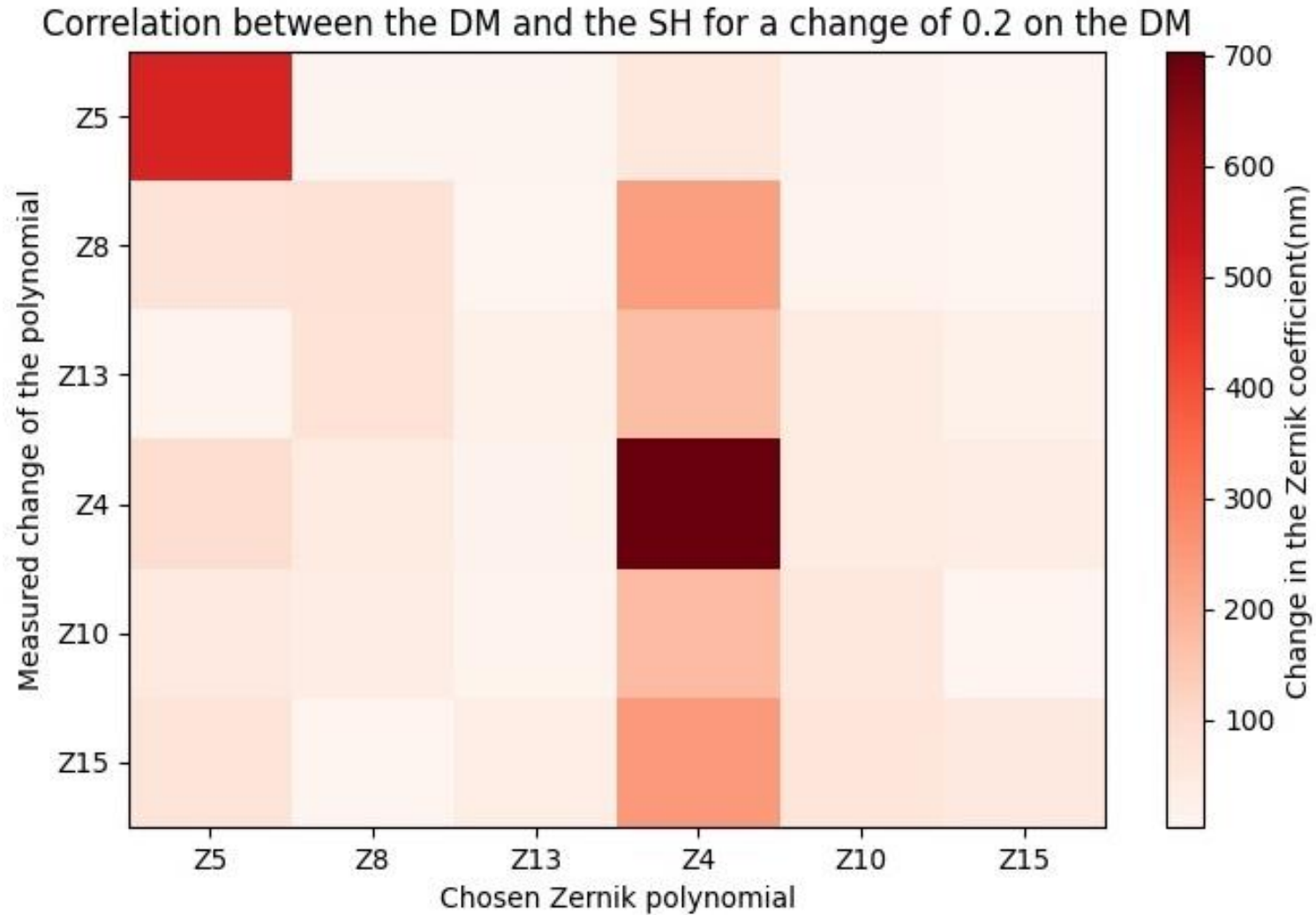


Correlation

Ideal correlation between the DM and the SH for a change of 0.2 on the DM



Correlation



Correcting the tilt

Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	765.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	310.9
Coma3	1 3	Z8	17.8



Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	-414.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	6.1
Coma3	1 3	Z8	27.3

Correcting the tilt

Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	765.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	310.9
Coma3	1 3	Z8	17.8



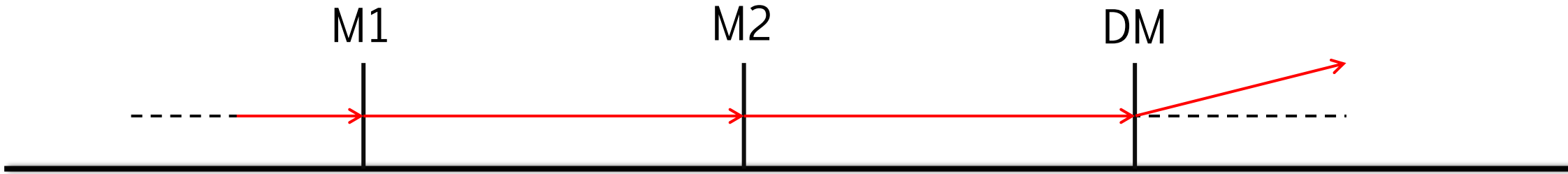
Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	-414.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	6.1
Coma3	1 3	Z8	27.3

Correcting the tilt

Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	765.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	310.9
Coma3	1 3	Z8	17.8



Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	-414.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	6.1
Coma3	1 3	Z8	27.3

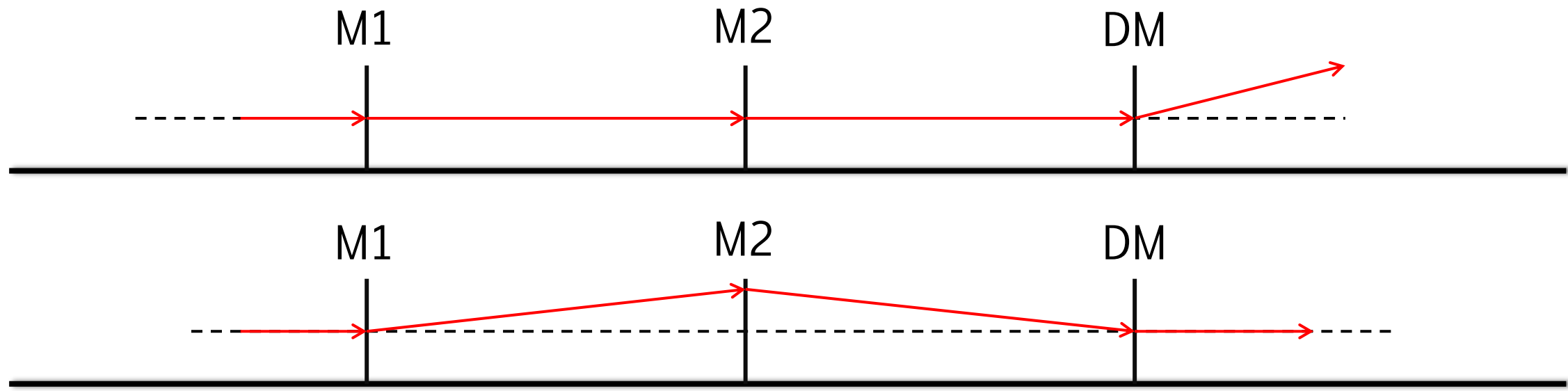


Correcting the tilt

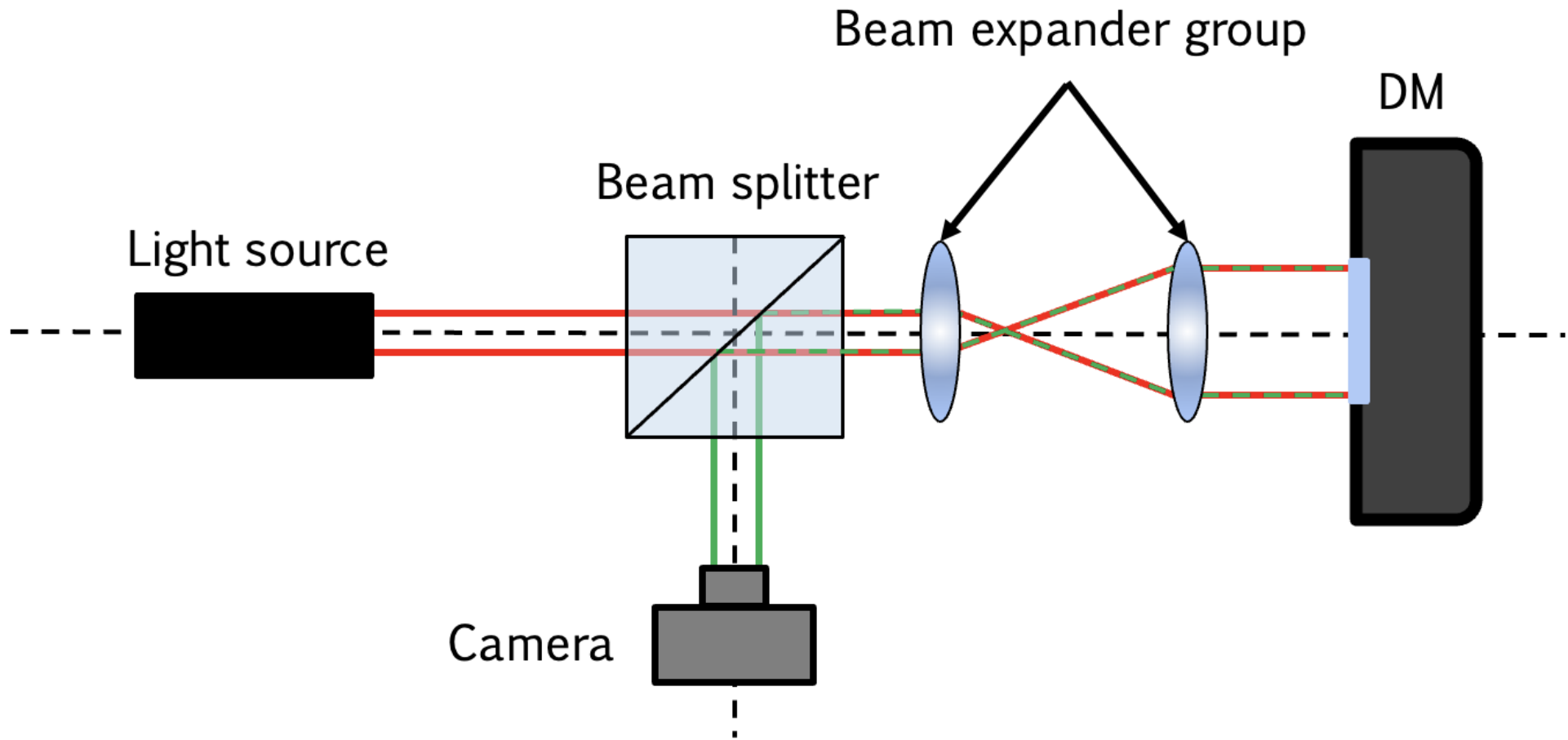
Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	765.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	310.9
Coma3	1 3	Z8	17.8



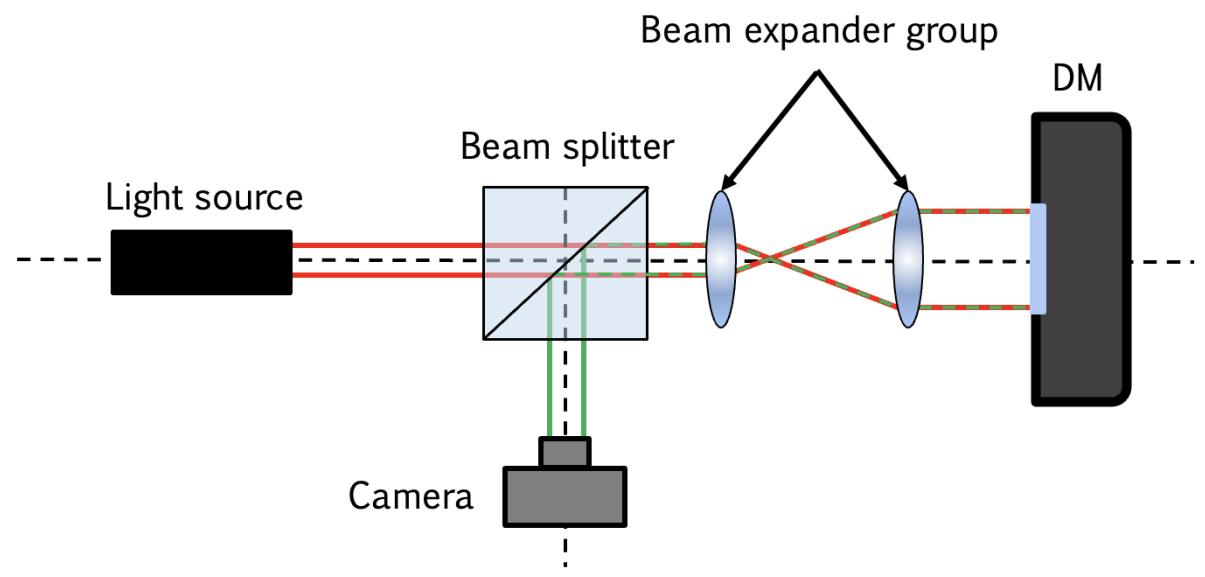
Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	-414.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	6.1
Coma3	1 3	Z8	27.3



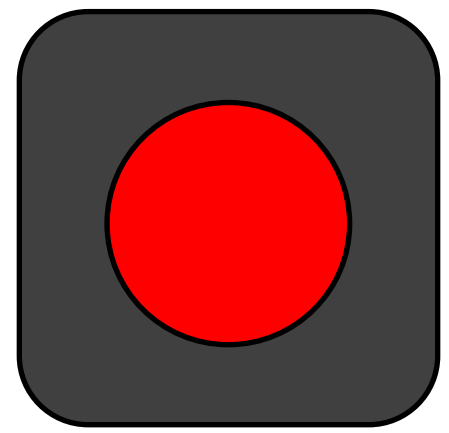
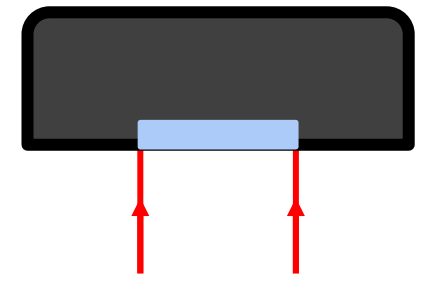
Using a beam splitter



Using a beam splitter



Angle of incidence 0



Full coverage

Conclusion

- We built a simplified replica of the imaging setup used at CESQ.
- We used optical tools and successfully corrected optical aberrations.
- We helped the team by making a detailed user guide.
- We provided the team with ideas to improve the correction efficiency.

Thank you!

