Characterizing and correcting aberrations in an optical system

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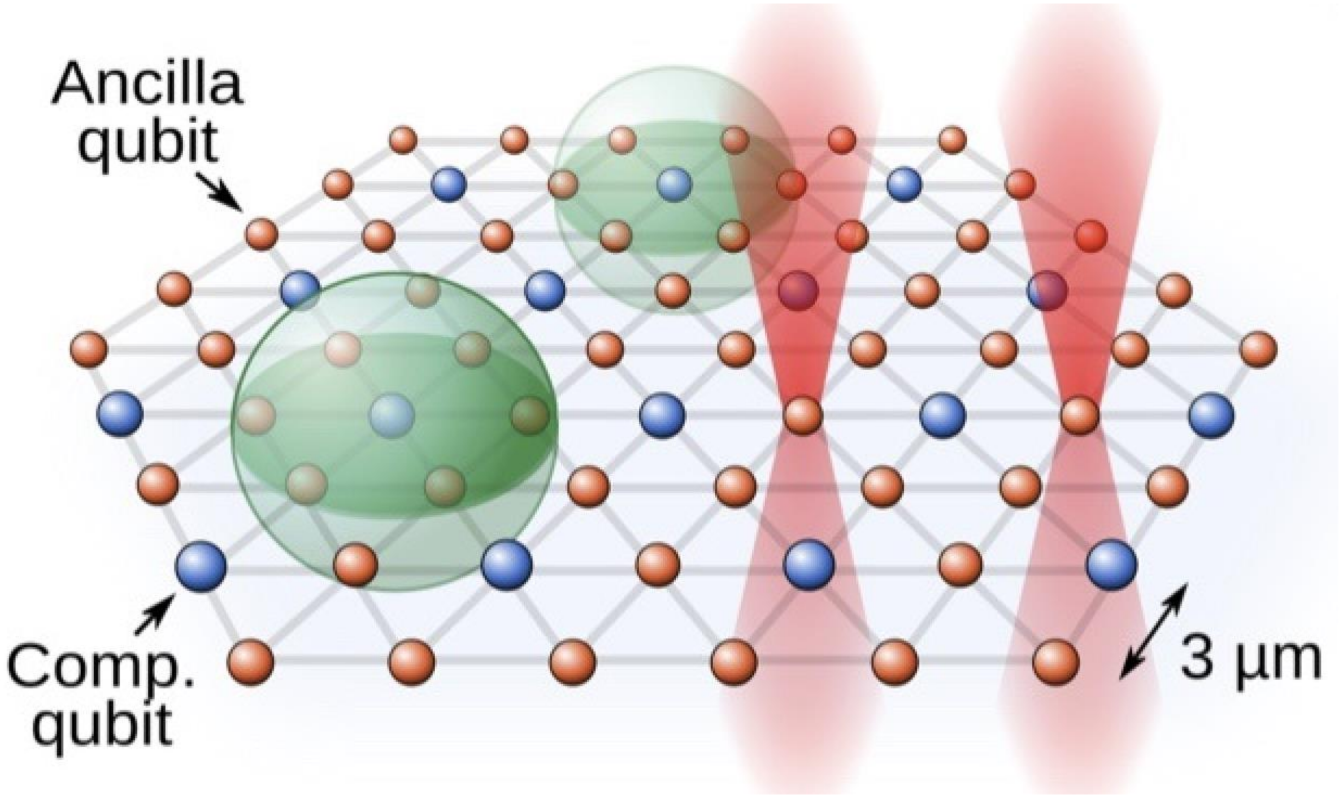
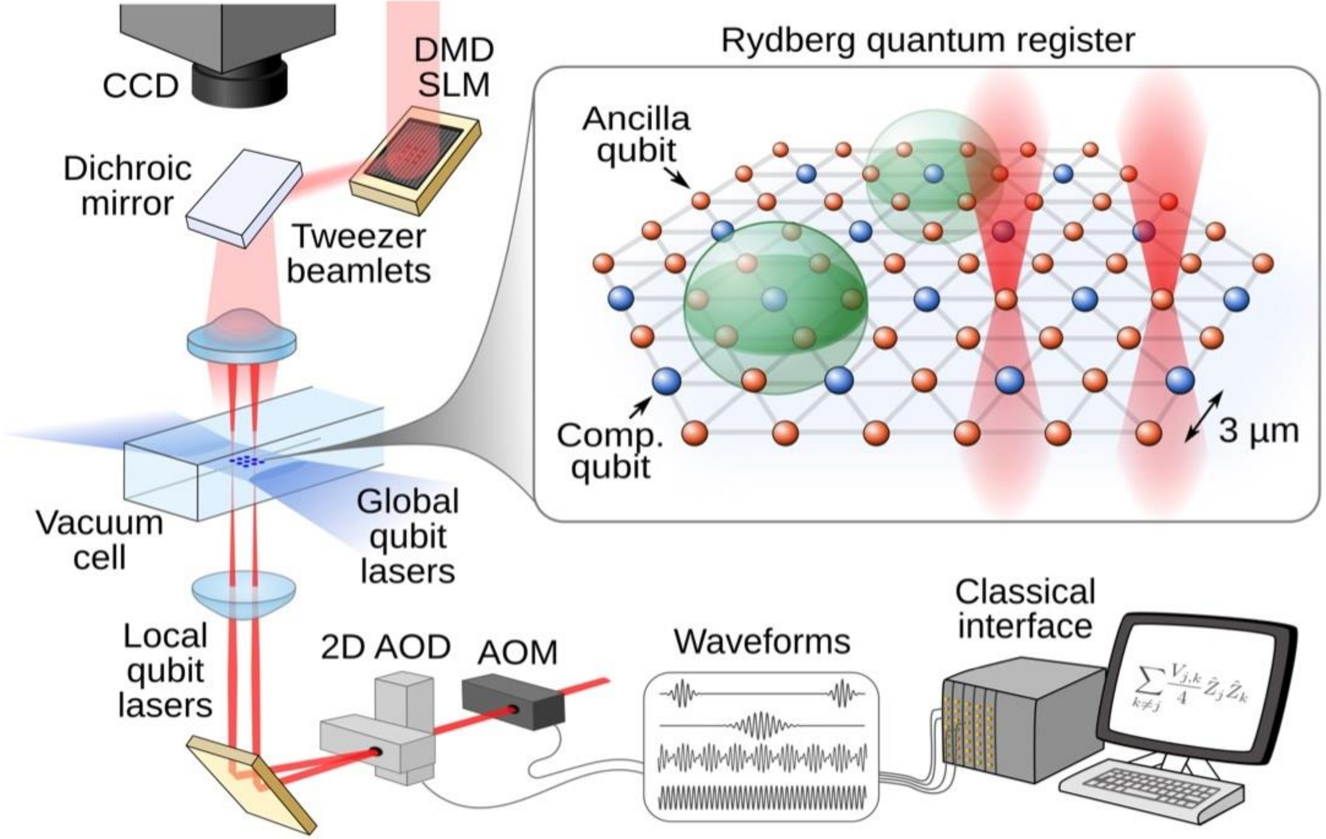
Quantum simulator



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

Optical setup



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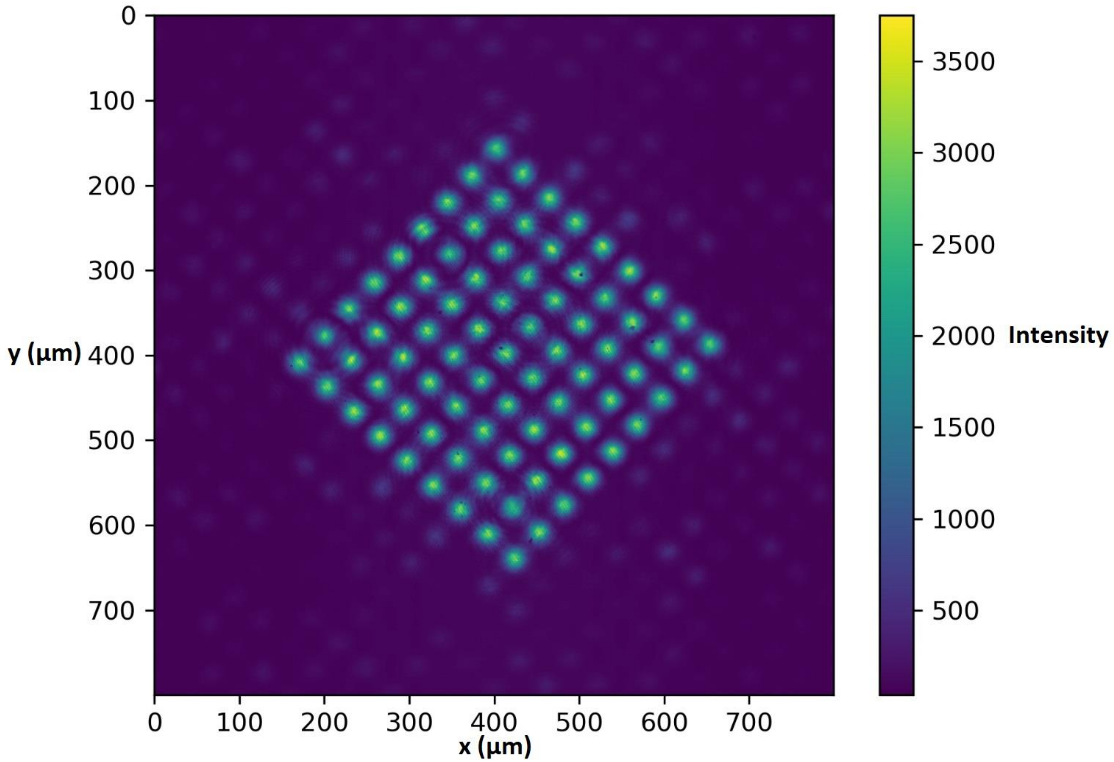
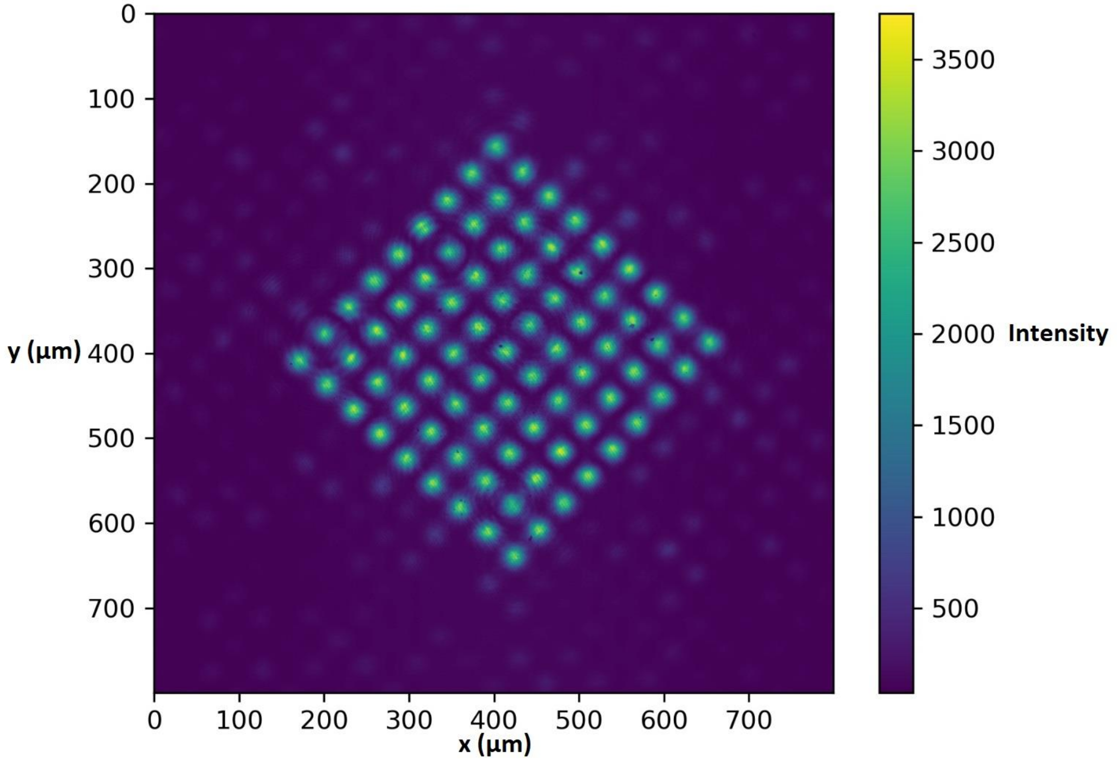
Problem : optical aberrations

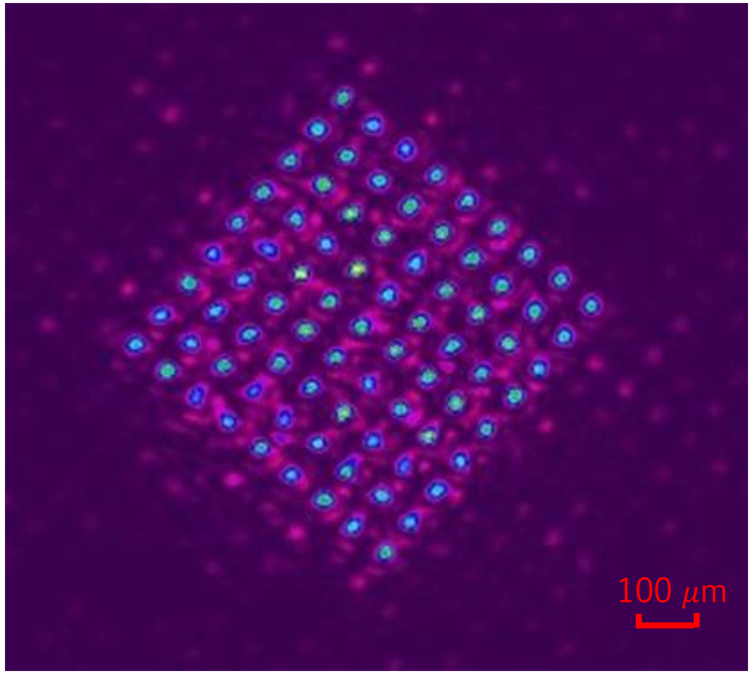


Before the vacuum chamber

Problem : optical aberrations



Before the vacuum chamber



After the vacuum chamber

What is an aberration?

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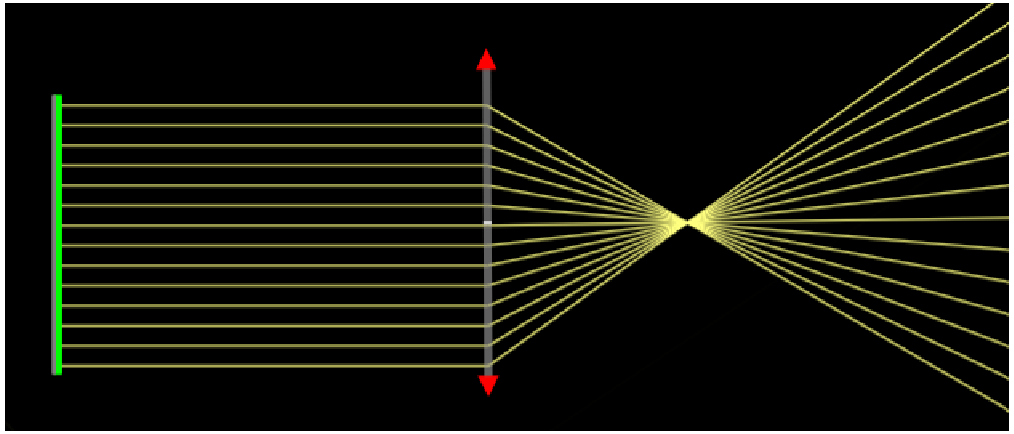
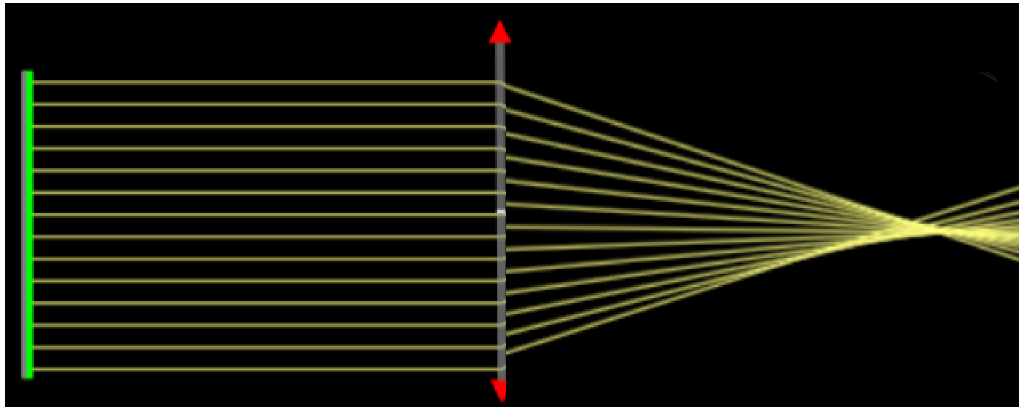
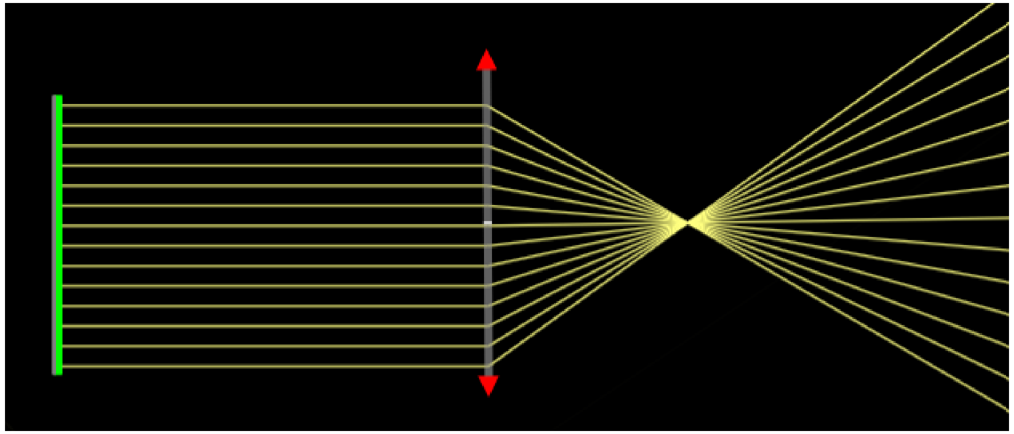
- Light is not focused to a point

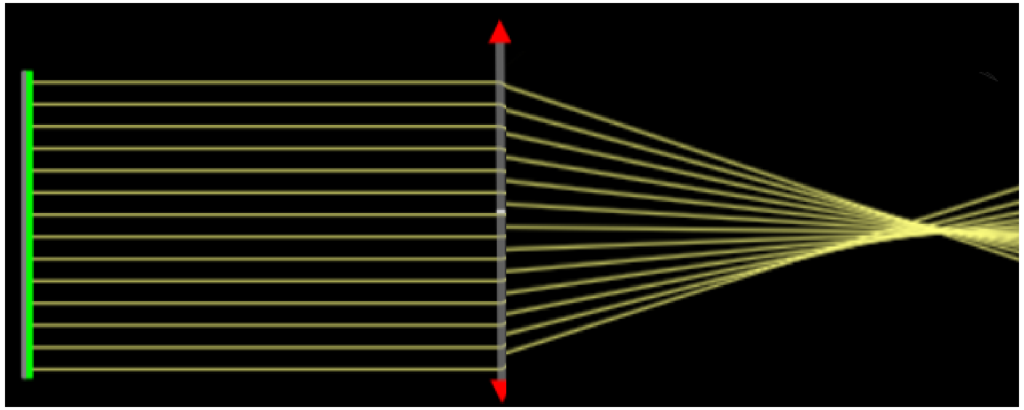




What is an aberration?

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





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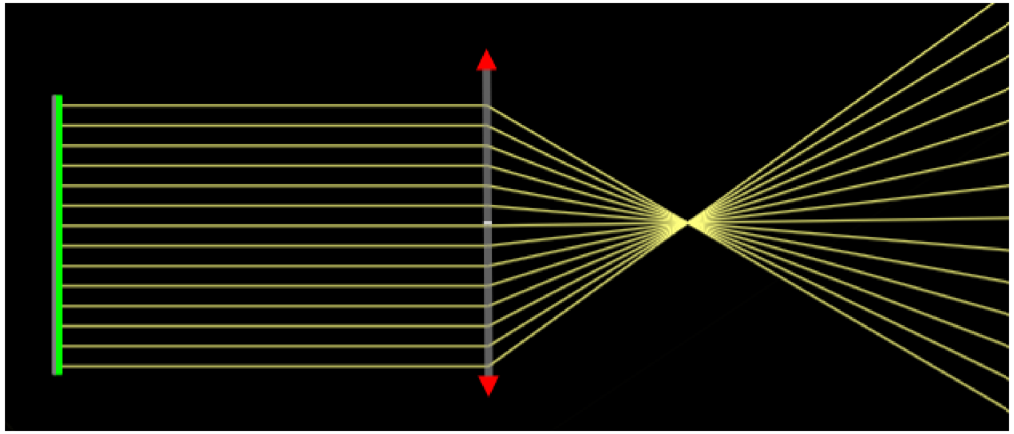

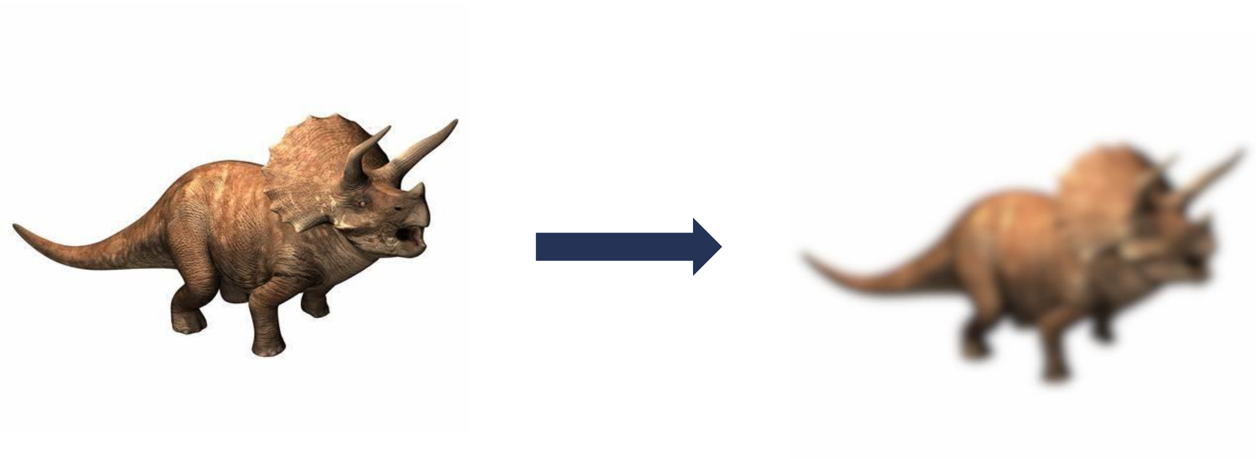

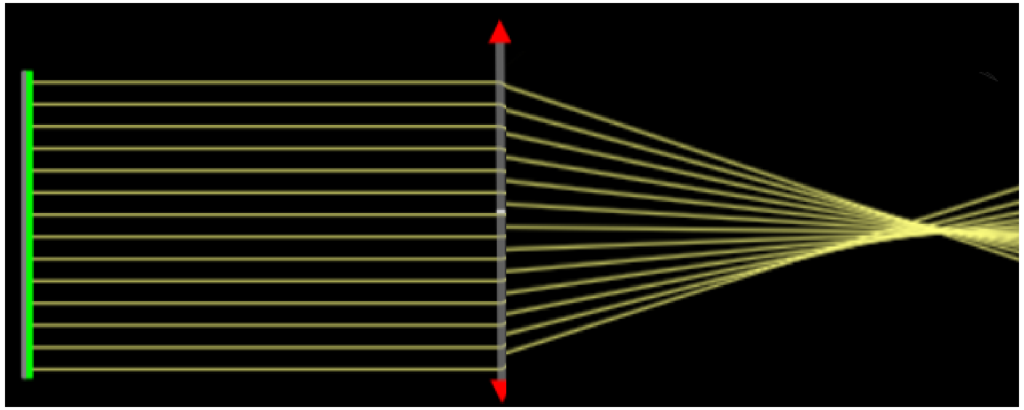

Zernike polynomials

Zernike polynomials

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

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

$$n = \left\lfloor \left(\sqrt{2j-1}+0.5\right) - 1 \right\rfloor,$$

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

Mathematical properties that are interesting

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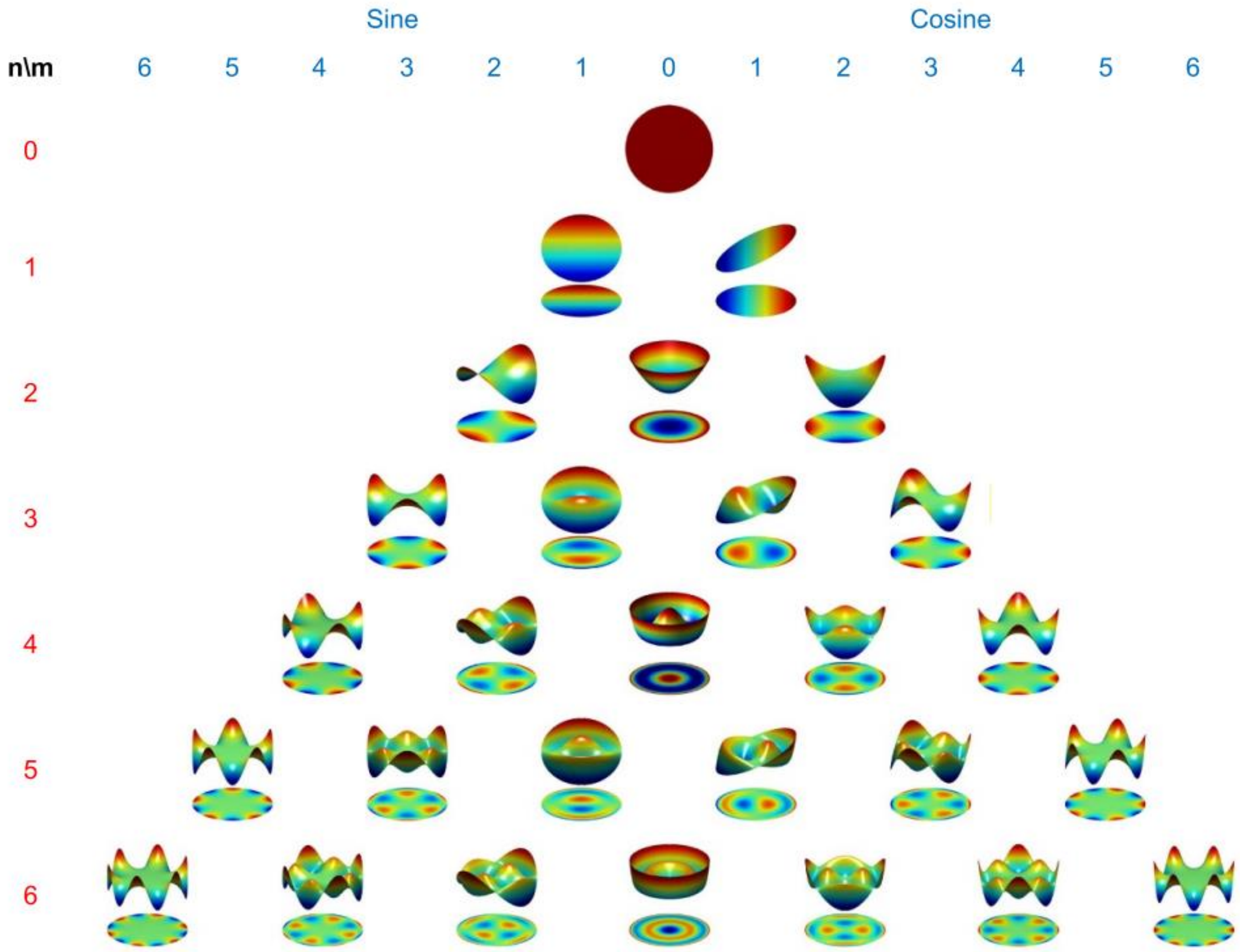
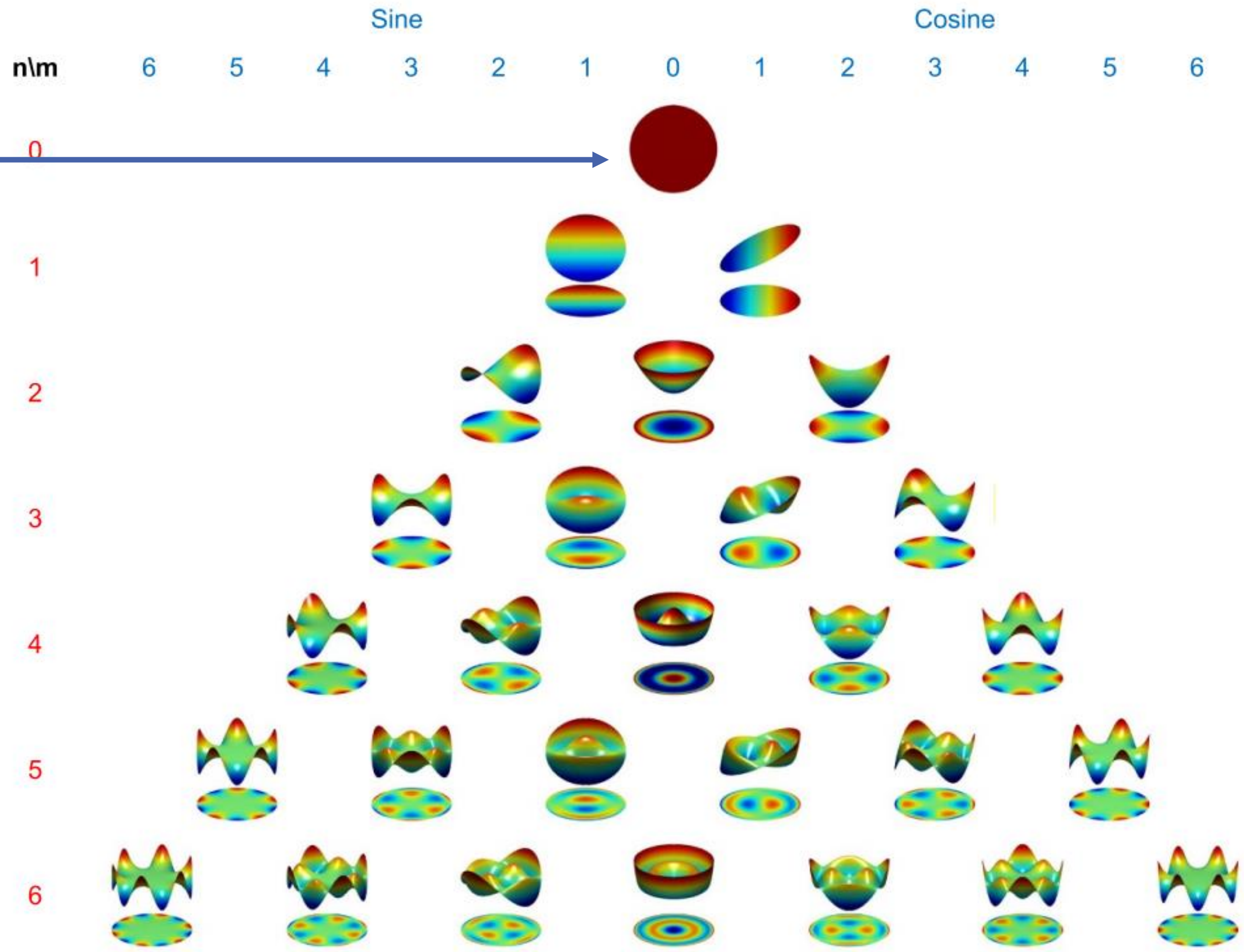
- Recurrence relations that allow for optimized calculations
- Good corresponding with classical aberrations: astigmatism, coma, spherical aberration

Usual aberrations



Usual aberrations

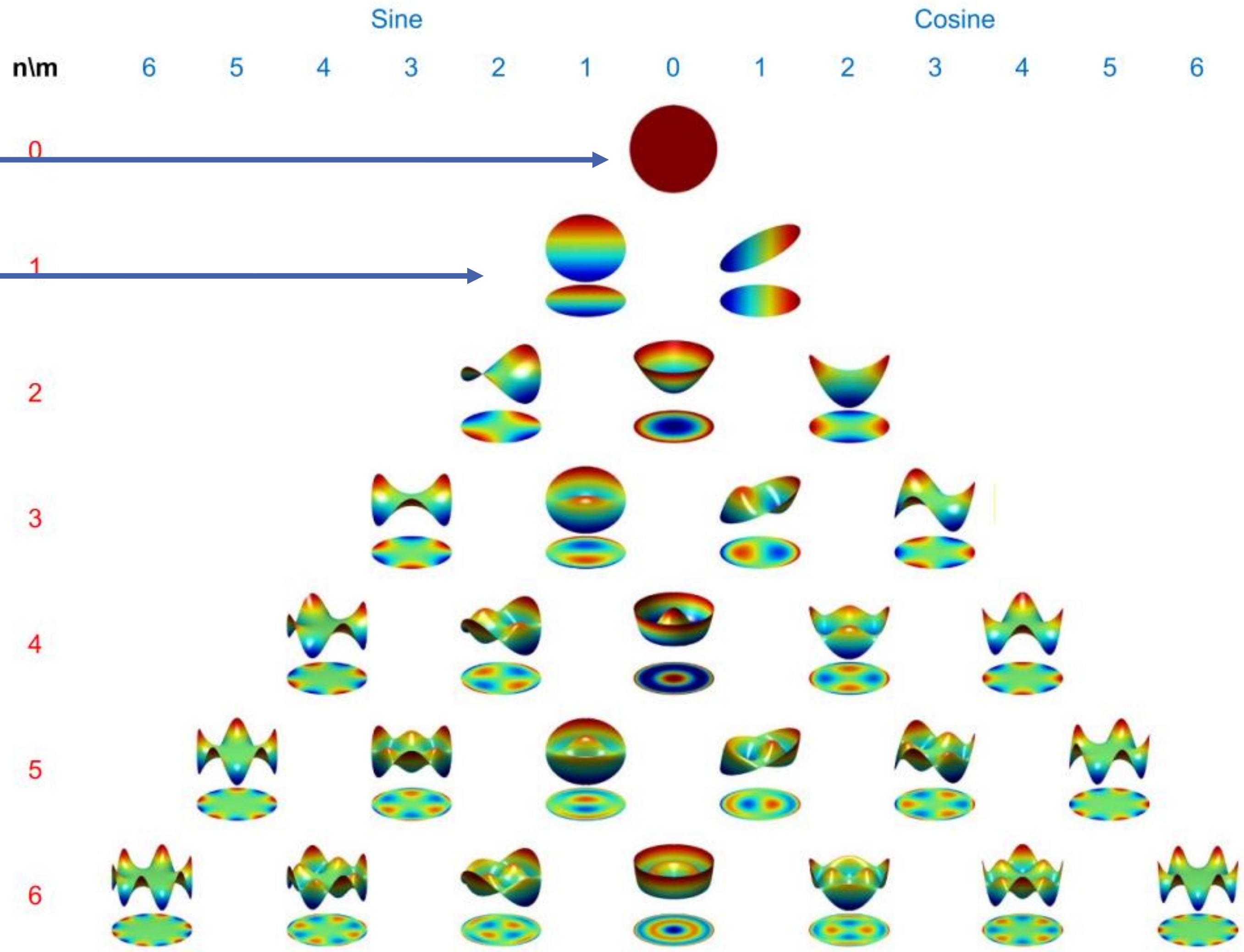
Flat



Usual aberrations

Flat

Tilt

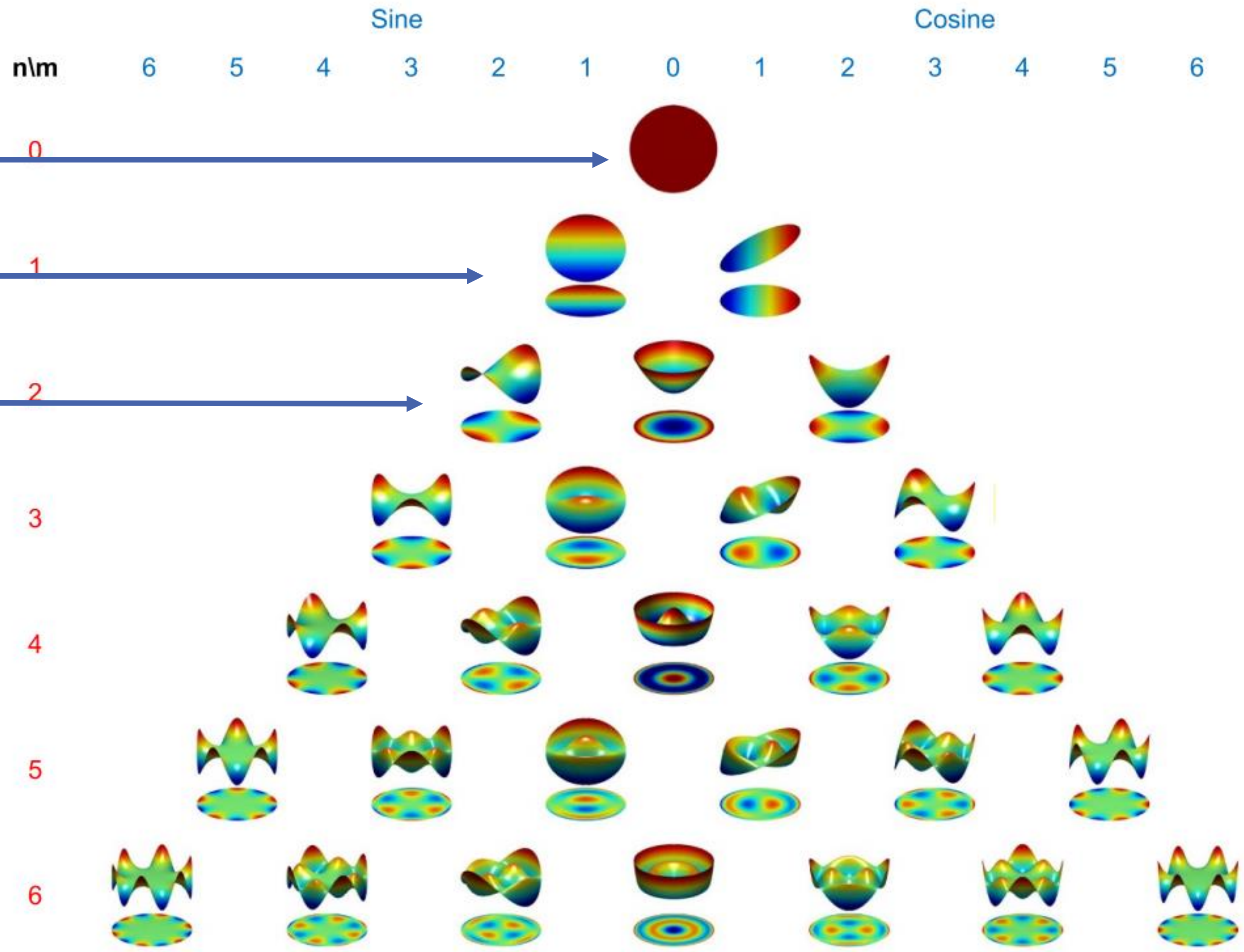


Usual aberrations

Flat

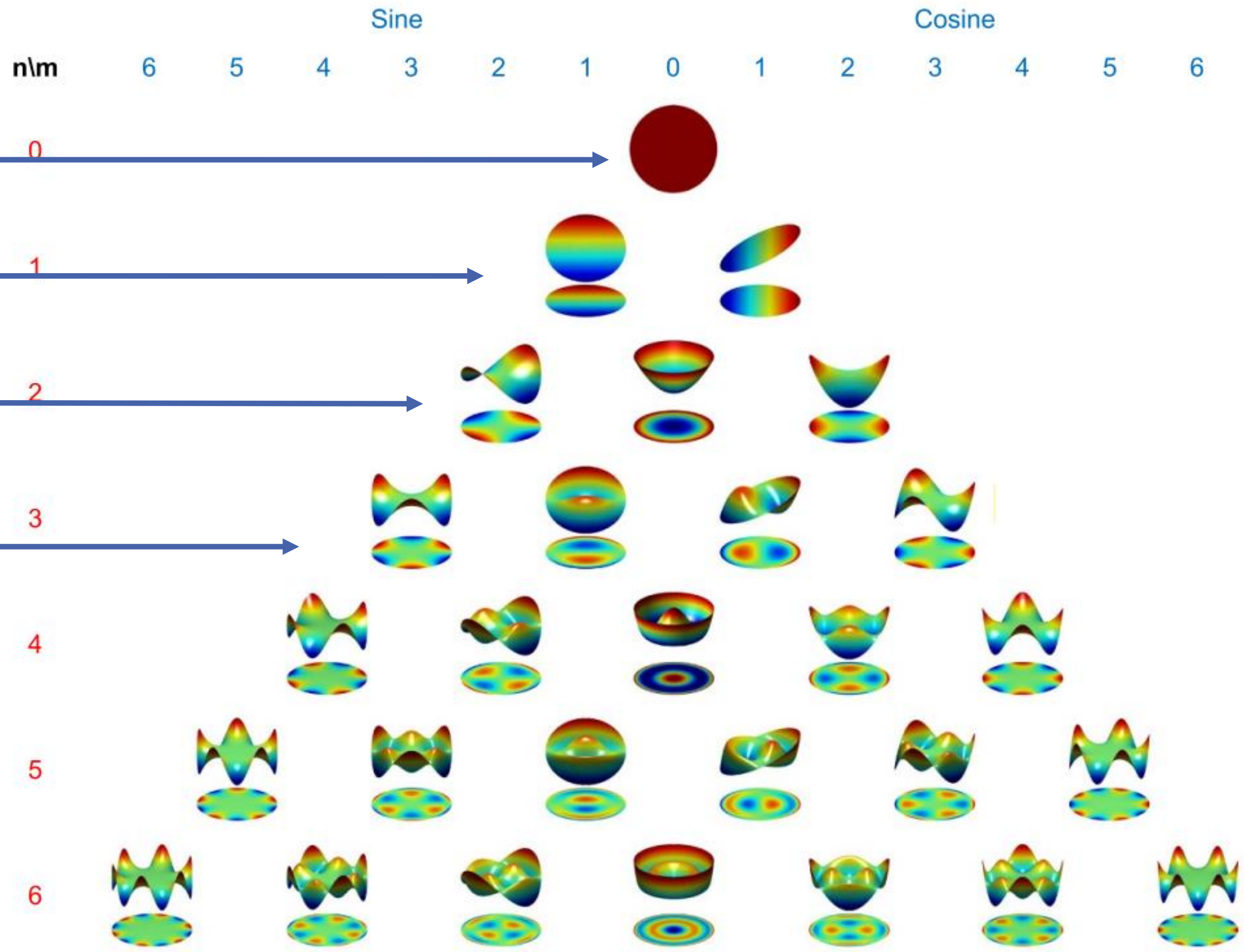
Tilt

Astigmatism



Usual aberrations

- Flat
- Tilt
- Astigmatism
- Coma



How does it work in practice ?

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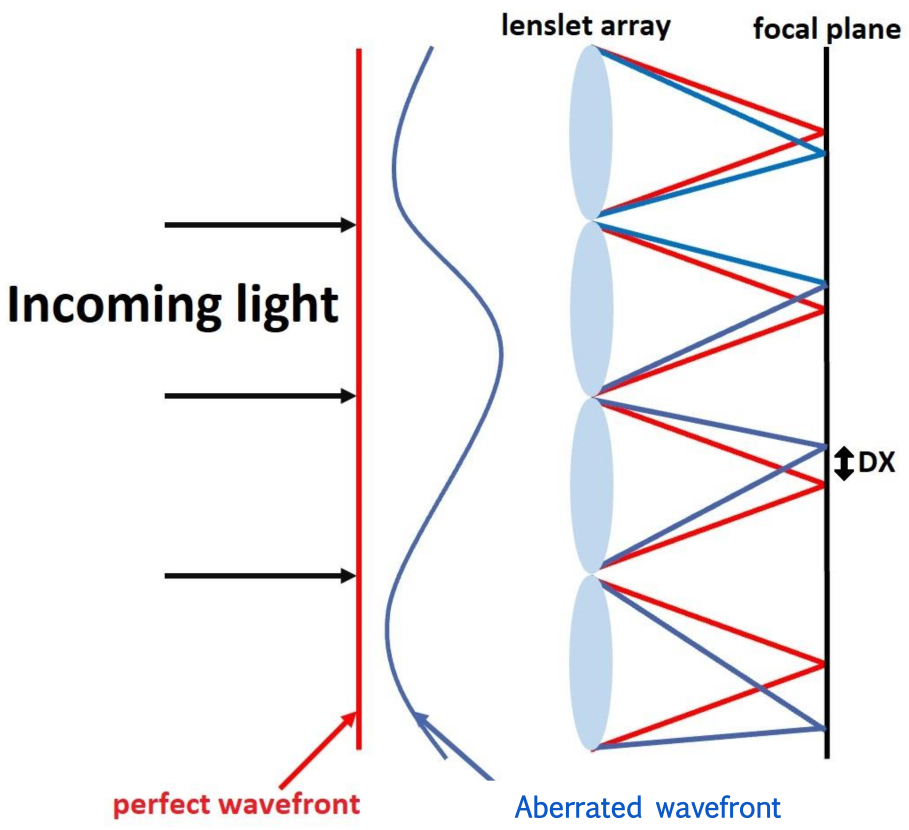
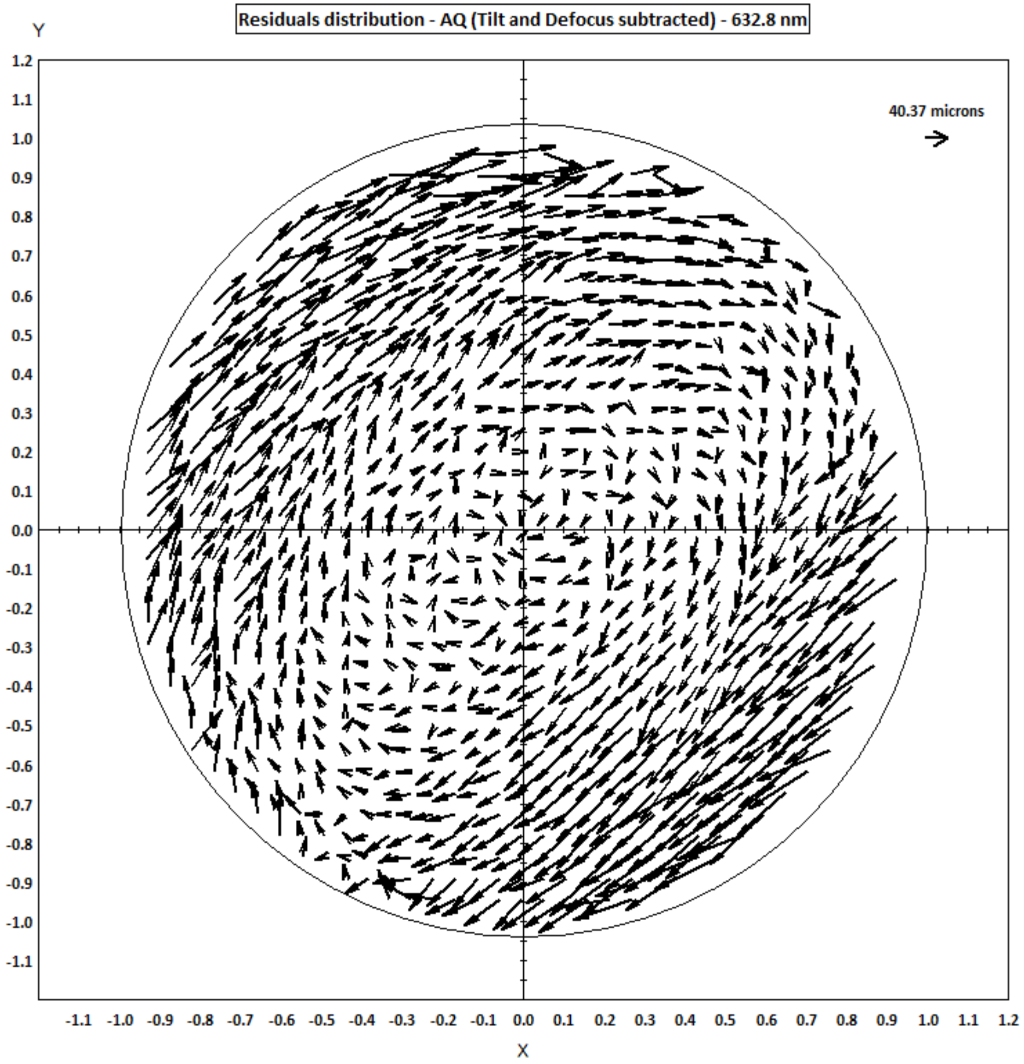


Shack-Hartmann wavefront sensor

How does it work in practice ?



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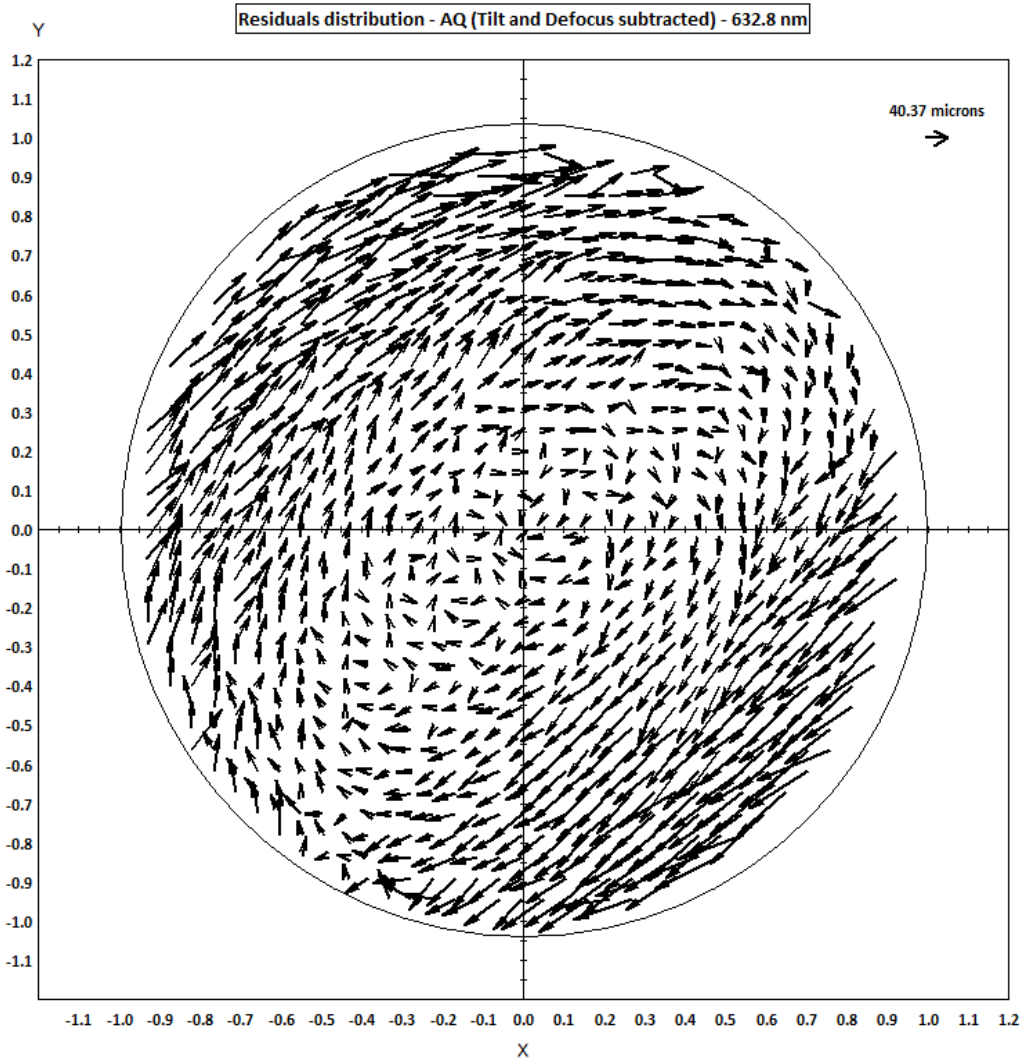

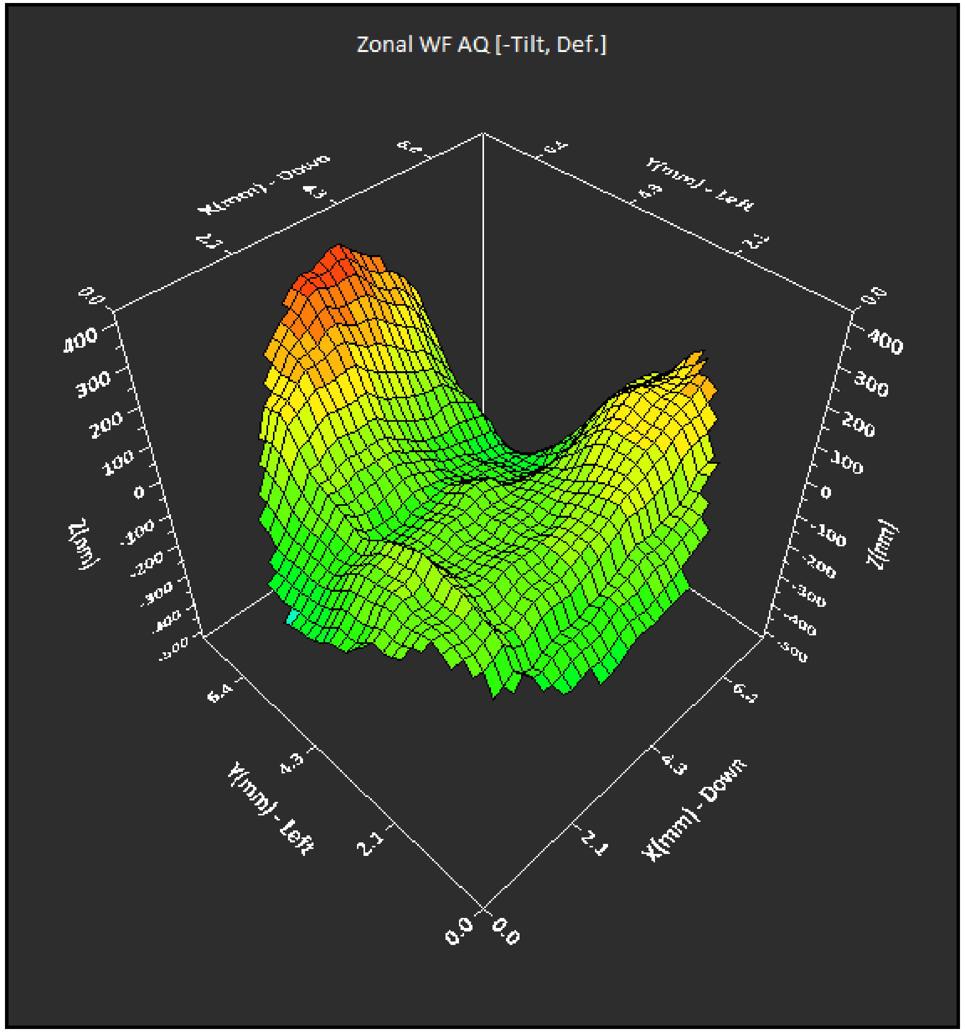

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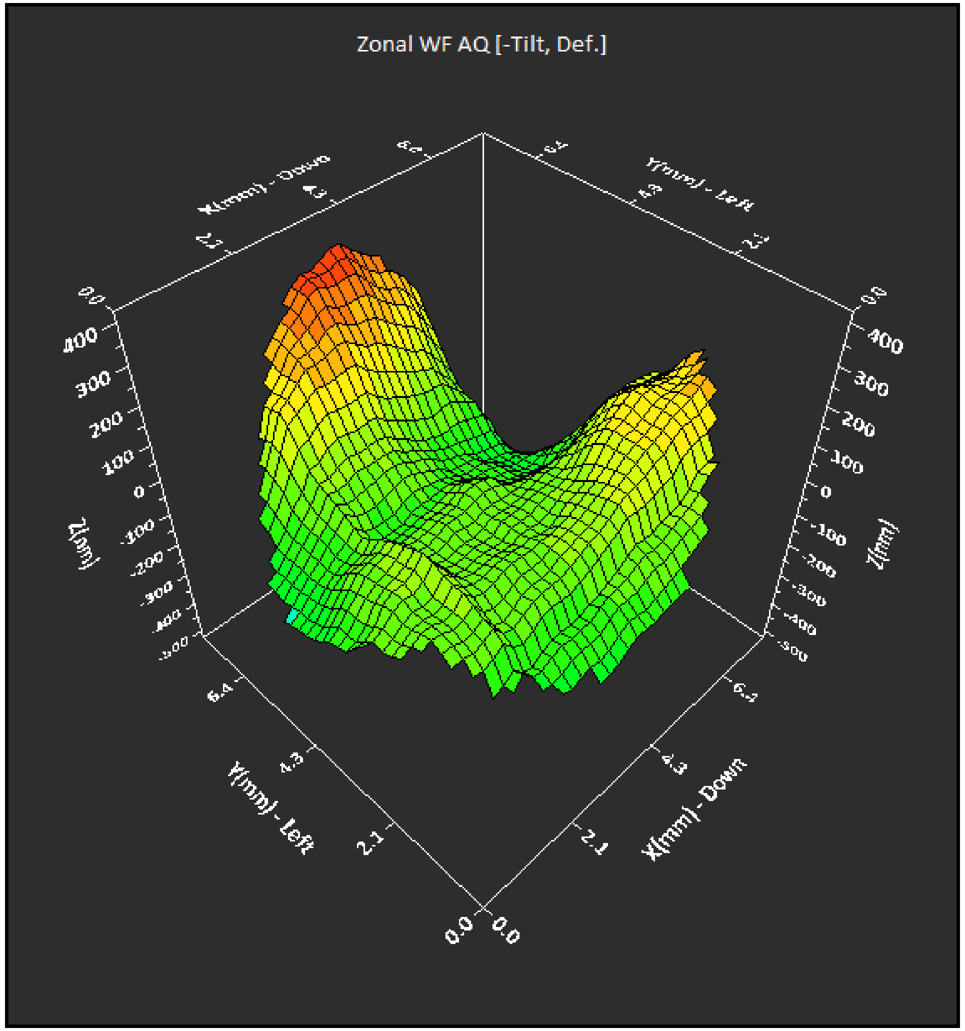

Standard Zernike coefficients - Noll notation

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 ?

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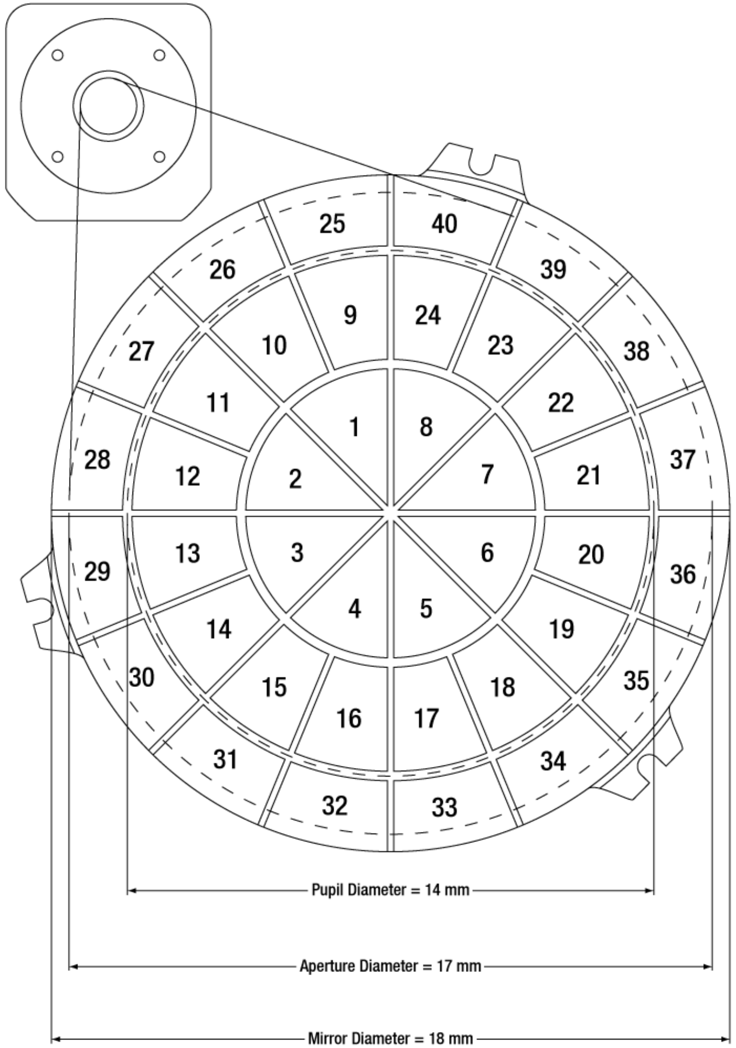
The deformable mirror



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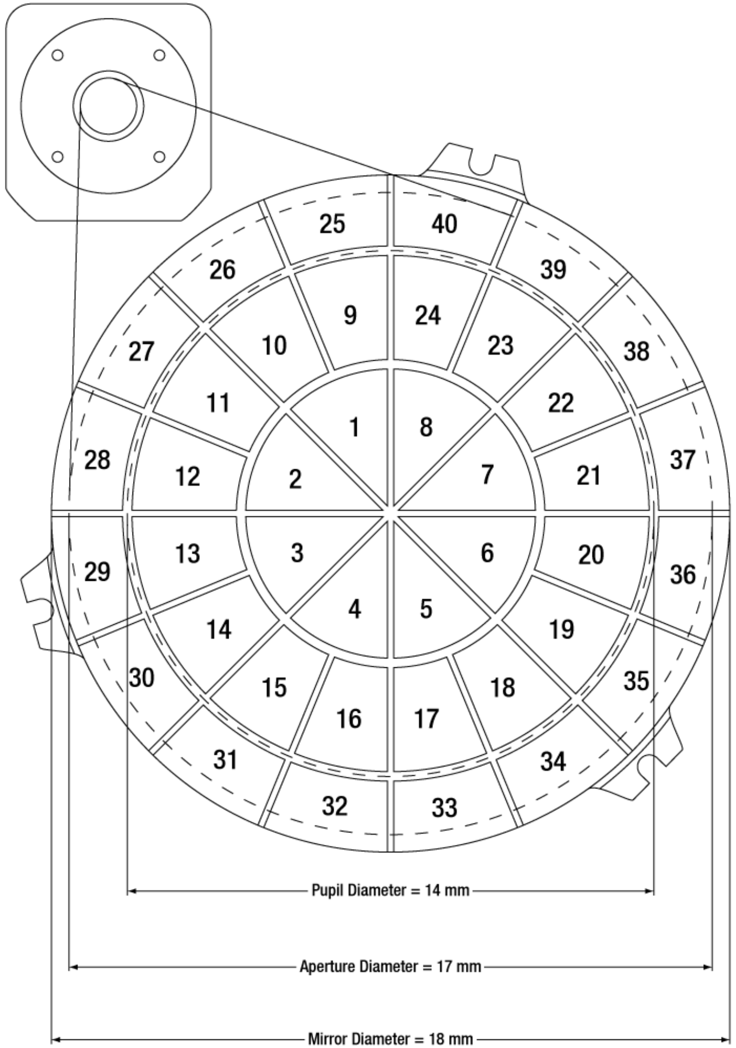
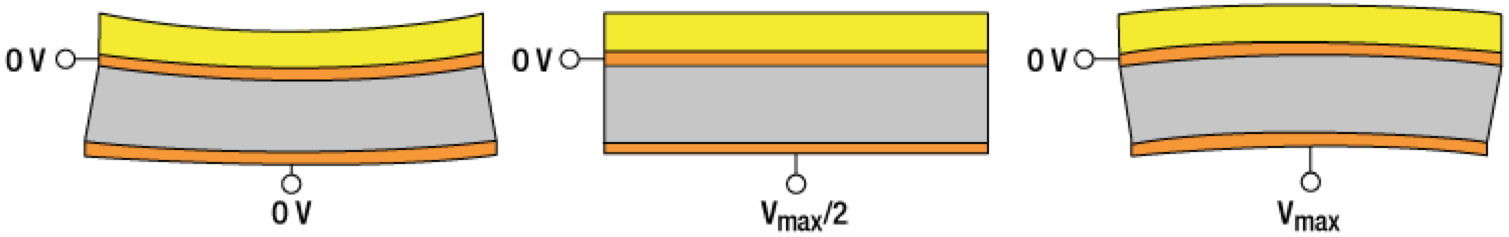
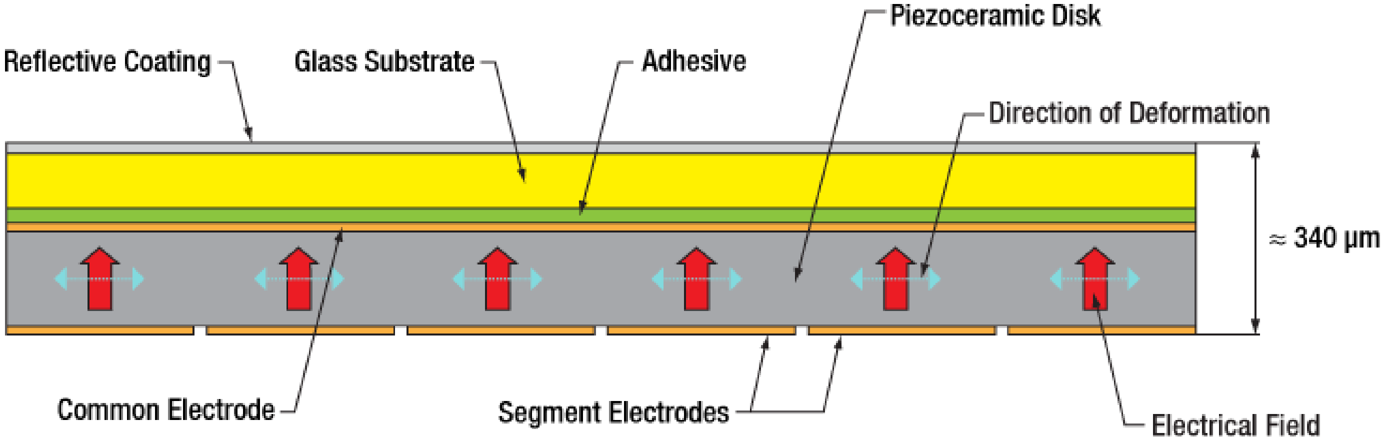
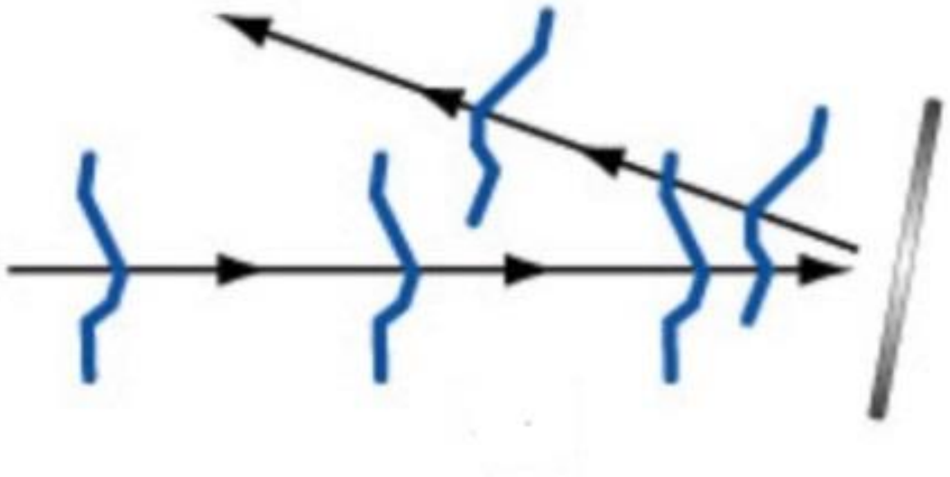


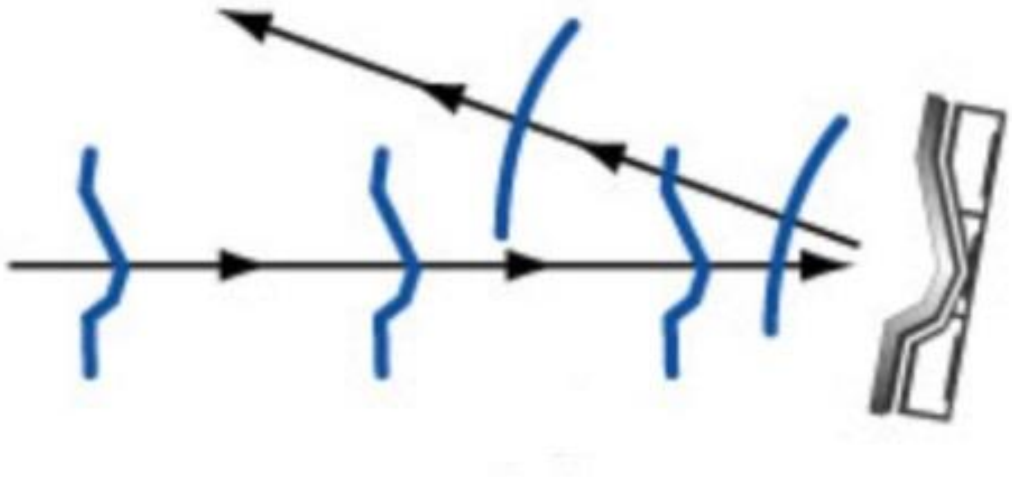




Aberration correction

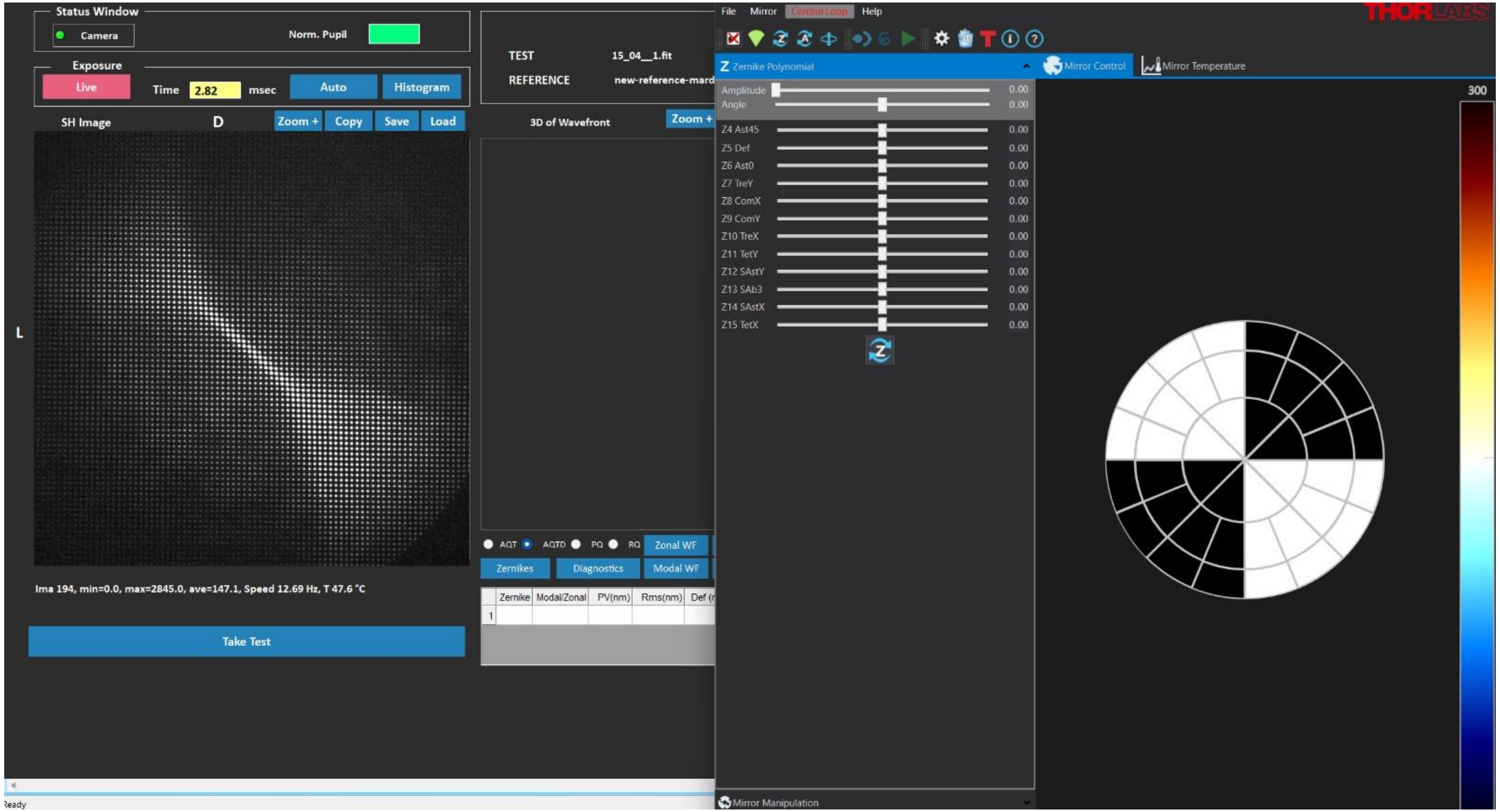


Regular mirror

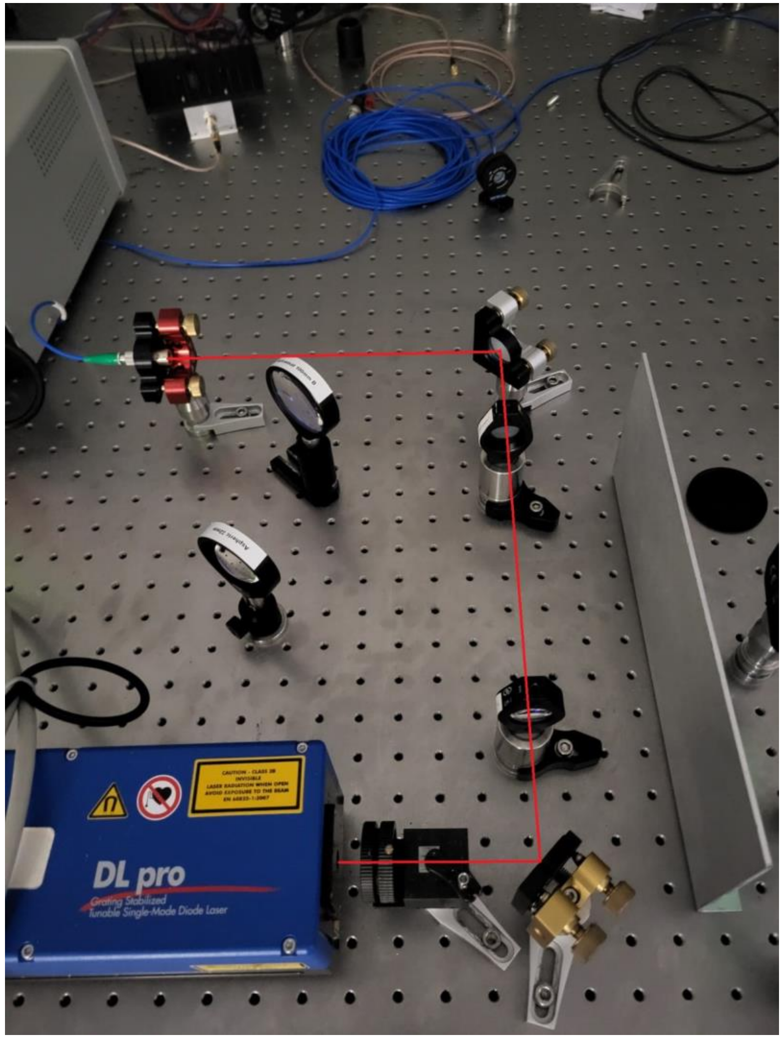


Deformable mirror

Aberration correction



Injection in the optical fiber



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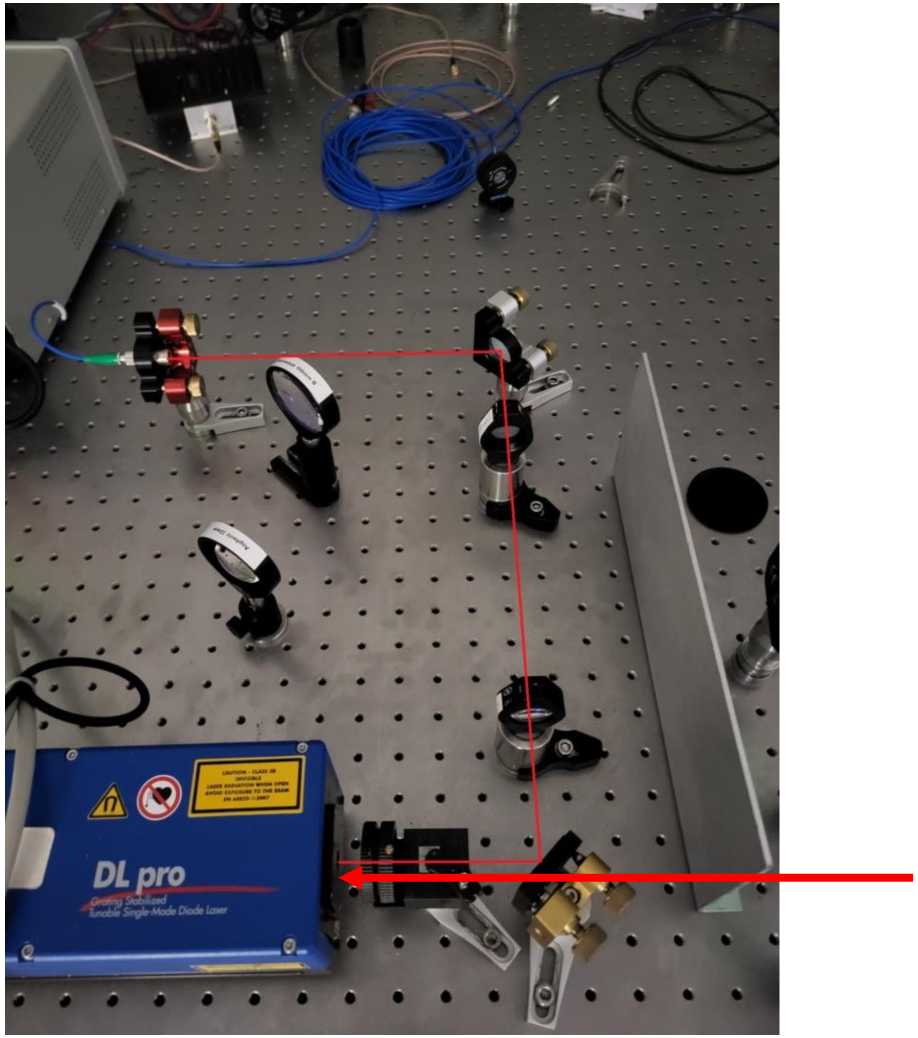

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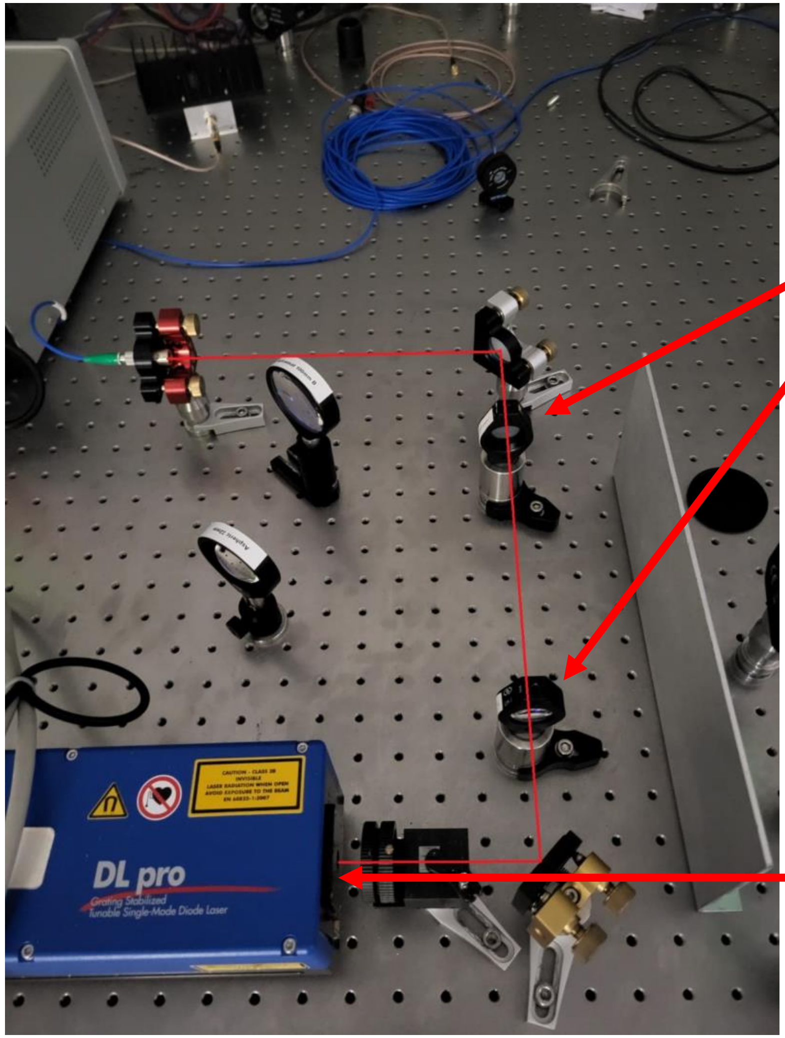
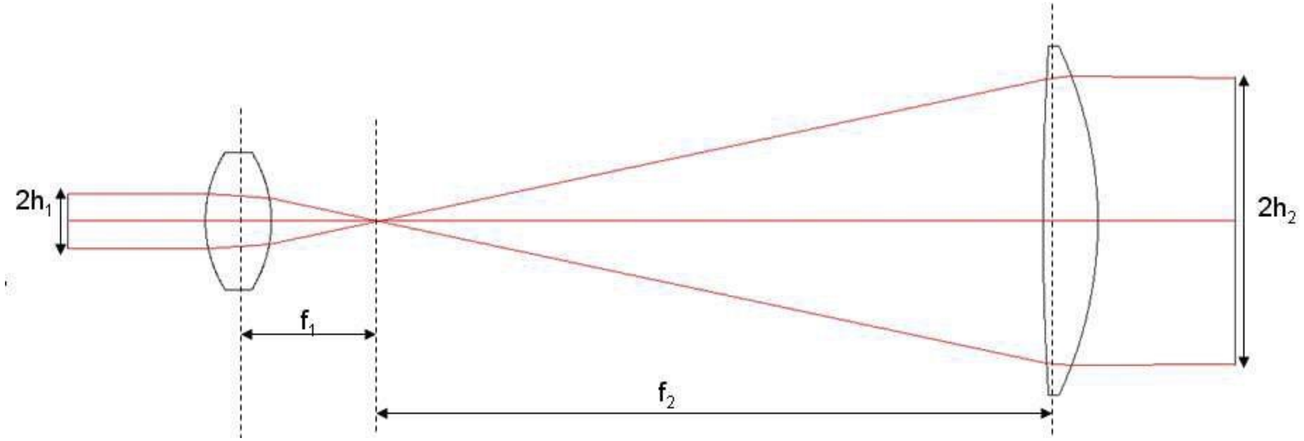


Beam expander group

Laser



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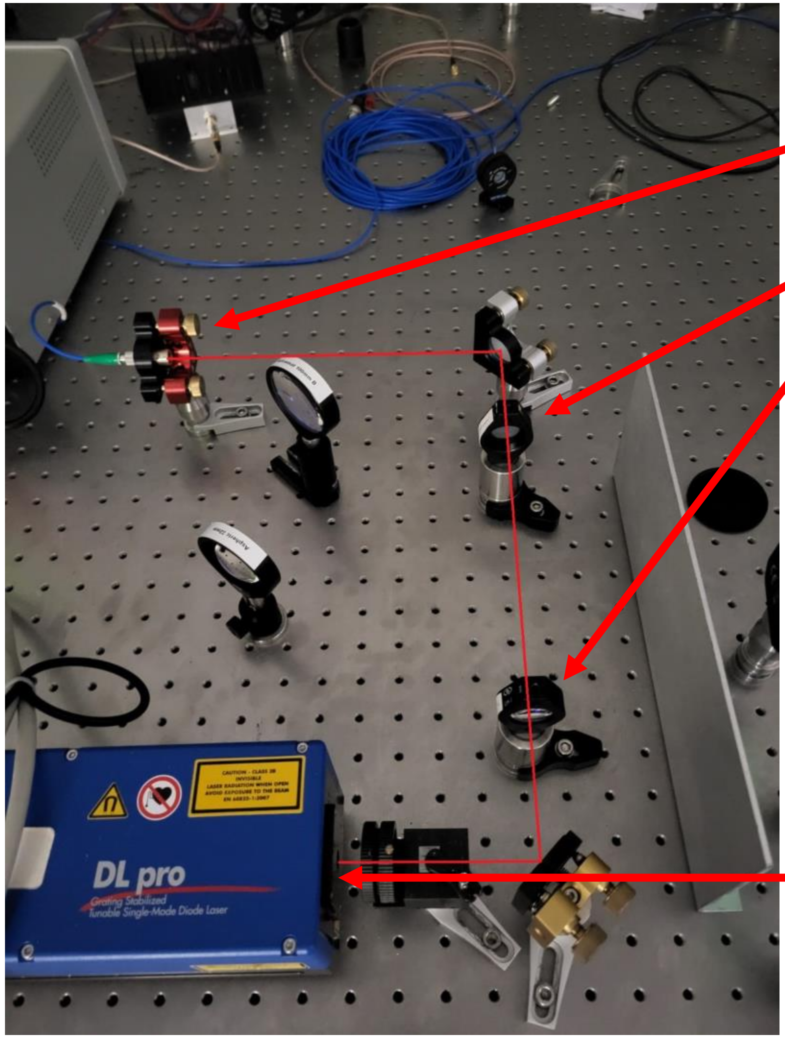
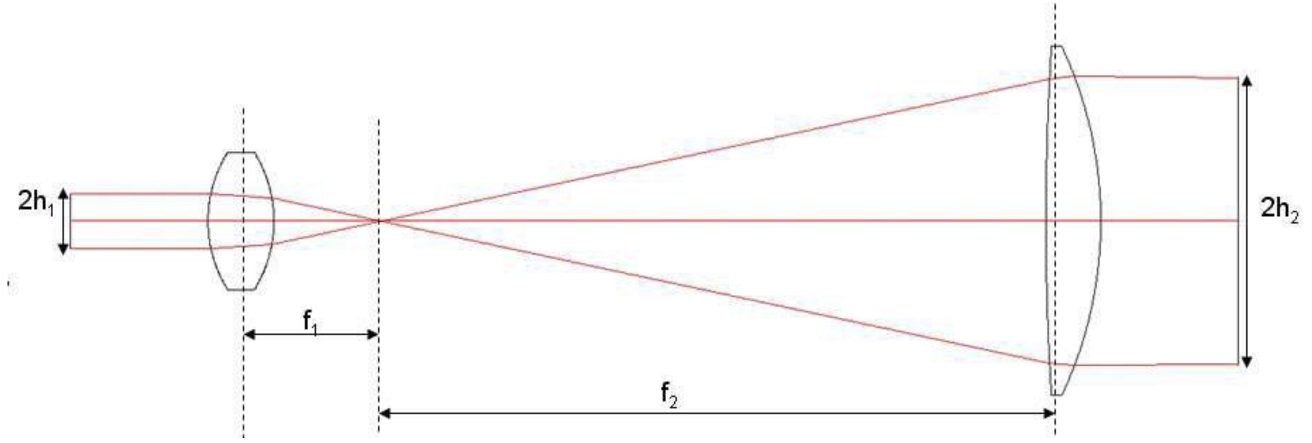


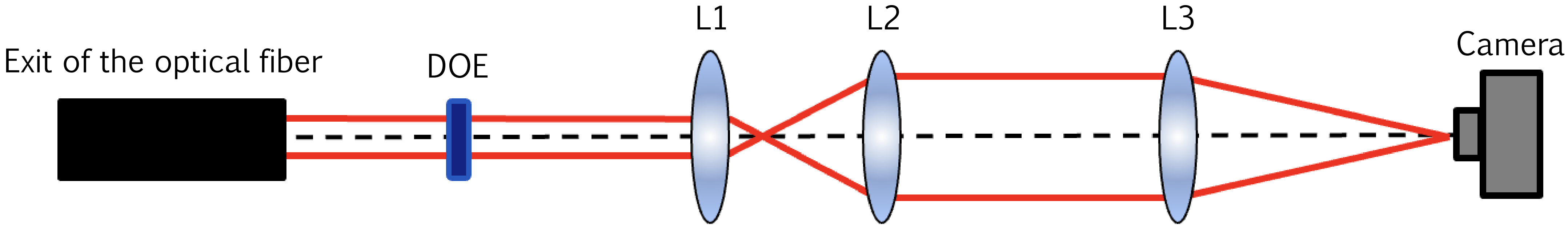
Start of the optical fiber

Beam expander group

Laser



Imaging setup



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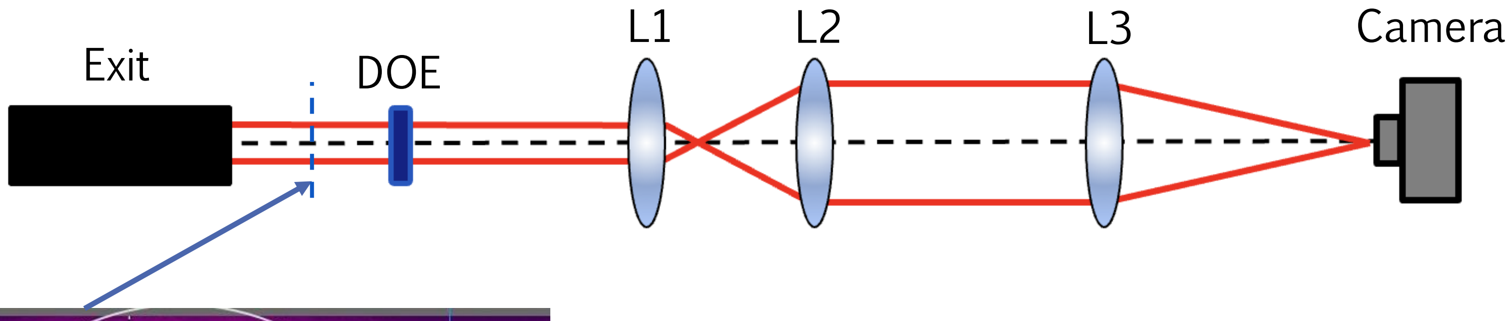

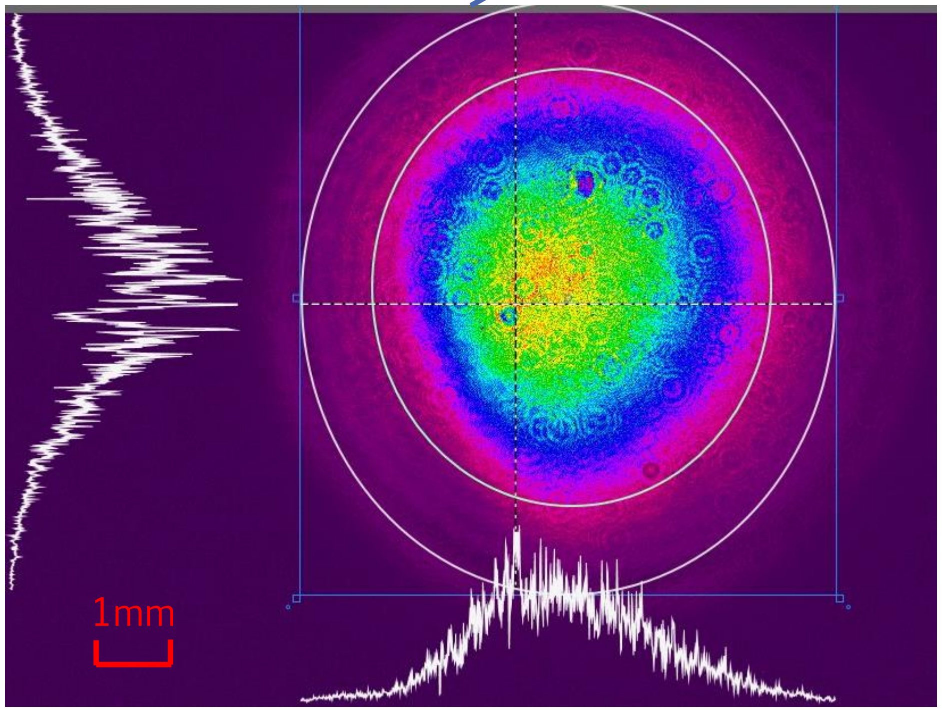

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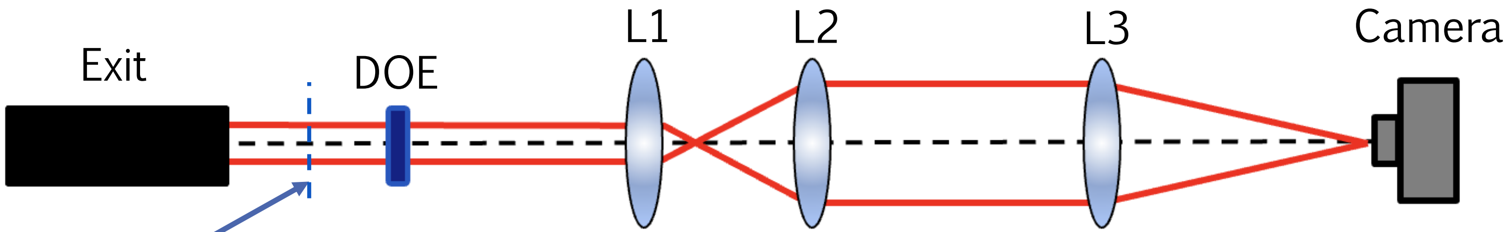
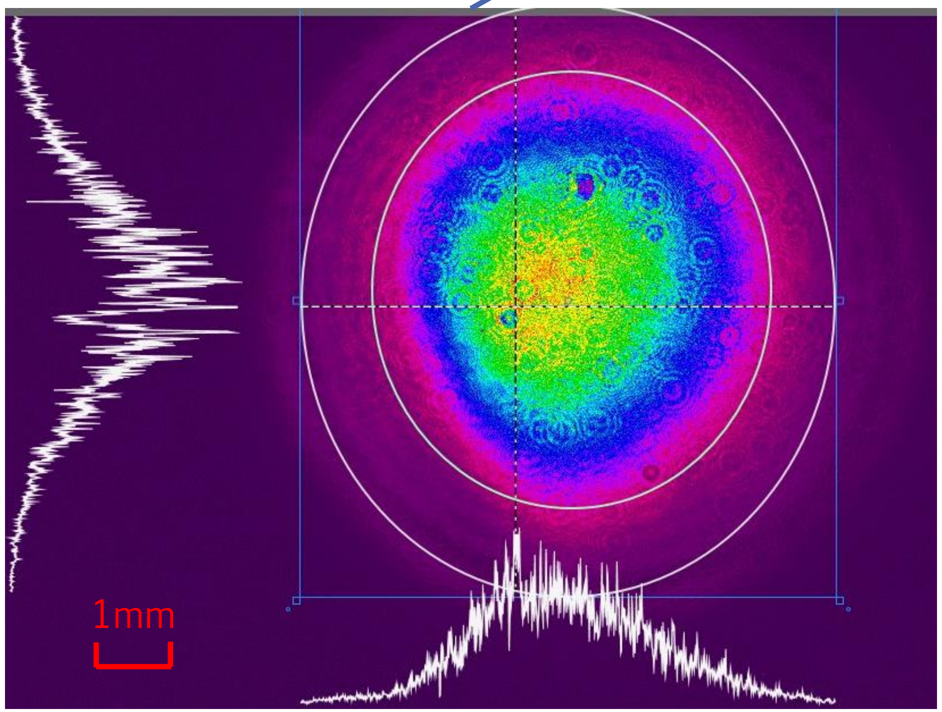
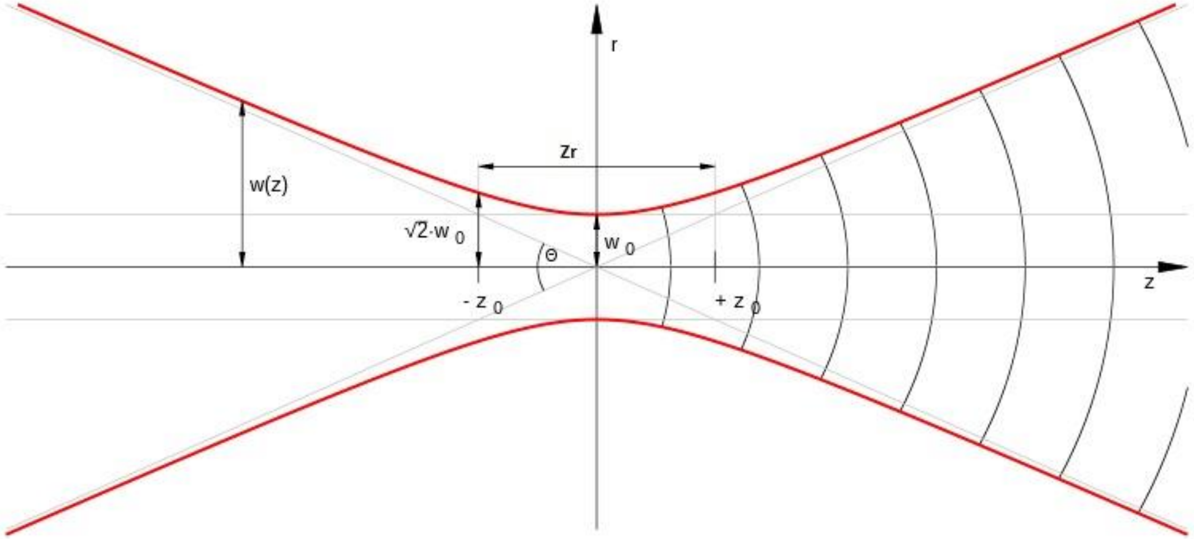
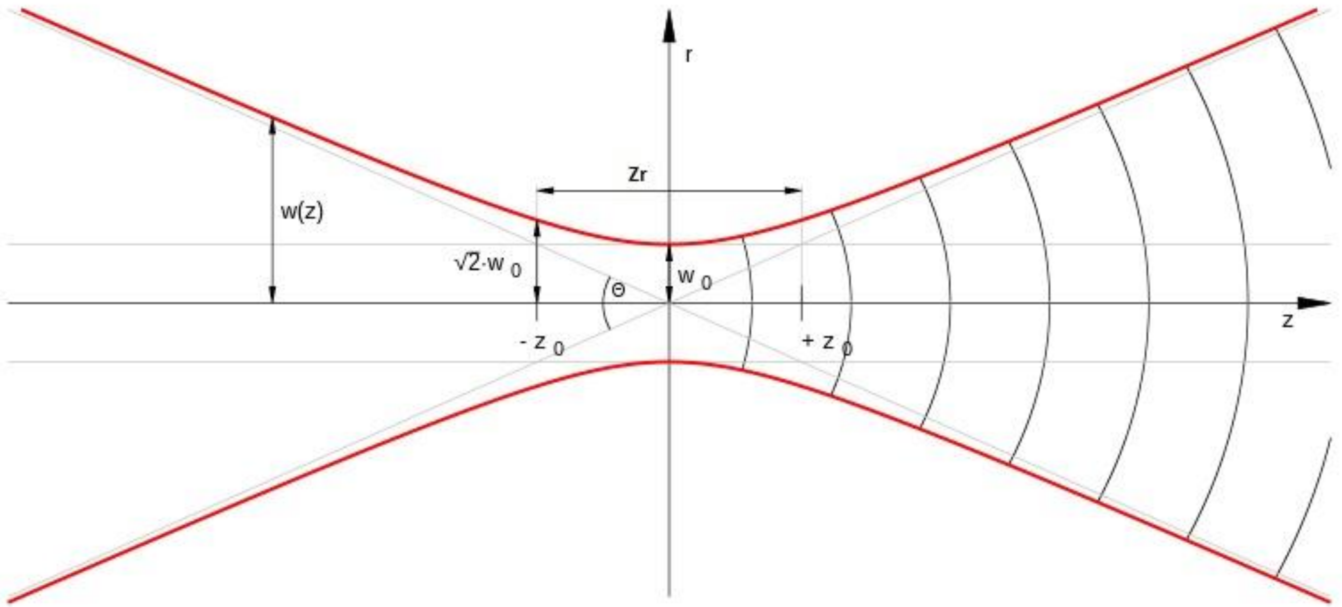






Wavefront of the laser beam



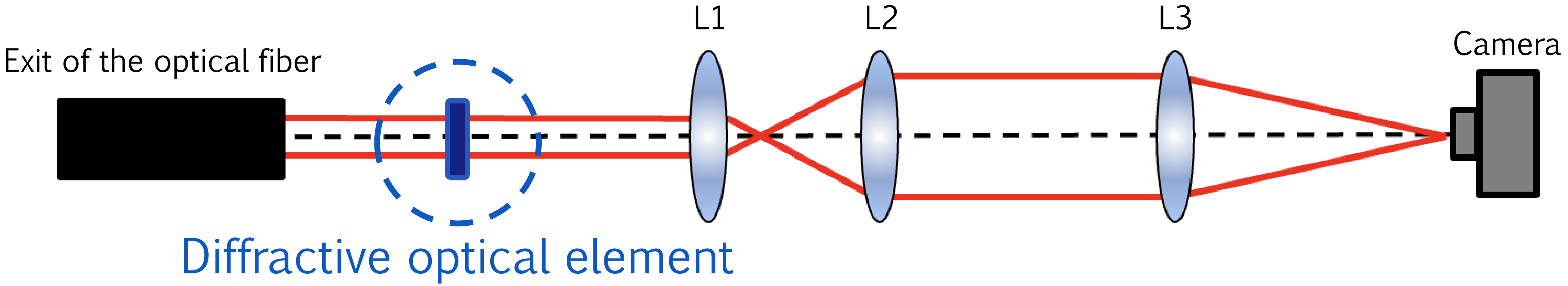
$$z_R = \frac{\pi w_0^2}{\lambda} = \frac{1}{2} k w_0^2$$

Rayleigh length

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

Curvature of the wavefront

Imaging setup



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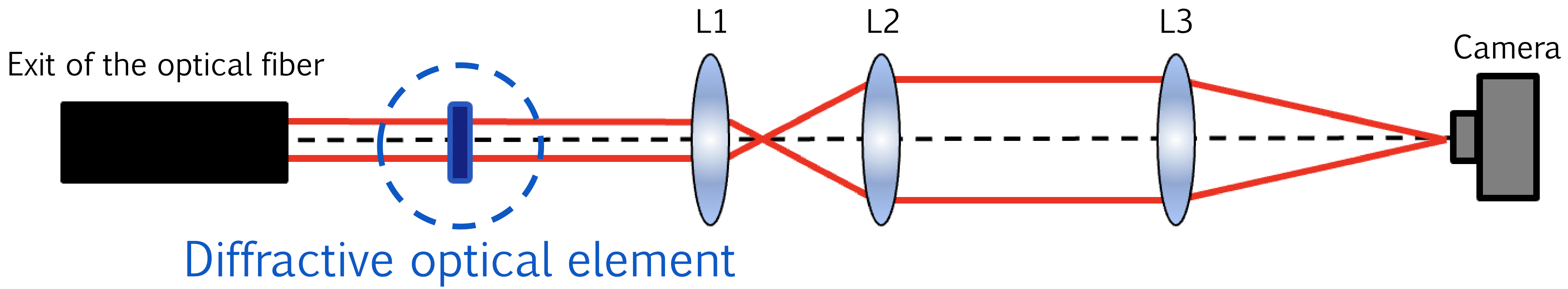

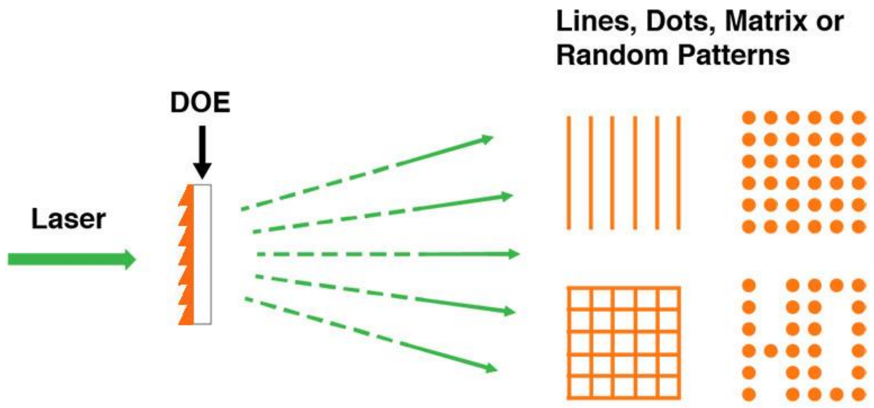

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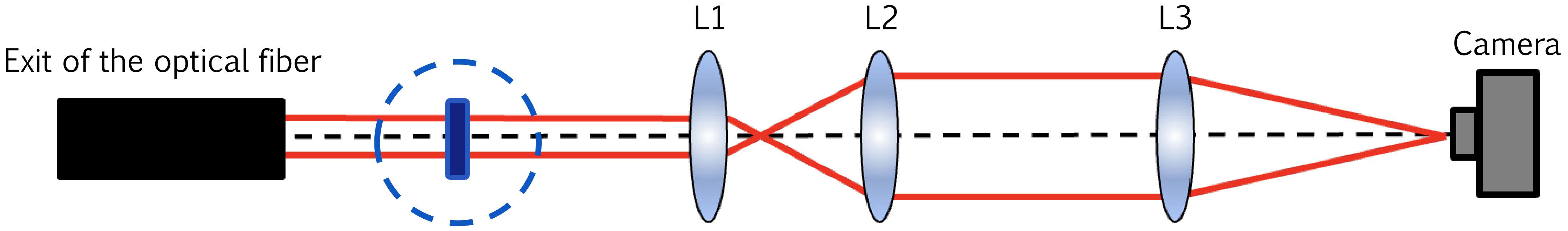
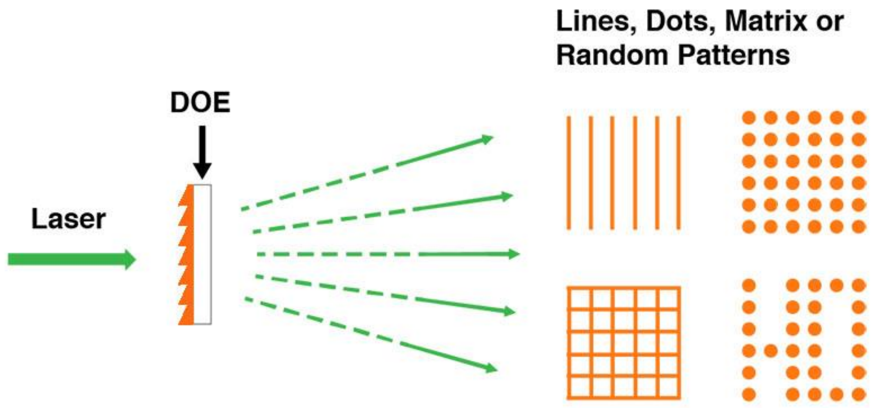
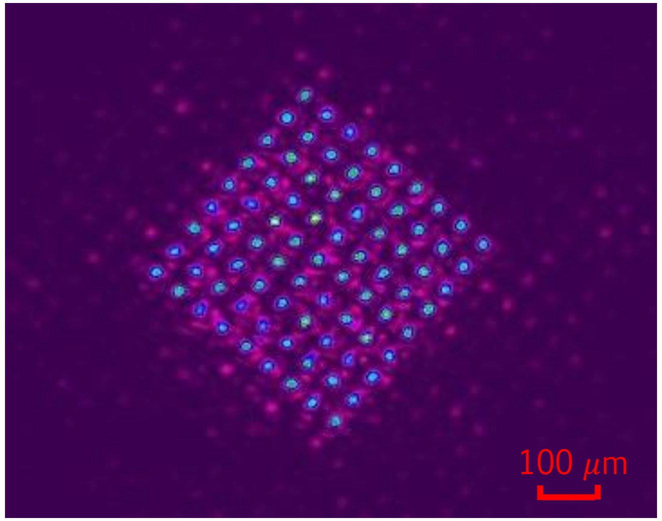


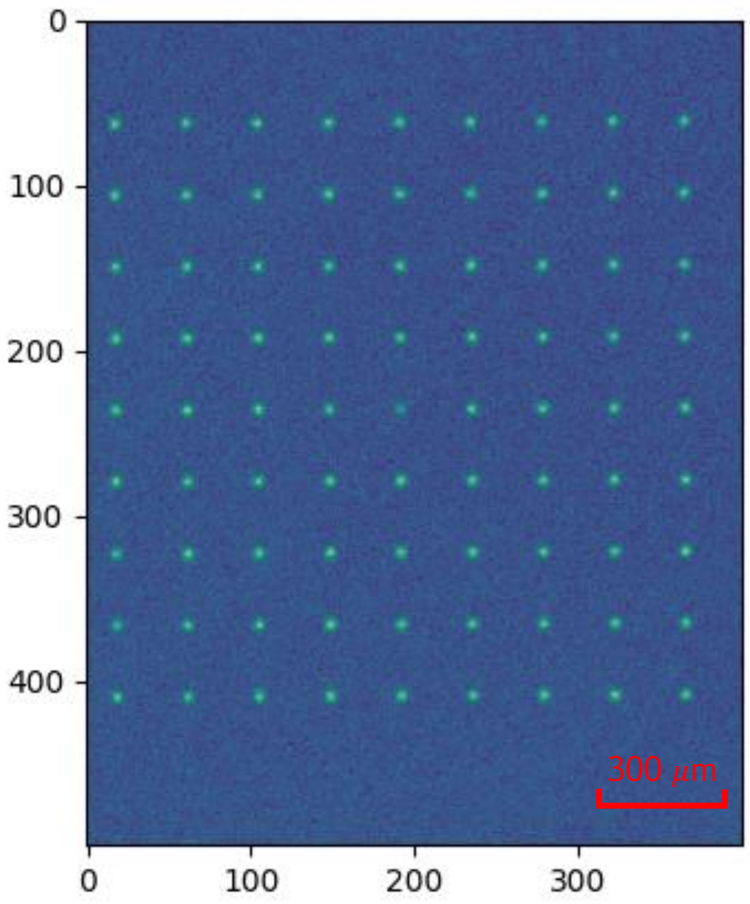
Diffractive optical element



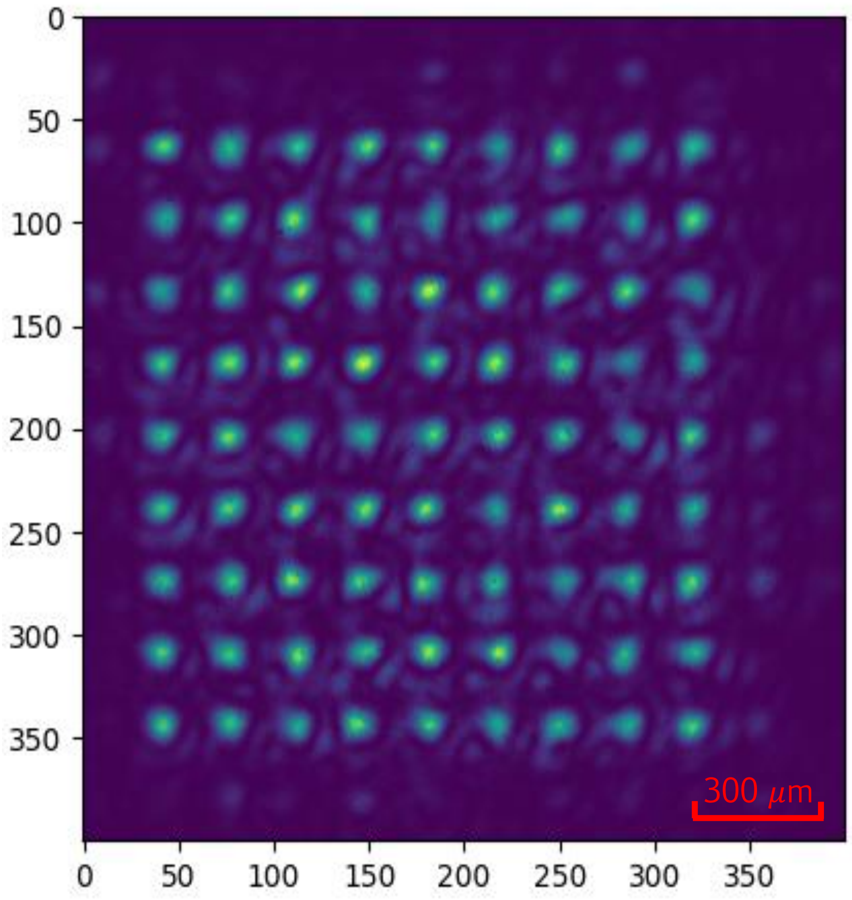
We get



Imaging the beam



Beam before the imaging system



Beam after the imaging system

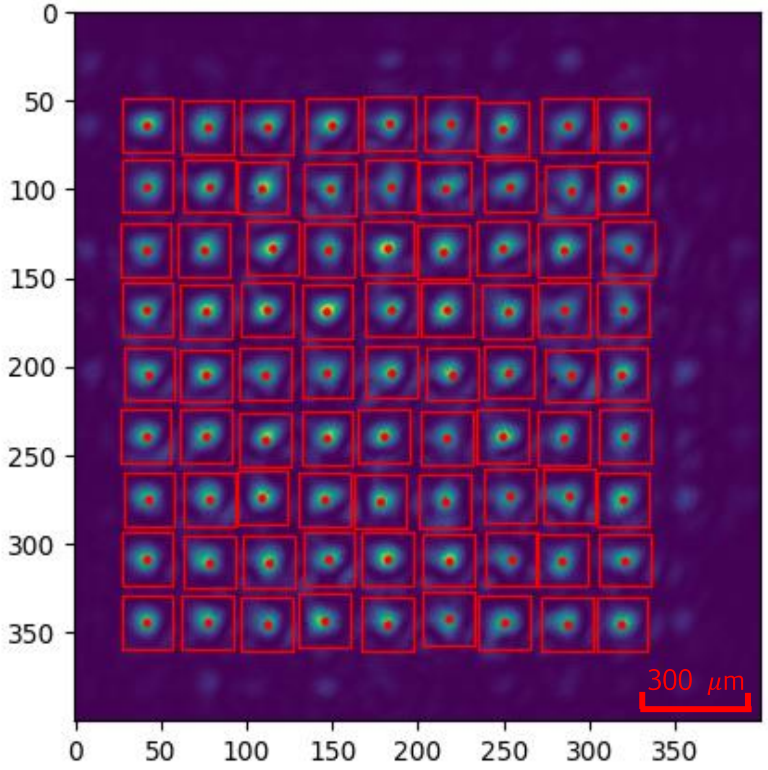
Characterization of the aberration

Step 1: Defining the regions of interest

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

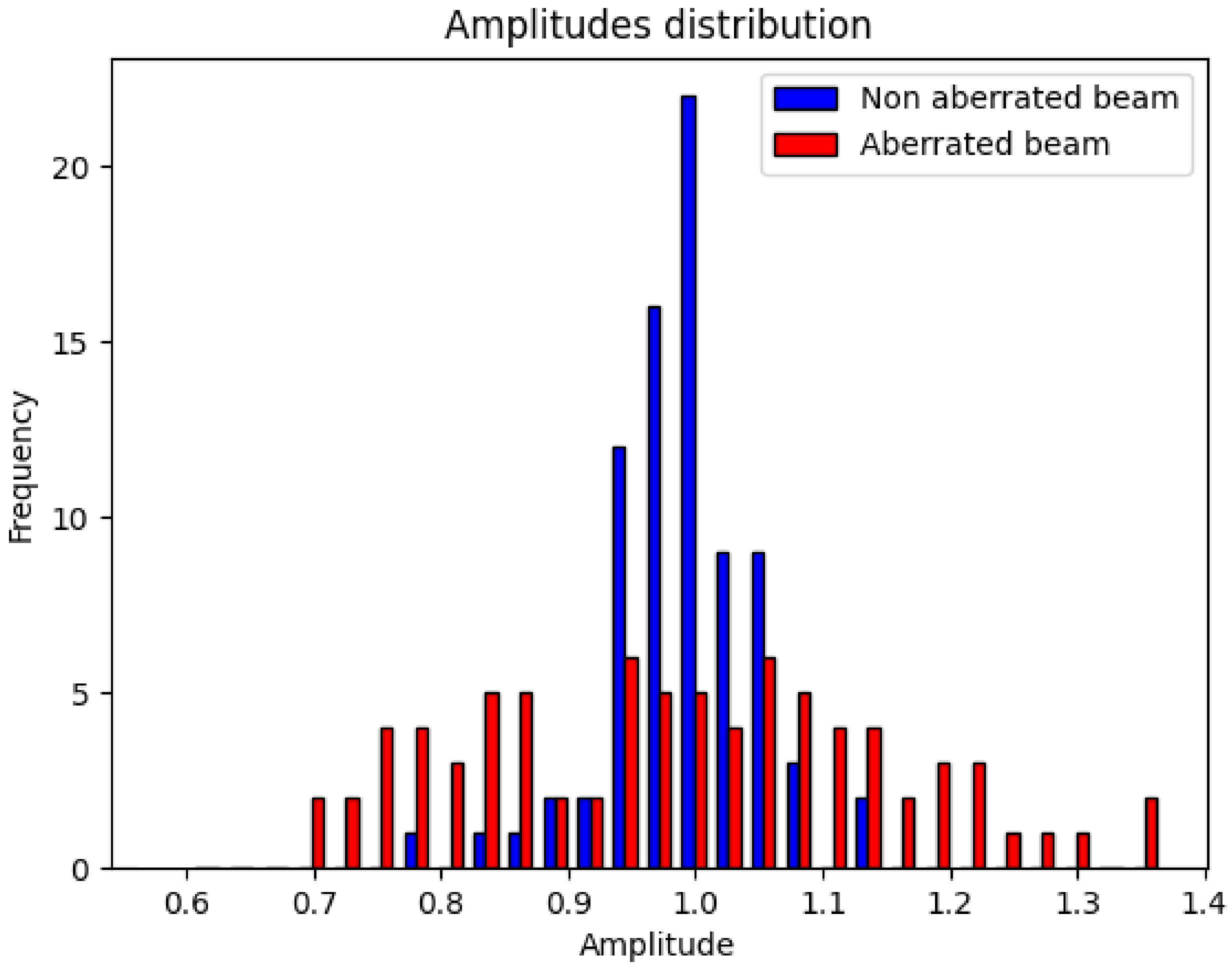
Step 2: Gaussian fit

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



Aberrated image with ROI

Characterization of the aberration



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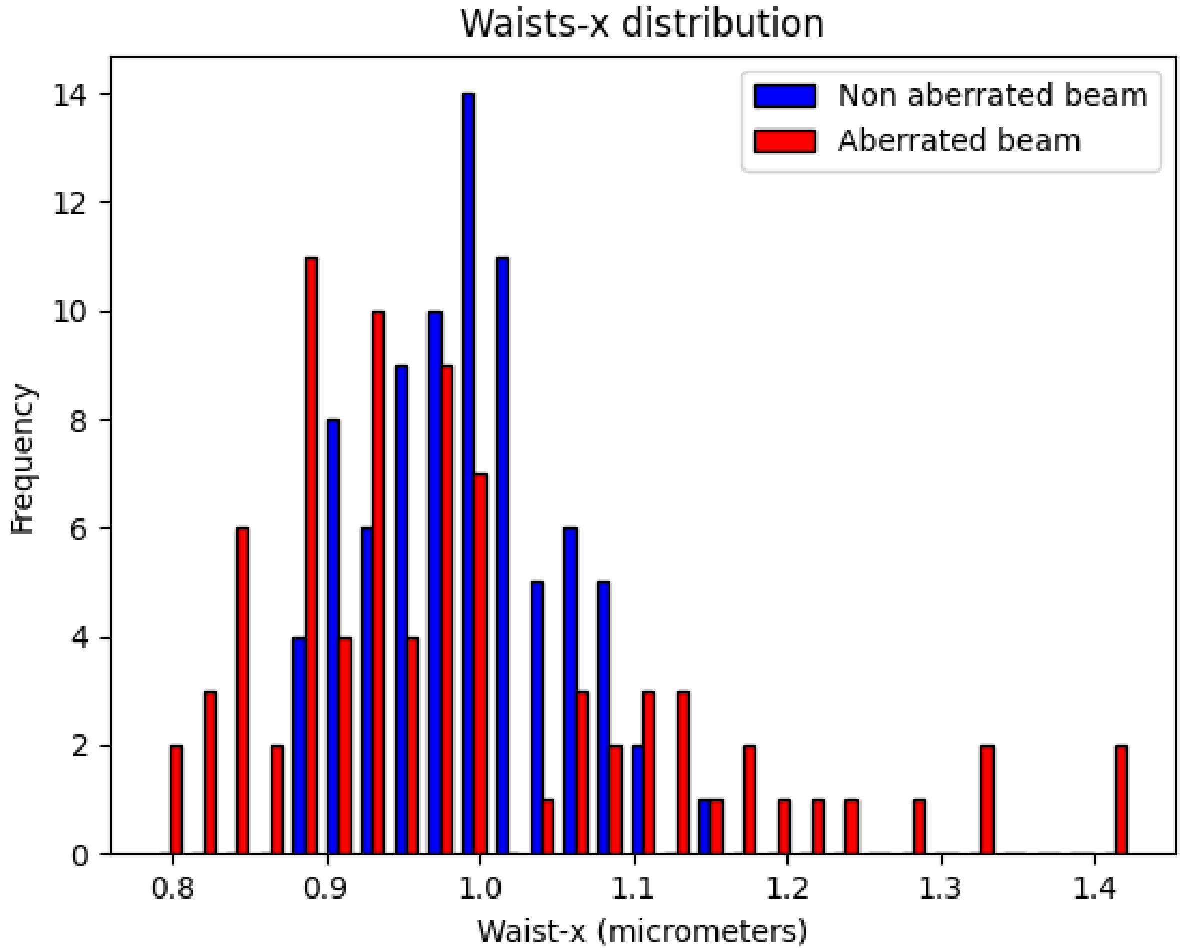
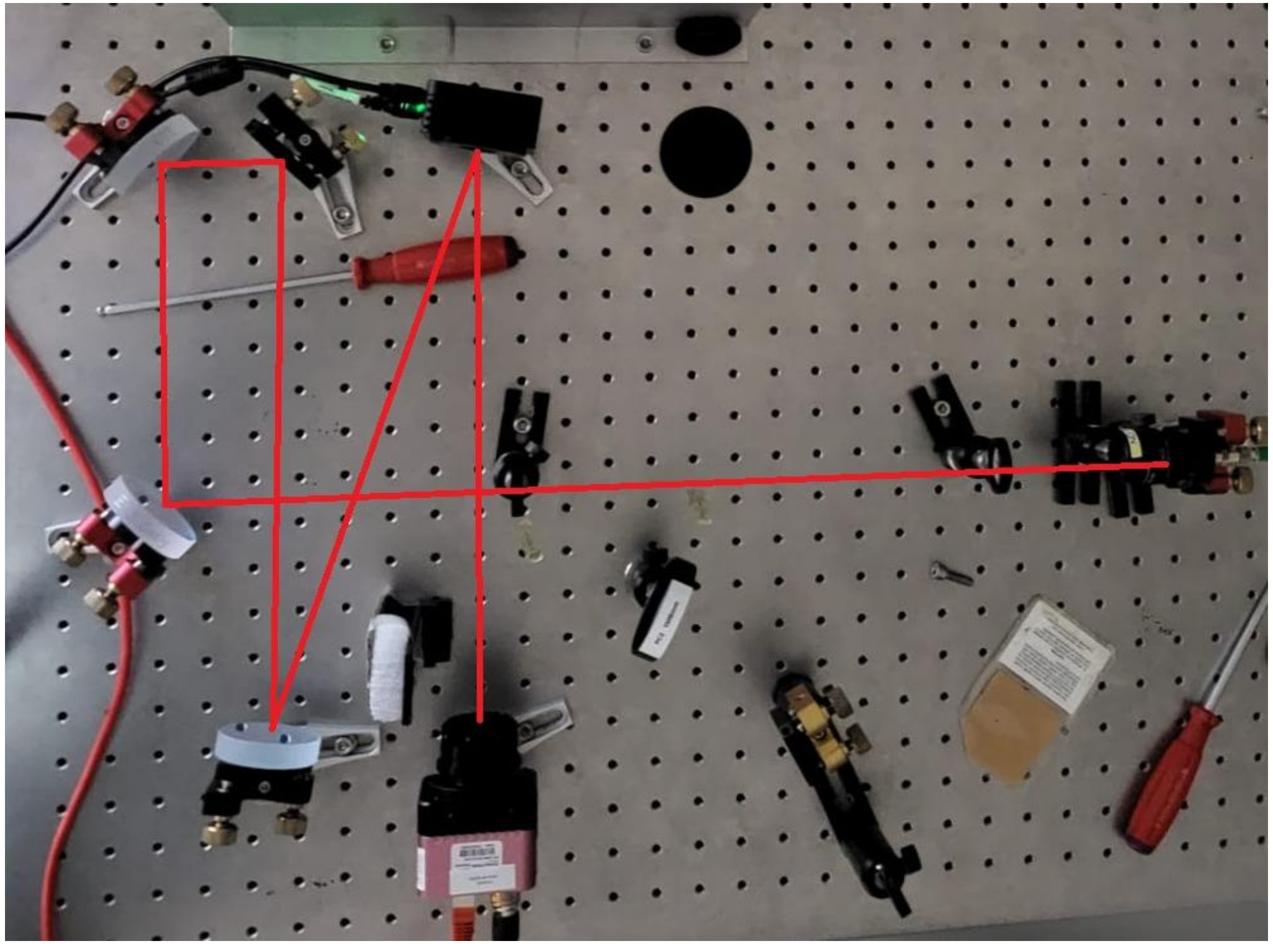


Correction setup



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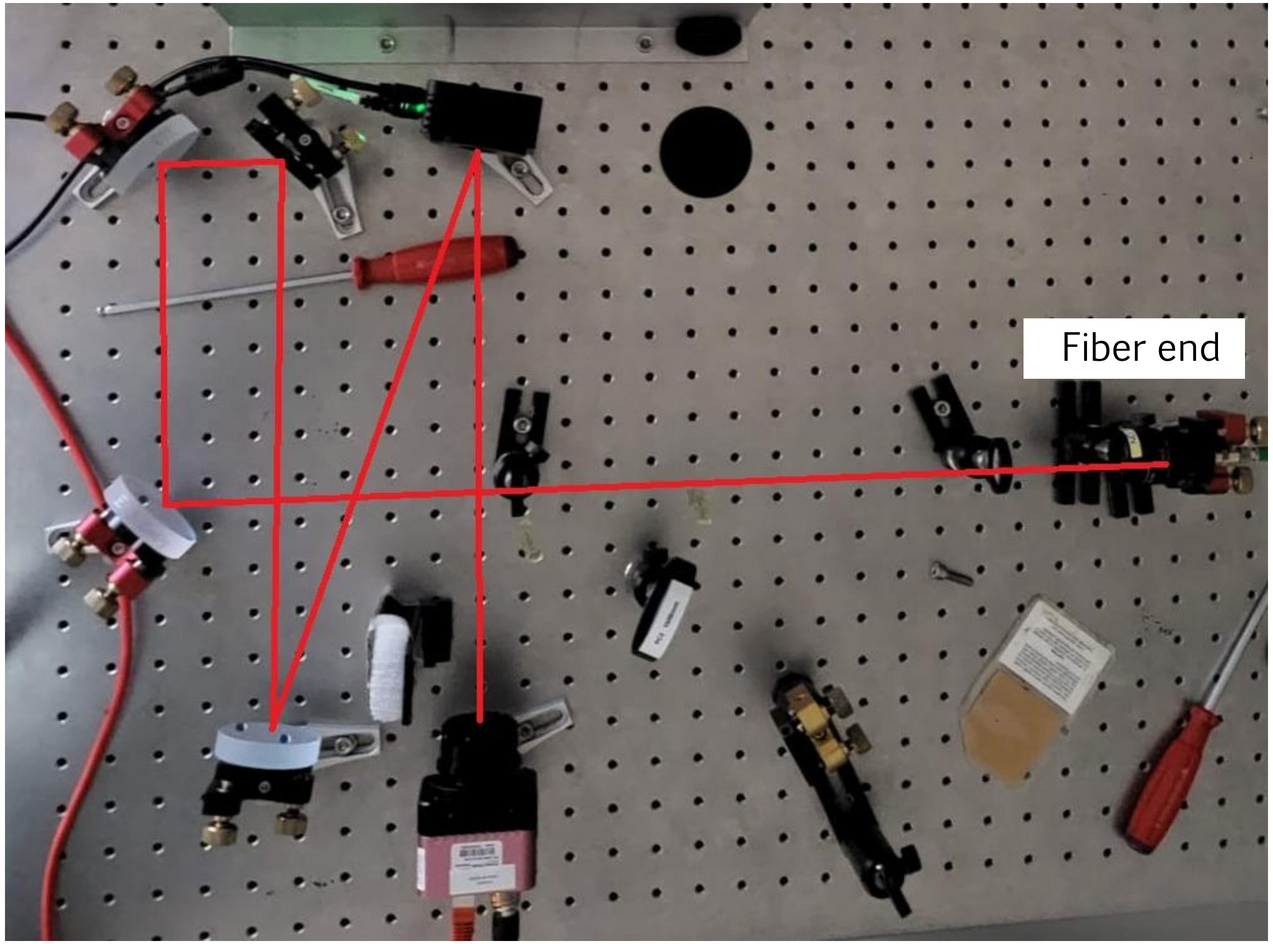

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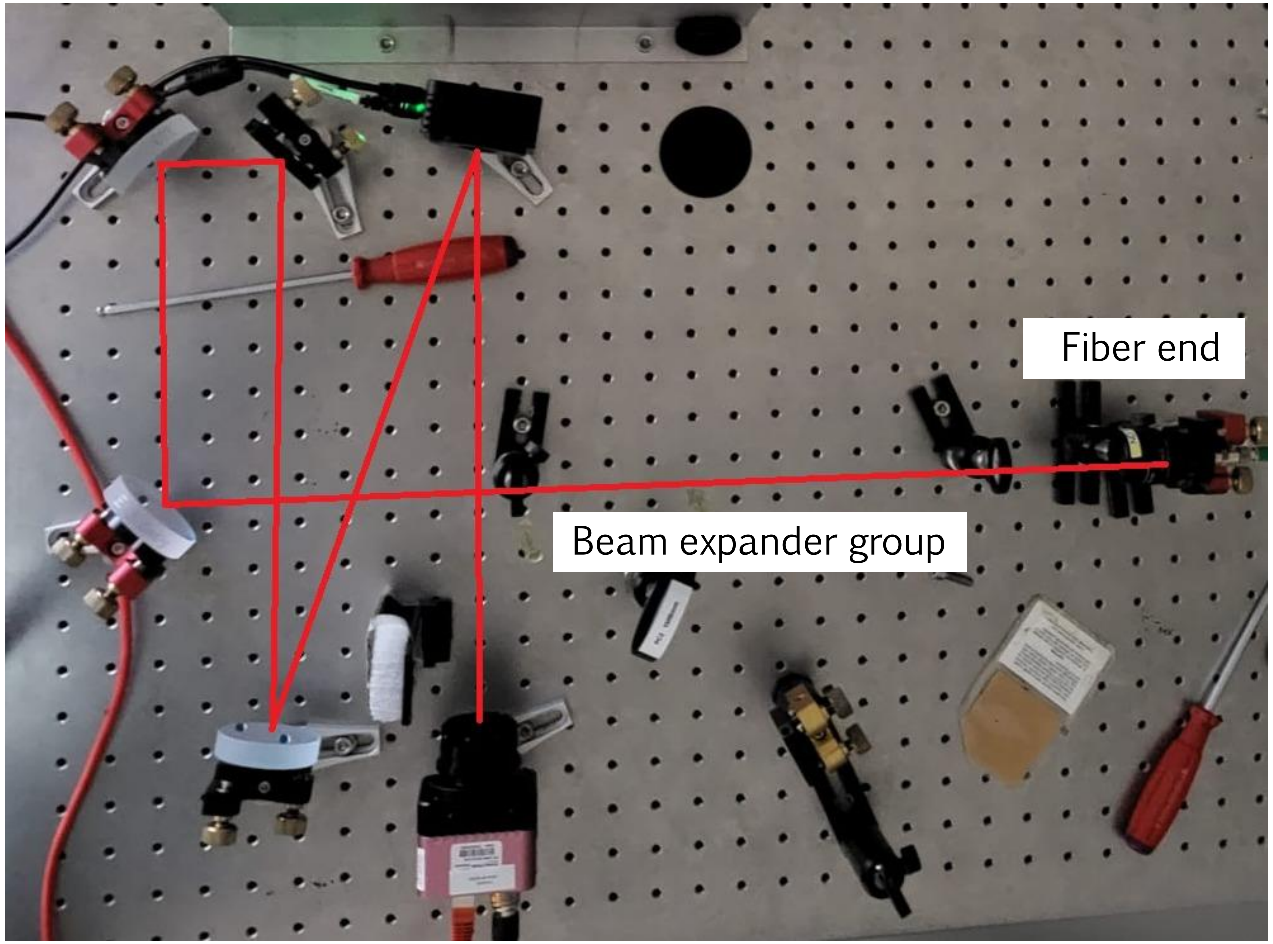

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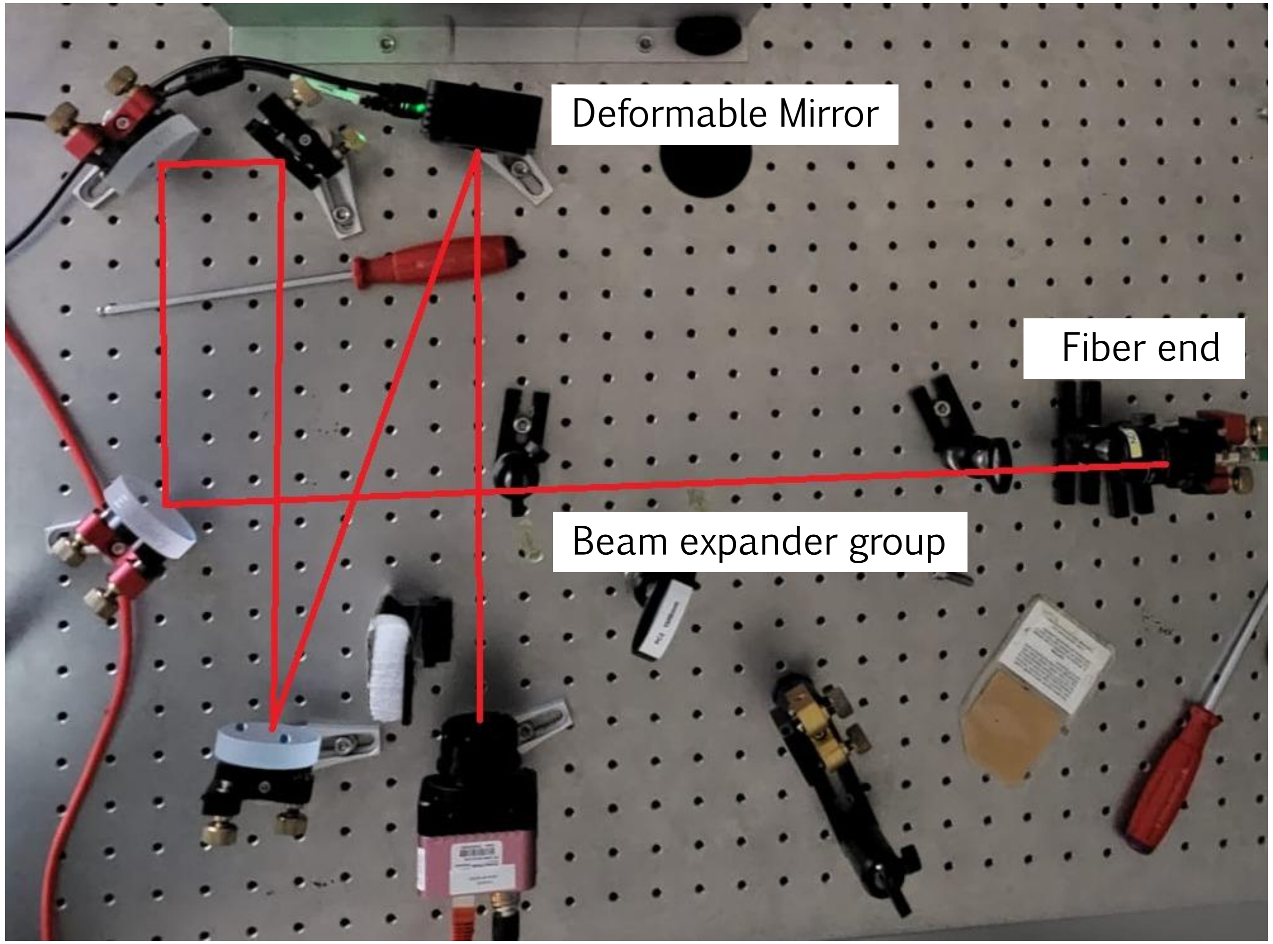

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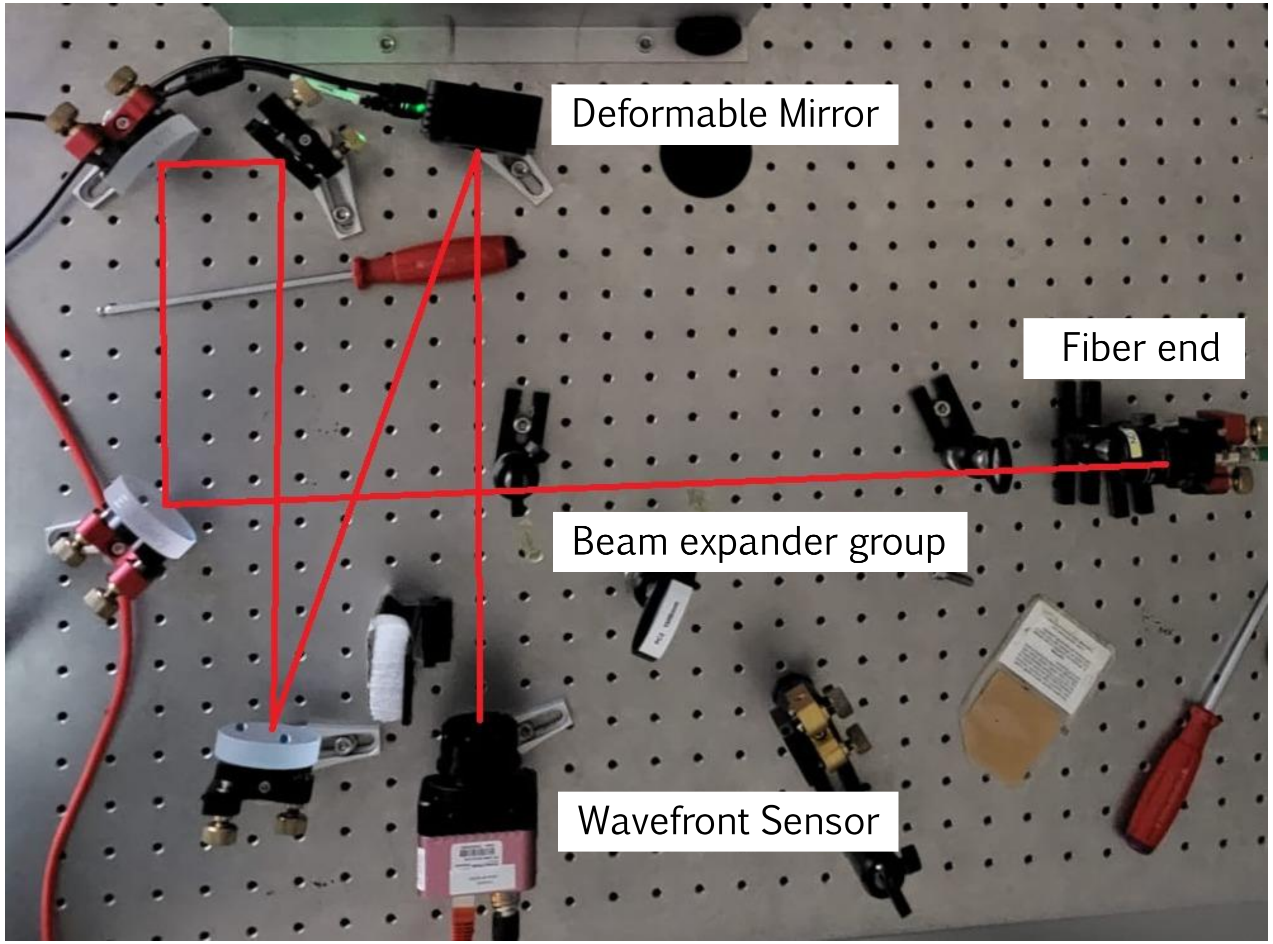
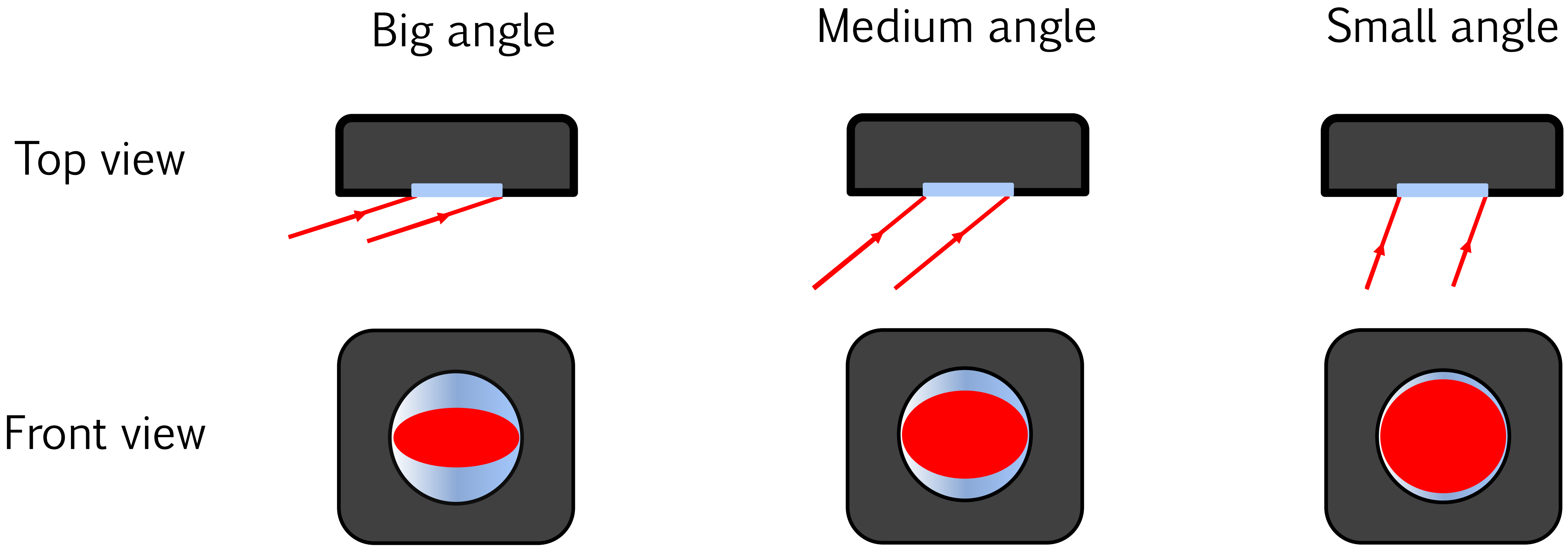
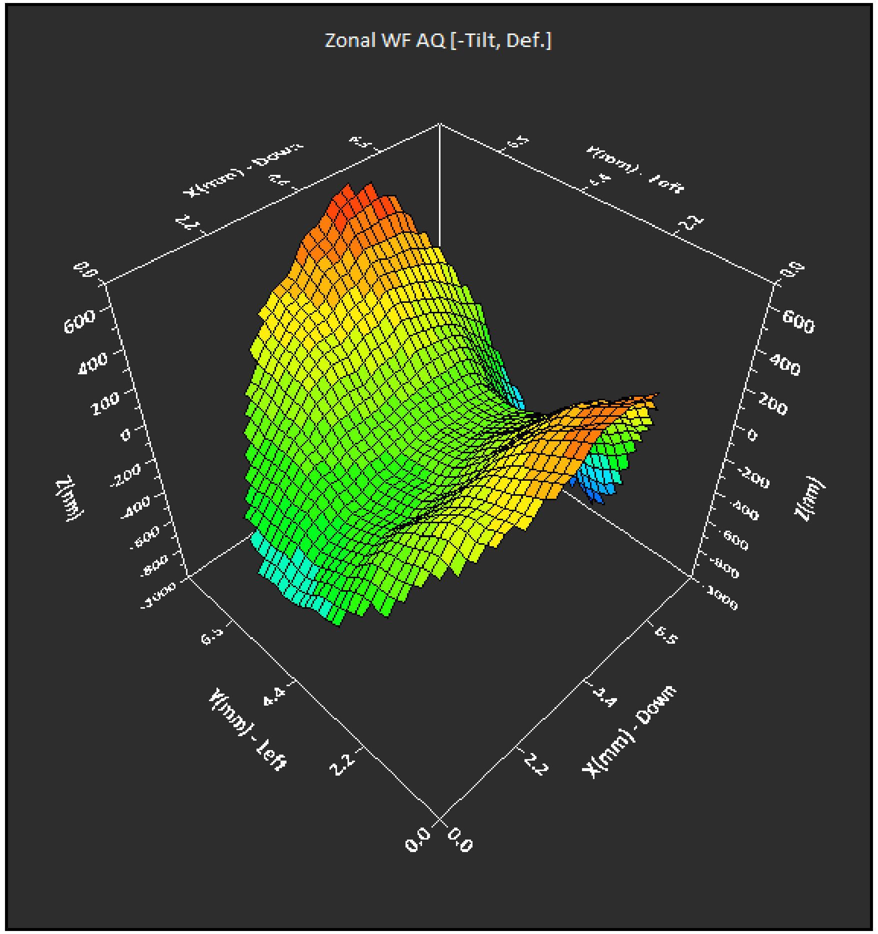


Angle of incidence on the DM



Correcting a specific aberration



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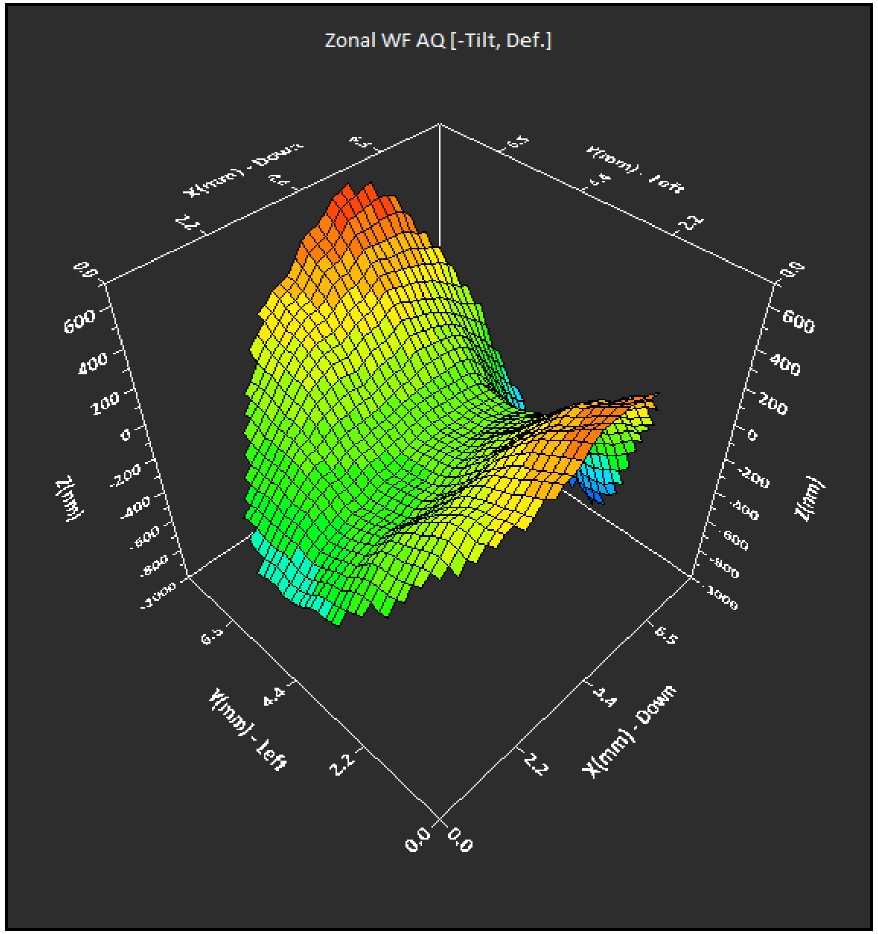
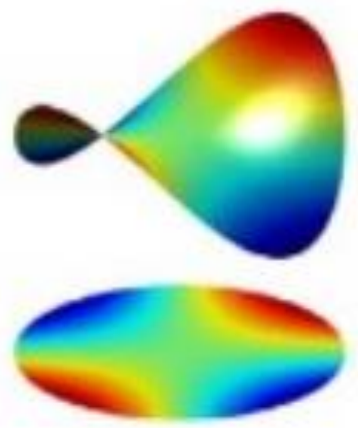
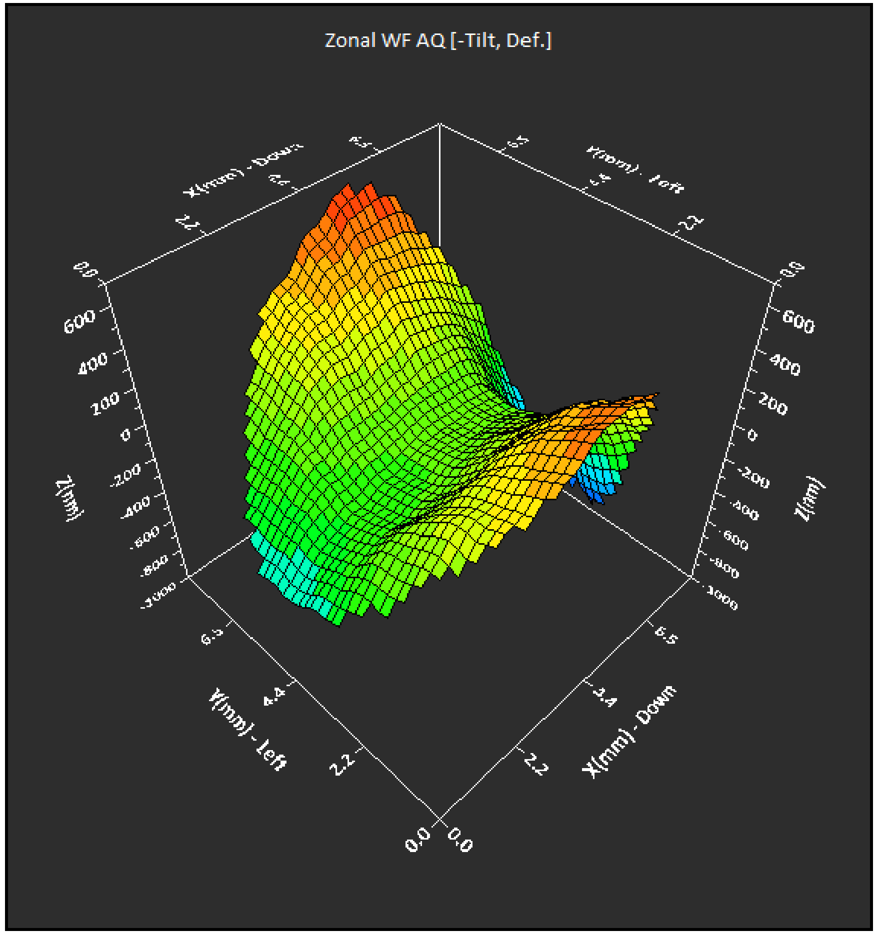
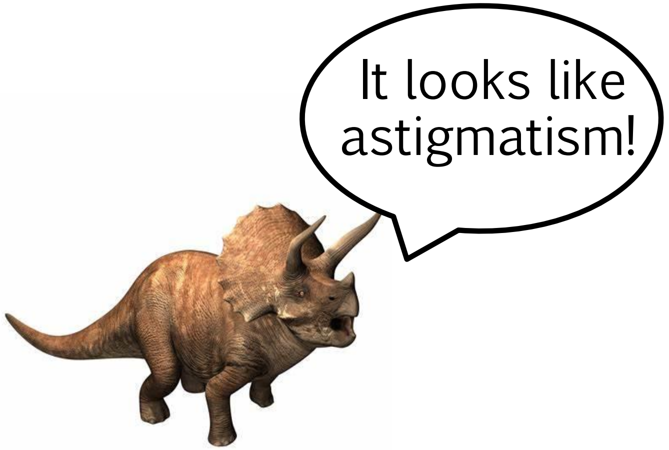
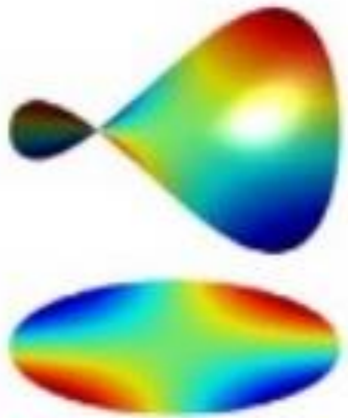




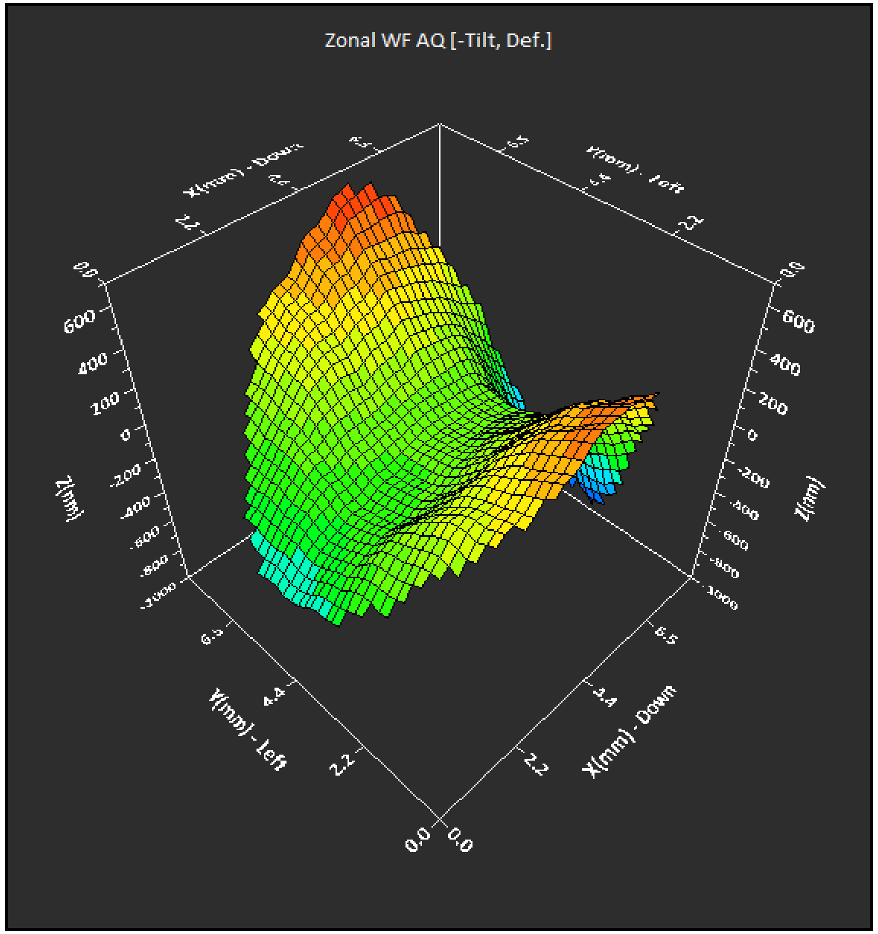
Correcting a specific aberration



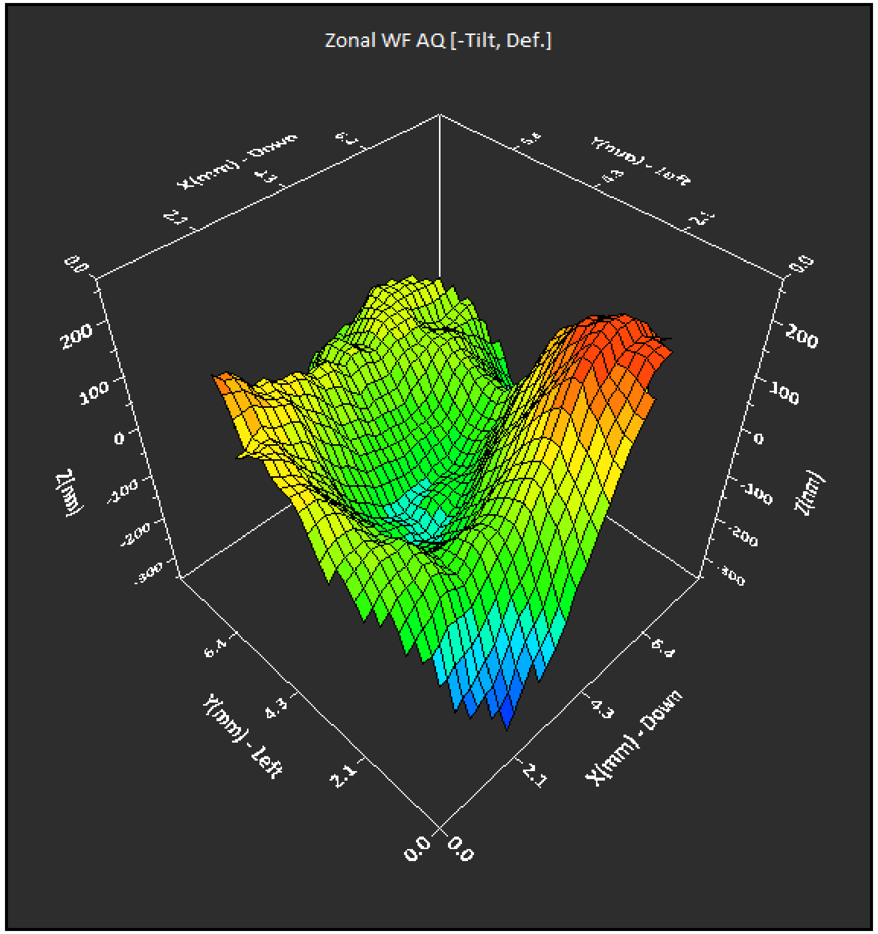




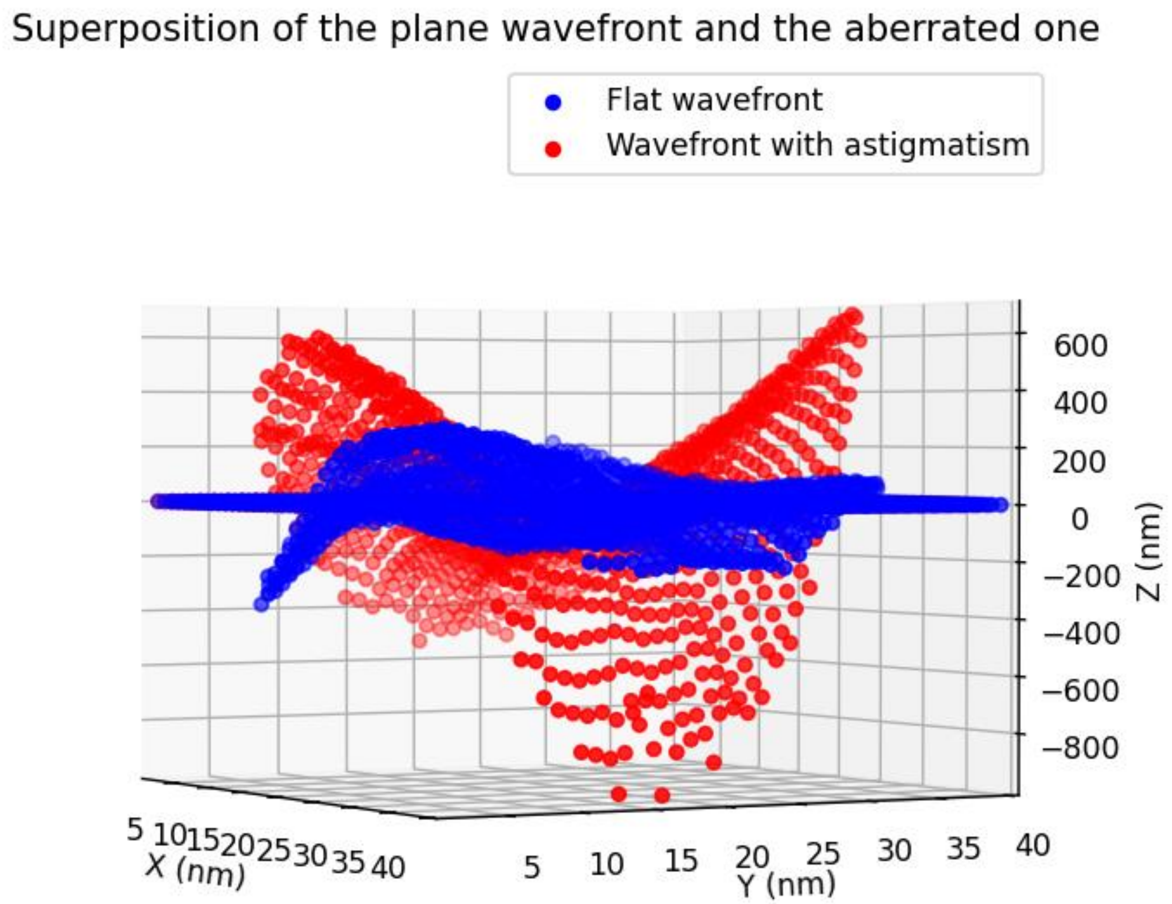
Correcting a specific aberration



After correction



Correcting a specific aberration



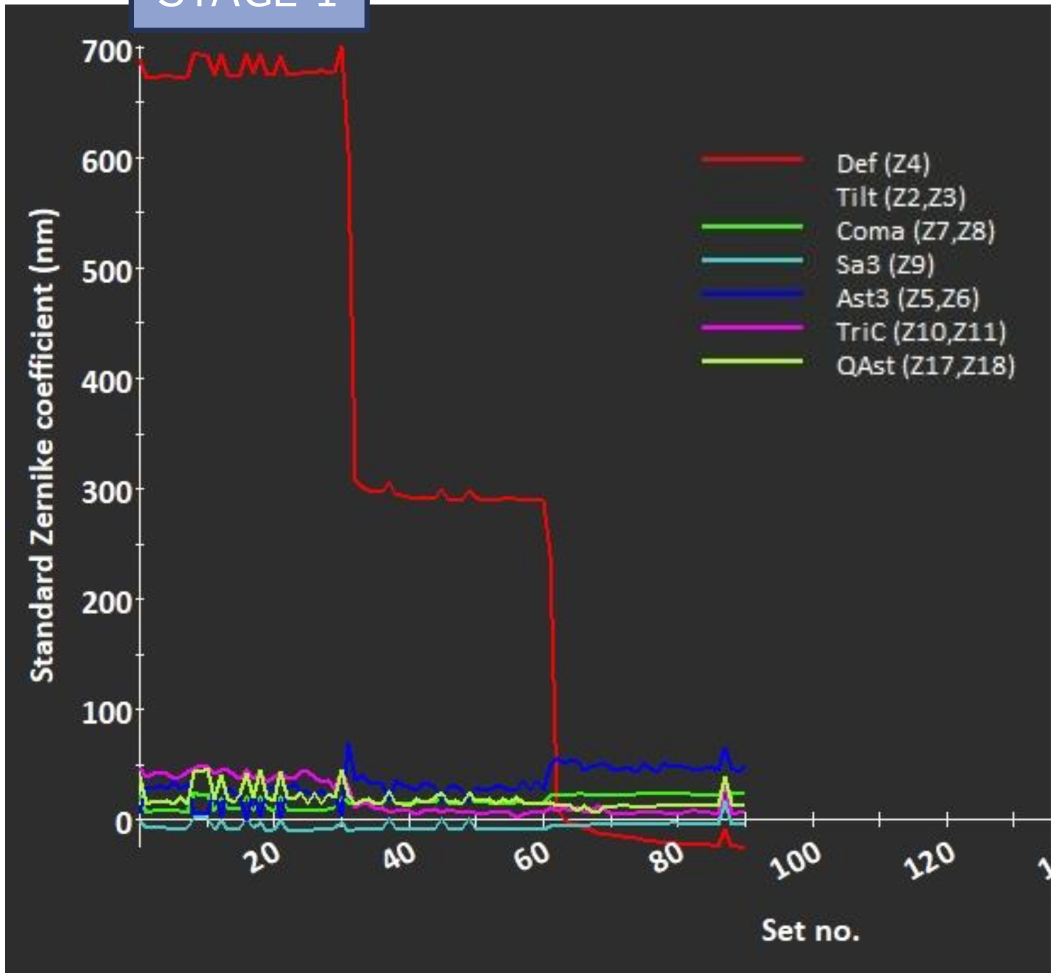
Aber	m n	Z	Z_e(nm)
Tilt	1 1	Z2	765.5
Defocus	0 2	Z4	
Ast3	2 2	Z6	310.9
Coma3	1 3	Z8	17.8

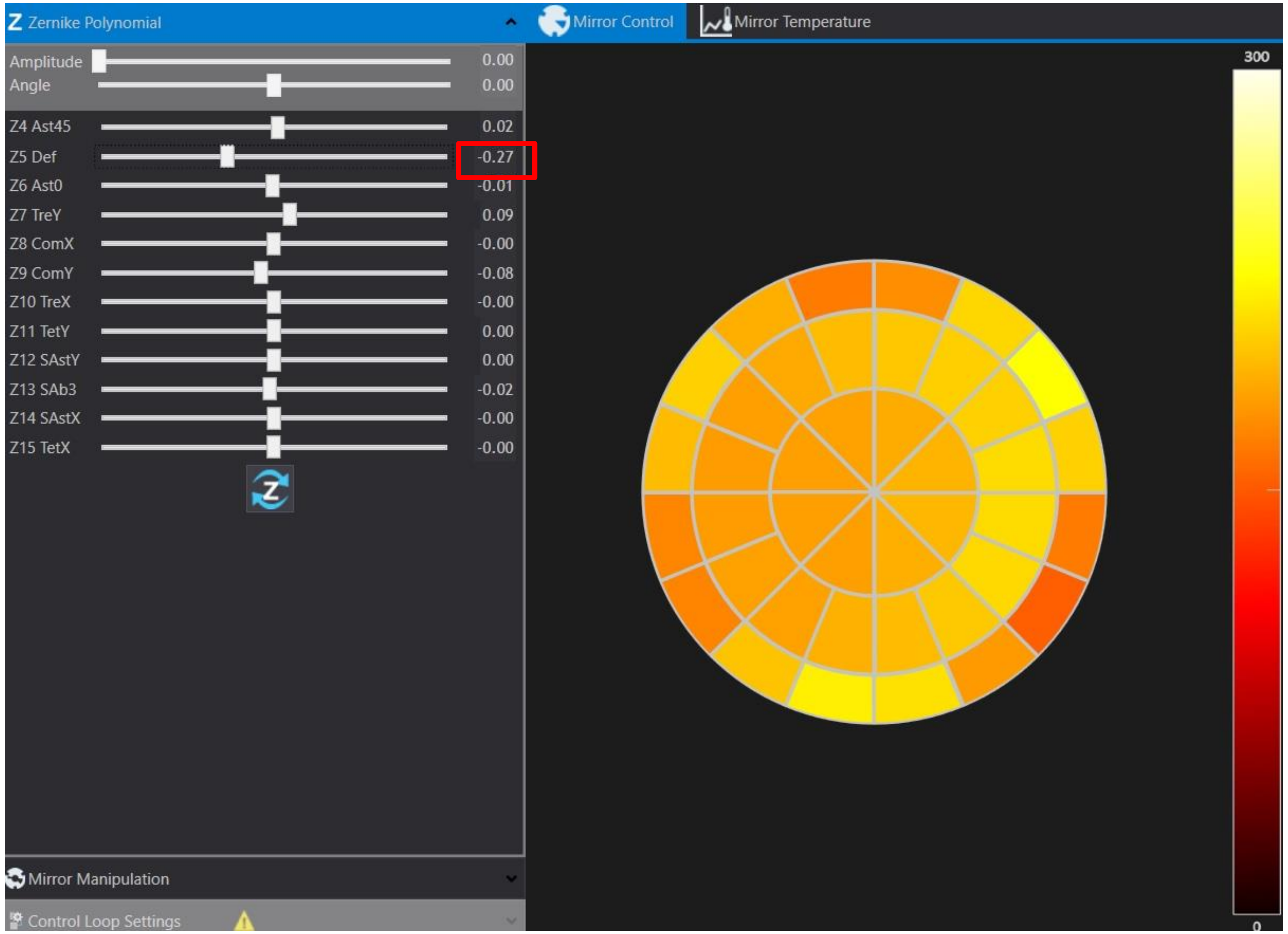
↓

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

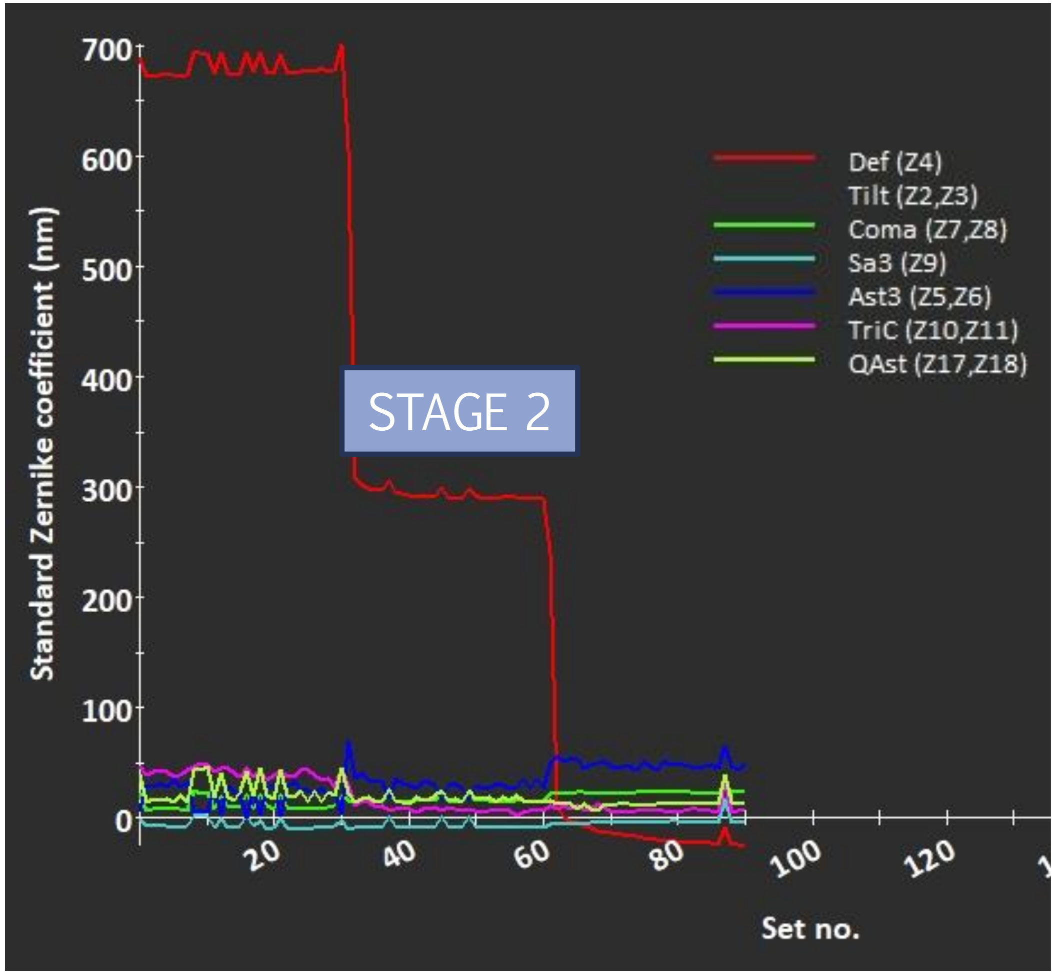
Another correction: defocus

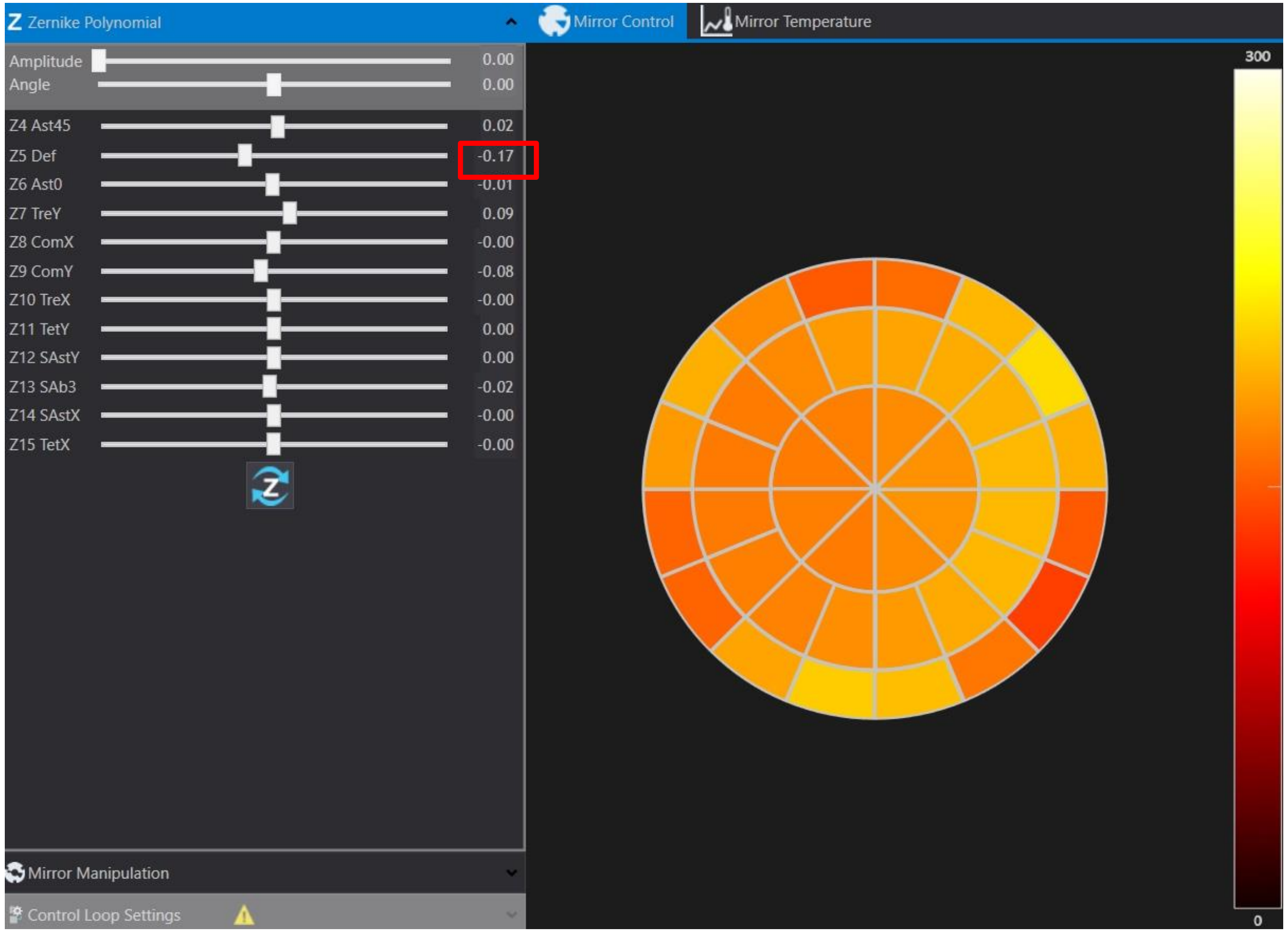
STAGE 1



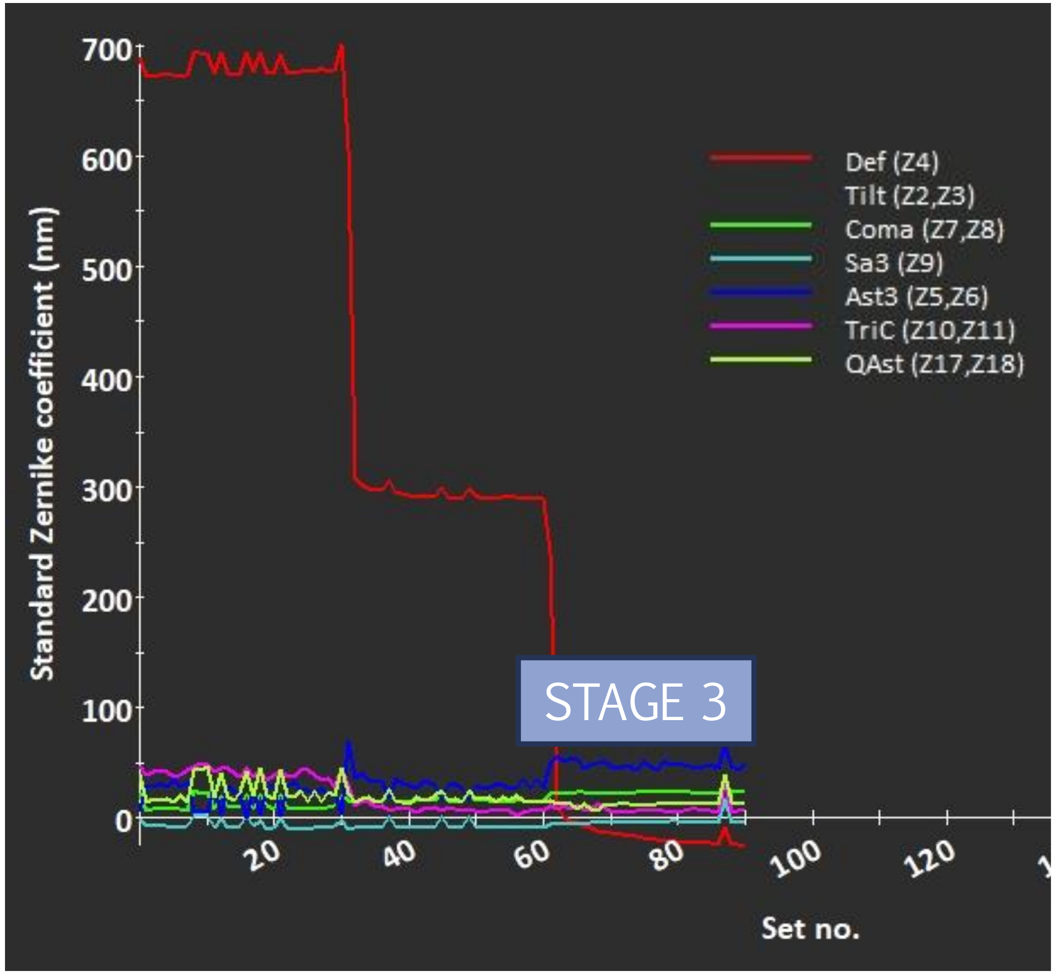


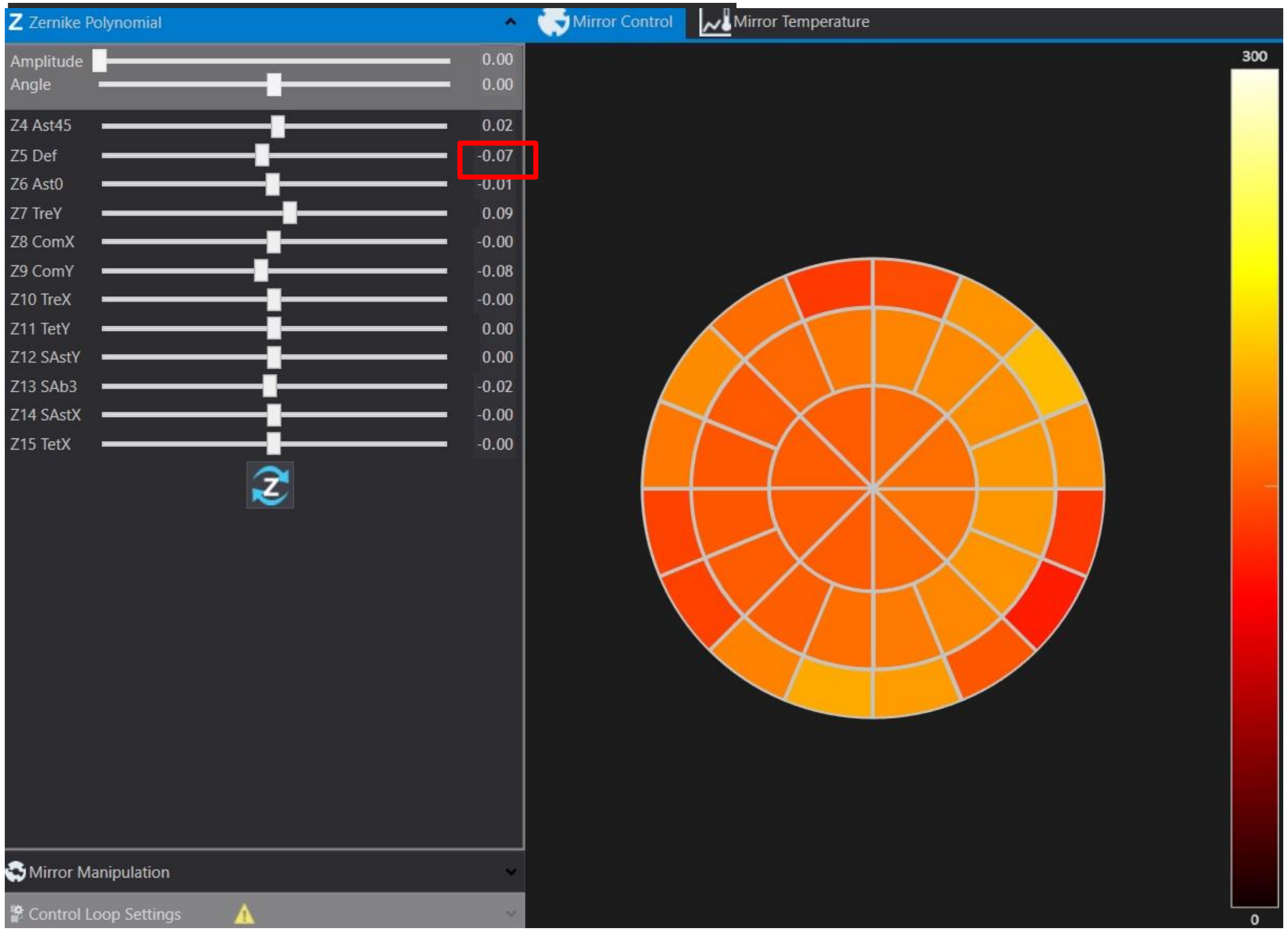
Another correction: defocus





Another correction: defocus





Problem with Zernike coefficients

Problem with Zernike coefficients

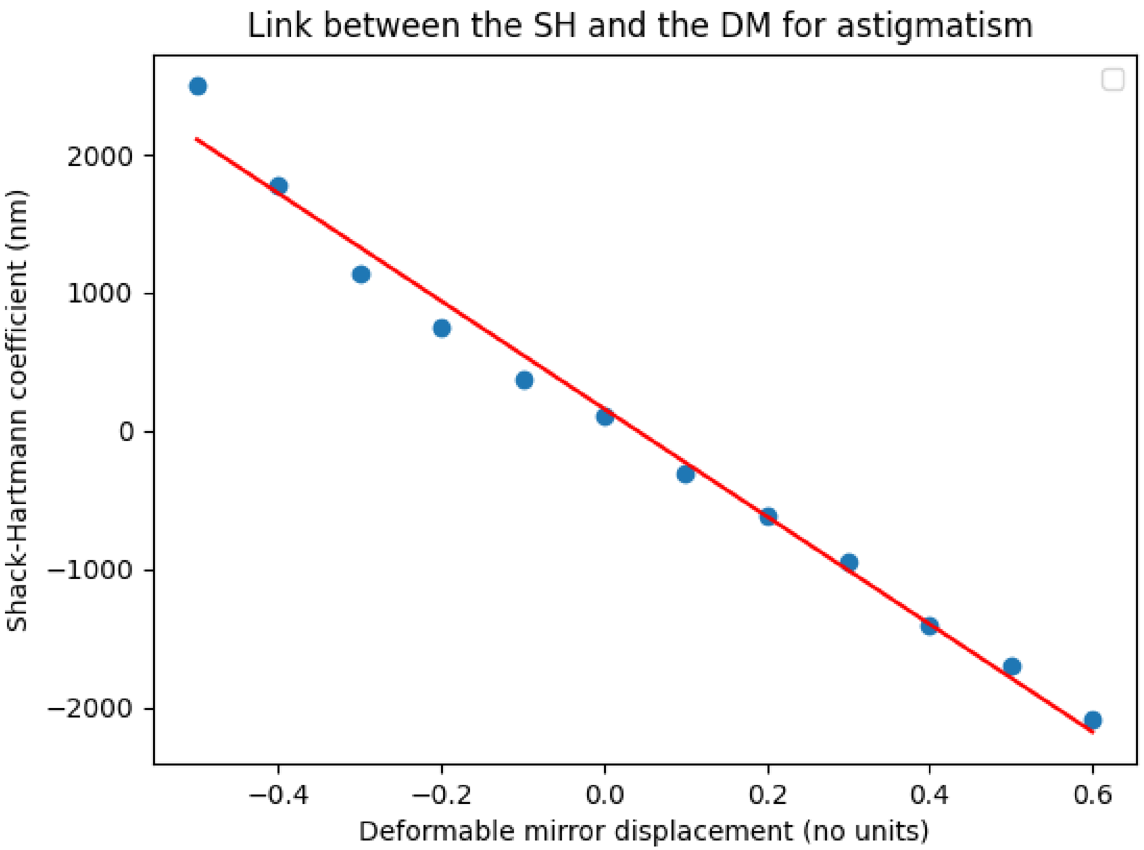
- Mismatching due to different Zernike conventions

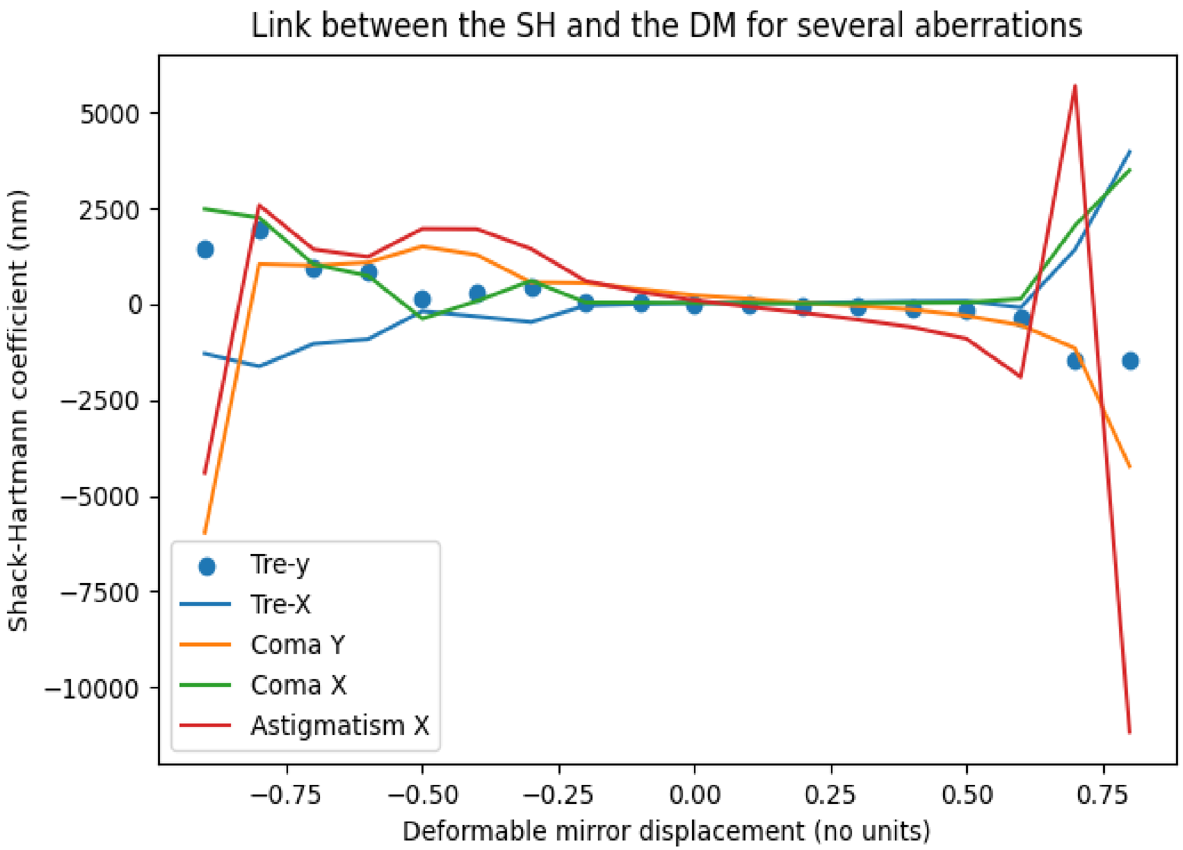
  A link had to be established between the coefficients of the SH and those of the DM

- Mismatching linked to the aberrations themselves

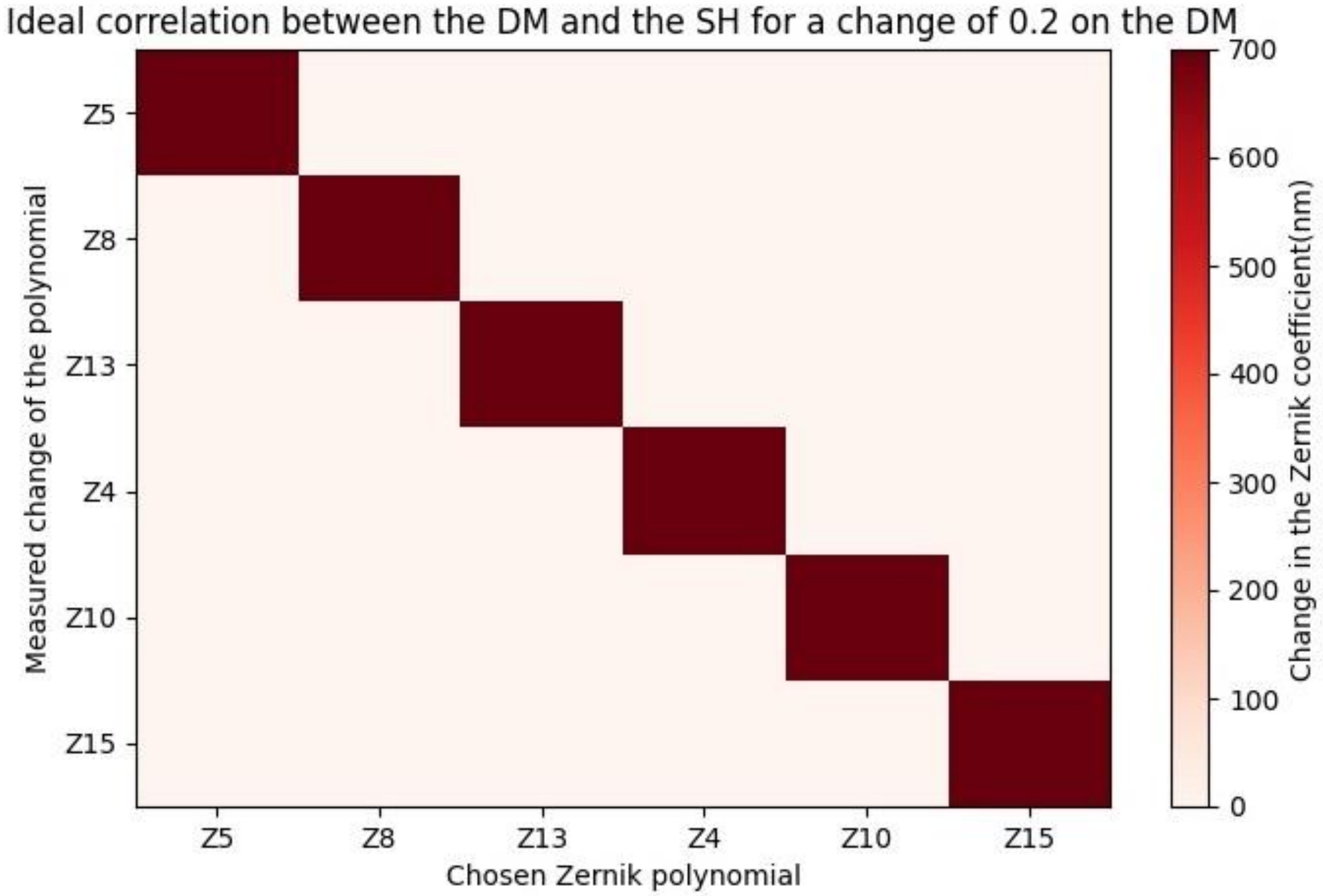
  No linearity between the applied coefficient on the DM and the response seen by the SH

Problem with Zernike coefficients

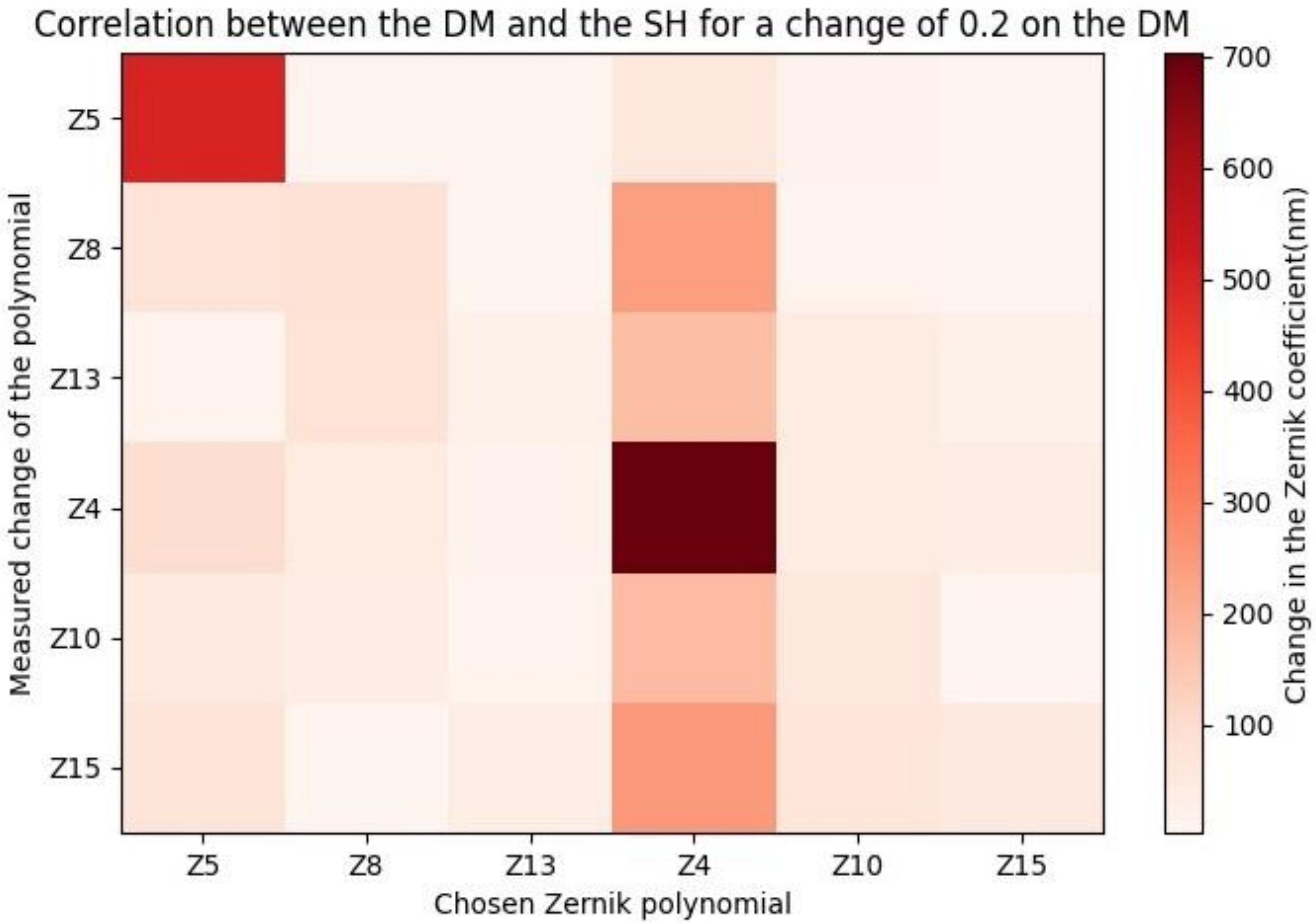




Correlation



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)
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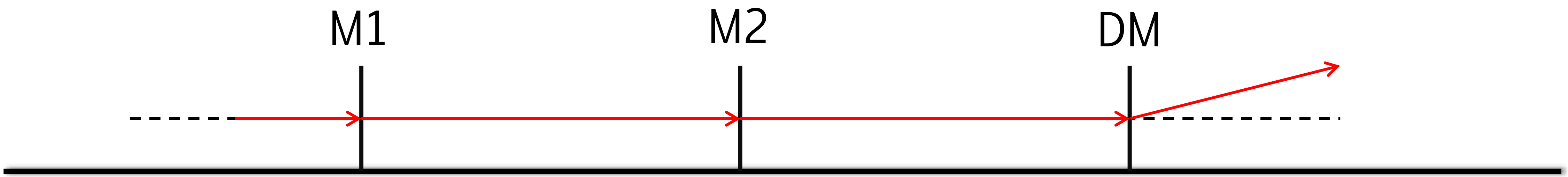

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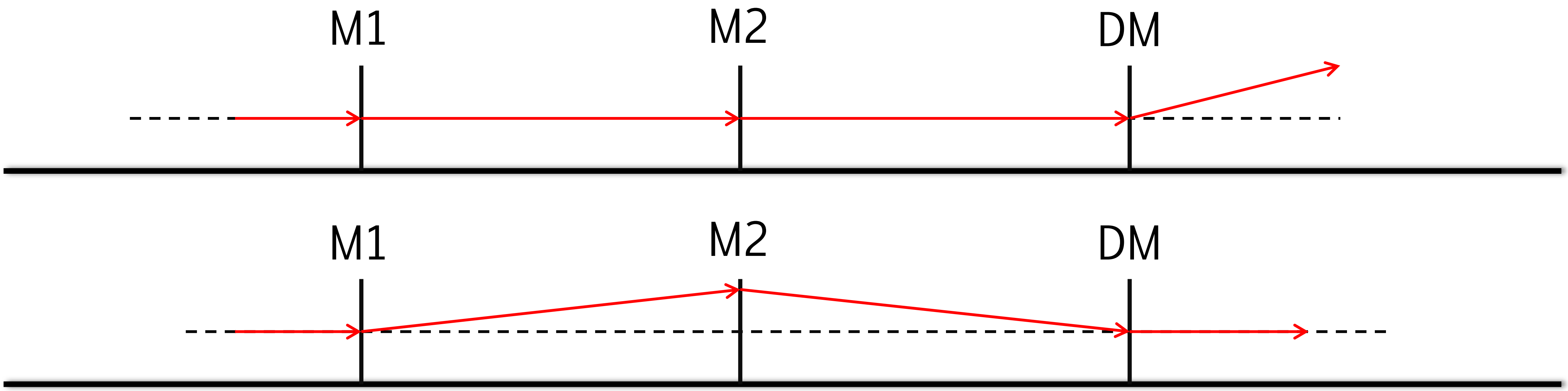
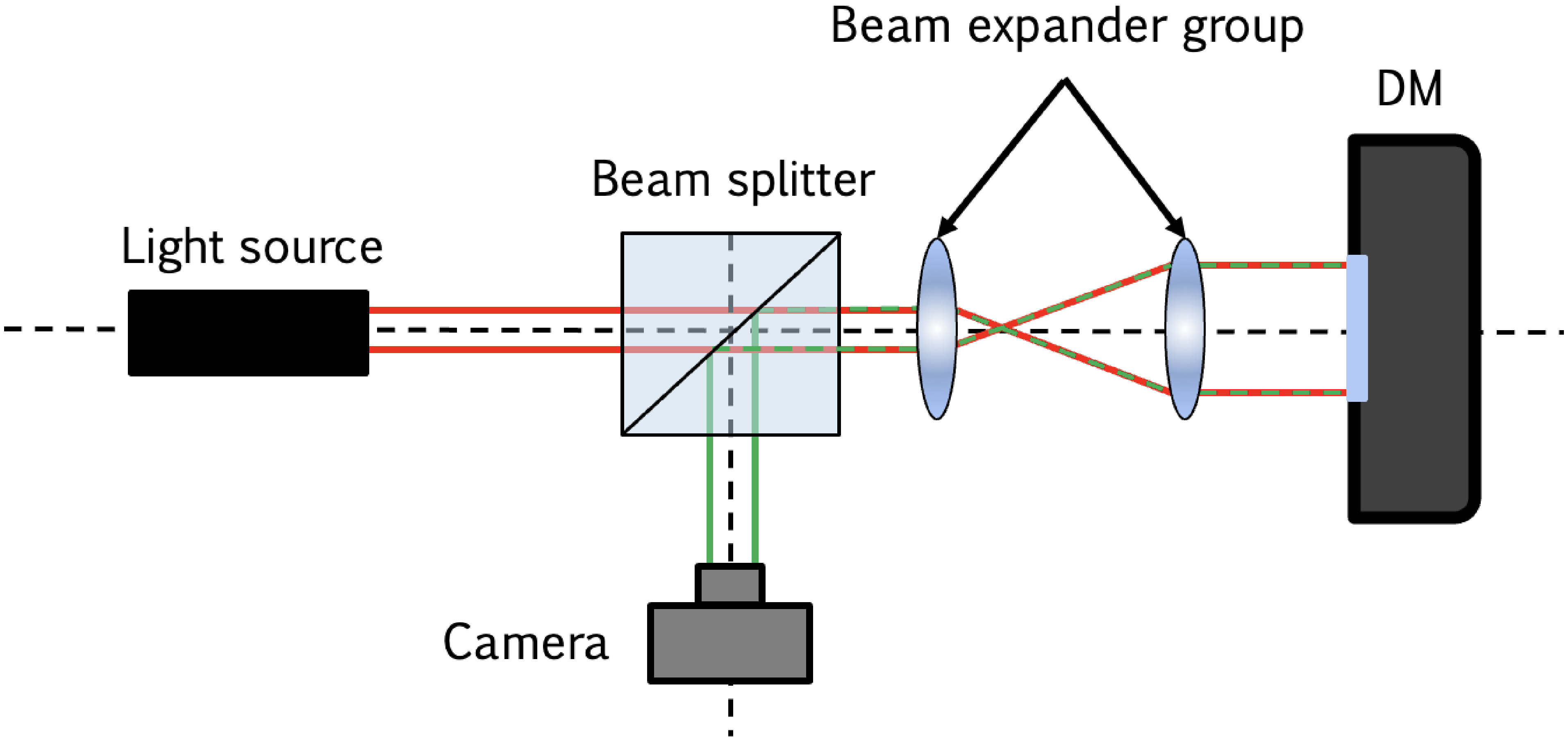
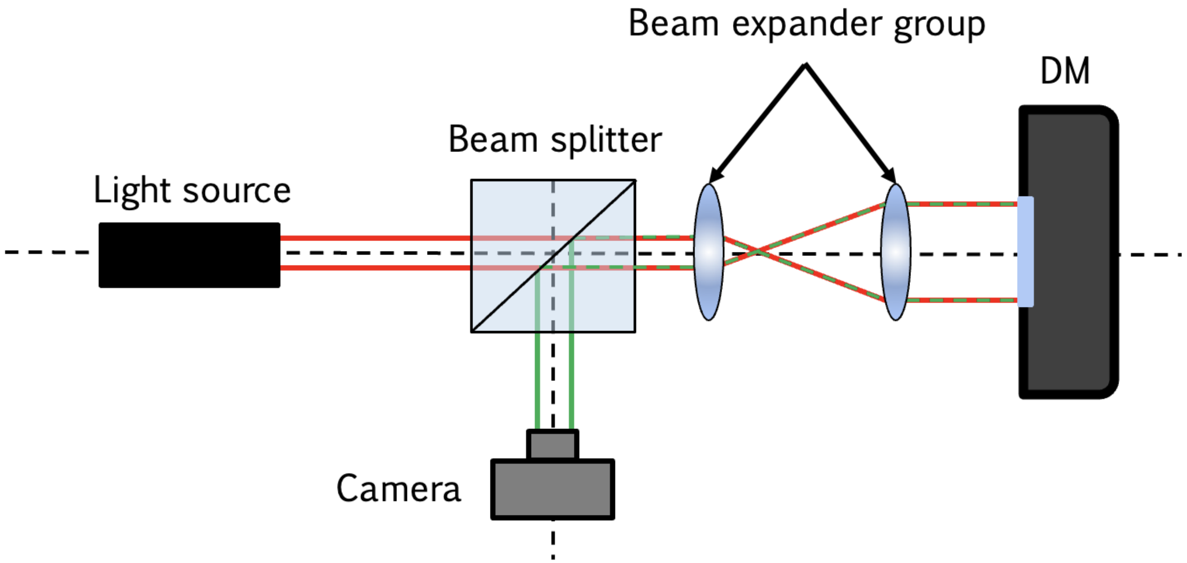


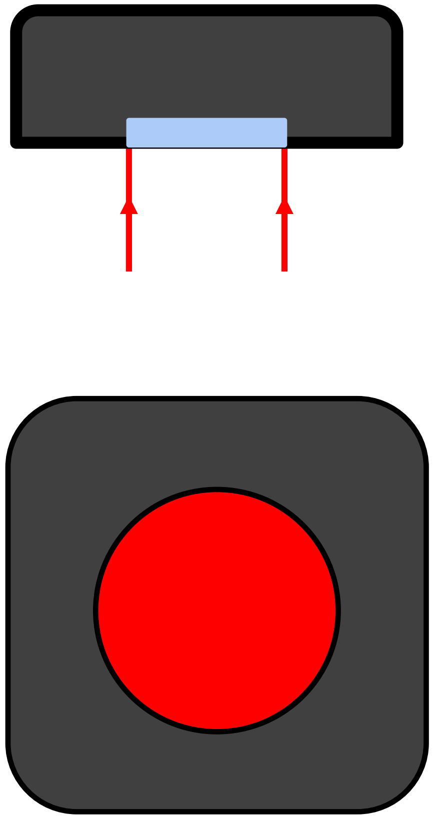
Using a beam splitter



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!