Personal notes: optics and related

Yahoo!

This is part of a series of personal notes which may be littered with terrible typographical errors, scattered with gregarious grammatical mistakes or cluttered with catastrophic conceptual blunders.

Contents

1 Basics

As a start, one shall assume only ray optics. Wave optics (Gaussian beam) shall not be considered. The following definitions may be helpful.

Lens surface profile:

- the lens profile may be any of the following: spherical, cylindrical, or aspheric

- spherical: surface is part of a sphere. Not the ideal shape for lens, but easy to manufacture. Spherical aberration can be a big problem.
- cylindrical: surface is part of a cylinder face, so lens is a cylindrical or semi-cylindrical shape. The lens surface has differing radii in the X and Y axes, and image magnification is in only a single axis [1]. This is a very useful property. See section 3.
- aspheric: neither spherical or cylindrical.

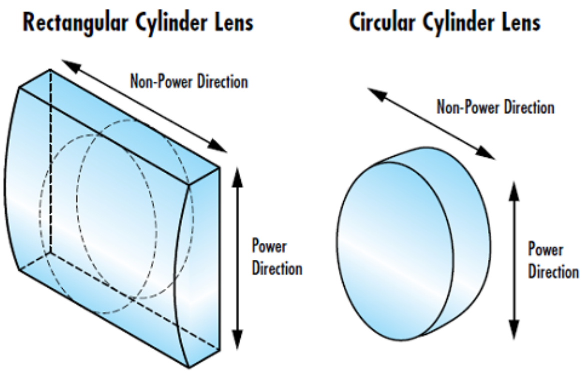

Fig. 1: Illustration of a cylinder lens [2].

Lens curvature: concave, convex

- concave: lens thinner at centre, with the lens surface "caving" in, hence the name. A collimated beam of light passing through such a lens surface will be diverged (spread)
- convex: lens thicker at centre, with the lens surface "convex-ing" or bulging out, hence the name. A collimated beam of light passing through such a lens surface will converge to a spot (a focus) behind the lens

Types of simple lens:

- $\overbrace{\text{biconvex, plano-convex, positive meniscus}}^{\text{positive lens, } f>0}$, $\underbrace{\text{negative meniscus, plano-concave, biconcave}}_{\text{negative lens, } f<0}$
- meniscus:
  - can be either positive or negative
  - depends on the relative curvatures of the two surfaces
  - ideal thin lens with two surfaces of equal curvature would have zero optical power (neutral effect: does not converge or diverge light)
  - a real non-zero thickness lens with identical curved surfaces will be slightly positive
  - a neutral meniscus lens must have slightly unequal curvatures to account for the effect of the lens' thickness
  - positive meniscus
    * $f > 0$: steeper convex surface and is thicker at the centre than at the periphery
    * commonly used to achieve tighter beam focusing when paired with a positive f optical system or to focus collimated beam (light source should be incident on convex surface)
    * minimise spherical aberration in a negative f optical system
    * in combination with another lens, will decrease f, and increase the numerical aperture of the system, while maintaining the angular resolution of the optical assembly

- negative meniscus
    - $f < 0$: steeper concave surface and is thinner at the centre than at the periphery
    - commonly used to diverge light source (light source should be incident on convex surface. YES! convex)
    - minimise spherical aberration in a positive f optical system
    - in combination with another lens, will increase f, and decrease the numerical aperture of the system

- convex:
  - when at least one surface is convex
  - Use: focus collimated light or to collimate a point source
  - plano-convex:
    - one flat surface and one convex surface
    - we ignore the effect of the planar side of the lens, by assuming that light enters perpendicular to the flat surface [3]. Then, the planar surface has neither a focusing nor de-focusing effect
    - best used when one conjugate point (object distance or image distance) is more than 5x the other (infinite conjugate applications)
    - converge collimated light, bringing it to a focus (collimated light source should be incident on the curved surface)
    - collimate/converge a point source (light source should be incident on the planar surface) [4]
    - introduce positive spherical aberration (if lens profile is spherical). Use concave lens to reduce or nullify effect (see below on plano-concave)
    - asymmetry of these lenses (plano-convex) minimises spherical aberration in situations where the object and image are located at unequal distances from the lens
  - biconvex:
    - best used when the object and image are on opposite sides of the lens and the ratio of the object to the image distance (conjugate ratio) is between 0.2 and 5 (c.f. plano-convex) [4]
    - or when used to create a virtual image from an object (formed if the object is located at a distance $< f$ from the converging lens)

- concave:
  - when at least one surface is concave
  - Use: collimate/diverge a converging beam or to diverge a collimated beam to a virtual focus.
  - plano-concave:
    - one flat surface and one concave surface.
    - likewise, we ignore the effect of the planar side of the lens
    - likewise, best used when one conjugate point (object distance or image distance) is more than 5x the other
    - diverge a collimated beam to a virtual focus (collimated light source should be incident on the curved surface)
    - collimate/diverge a convergent beam (converging light source should be incident on the planar surface)
    - introduce negative spherical aberration (if lens profile is spherical). Use convex lens to reduce or nullify effect (see above on plano-convex)

Focal length, $f = \frac{1}{P}$

- a measure of how strongly the system converges or diverges light
- f has small value means the system or lens bends the rays more sharply, bringing them to a focus in a shorter distance or diverging them more quickly

- $f > 0$ indicates that a system is positive or one which converges light, f is then the distance over which initially collimated (parallel) rays are brought to a focus. A simple converging / convex lens will have a center that is thicker than at the edges.
- $f < 0$ indicates that the system is negative or one which diverges light. f indicates how far in front of the lens a point source must be located to form a collimated beam. A simple diverging / concave lens will have a center that is thinner than at the edges.
- front focal length (FFL): distance from the front focal point of the system to the vertex of the first optical surface
- back focal length (BFL): distance from the vertex of the last optical surface of the system to the rear focal point
- effective focal length (EFL): the overall focal length of an optical system

Optical power, $P = \frac{1}{f}$

- the degree to which a lens, mirror, or other optical system converges or diverges light
- high optical power corresponds to short focal length (reasonable! since $P = \frac{1}{f}$)
- each optic surface has a corresponding power, but for single lens, it is roughly equal to the sum of the powers of each surface
- similarly, for two or more thin lenses close together, the optical power of the combined lenses is approximately equal to the sum of the optical powers of each lens

f-number = f/N, or focal ratio / f-stop / $N = \frac{f}{D}$

- ratio of the system's focal length f to the diameter of the effective aperture, D
- usually written as f/N, i.e. if $f = 50$ mm, $D = 25$ mm, then $N = 2$. f-number reported as $f/2$
- for a fixed f,
  a larger diameter, $D \implies$ larger aperture $\implies$ smaller f-stop, N (but larger f-number, f/N!)

Numerical aperture

- a dimensionless number that characterizes the range of angles over which the system can accept or emit light

Collimation

- when every ray within a beam is parallel to every other ray
- To produce collimated light:
  - place an infinitesimally small source exactly one focal length away from an optical system with a positive focal length
  - observe the point source from infinitely far away
  - but neither are possible in practice
  - in addition, due to diffraction, light emitted from any source will diverge

Divergence, θ

- an angular measure of the increase in beam diameter with distance from the optical aperture from which the beam emerges

- the half-angle divergence, θ_o, is defined as:

$$\tan\theta_o = \frac{\frac{D_L - D_o}{2}}{L}$$

- the divergence angle influences the output beam diameter [5], see Fig. 2

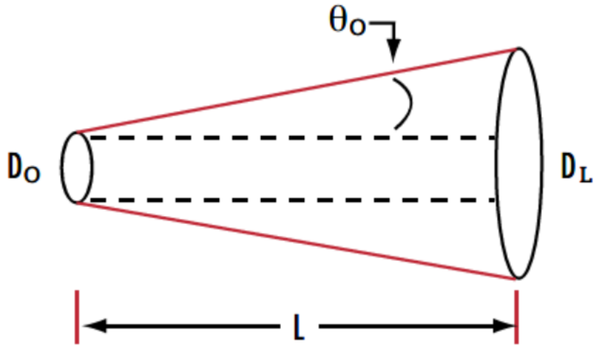

Fig. 2: Divergence of a laser beam [6].

Magnification: M

- is the ratio of image (apparent) size to object (real) size
- for a thin lens,

$$\begin{aligned} M &= \frac{h_i}{h_o} \\ &= -\frac{d_i}{d_o} \\ &= \frac{f}{f - d_o} \end{aligned}$$

- for a telescope,

$$\begin{aligned} M &= \frac{h_i}{h_o} \\ &= \frac{f_{\text{image lens}}}{f_{\text{objective lens}}} \\ &= \frac{R_2}{R_1} \end{aligned}$$

where R_2 and R_1 is the radius of curvature of the image lens and objective lens respectively.

- realise that this is a fundamental limitation on the geometry of an optics system [7]
- if an optical system of a given size is to produce a particular magnification, then there is only one lens position that will satisfy that requirement
- but a big advantage is that one does not need to make a direct measurement of the object and image sizes to know the magnification; it is determined by the geometry of the imaging system itself

Spot size (of a laser beam)

- typically defined as the radial distance from the center point of maximum irradiance to the point where the intensity drops to $\frac{1}{e^2}$ of the initial value, as shown in Fig. 3.

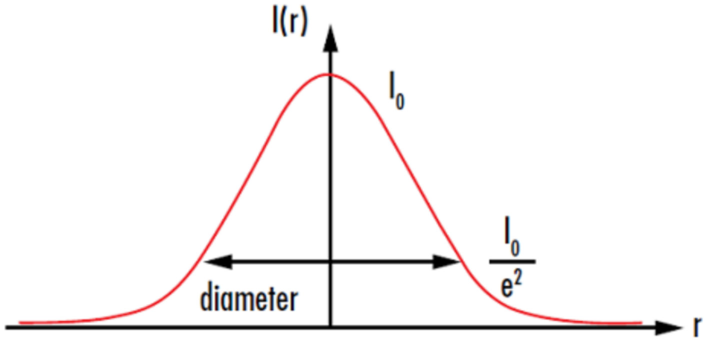

Fig. 3: Illustration the calculation of spot size.

Eyepiece

- type of lens or a collection of lens that is attached to a variety of optical devices such as telescopes and microscopes
- closest to the eye when someone looks through the device, hence the name eyepiece
- objective lens or mirror collects light and brings it to focus creating an image
- eyepiece is then placed near the focal point of the objective lens to magnify this image

Objective (lens)

- a single (or a group of) optical element(s) that gathers light from the object being observed and focuses the light rays to produce a real image
- closest to the sample / object

Aberration:

- a property of optical systems that causes light to be spread out over some region of space rather than focused to a point
- wave phenomena of light beam cause aberrations [8]
- two types of aberration: chromatic and monochromatic
- Chromatic aberration (CA)
  - due to dispersion, as the refractive index of the lens elements varies with the wavelength of light
  - consequentially, different wavelengths in a light beam are not focused to the same point (the focal point)
  - reasonable to expect that the focal points of red and blue (the extremes of the visible light spectrum) are the greatest apart
  - may be either lateral or axial
  - in photography,
    * you will step down the aperture to reduce axial chromatic aberration. Because with the increase in depth of field, though the different wavelengths focus at different distances, they will still be in acceptable focus.
    * but lateral not rectified by stepping down. Lateral CA does not occur in the center of the image and increases towards the edges

- Monochromatic aberration
  - independent of the different wavelengths in a light beam
  - much more varied (tilt, defocus, spherical, coma, astigmatism, field curvature, distortion)
- Spherical aberration
  - one type of monochromatic aberration
  - can be a major issue in laser applications
  - spherical surface is easy and cheap to manufacture but far from ideal
  - light focusing at different locations ("smeared-out focus") as a result of light rays not hitting the spherical surface at the optical axis.
  - the further the rays are from the optical axis, the more bent the rays will be, the earlier they intersect the optical axis (positive spherical aberration)
  - if off-centre rays intersect the optical axis later than expected, it is negative spherical aberration
  - effect $\propto \frac{D^4}{f^3}$, so it is much more pronounced at short focal ratios [1]

2 Refracting telescope

A type of optical telescope that uses a lens as its objective to form an image (also referred to a dioptric telescope). The principle has been applied to various optical devices such as binoculars, zoom lenses, telephoto lens, and long-focus lens. It is also applied to laser beam expanders / reducers [6].

We shall consider the most basic form: a telescope consisting of two lenses. Several points / definitions to note:

- light source on the left, with light rays travelling from left to right
- the first lens (counting from the left) will then be the lens closer to the light source / source image / object being viewed, the objective lens
- the second lens (counting from the left) will then be the lens further away from light source / closer to the eye / image being created, the image lens
- input light beam assumed to be collimated
- aim is to get a collimated output light beam as well!
- the magnification of a two lens system (be it Galilean or Keplerian) is equal to $\frac{f_2}{f_1} = \frac{f_{\text{image lens}}}{f_{\text{objective lens}}}$, ratio of focal length of the second lens (image lens) to that of the first lens (objective lens). $M > 1, < 1, = 1$ are all possible. Magnification and magnifying power are different!
- similarly, regardless of the principle, spacing between the two lenses is equal to: $f_1 + f_2$

2.1 Galilean telescope

- objective lens is a positive one ($f > 0$), image lens is a negative lens ($f < 0$)
- plano-convex for objective, plano-concave for image lens
- planar surfaces facing each other, to reduce aberrations
- collimated light beam hits the convex surface $\rightarrow$ emerges out converged $\rightarrow$ converging beam hits the planar surface of the plano-concave $\rightarrow$ emerges out collimated from the concave surface
- no focal point between the lenses $\implies$ non-inverted and upright image
- optical track length $= f_1 + f_2$, where $f_2 < 0$, so is a more compact system

[1] For a fixed f, a larger aperture leads to greater aberration. Reasonable! since in photography, a lens wide open usually has more aberration, with images appearing less sharp.

2.2 Keplerian telescope

- both objective and image lens are both positive ($f > 0$)
- plano-convex for both lens
- planar surfaces facing each other, to reduce aberrations
- collimated light beam hits the convex surface $\rightarrow$ emerges out converged $\rightarrow$ converging beam forms a focal point at some point between the two lens $\rightarrow$ light ray diverges from this focal point $\rightarrow$ diverging rays hit the planar surface of the plano-convex $\rightarrow$ emerges out collimated from the convex surface
- presence of focal point between the 2 lenses $\implies$ inverted image (need a relay lens to correct image orientation)
- optical track length $= f_1 + f_2$, where $f_1 > 0$, so the optical system will span longer

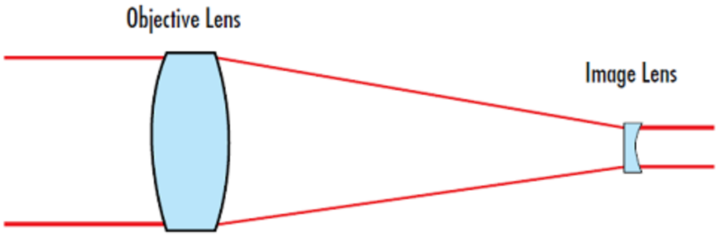

Fig. 4: Optics diagram of a galilean telescope [6].

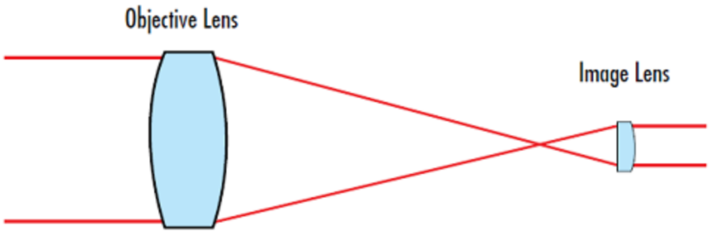

Fig. 5: Optics diagram of a keplerian telescope [6].

2.3 Refracting telescope: application to a beam expander

The principles of both Galilean and Keplerian telescopes can be applied to a beam expander. However, the positions of the lens will have to be swapped, i.e.
For a Galilean:

- the plano-convex lens in Galilean telescope used as objective will be used as an image lens in Galilean beam expander
- the plano-concave lens in Galilean telescope used as image lens will be used as an objective in Galilean beam expander
- again, the plano surfaces shall face each other, to reduce aberrations
- lack of an internal focus (a focal point between the two lenses) $\implies$ better suited for high-power laser applications

For a Keplerian:

- both image and objective lens are plano-convex, so o.k.
- again, the plano surfaces shall face each other, to reduce aberrations
- presence of a focal point between the two points $\implies$ heats the air between the lenses $\implies$ deflects light rays from their optical path $\implies$ potentially leads to wavefront errors especially in high-power laser applications
- but offers high expansion ratios and allow for spatial filtering
- at the focal point, the laser's energy is concentrated. A pinhole can be positioned there to clean up the beam
- need to make sure that the energy density of the beam at the focal point does not exceed the damage threshold limitation of the pinhole material

In either case, one would also have to take note of the following:

- $d_1 > d_i$, diameter of first lens (objective) must be larger than the diameter of the input beam, to avoid clipping the beam
- $d_2 > d_o$, diameter of second lens (image) must be larger than the diameter of the expected output beam
- the useable diameter of a lens is usually specified at 90% of the actual lens diameter
- to further reduce aberrations, only the central portion of the lens should be illuminated, so choosing oversized lenses is often recommended
- the formula magnification is same as that of a telescope: $M = \frac{f_2}{f_1} = \frac{h_2}{h_1} = \frac{R_2}{R_1}$. Of course, in the case of beam expander, $h_2 > h_1$.
- contrary to intuition [9], a beam expander may be used to create a smaller beam diameter far from the laser aperture.
  - a beam expander increases the input laser beam by a specific expansion power
  - while decreasing the divergence by the same expansion power
  - this results in a collimated beam with a smaller divergence at a large distance. See Fig. 7.

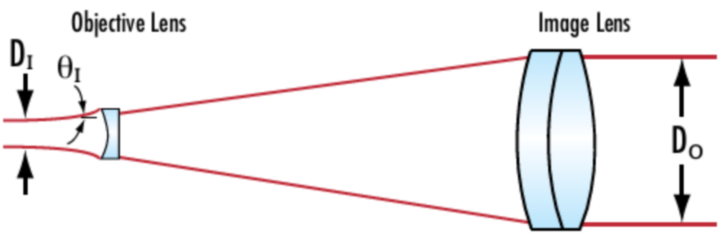

Fig. 6: Optics diagram of a galilean beam expander [6].

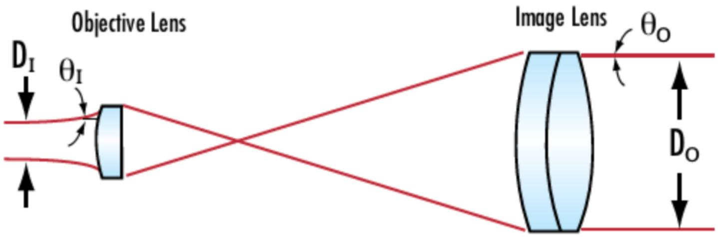

Fig. 7: Optics diagram of a keplerian beam expander [6].

2.4 Refracting telescope: application to a beam reducer

As you have probably guessed by now, a telescope is a beam reducer! So, the image lens is a plano-concave, and the objective is a plano-convex (for the case of a Galilean telescope). A beam reducer built using the principle of Keplerian will have plano-convex for both image and objective lens.

3 Beam shaping (using cylindrical lens)

Recall that cylindrical lenses focus or expand light in one axis only. See section 1. Makes it very useful when one intends to alter the optics behaviour in a particular direction. Some possible applications are discussed below.

3.1 What if... you want to circularise a laser beam?

A laser beam is never perfect so for sure, it will diverge. To make matter worse, it may diverge in an asymmetrical pattern [9].
Correction with a spherical lens:

- a spherical lens has a uniform surface profile in all directions
- light rays of all directions will thus be corrected equally
- the loop-sided divergence still exists $\implies$ spherical lens will not work
- need additional correction in the direction which has more divergence $\implies$ cylindrical lens

Correction with cylindrical lens(es):

- Approach:
  - consider as two 1-D problems
  - apply collimation correction in one dimension with a single cylindrical lens
  - then correcting the orthogonal dimension with a second cylindrical lens
  - use of a convex cylindrical (it makes more sense to try and converge/collimate a diverging light source, than to use a concave lens, and try to further alter the divergence angle to the desired value!)
- Optics in detail:
  - to achieve a symmetrical beam shape, the ratio of the focal length of the two lenses should be approximately equivalent to the ratio of the beam divergences, $\frac{\theta_1}{\theta_2} = \frac{f_1}{f_2}$
  - laser is approximated as a point source, so lenses should be positioned at distance $= f_1$ and f_2 respectively to create a collimated output
  - principal planes of the two lenses should then be spaced at a distance apart equal to the difference of their focal lengths, $f_2 - f_1$.
  - actual spacing between plano-surfaces of the lenses is then: $\mathrm{BFL}_2 - \mathrm{BFL}_1$
  - collimated rays should hit the convex surfaces of the cylindrical lenses, to minimise aberrations
  - again, keep in mind that beam width should not exceed 90% of lens diameter
- End result:
  - a (more-or-less) circularised beam,
  - with equal divergence in both directions

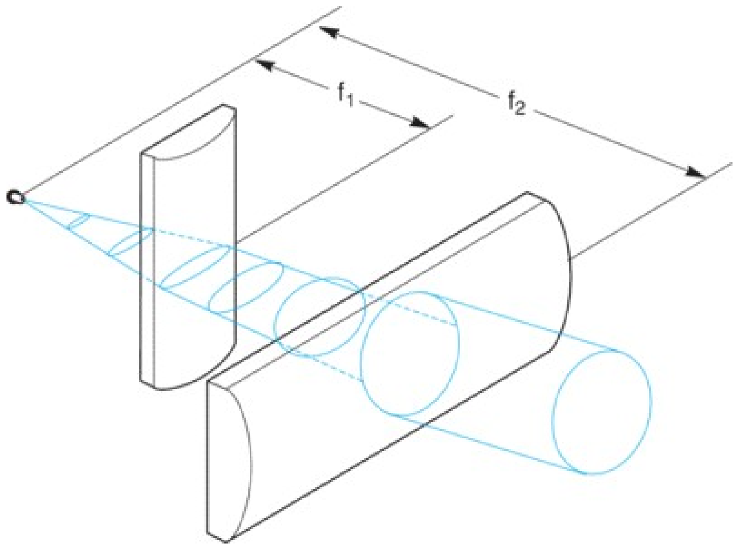

Fig. 8: Circularising a beam (correct for unequal divergence angle in a beam) [9]

3.2 What if... you want to have a laser line (viewed 1D) or laser sheet (viewed 2D)?

From [9]: since cylindrical lens can focus or expand light in one axis only, it is possible to generate a line of sight (1D) or laser sheet (2D). Correction with two cylindrical lenses:

- Approach:
  - use a plano-concave cylindrical lens to expand/diverge beam in a direction, creating a line in this 1D direction
  - use a second plano-convex cylindrical lens (may be placed before or after the plano-concave lens) to focus the beam in the orthogonal direction, focusing the beam as much as possible to a point [2]
- Optics in detail:
  - a collimated laser beam with a radius of r_0 strikes the concave surface of a plano-concave cylindrical lens of focal length f
  - beam exits the plano-surface diverged
  - the beam diverges / expands with a half-angle, θ, appearing to expand from a virtual source placed at a distance f behind the lens:

$$\tan\theta = \frac{r_0}{f}$$
$$\theta \approx \frac{r_0}{f}$$

  - at a distance z after the lens, and in the orthogonal direction to which the cylindrical lens has an effect on, the laser beam will have a thickness of $2r_0$
    * reasonable! since this direction, being orthogonal to the previous direction, is unaltered by the concave cylindrical lens
    * of course, we also ignore the wave properties of the beam, i.e. ignore any expansion of beam diameter due to its inherent Gaussian profile

[2] of course, the point will still have a finite diameter. This finite diameter will be the thickness of the sheet

– the length of the laser beam line, L, is given by (note that $L \propto z$, which is logical!):

$$\begin{aligned}
\tan\theta &= \frac{\frac{L}{2}}{z+f} \\
\frac{r_0}{f} &= \frac{\frac{L}{2}}{z+f} \\
L &= 2\frac{r_0}{f}(z+f) \\
&= 2\frac{r_0}{f}z \qquad \text{if } z \gg f
\end{aligned}$$

– may reduce the thickness $2r_0$ by inserting a plano-convex clindrical lens just before/after the plano-concave lens, with a focal length of $f \approx z$ [3]

- End result:
  – result is a thin laser sheet (2D)
  – note that laser sheet is not rectangular or square
  – light rays are diverging, so it is an isosceles triangle (assuming that the centre of the laser beam is aligned to the optic centre of the plano-concave lens!)
  – not always ideal to make the laser sheet as thin as possible. For a planar (2D) PIV, maybe.
  – But for stereoscopic PIV, when one wishes to capture velocity components in all 3 directions, may be good to have a thicker sheet (to illuminate seeding particles, not just in-plane 2D, but more of a small-volume-ish sheet)

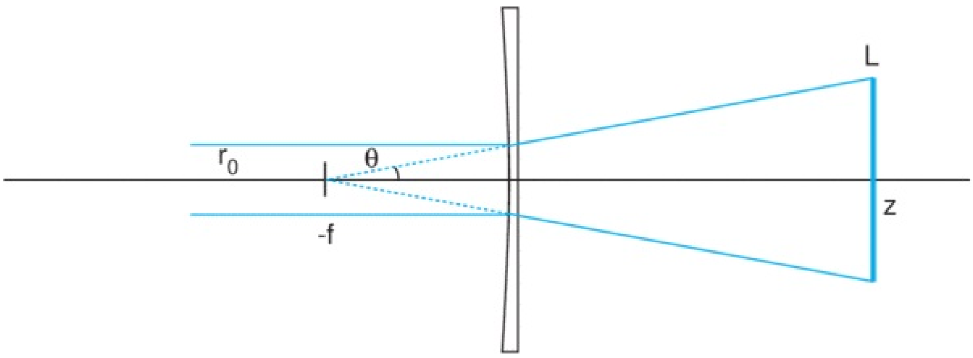

Fig. 9: Generating a laser line of sight from a plano-concave cylindrical lens. The half angle θ is exaggerated. [9]

4 Optics - Appendix

4.1 Gaussian thin lens equation

Proof of the thin lens equation. Note the following:

- consider a thin lens of focal length f
- assume thin lens $\implies$ a lens whose thickness is sufficiently small that it does not contribute to its focal length
- then, change in the path of a beam going through the lens can be considered to be instantaneous at the center of the lens

[3]ideal would be having focal length of plano-convex to be $f = z + t$, where t is the distance between the plano-concave and the plano-convex lens. t may be < 0 (convex placed after concave) or > 0 (convex placed before concave). By choosing to place the convex lens directly before or after the concave lens, we can approximate as: $f = z + t \approx z$

- also assume paraxial approximation $\implies$ angles are small and we can substitute θ in place of $\sin\theta$ and $\tan\theta$.
- Three rays are shown in Fig. 10. Any two of these three rays fully determine the size and position of the image.
  - one ray (top ray) emanates from the object parallel to the optical axis of the lens
  - a second ray (bottom ray) passes through the optical axis at a distance f in front of the lens
  - the third ray (centre ray) passes through the center of the lens

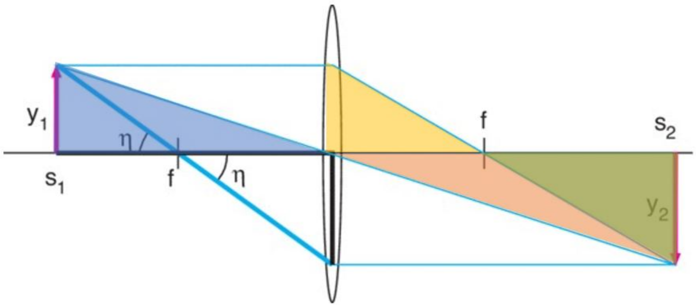

Fig. 10: R
ay diagram with coloured triangles to prove lens equation [7].

Main idea of proof: use of similar triangle

- consider blue triangle and green+orange coloured triangle

$$\frac{y_1}{s_1} = \frac{y_2}{s_2} \tag{1}$$

- consider yellow triangle and green triangle

$$\frac{y_1}{f} = \frac{y_2}{s_2 - f} \tag{2}$$

- Express y_1 in Eqn. 1 using Eqn. 2

$$\frac{\frac{y_2}{s_2-f}f}{s_1} = \frac{y_2}{s_2} \tag{3}$$

$$\frac{f}{s_1} = \frac{s_2 - f}{s_2} \tag{4}$$

$$\frac{1}{s_1} = \frac{1}{f} - \frac{1}{s_2} \tag{5}$$

This is the lens equation, where s_1 is object distance, s_2 is image distance, and f is focal length.

4.2 Optical invariant

- also called the Lagrange Invariant or the Smith-Helmholz Invariant
- for any optical system comprising only lenses, the product of the image size and ray angle is a constant, or invariant, of the system
- so, to improve the collimation by a factor of two, you need to increase the beam diameter by a factor of two [10]

From Fig. 11,

$$\tan\theta_1 \approx \theta_1 = \frac{x}{s_1} \tag{6}$$

$$\tan\theta_2 \approx \theta_2 = \frac{x}{s_2} \tag{7}$$

We can also write the magnification of the optical system as:

$$\frac{y_1}{s_1} = \frac{y_2}{s_2}$$
$$s_2 = \frac{y_2}{y_1} s_1$$

Sub the magnification equation into Eqn. 7

$$\theta_2 = \frac{x}{s_2}$$
$$= \frac{x}{\frac{y_2}{y_1} s_1}$$
$$y_2\theta_2 = \frac{x}{s_1} y_1$$
$$y_2\theta_2 = \theta_1 y_1$$

Presence of aberrations will only increase the product as the light beam travels further , so a more appropriate way to write the invariant is:

$$y_2\theta_2 \geq \theta_1 y_1$$

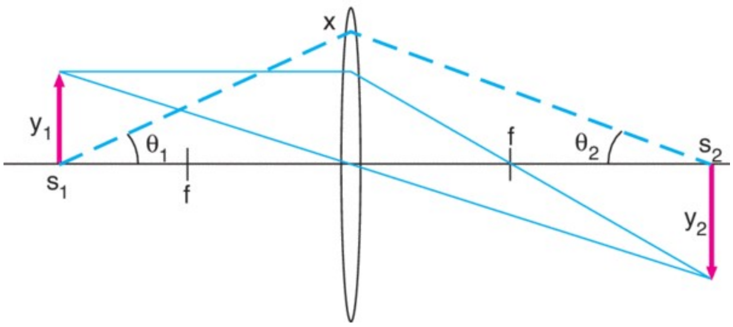

Fig. 11: An arbitrary ray (in this case, it is the maxima ray: the ray that makes the maximal angle with the optical axis as it leaves the object) being considered to prove the optical invariant [7].

5 PIV

6 References

[1] Edmund Optics. (). What are cylinder lenses? — edmund optics. Library Catalog: www.edmundoptics.com, [Online]. Available: https://www.edmundoptics.com/knowledge-center/application-notes/optics/what-are-cylinder-lenses/ (visited on 07/11/2020).

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