Summary of student’s training coarse for the adjustment of parabolic mirror, and outlook beyond

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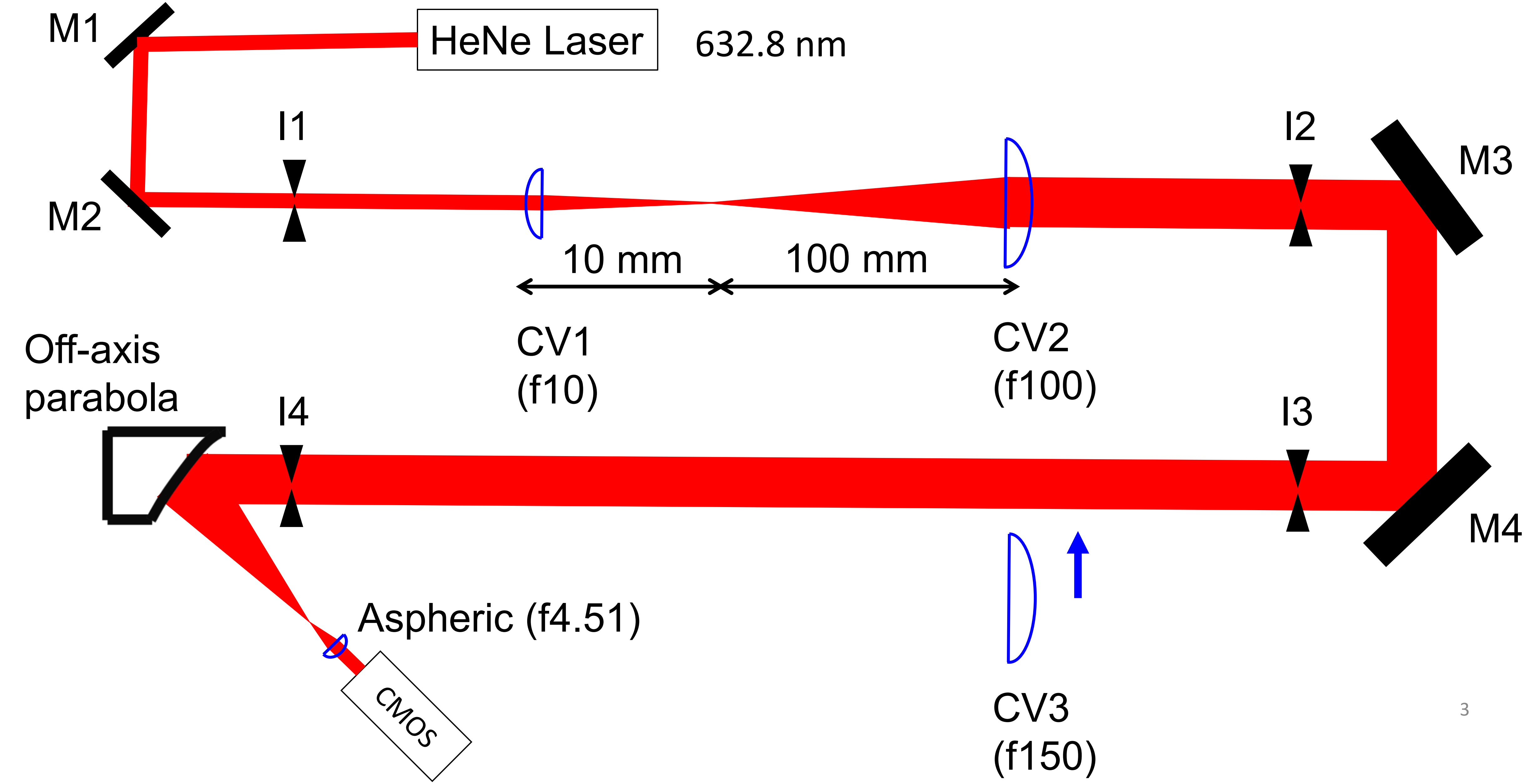
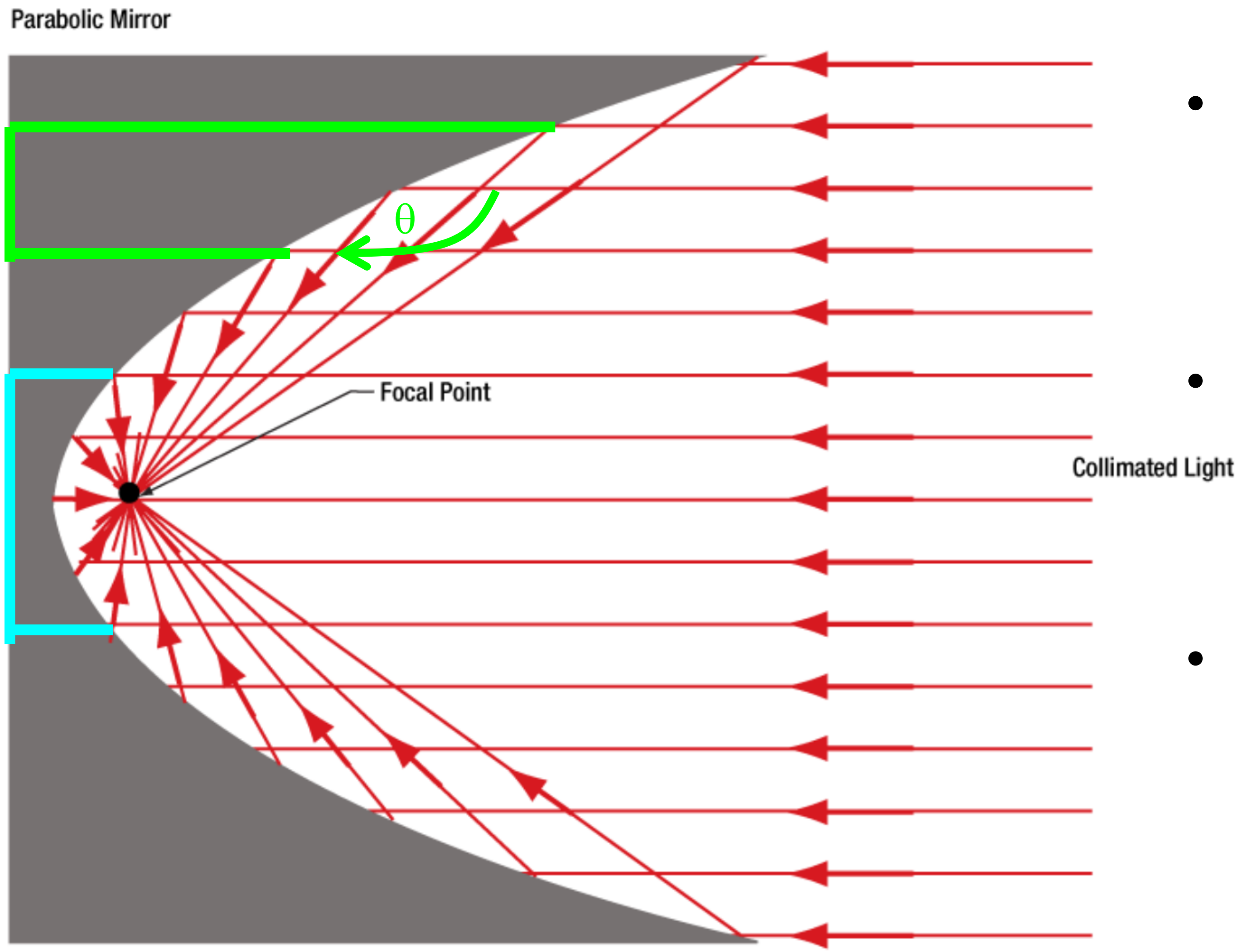
Section 1)
Summary of student's training coarse for the alignment of off-axis parabolic mirror

Typical optical setup in laboratory



Reminder of properties of off-axis parabolic mirror

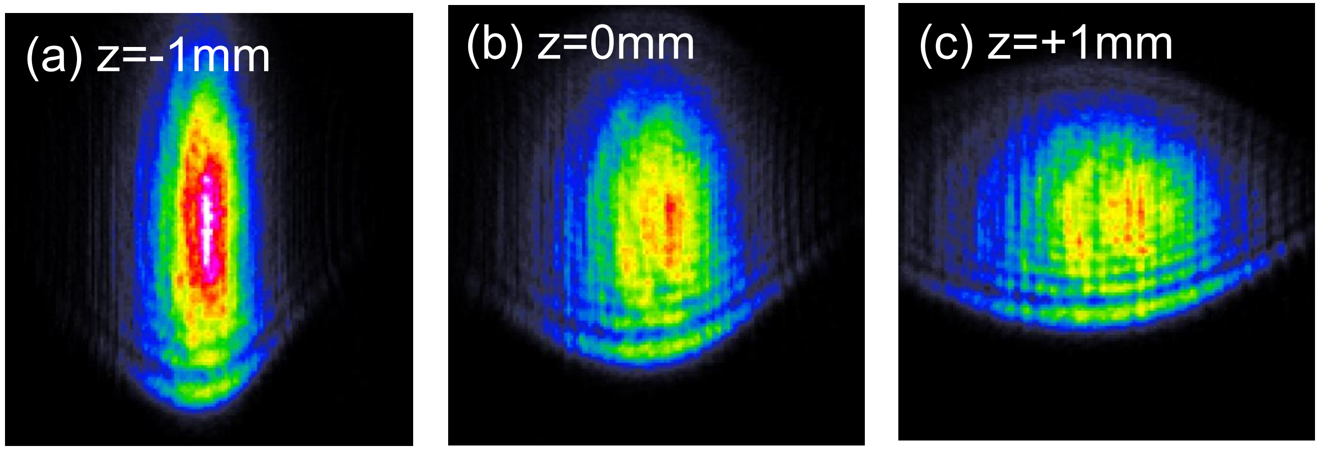


- If one cuts paraboloid according to light blue line
  -> On-axis parabolic mirror
- If one cuts paraboloid according to light green line
  -> Off-axis parabolic mirror
- Angle of Off-axis parabolic mirror is defined as θ (Full-angle) or $\theta/2$ (AOI, angle of incidence) in specification

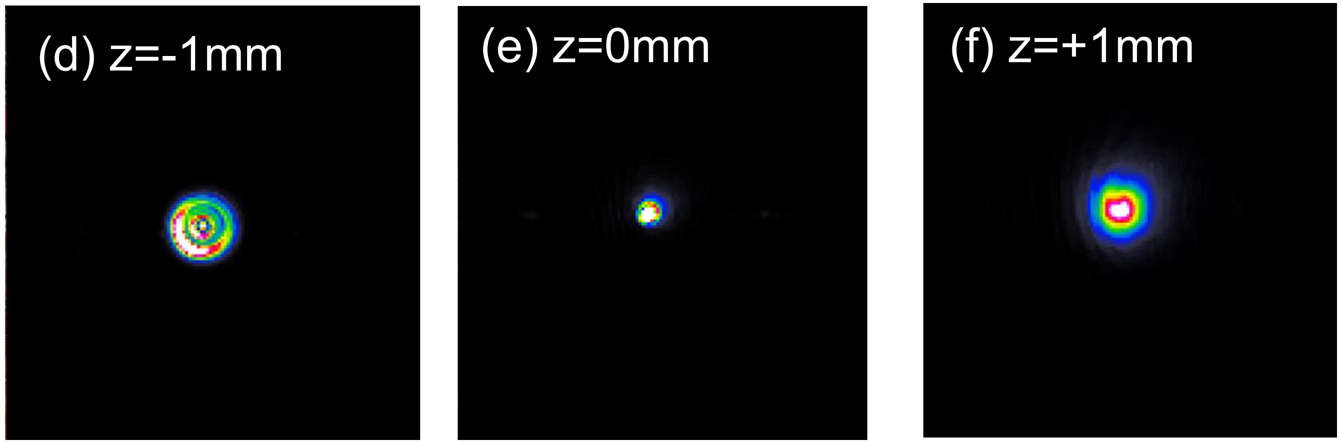
Illustration is cited from Thorlabs page:
https://www.thorlabs.co.jp/newgrouppage9.cfm?objectgroup_id=14211

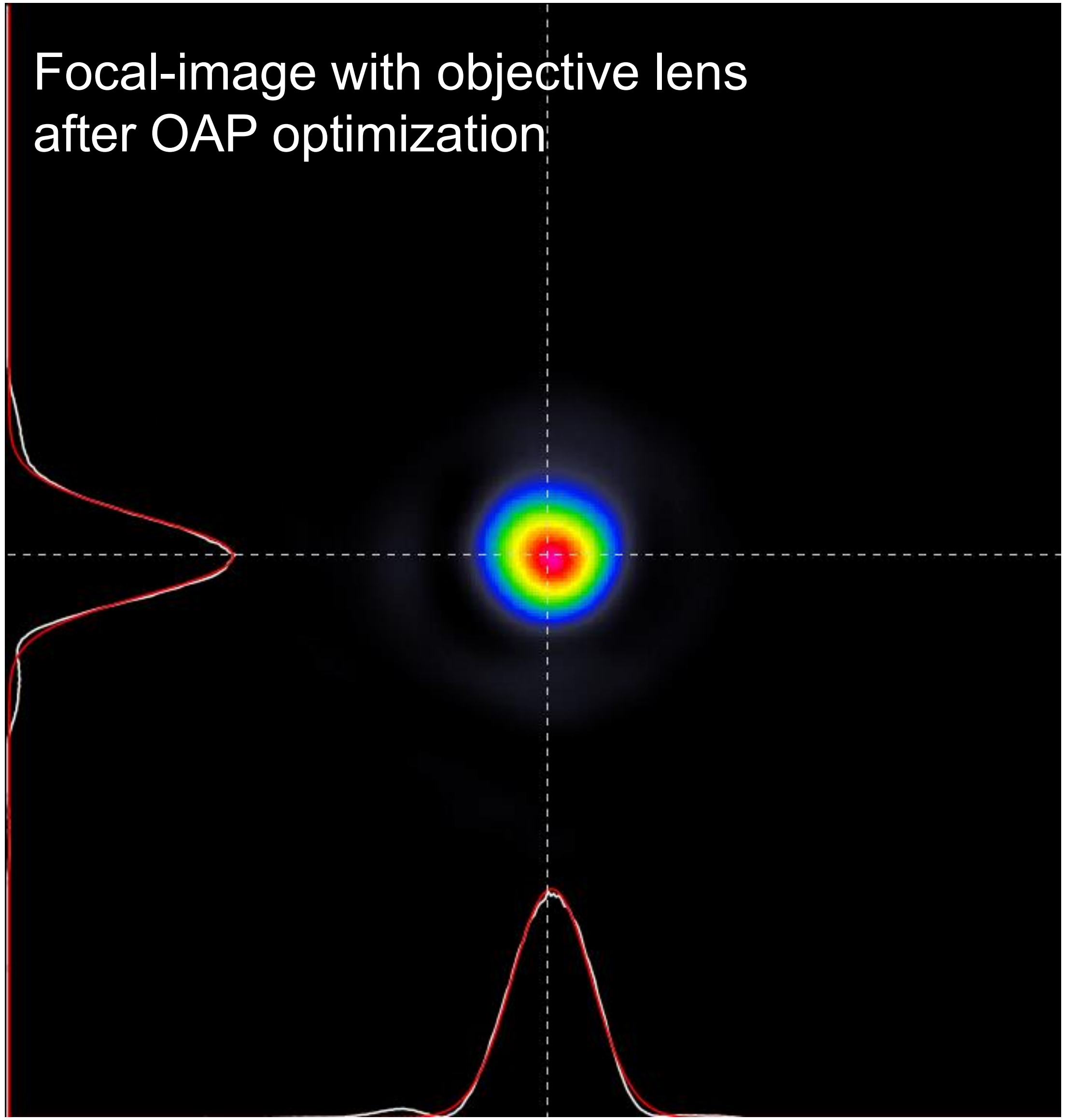
Spatial image focusing by off-axis parabolic mirror

Astigmatic case (misaligned at a few degrees)



Little astigmatic case





Did you get 2D Gaussian focal image ?

Important mindset to tackle the experimental research

- Make a good practice to keep asking "reasoning" to yourself when you take any actions. Improving level of consciousness is important for scientific discussion
  - You can explain your optical configuration with the principle behind the setup
  - You can explain things with the precision
  - You can make your reference to consider unknown issues in real experiment
- Basic cycles for experimental research
  - Define your way scientifically (i.e. make hypothesis & reference)
  - Execute your way
  - Evaluate your way, that is, consider why your way is correct or wrong
  - Modify your way if it is imperfect
  - Conclude your study
  - Outlook your study for the future

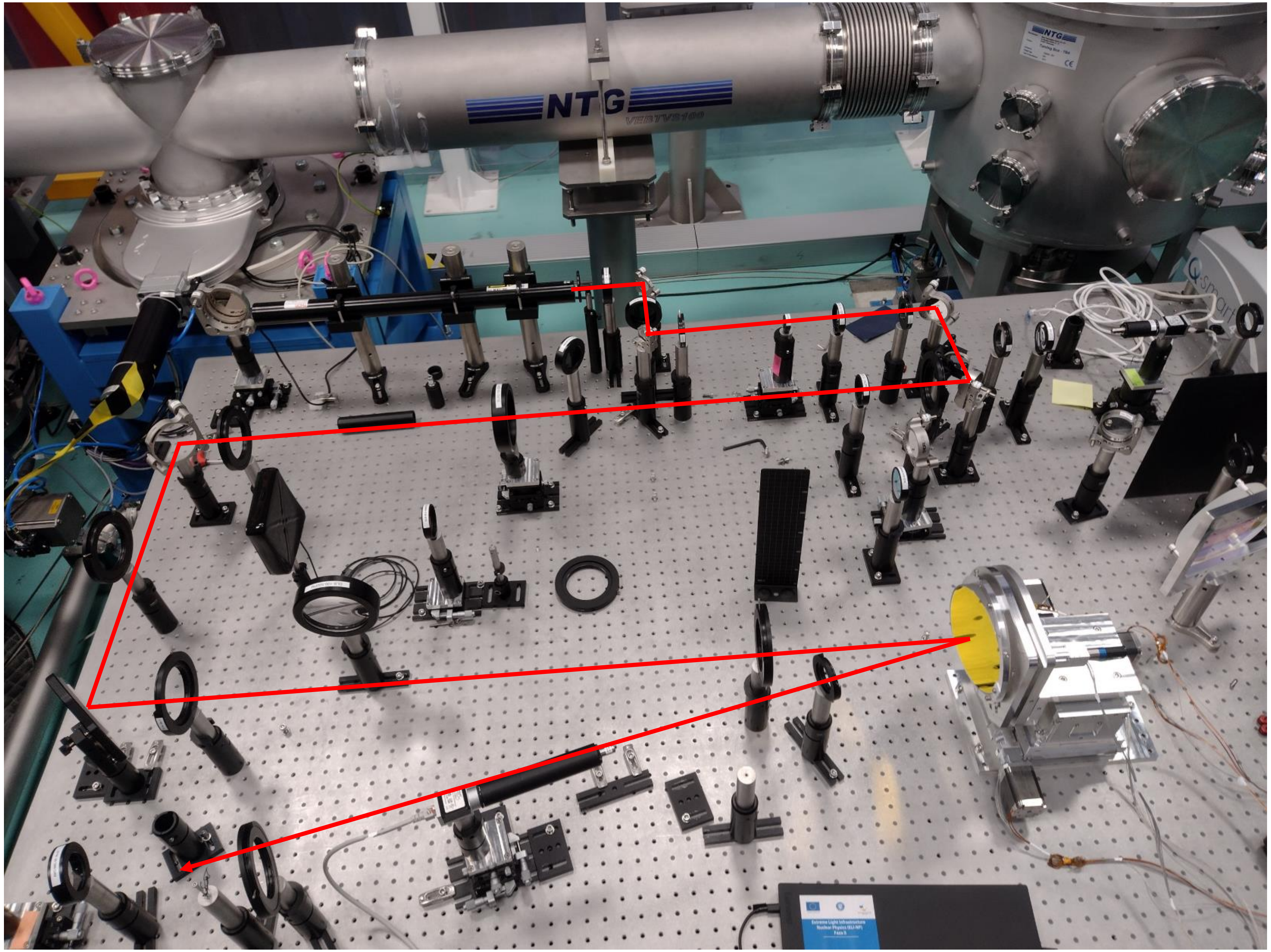
What you learned though this training ?

You should learn how to

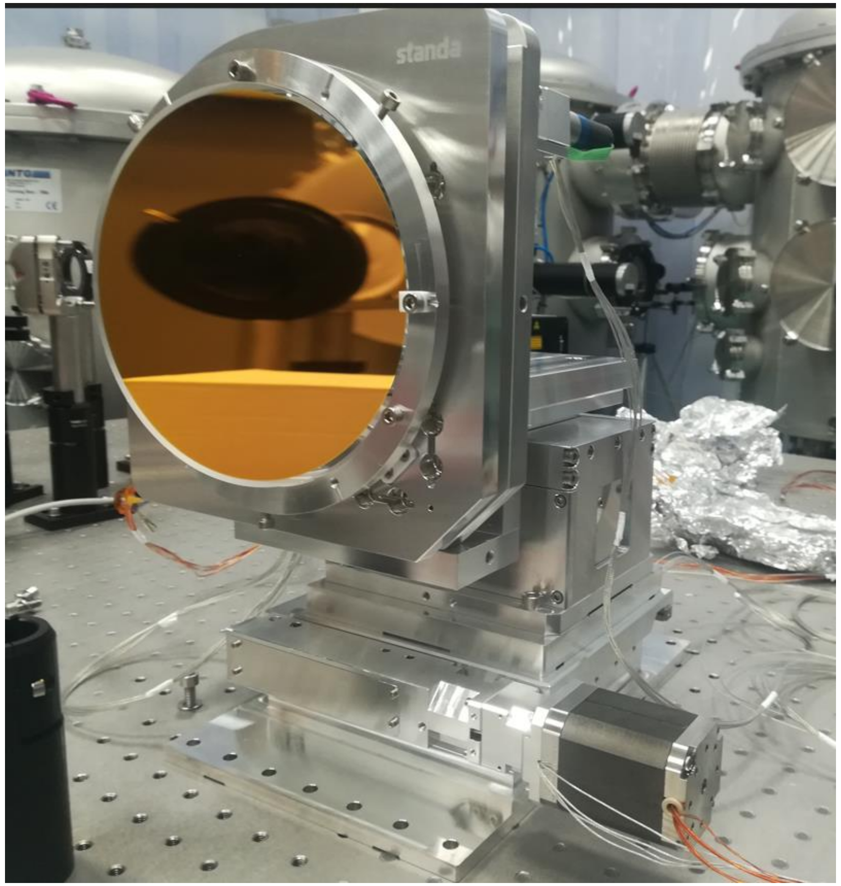
- Make Alignment of mirrors and beam expander
- Control divergence of beam expander (Collimated laser beam)
- Make alignment towards OAP (angle of incidence to OAP)
- Make alignment of OAP (angle of outgoing from OAP)
- Calibrate magnification
- Optimize focal-spot image
- Evaluate focal-spot size (data analysis)
- Present your activities to the audiences

Section 2)
Reality of handling off-axis parabolic mirror for PW-class experiment with Ti:Sa. high-power laser system

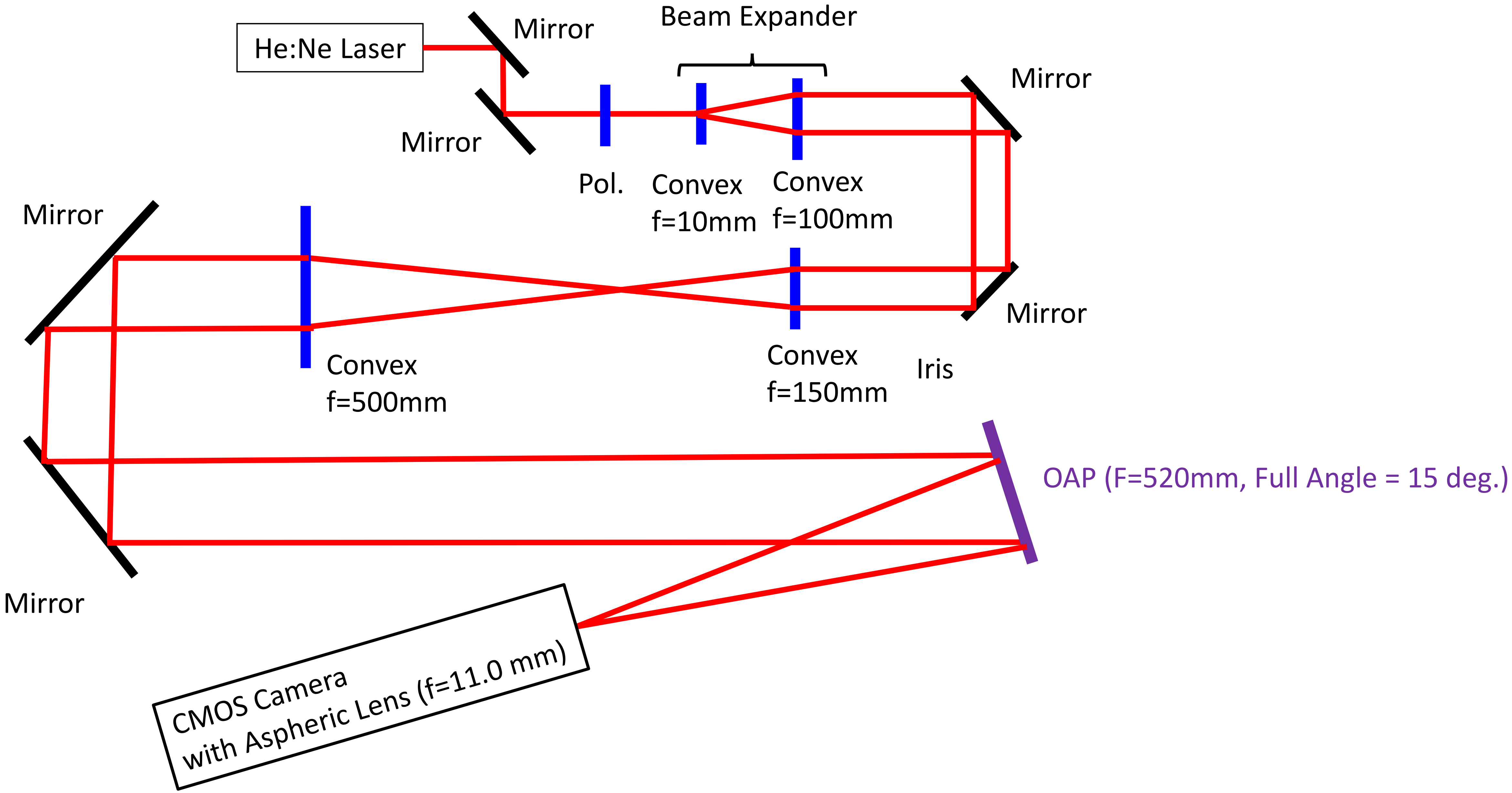
Preparatory alignment of parabolic mirror with HeNe Laser



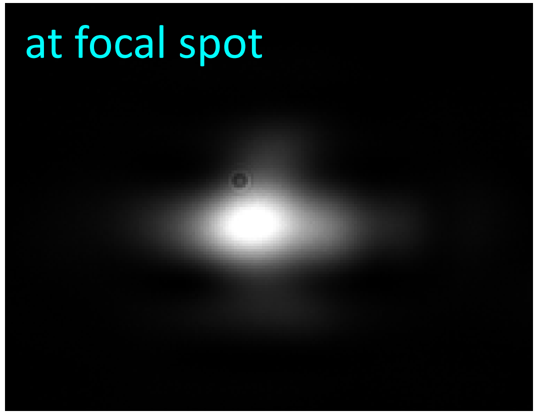
CV lens with F500 mm
OAP with F520 mm

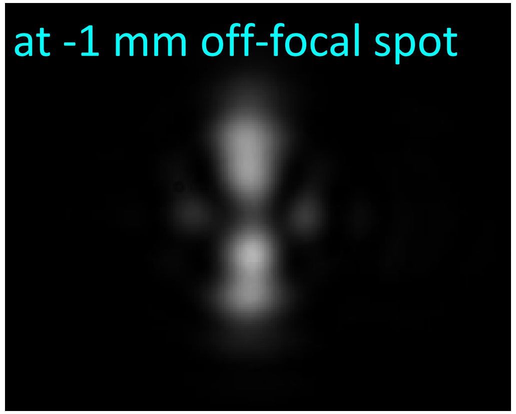


Preparatory alignment of parabolic mirror with HeNe Laser

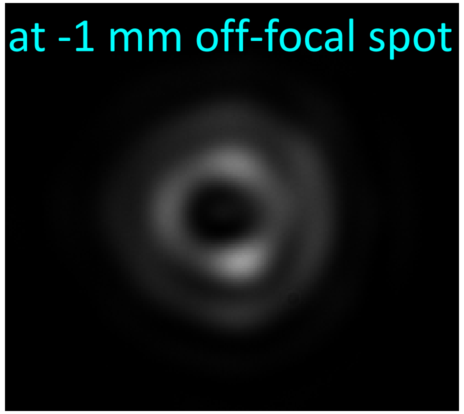


Preparatory alignment of parabolic mirror with HeNe Laser





Before Adjustment

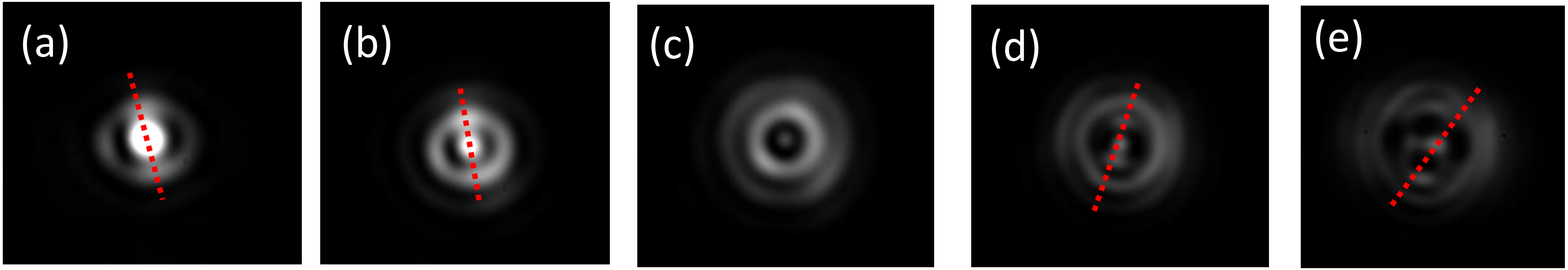


After Adjustment

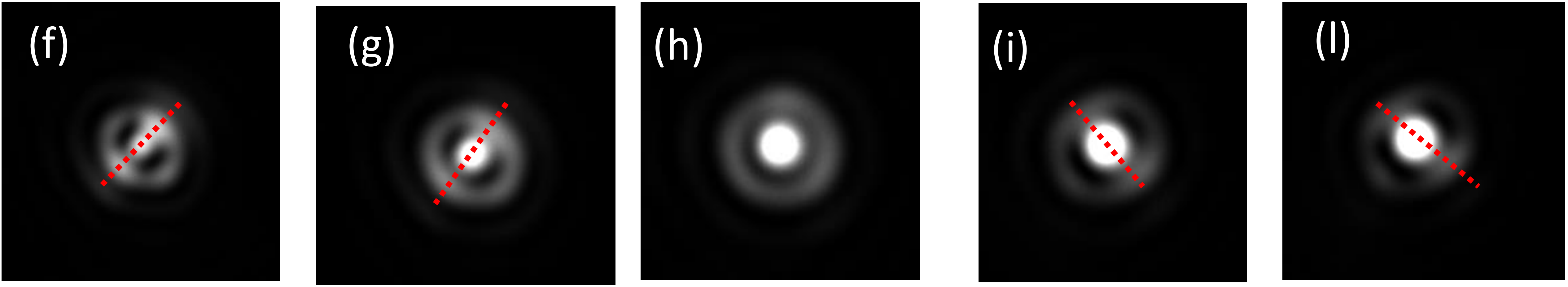
- Set the camera position and set the Camera gain to see the change of astigmatism clearly.
- Adjust Yaw & H to keep the image on the camera center to get symmetric ring pattern.
- Adjust Pitch & V to keep the image on the camera center to get symmetric ring pattern.
    - Pitch & V would be almost fine by default because it is less sensitive to off-axis angle direction.

Fine adjustment with ring pattern

For Yaw & H.

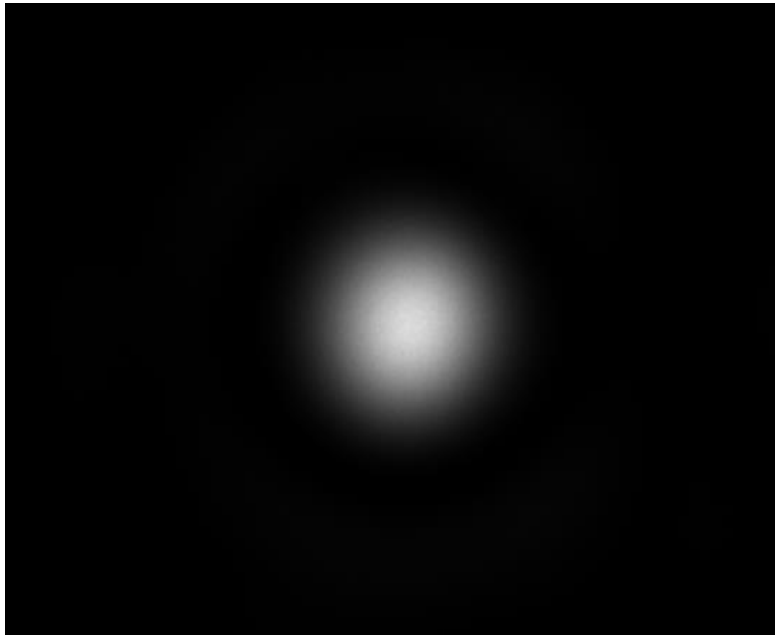


For Pitch & V.



Red dotted line is eye guide for you

Fine adjustment with focal-image and intensity



- Move the camera in laser propagation direction to look at focal spot.
- Adjust Yaw & H to keep the image on the camera center to get the smallest spot size as well as the highest intensity spot.
- Adjust Pitch & V to keep the image on the camera center to get the smallest spot size as well as the highest intensity spot.

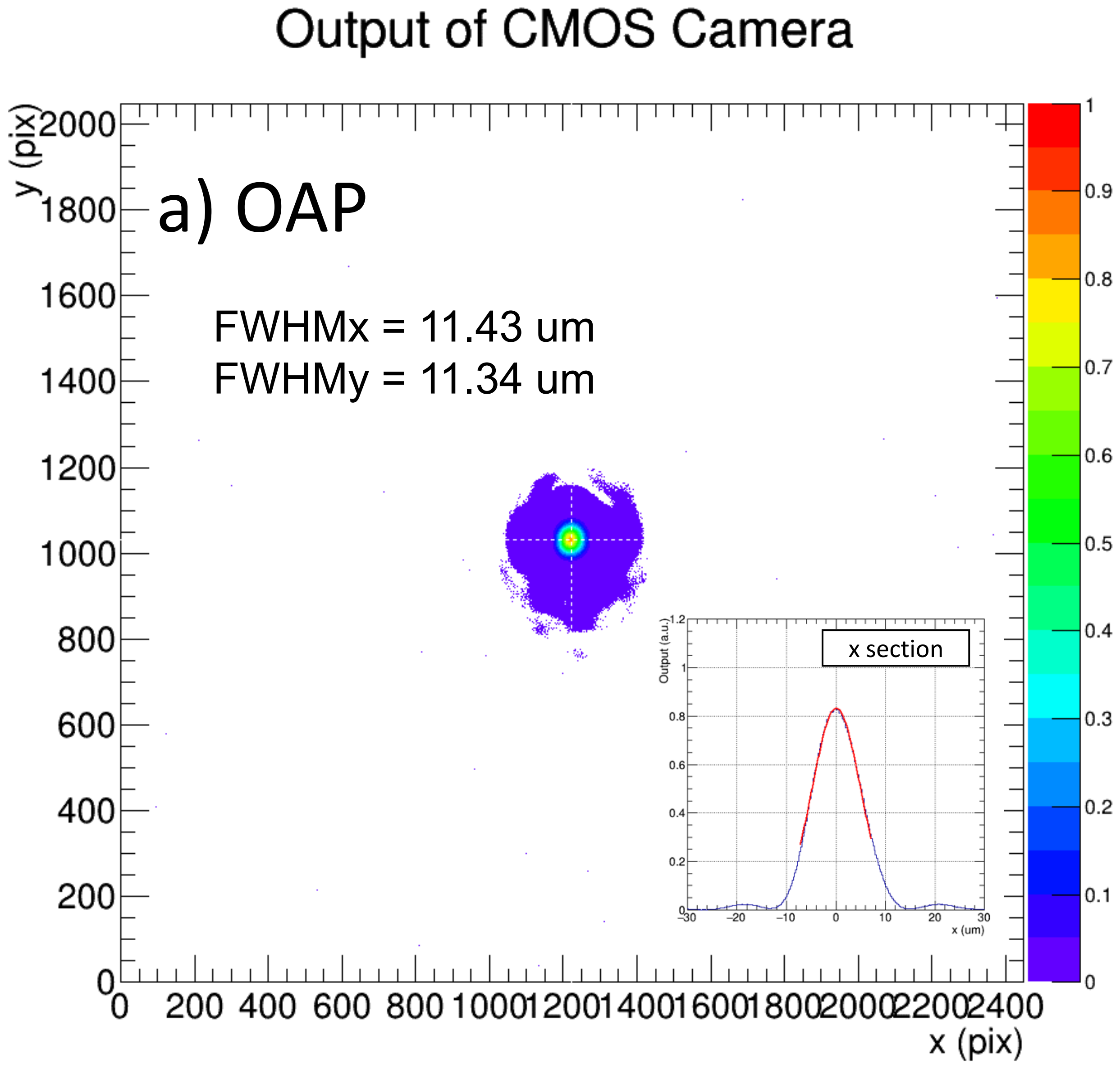
Appendix) Adjustment of Yaw & H or Yaw & L

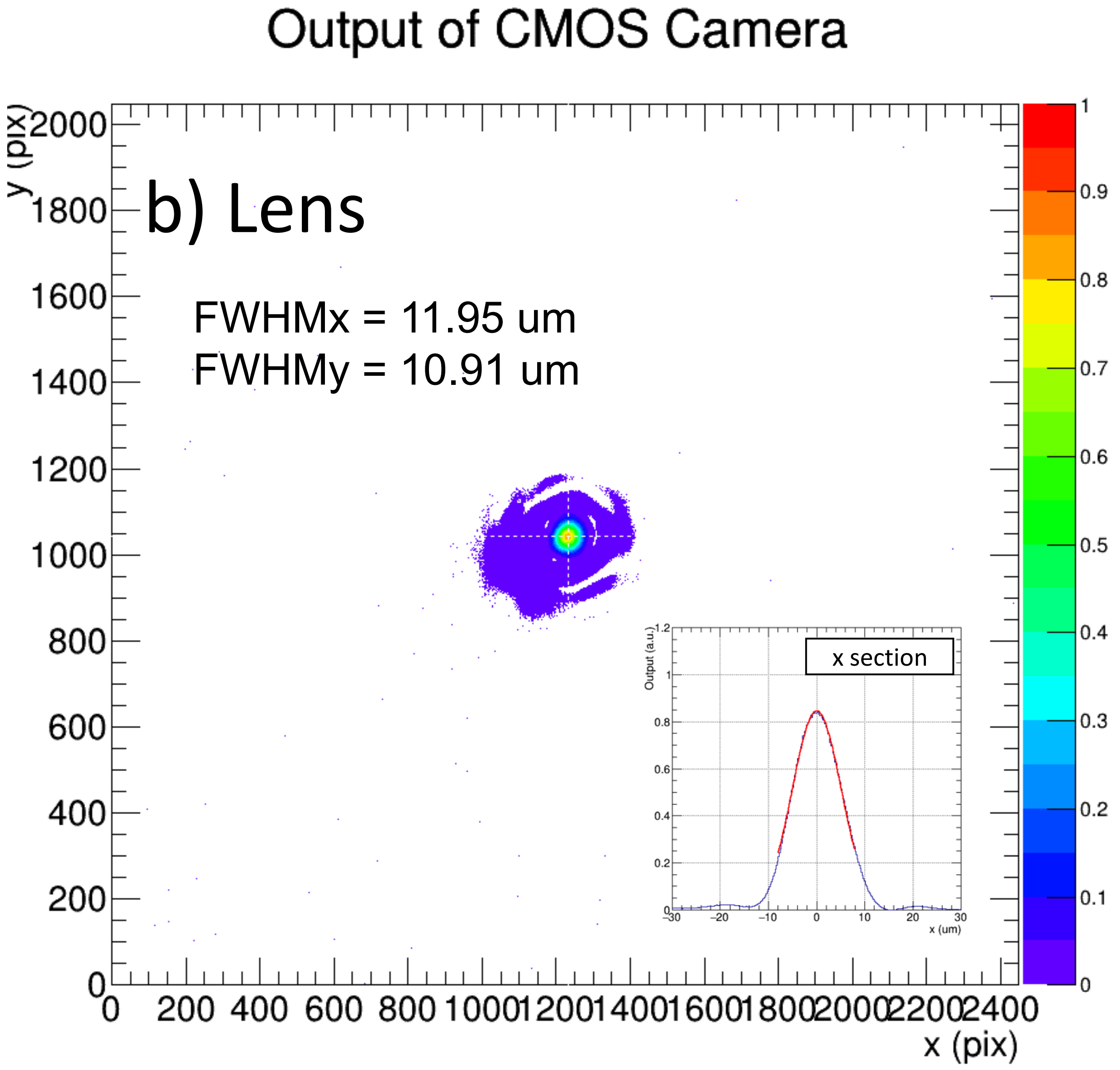
- Adjustment of Yaw & H was mainly shown in this training to minimize astigmatism resulting in a beautiful focal beam shape.
- Another consideration is the adjustment of Yaw & L. The both adjustments should have advantages/disadvantages as well as easiness/difficulty, in particular it depends on the off-axis angle of your parabolic mirror.
- Different choices of the way can change sensitivity to the angular correction, shifting effect of the beam position from the center of mirror surface, movability of your target at focus, chang of focal point by the operation.

➔ We leave this point an open question.

➔ Consider this point next chance when you are involved in the experiment under the realistic constraints !

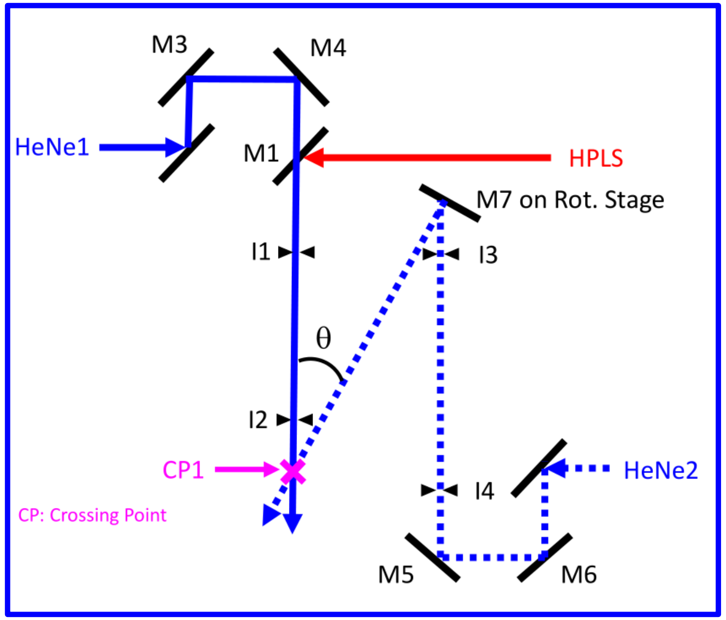
OAP commissioning with He:Ne Laser for 0.1 PW experiment

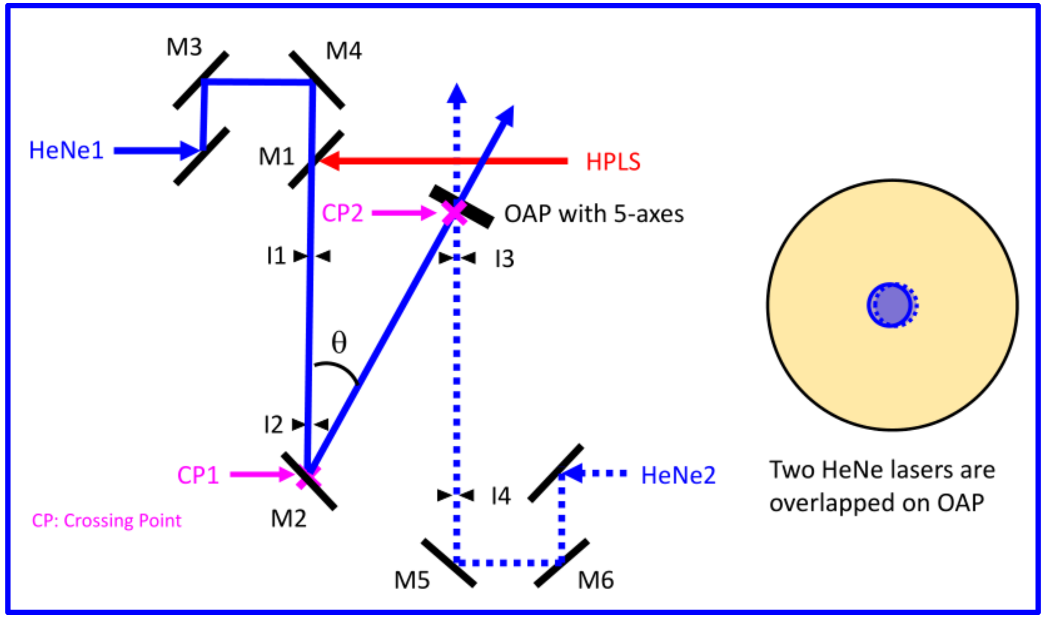


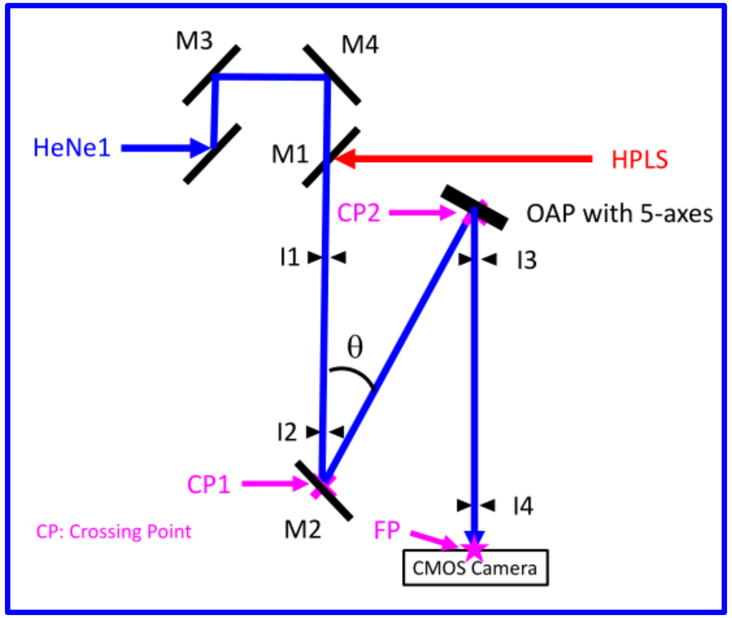


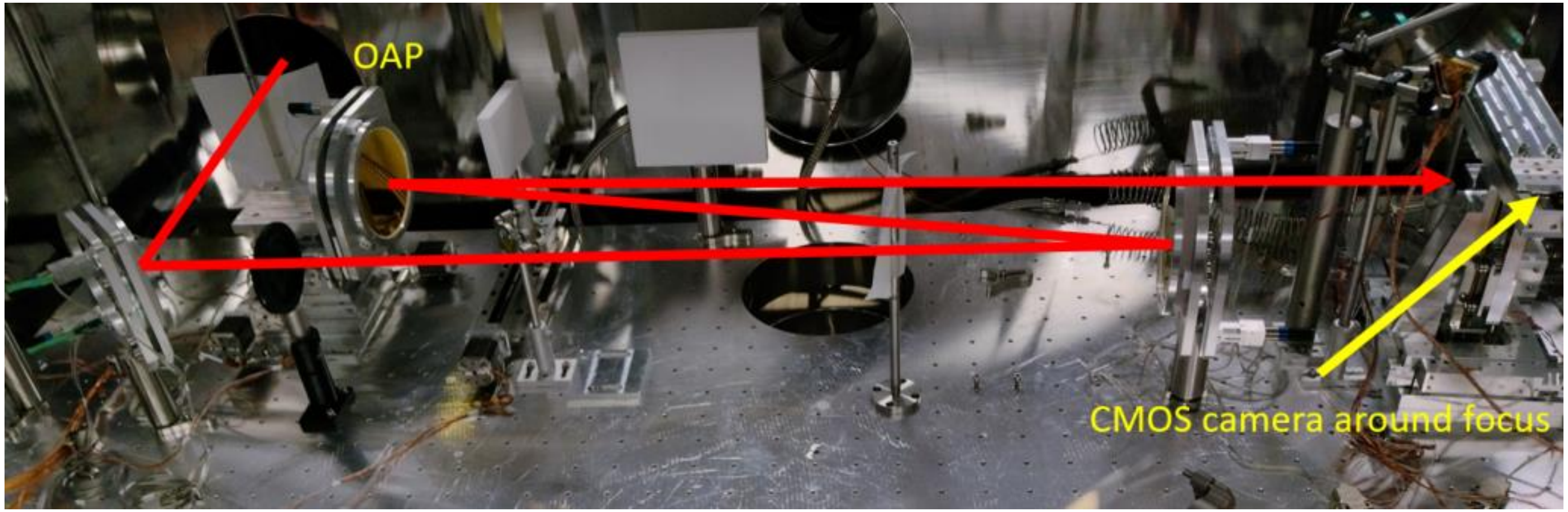
5% difference b.t.w (a) and (b)

Another example



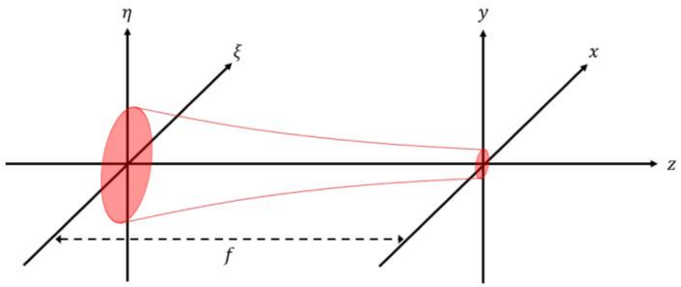






Ideal 2D focal image for gaussian beam and flat-top beam

2D spatial profile before focus	~ 2D Fourier Transform (Under Paraxial condition) →	2D spatial profile at focus
2D Gaussian field		2D Gaussian field
2D circular flat-top field		2D Airy-disk field



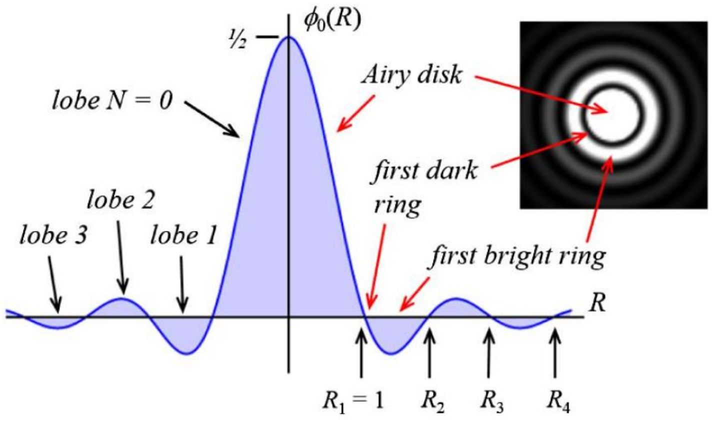
$$E_f(x,y) \propto \iint_{-\infty}^{\infty} E_i(x_0,y_0) e^{-i\frac{k}{f}(xx_0+yy_0)} dx_0 dy_0$$

↑ Your output field after focusing

↑ Your input field before focusing

$$n_f(x,y) \propto \left|E_f(x,y)\right|^2$$

$E_f(x,y)$



Note: Your observable on camera is relevant to # of photons $n_f(x,y)$
(# of photron ∝ square of output field)

Figure is cited from
I. Gris-Sánchez, D. Van Ras, and T. A. Birks, Optica 3, 270-276 (2016).

Gaussian image at focus (Circular Gaussian beam input)

Gaussian function

$$f(r) = \exp\left(-\frac{2r^2}{w_0^2}\right)$$

$$w_0 \sim \frac{2}{\pi}\lambda f/\#$$

$$f/\# = \frac{f}{\Phi}$$

Φ: diameter before focusing
f: focal distance
f/#: f-number
λ: wavelength

Beam-waist diameter at e^{-2}

$$\phi_{waist} \sim 2w_0 = \frac{4}{\pi}\lambda f/\#$$

(analytical but paraxial condition)

Beam diameter at HM

$$\phi_{HM} = 2\sqrt{2\ln 2}\sigma$$
$$= \sqrt{2\ln 2}w_0$$
$$\sim 1.177 w_0$$
$$\sim 0.75\lambda f/\#$$

Note: $f(r)$ is square of electric field and the peak is normalized to be unity

Airy disk image at focus (Circular flat-top beam input)

Airy-disk function

$$f(r) = \left(\frac{2J_1(a)}{a}\right)^2,$$

$$a = \frac{\pi}{\lambda f/\#} r,$$

$$f/\# = \frac{f}{\Phi},$$

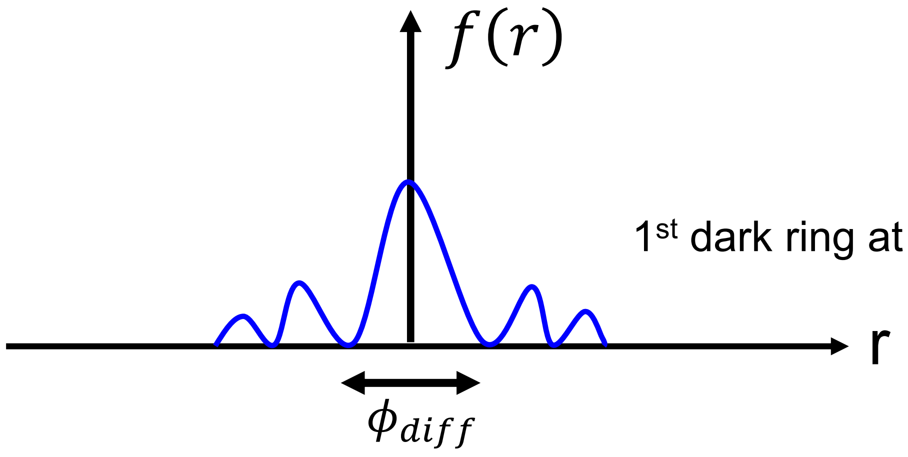
Φ: diameter before focusing
f: focal distance
f/#: f-number
λ: wavelength

Diffraction-limited diameter

$$\phi_{diff} = 2.44\lambda f/\#$$ (analytical)

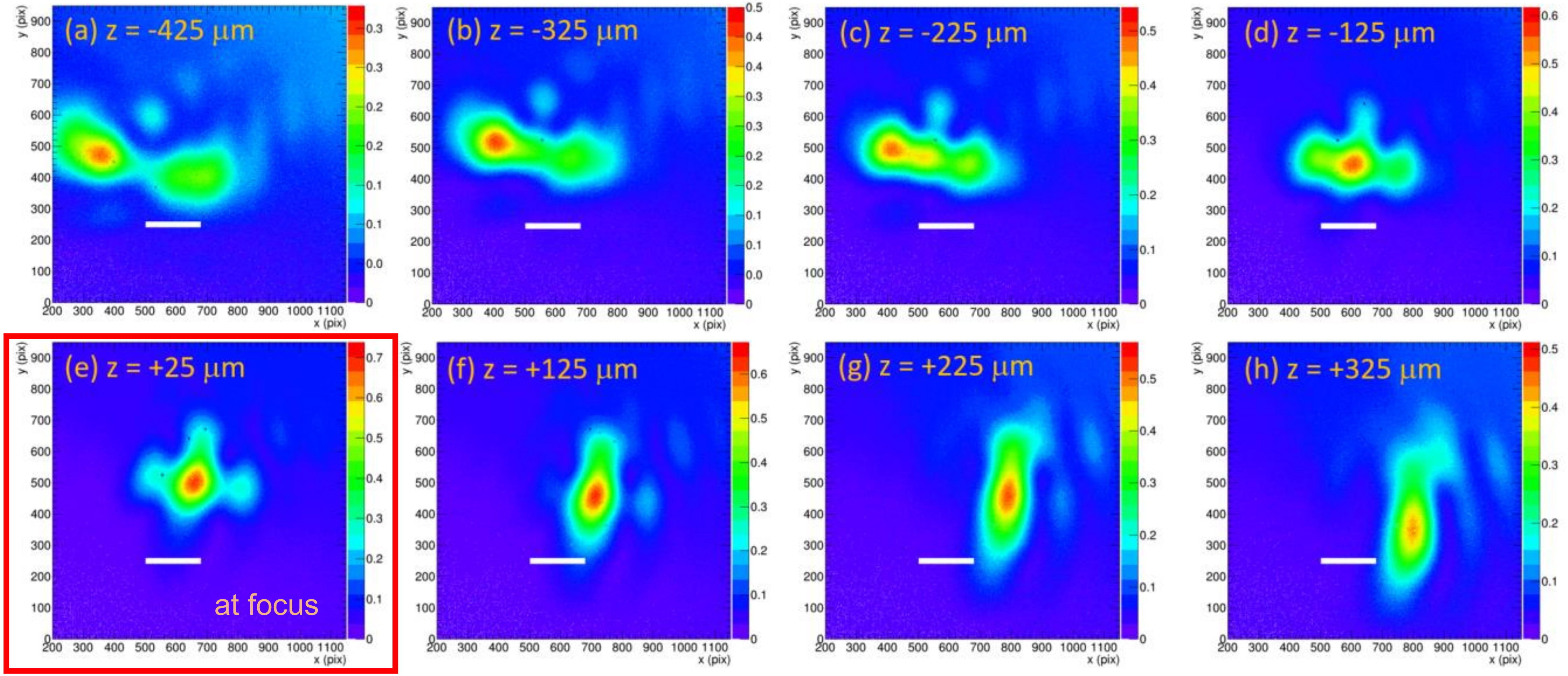
Diffraction-limited diameter at HM

$$\phi_{HM} \sim 1.02\lambda f/\#$$ (numerical)



Note: $f(r)$ is square of electric field and the peak is normalized to be unity

Focal spot image in 0.1 PW Ti:Sa. real beam **BEFORE** DM optimization



Even after optimizing OAP position by HeNe laser, real beam is not close to ideal focal beam

-> Need optimization by deformable mirror in practice.

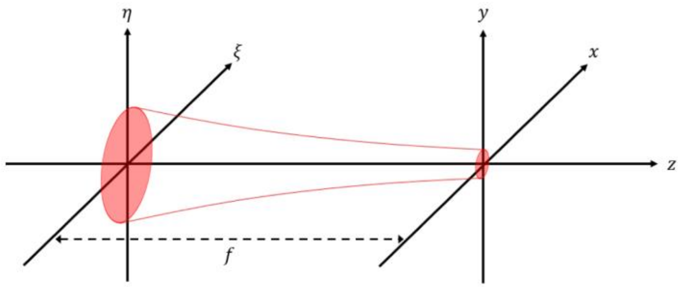
Controlled parameters for real beam

2D spatial profile before focus

2D Gaussian field

2D circular flat-top field

2D Fourier Transform
(Under Paraxial condition)



2D spatial profile at focus

2D Gaussian field

2D Airy-disk field

$$E_f(x,y) \propto \iint_{-\infty}^{\infty} E_i(x_0,y_0) e^{-i\frac{k}{f}(xx_0+yy_0)} dx_0 dy_0$$

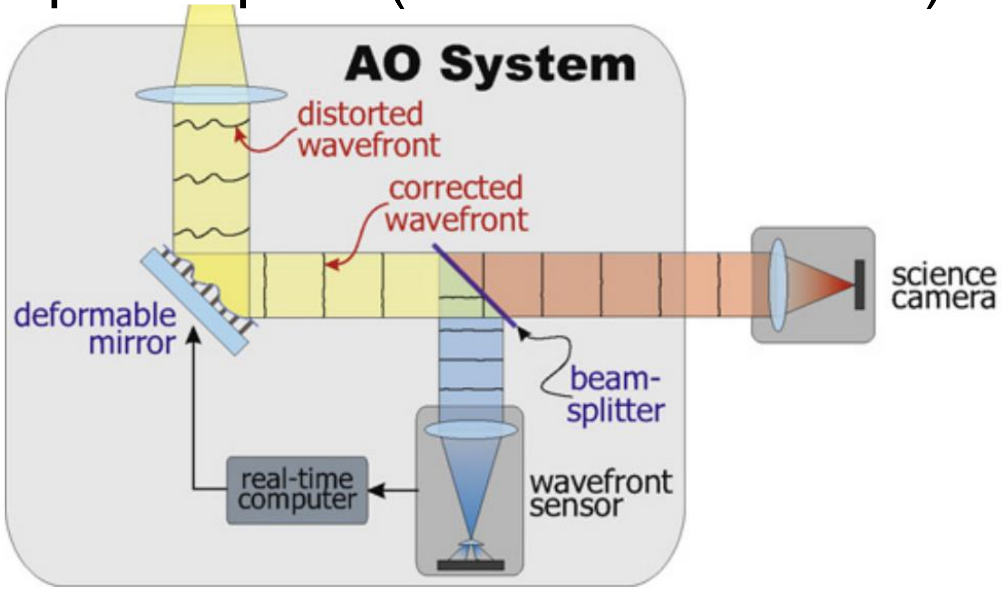
$$E_i(x_0,y_0) \coloneqq A(x_0,y_0) e^{iW(x_0,y_0)}$$

$A(x_0,y_0)$: Field Amplitude
$W(x_0,y_0)$: Wavefront

Aberration (Astigmatism etc) <-> wavefront distortion

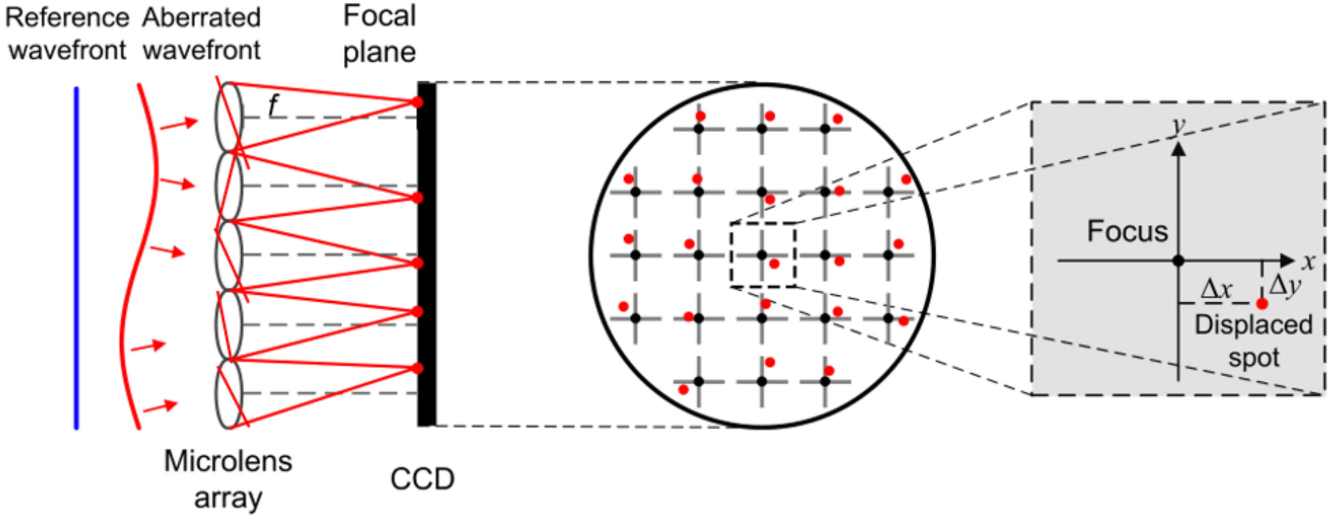
Wavefront control

Adaptive optics (Deformable mirror)

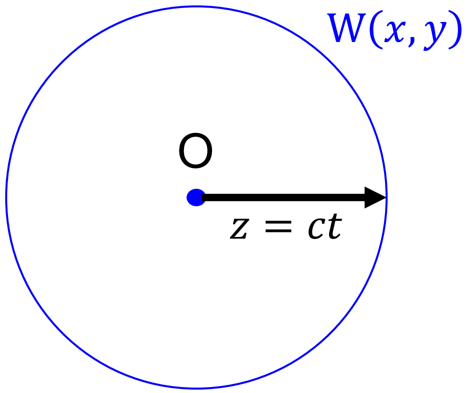


Richard Davies, New Astronomy Reviews 52 (2008) 307–322

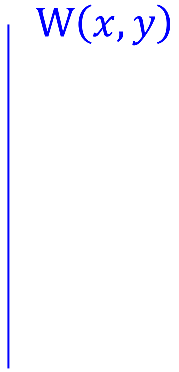
Shark-Hartmann wavefront censor



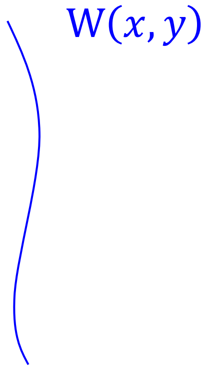
Kuo Niu and Chao Tian 2022 J. Opt. 24 123001 (2024)



Point-source generation



Plane wave (forward direction on-axis)



Real wave (forward direction on-axis)

Expression of wavefront by Zernike polynomials

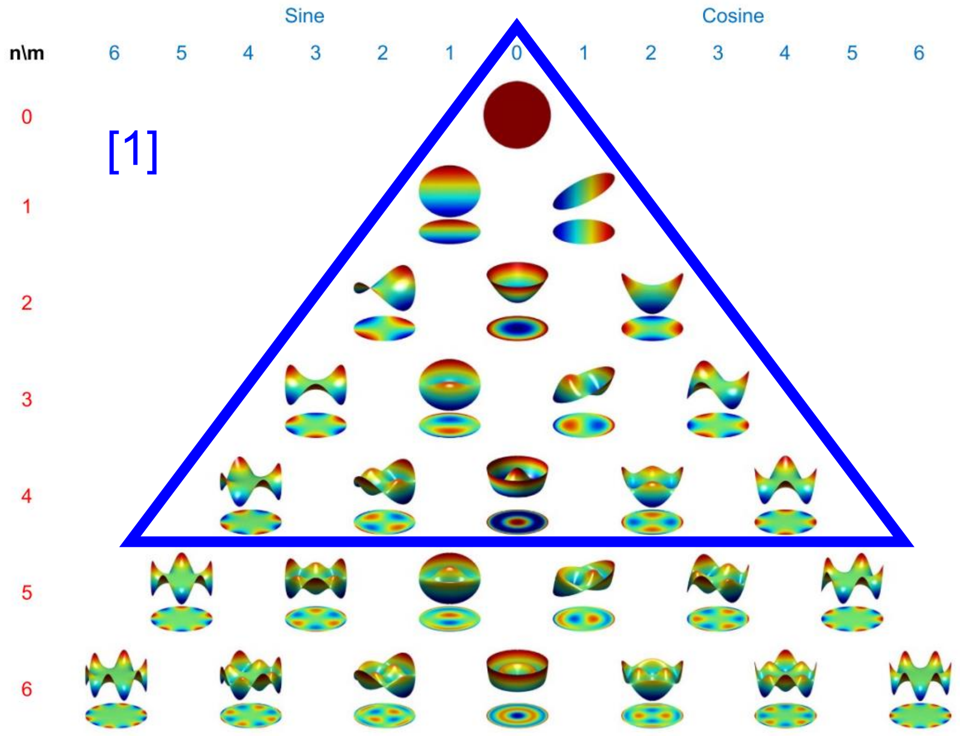


Figure 7. Pyramid of the non-normalized Zernike circle polynomials up to the sixth degree under the Noll indexing scheme.

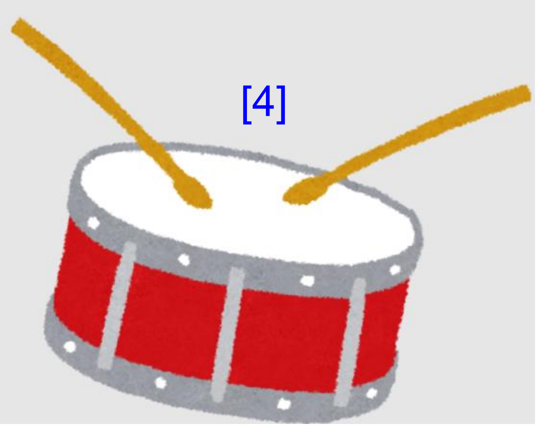
Table 2. First 37-term orthonormal Zernike circle polynomials under the Noll indices [25, 36]. [2]

j	n	m	$Z_j(\rho, \theta)$	$Z_j(x, y)$	Aberration
1	0	0	1	1	Piston
2	1	1	$2\rho\cos\theta$	$2x$	x-tilt
3		1	$2\rho\sin\theta$	$2y$	y-tilt
4	2	0	$\sqrt{3}(2\rho^2-1)$	$\sqrt{3}[2(x^2+y^2)-1]$	Defocus
5		2	$\sqrt{6}\rho^2\sin 2\theta$	$2\sqrt{6}xy$	45° Primary astigmatism
6		2	$\sqrt{6}\rho^2\cos 2\theta$	$\sqrt{6}(x^2-y^2)$	0° Primary astigmatism
7	3	1	$\sqrt{8}(3\rho^3-2\rho)\sin\theta$	$\sqrt{8}y[3(x^2+y^2)-2]$	Primary y-coma
8		1	$\sqrt{8}(3\rho^3-2\rho)\cos\theta$	$\sqrt{8}x[3(x^2+y^2)-2]$	Primary x-coma
9		3	$\sqrt{8}\rho^3\sin 3\theta$	$\sqrt{8}y(3x^2-y^2)$	
10		3	$\sqrt{8}\rho^3\cos 3\theta$	$\sqrt{8}x(x^2-3y^2)$	
11	4	0	$\sqrt{5}(6\rho^4-6\rho^2+1)$	$\sqrt{5}[6(x^2+y^2)^2-6(x^2+y^2)+1]$	Primary spherical aberration
12		2	$\sqrt{10}(4\rho^4-3\rho^2)\cos 2\theta$	$\sqrt{10}(x^2-y^2)[4(x^2+y^2)-3]$	0° Secondary astigmatism
13		2	$\sqrt{10}(4\rho^4-3\rho^2)\sin 2\theta$	$2\sqrt{10}xy[4(x^2+y^2)-3]$	45° Secondary astigmatism
14		4	$\sqrt{10}\rho^4\cos 4\theta$	$\sqrt{10}[(x^2+y^2)^2-8x^2y^2]$	
15		4	$\sqrt{10}\rho^4\sin 4\theta$	$4\sqrt{10}xy(x^2-y^2)$	

$$Z_j(\rho,\theta) = Z_n^m(\rho,\theta) = \begin{cases} \sqrt{2(n+1)}R_n^m(\rho)\cos m\theta, \; m \neq 0, \; j \text{ is even}, \\ \sqrt{2(n+1)}R_n^m(\rho)\sin m\theta, \; m \neq 0, \; j \text{ is odd}, \\ \sqrt{(n+1)}R_n^m(\rho), \; m = 0, \end{cases} \tag{3}$$

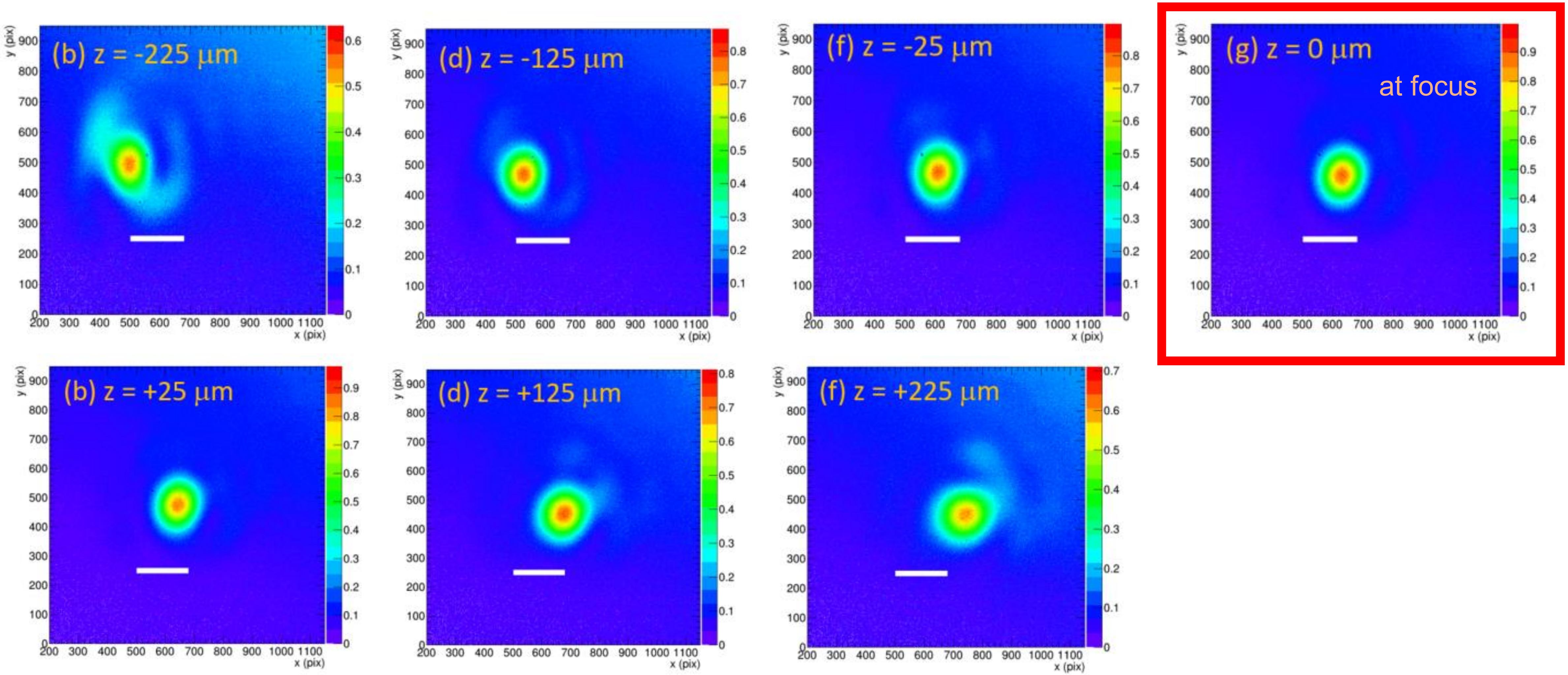
[3]

Blue triangle: Tunable range by typical deformable mirror



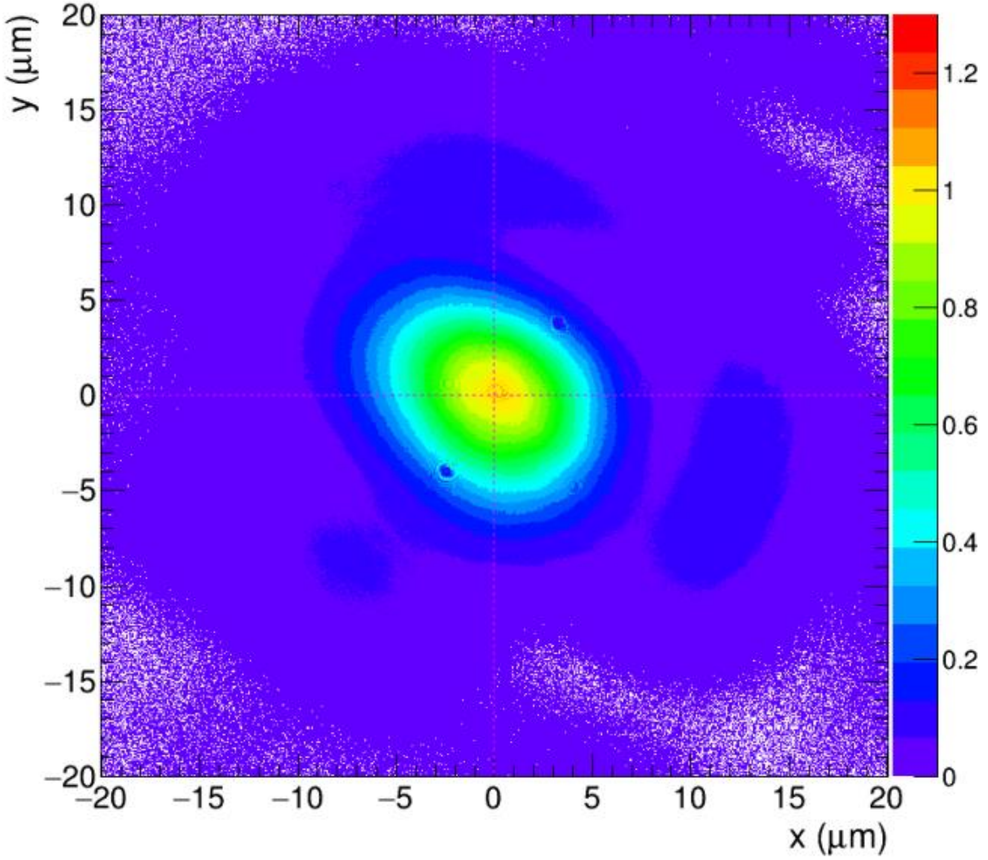
[1] – [3] : Kuo Niu and Chao Tian 2022 J. Opt. 24 123001 (2024)
[4]: https://www.irasutoya.com/2013/02/blog-post_6105.html

Focal spot image in 0.1 PW Ti:Sa. real beam **AFTER** DM optimization

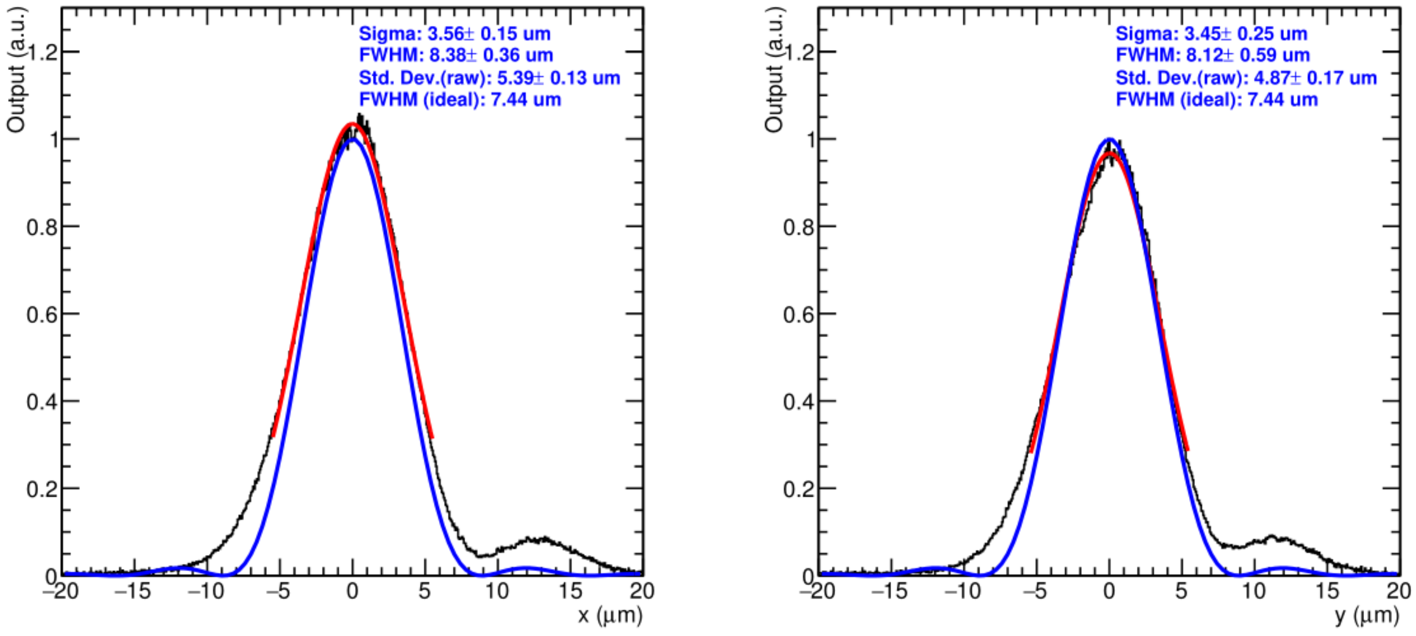


Focal spot image gets round shape after optimizing deformable mirror
If you still see elliptical shape horizontally (long axis horizontally), it might come from angular chirp effect (i.e. parallelism of gratings is lost)

Focal spot image in 0.1 PW Ti:Sa. real beam (after DM optimization)



(a) 2D image at focus



(b) 2D image at focus

Black shows data

Blue shows theoretical curve for 800 nm

Theoretical curve give an evaluator how good your focal image is.

But note theoretical curve itself has some uncertainties (Supper-Gaussian beam, broadband etc.)

Angular-chirp by compressor

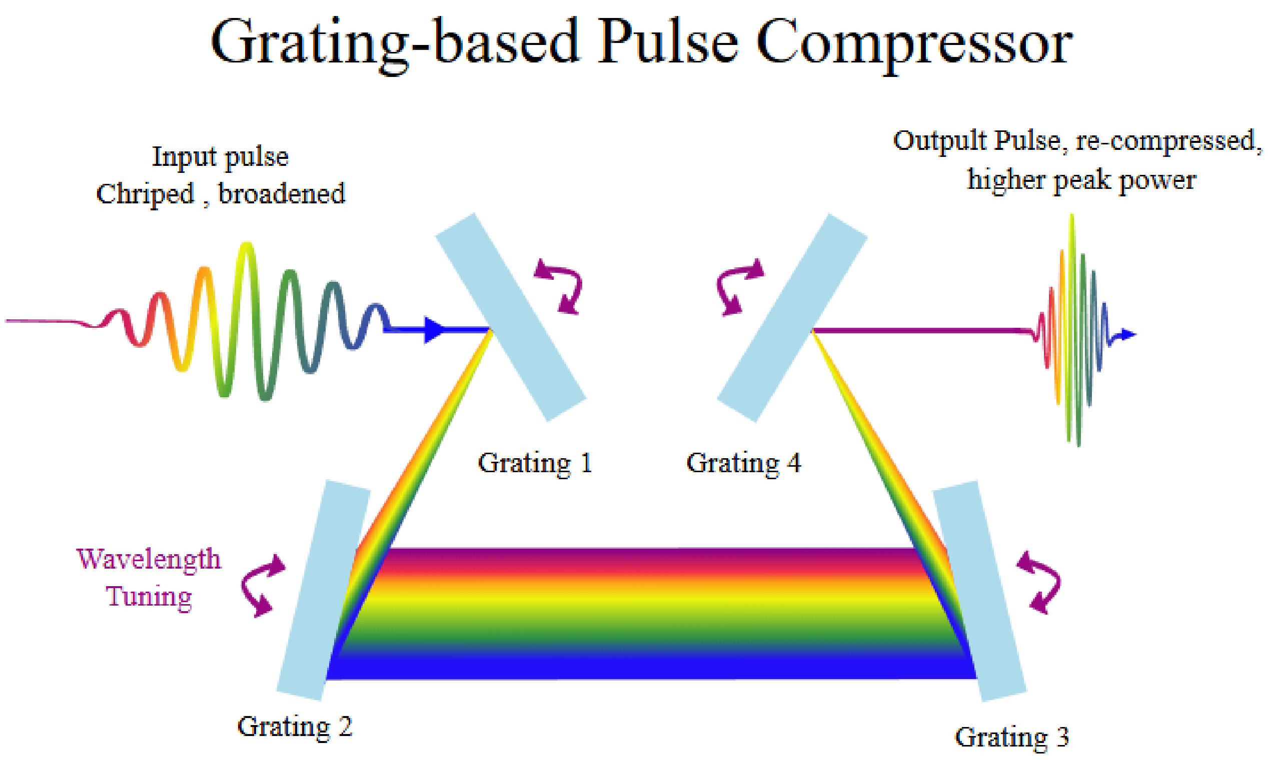


Figure 3: Principle of a Grating Compressor.

Figure is cited from
https://www.meetoptics.com/academy/pulse-compressors

Pair 1) Gr1 + Gr2
Pair 2) Gr3 + Gr4

- If Pair 1 and Pair 2 don't have symmetric angle, horizontal spatial spreads is created as output from Gr4.
- It results in asymmetric divergence for the laser beam, so your focal spot should be elliptical
- Wavelength dependent focal shape can be found if angular chirp occurs.

Steps to the best focus for real experiment at Ti:Sa. HPLS

- Optimize the alignment of off-axis parabolic mirror by using a reliable calibration light source such as HeNe
- Confirm the alignment of pulse compressor at laser system
- Understand aberration of real Ti:Sa. laser in your focusing system
- Wavefront correction by deformable mirror
- If necessarily, angular chirp correction ((= Fine correction of alignment of gratings) can be made at laser system with careful discussion

Summary

Summary

- You got some hints for actual alignment of off-axis parabolic mirror for real experiments with 0.1/1/10 PW laser system.
- You had some reference experience to consider something when you are faced on the problem of focal-spot image for your future activities.

Acknowledgement

- I would like to acknowledge Ms. Ioana Fidel for organizing the training, and your participation !