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Characterization of a phase plate for the creation of an optical top hat potential

Semester Project

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Abstract

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Chapter 1

Introduction

Predicting the behaviour of complex systems has always been an important goal of scientific research. From predicting the motion of stars and planets in our solar system, to understanding the behaviour of systems showing chaotic behaviours. In history, before scientists were able to find analytical solutions to many problems, they often relied on simulations. A celebrated example are the astronomical clocks that were built in Asia and Europe in the period between 1000 and 1500, such as the famous astronomical clock in Prague (1410) or the Zytglogge in Bern (1530). They were used to predict the position of the planets and the constellations, the phases of the moon and its eclipses [1].

With the advent of quantum mechanics, a new kind of problems for which no analytical solution is possible was found. Given the high dimensionality of the Hilbert space of quantum many-body systems, classical computers cannot be used to find numerical solutions to this kind of problems. For example, simulating a system of $N = 36$ qubit using two double-precision floating-point numbers to store a complex number, would require approximately $2^{N+1} \times 8$ byte = 1 Terabyte of memory. For every additional qubit, this number would double.

Richard Feynman was the first to propose to use a quantum system to handle this complexity making use of the law of quantum mechanics itself. In 1982, he proposed to make use of “one controllable quantum system [to] simulate another” [2]. In this way, a system of N quantum particles could be simulated using another system of N qubits. The problem is then shifted to finding a system that can be easily tuned and controlled, such that it can be used to simulate a wide range of problems.

1.1 Analog and digital quantum simulation

Two different approaches have arisen in the past years: (digital) quantum computation and (analog) quantum simulation. In the first case, the information is encoded in qubits that can be in two computational states $|0\rangle$ and $|1\rangle$. In the latter, a direct mapping between the original problem (i.e. its Hamiltonian) and the simulating system is realized. Among the most promising platforms for quantum computation, we cite the use of superconducting circuits [3], Rydberg atoms [4] and trapped ions [5]. Whereas for quantum simulation, the use of ultracold quantum gases has gained increasing popularity [1].

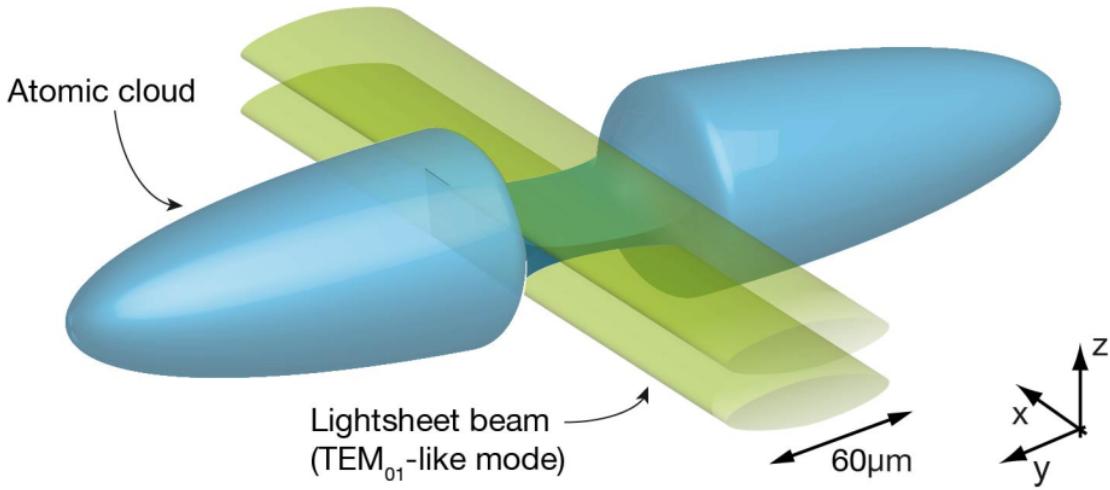


Figure 1.1: Experimental setup. A cloud of atoms is trapped in a cigar-shaped potential. A blue-detuned TEM_{01} laser mode propagating in the x direction defined a quasi-2D channel connecting two smoothly connected reservoirs. Figure from Krinner [13].

For example, a system of electrons moving in an ionic periodic lattice potential, can be simulated using a gas of fermionic atoms trapped in an optical lattice potential. Here, the periodic potential through which the particles move is generated externally by making use of the interference pattern of overlapping laser beams [6]. It is performing an experiment of this kind that Bloch oscillations, predicted in 1929 by Felix Bloch [7], were directly observed in 1996 in a cloud of ultracold Caesium atoms [8], after being observed in 1992 through the emission of THz radiation by the electrons in a semiconductor super lattice [9].

In the following years, new interesting experiments were proposed to simulate the behaviour of different quantum systems. Among them, we cite the use of optical lattices to investigate insulating and superfluid quantum phases [10], the use of cavities to mediate long range interactions [11] and the observation of quantized conductance in neutral matter [12]. In this report, we will focus on the latter, since the project was closely related to it.

1.2 Transport experiments

Transport experiments study the transport properties of particles moving from one reservoir to another. With an experiment of this kind, Krinner *et al.* were able to observe quantized conductance in the transport of neutral atoms driven by a chemical potential bias [12]. Their experiment let them investigate quantum conductors with wide control not only over the channel geometry, but also over the reservoir properties, such as interaction strength, size and thermalization rate.

The basic setup of the experiment is shown in Fig. 1.1. A cloud of atoms is radially trapped with a dipole trap realized with a red-detuned laser. Along the y axis the confinement is produced by the magnetic field curvature of the Feshbach coils. This defines a cigar-shaped

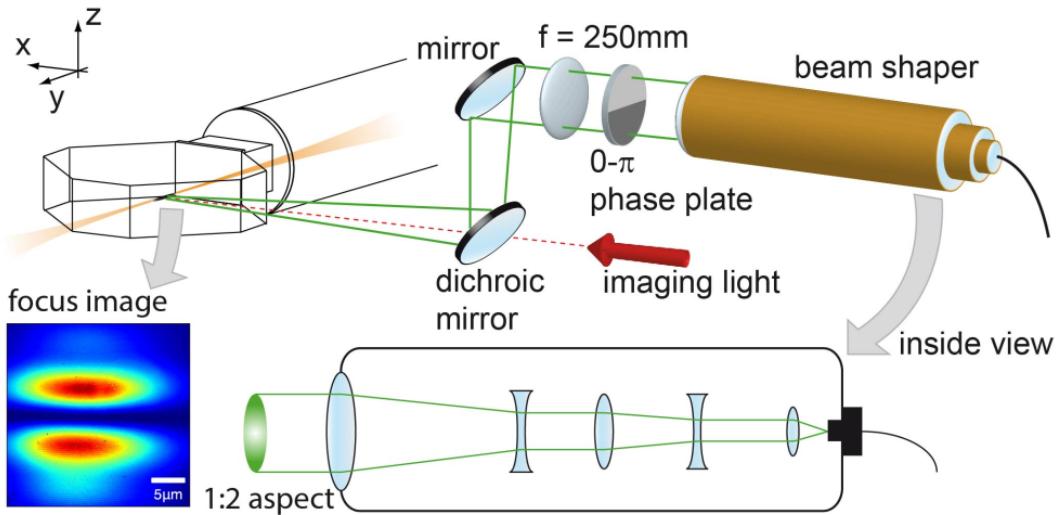


Figure 1.2: Generation of the TEM_{01} mode for the creation of 2D channel. A set of spherical and cylindrical lenses is used to expand the beam in the z direction. The beam is then sent to a $0 - \pi$ phase plate and focused through a 250 mm lens on the atomic cloud. Figure from Krinner [13].

cloud elongated in the y direction. The cloud is then split in two reservoir connected by a quasi-2D channel sending a blue-detuned TEM_{01} laser mode in the x direction. The blue-detuned laser creates a repulsive potential that confines the atoms in a quasi-2D region. The experiment is then carried on creating a chemical potential imbalance between the two reservoir and studying the conduction of atoms between them. Different experiments can be realized creating a temperature imbalance or a spin imbalance between the reservoirs.

The focus of this thesis is on the blue-detuned laser generating the 2D channel. In the current experiment, the laser is in a TEM_{01} mode. The beam is shaped through a series of optical components shown in Fig. 1.2. It is clear that the potential inside the channel region is not uniform along the y direction. The conductance is influenced by this varying potential, and it would be desirable to have a uniform region connecting the two reservoir. The opportunity to create such a uniform 2D channel was previously investigated by Moritz Schmidt in his semester project [14]. Schmidt considered two options for generating a uniform light sheet: the use of liquid-crystal spatial light modulators and of custom-made glass $0 - \pi$, top-hat phase-plates. It was found that this second option is more suitable to the experiment, being at the same time able to satisfy the experimental requirements and considerably cheaper.

1.3 Outline

In this report, we analyse and characterize the custom-made phase plate ordered for the creation of the uniform light sheet. We will start reviewing the theory behind spatial light modulation, focusing on how a phase plate can be used to shape light beams. Then we will present the apparatus used to characterize the phase plate and the results that were found.

Chapter 2

Theoretical background

In this chapter we focus on how we can generate an arbitrary potential for a cloud of ultracold atoms. To understand it, we first need to review the basics of quantum optics that explain how atoms and light interact. We will see that this interaction creates a dipole force that can be used to trap the atoms. We will then focus on the theory of spatial light modulation. For it, we will present a discussion on Fourier optics and use it to understand how a phase plate can be used for such a purpose.

2.1 Atom-light interaction

It is well known that atoms can interact with light. At the quantum level, the interaction is usually interpreted as the absorption or emission of photons by the atoms. Despite this picture being accurate, matter can also interact with light through virtual absorption or emission processes, which have interesting behaviours. For this to happen, the frequency of light must be far detuned from the excitation energy of the atoms. An important effect of this type of interaction is the dipole force exerted by light on atoms. To understand the origin of this force, it is sufficient to remember that photons, besides energy, also carry momentum. When a photon is scattered by an atom, its momentum is transferred, generating an effective force that acts on the latter.

2.1.1 The dipole force

To study this force in more detailed, we model the atom as a two level system, where the energy levels are separated by an energy $\hbar\omega_{eg}$. We also consider light made of a single mode of frequency $\omega/2\pi$, like the light emitted by a laser. The following discussion is adapted from Jonathan Home's lecture notes on Quantum Optics.

We start by writing the interaction Hamiltonian in the dipole approximation

$$H_{\text{int}} = \mathbf{d} \cdot \mathbf{E}(\mathbf{r}) \quad (2.1)$$

where \mathbf{d} is the dipole moment operator, \mathbf{E} the electric field and \mathbf{r} the position of the atom.

The Hamiltonian of the atom without the interaction term is

$$H_0 = \frac{\hbar\omega_{eg}}{2}\sigma_z + \frac{\mathbf{p}^2}{2m} \quad (2.2)$$

where σ_z is the third Pauli matrix and \mathbf{p} is the momentum operator. Furthermore, we consider a classical electric field

$$\mathbf{E} = \frac{1}{2}E_0 f(\mathbf{r}) \left(e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \right) \boldsymbol{\epsilon} \quad (2.3)$$

where E_0 , ω and $\boldsymbol{\epsilon}$ are the field strength, frequency and polarization respectively. The function $f(\mathbf{r})$ allows the field amplitude to vary spatially. The interaction Hamiltonian can be rewritten as

$$H_{\text{int}} = (\boldsymbol{\mu}_{eg} \cdot \hat{\boldsymbol{\epsilon}} E_0) \frac{f(\mathbf{r})}{2} (\sigma_+ + \sigma_-) \left(e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \right) \quad (2.4)$$

where $\mu_{eg} = \langle e | \mathbf{d} | g \rangle$. It is useful to move to the rotating frame with respect to the laser frequency. After transforming the Hamiltonian and performing the rotating wave approximation, we are left with

$$H = -\frac{\hbar\delta}{2}\omega_z + \frac{\mathbf{p}^2}{2m} + \frac{\hbar\Omega(\mathbf{r})}{2} (\sigma_+ e^{i\mathbf{k} \cdot \mathbf{r}} + \sigma_- e^{-i\mathbf{k} \cdot \mathbf{r}}) \quad (2.5)$$

with $\Omega(\mathbf{r}) = \boldsymbol{\mu}_{eg} \cdot \hat{\boldsymbol{\epsilon}} E_0 f(\mathbf{r}) / \hbar$ and $\delta = \omega - \omega_{eg}$.

We can find the resulting force applied on the atom by using Heisenberg's equation of motion

$$\begin{aligned} \mathbf{F} &= \frac{d\mathbf{p}}{dt} = \frac{i}{\hbar} [H, \mathbf{p}] \\ &= -\frac{\hbar}{2} \nabla \Omega(\mathbf{r}) (\sigma_+ e^{i\mathbf{k} \cdot \mathbf{r}} + \sigma_- e^{-i\mathbf{k} \cdot \mathbf{r}}) - \frac{\hbar}{2} \Omega(\mathbf{r}) i\mathbf{k} (\sigma_+ e^{i\mathbf{k} \cdot \mathbf{r}} - \sigma_- e^{-i\mathbf{k} \cdot \mathbf{r}}) \end{aligned} \quad (2.6)$$

We observe that we get two terms. The first, proportional to the spatial derivative of the field strength, includes a contribution in phase with the light field. It is the term that results in the dipole force exerted by the field on the atom, the one we are interested in. The second term is proportional to the field strength, and it is out of phase of a factor of π with respect to the field. It is responsible for the scattering force, essential for cooling atoms. The second term is dominated by the first for large detuning δ , and it will then be neglected in the following discussion.

We will now make use of two approximations to simplify the calculations. We first make use of a mean-value approximation for the centre-of-mass degree of freedom. This means that we evaluate the internal states operators appearing in $d\mathbf{p}/dt$ using the mean position $\mathbf{r} = \langle \mathbf{r} \rangle + \langle \mathbf{v} \rangle t$, where \mathbf{v} is the velocity of the atom. Moreover, since the timescale on which the internal degrees of freedom of the atom evolve are much faster than the timescale associated to the movement of it, we only consider the steady state solution of the atomic dynamics.

Making use of the approximations explained above, in the limit $\delta \gg \Omega, \Gamma$, where Γ is the decay rate, we find

$$\mathbf{F}_{\text{dip}} = \left\langle \frac{d\mathbf{p}}{dt} \right\rangle = -\frac{\hbar}{2} \frac{\Omega}{\delta} \nabla \Omega \quad (2.7)$$

We notice that the dipole force is proportional to the field strength and its gradient, and inversely proportional to the detuning. Moreover, its sign depends on the sign of the detuning. Red-detuned light ($\delta < 0$) generates an attractive potential and can be used to create optical tweezers. This is exploited in our experiment for the creation of the cigar-shaped cloud. On the other hand, blue-detuned light ($\delta > 0$) generates a repulsive potential. This is what we need for the creation of the 2D channel. In the experiment, we use a 660 nm laser, blue-detuned with respect to the Lithium atomic transition of 671 nm.

2.2 Spatial light modulation

Now that we know how light interacts with atoms, we are interested in the techniques that can be used to arbitrary shape a light beam. At the basis of these techniques there is Fourier optics, which will be explained in the next section. We will then look at the different tools that can be used to achieve this goal, focusing on the use of phaseplates.

2.2.1 Fourier optics

Fourier optics is essential to understanding how spatial light modulation works. The basic idea is that a lens returns the Fourier transform of an incident beam on its focal plane. This can be used to transform a phase modulation in an intensity modulation. We will now look at this concept in more detail, providing a short introduction to Fourier optics adapted from Saleh and Teich [15] and Schmidt's previous work [14].

Let's suppose we have a monochromatic wave of wavelength λ propagating in the z direction. In the $z = 0$ plane, we can denote its complex amplitude with a function $f(x, y)$. The function $f(x, y)$ can be Fourier transformed and decomposed in plane waves propagating in the x and y directions

$$f(x, y) = \int d\nu_x d\nu_y F(\nu_x, \nu_y) e^{-2\pi i(\nu_x x + \nu_y y)} \quad (2.8)$$

where $\nu_x = k_x/2\pi$, $\nu_y = k_y/2\pi$ and

$$F(\nu_x, \nu_y) = \int dx dy f(x, y) e^{2\pi i(\nu_x x + \nu_y y)} \quad (2.9)$$

Each plane wave travels in a direction $\theta_x = \sin^{-1}(k_x/k) = \sin^{-1}(\lambda\nu_x)$ and $\theta_y = \sin^{-1}(k_y/k) = \sin^{-1}(\lambda\nu_y)$ and has an amplitude $F(\nu_x, \nu_y)$

One way to separate the Fourier components of a wave is by using a lens. A thin spherical lens transforms a plane wave incident on it into a paraboloidal wave focused on a point on the focal plane of the lens (Saleh and Teich Sec. 2.4 [15]). As shown in Fig. 2.1, a plane wave incident at a small angle (θ_x, θ_y) if focused to the point $(x, y) = (\theta_x f, \theta_y f)$, where f is the focal length of the lens. The complex amplitude $g(x, y)$ at $z = f$ is therefore proportional to the Fourier transform of $f(x, y)$ evaluated at $\nu_x = x/\lambda f$ and $\nu_y = y/\lambda f$.

$$g(x, y) \propto F\left(\frac{x}{\lambda f}, \frac{y}{\lambda f}\right) \quad (2.10)$$

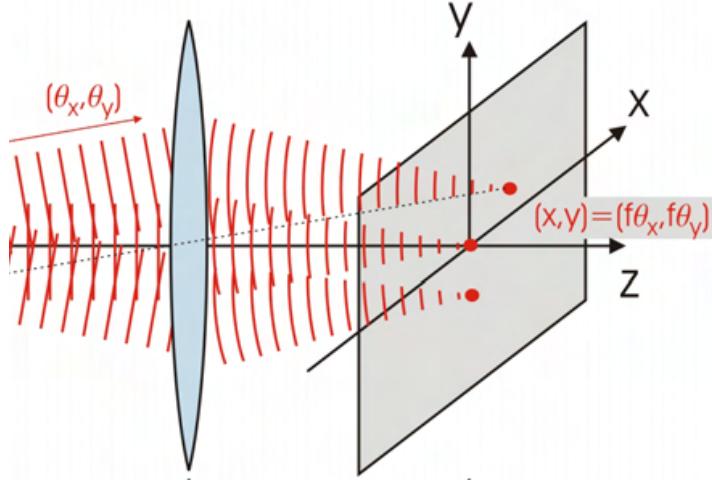


Figure 2.1: Focusing of a plane wave into a point. A direction (θ_x, θ_y) is mapped into a point $(x, y) = (\theta_x f, \theta_y f)$. The lens is positioned at $z = 0$ and the focal plane at $z = f$. Image from Heine [16]

To find the proportionality factor, we trace the propagation of every plane wave in which we have decomposed the input beam through the optical system. Then we integrate over all these plane waves at the output to obtain $g(x, y)$. In the following, we will make use of the Fresnel and paraxial approximations.

A field $F(k_x, k_y)$ can be propagated from the $z = 0$ plane to the $z = f$ plane by applying a phase factor $e^{-ik_z z}$

$$G(k_x, k_y) = F(k_x, k_y) e^{-ik_z z} = H(k_x, k_y, z) F(k_x, k_y) \quad (2.11)$$

with $k_z = \sqrt{k^2 - k_x^2 - k_y^2}$ and $H(k_x, k_y, z) = e^{-ik_z z}$. We can now perform the Fresnel approximation, which states that for plane waves travelling at small angles ($k_x, k_y \ll k$),

$$H(k_x, k_y, z) = e^{-ik_z z} = e^{-iz\sqrt{k^2 - k_x^2 - k_y^2}} \approx e^{-ik_z} e^{i\frac{k_x^2 + k_y^2}{2k} z} \quad (2.12)$$

H is defined in the Fourier space, so we can bring it back to the real space applying an inverse Fourier transform

$$h(x, y, z) = \mathcal{F}^{-1}(H(k_x, k_y, z)) = \frac{i}{\lambda z} e^{-ik_z} e^{ik \frac{x^2 + y^2}{2z}} \quad (2.13)$$

Now we have to take into account the effect of the lens on the beam. A parabolic lens of focal length f will apply a phasor $\phi(x, y) = \exp\left(-ik \frac{x^2 + y^2}{2f}\right)$ in addition to the phase acquired by the propagation of the beam. Overall, at $z = f$

$$g(x, y) = h(x, y, f) \otimes [\phi(x, y) f(x, y)] = \frac{i}{\lambda f} e^{-ikf} F\left(\frac{x}{\lambda f}, \frac{y}{\lambda f}\right) \quad (2.14)$$

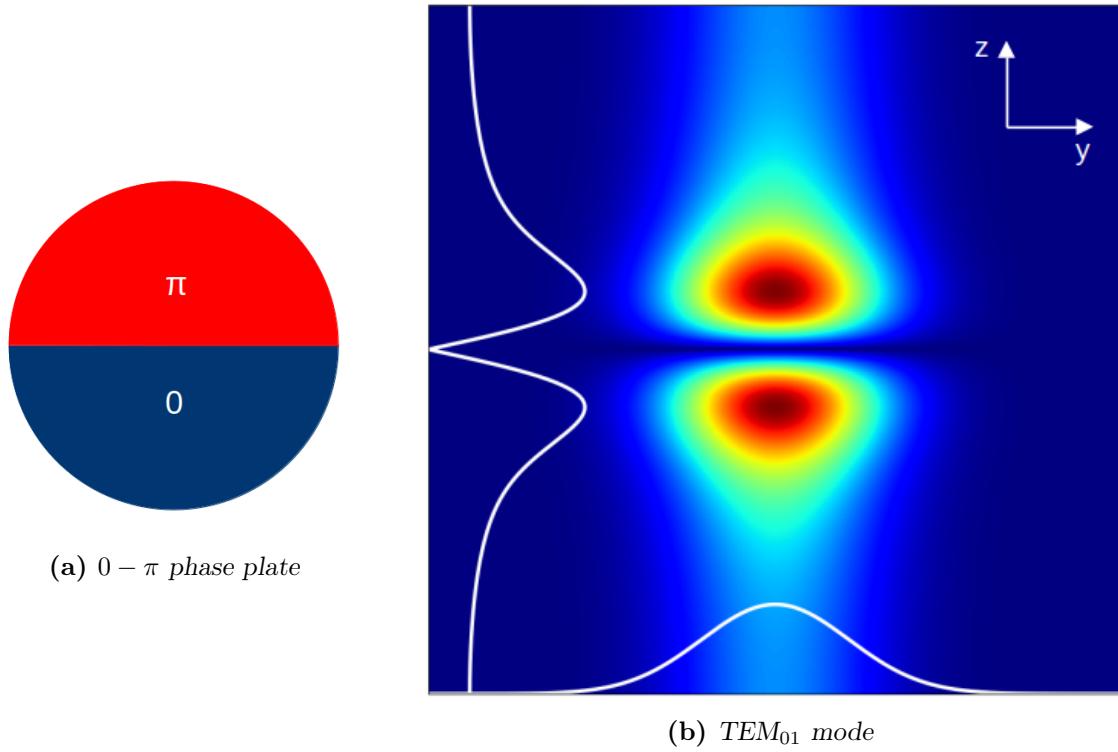


Figure 2.2: TEM_{01} mode generated by a $0 - \pi$ phase plate. In the figure on the right, the intensity profile at the focal plane is shown together with the integrated intensity along the two axes.

The proportionality factor is therefore found to be $1/\lambda f$ and the intensity $I(x, y)$ at the focal plane

$$I(x, y) = \frac{1}{(\lambda f)^2} \left| F\left(\frac{x}{\lambda f}, \frac{y}{\lambda f}\right) \right|^2 \quad (2.15)$$

To sum up, a lens returns a Fourier transform of the incident beam at a distance equal to the focal length. This can be used to modulate the intensity profile of the beam.

2.2.2 Spatial light modulators: the phase plate

The theory described above can be used as the working principle of numerous devices used for spatial light modulation. Among the ways light can be shaped, it is worth mentioning the use of acusto-optic modulators (AOMs), digital micromirror devices (DMDs), liquid crystals spatial light modulators (LC-SLMs) and phase plates. All these options are good for different purposes. The first three have the advantage of being controllable, allowing the creation of arbitrary shapes simply changing the input signal. The latter is cheaper, but once it has been manufactured, it cannot be modified. The use of an LC-SLM for the creation of a uniform light sheet was investigated by Schmidt in his semester project [14]. However, it was found that a phase plate would offer a cheaper and more reliable alternative. These advantages come at the cost of not having the possibility of changing the phase profile at a later moment.

The working principle of a phase plate is very simple. A wave travelling in a transmissive medium has a lower speed than a wave travelling in air. Designing a plate with variable thickness, it is possible to add an arbitrary phase to a beam. The points where the plate is thicker will be delayed with respect to the points where it is thinner. Placing a lens after the plate will result in the desired intensity modulation at the focal plane.

One of the simplest example of phase plates is the $0 - \pi$ phase plate, shown in Fig. 2.2. The plate is divided in two halves, with the upper half out of phase by a factor of π with respect to the lower half. For a beam propagating in the x direction, the phase profile is then (see Fig. 2.2)

$$\phi(y, z) = \begin{cases} 0 & z < 0 \\ \pi & z > 0 \end{cases} \quad (2.16)$$

This is the phase plate currently used in the experiment, and it generates the TEM₀₁ mode shown in Fig. 2.2b.

As it is clear from Fig. 2.2b, the intensity (and therefore the potential) is not uniform along the y direction. On the contrary, it has Gaussian shape, with a peak at the centre. What we would like to achieve is a so-called top-hat potential, shown in Fig. 2.3. It differs from the standard $0 - \pi$ phase plate in the y direction. Instead of having a Gaussian profile, it initially ramps up from 0 to 1 (in a.u.), then it remains flat in the central region, and it finally decreases back to 0. In the ramp up region, the profile is Gaussian. In the z direction, it generates the same kind of intensity modulation as the $0 - \pi$ phase plate. The region we are interested in is the central region. The phase plate was designed to create an intensity profile as uniform as possible, and this is what we have tried to achieve experimentally.

2.2.3 Required specifications

We now turn our attention towards the specifications that the phase plate has to satisfy in order to be useful for our experiment. The three main aspects we want to focus on are the width of the flat region, the darkness D and the trapping frequency ω_z .

The phase plate was designed to create a flat region of $40\text{ }\mu\text{m}$, with a ramp up region of $15\text{ }\mu\text{m}$. The specifications are relative to the intensity profile generated by the phase plate in combination with a lens of focal length $f = 100\text{ mm}$. However, in the final experiment it is preferable to use a $f = 250\text{ mm}$ lens. Therefore all the features will be scaled up by a factor of 2.5. For example the flat region will be $100\text{ }\mu\text{m}$ long instead of $40\text{ }\mu\text{m}$.

The darkness is the most important parameter of the phase plate. It gives us a measure of how dark is the dark region at the centre of the light sheet compared to the bright region around. Taking inspiration from Krinner's PhD thesis [13], we define it as

$$D = \frac{I_{\text{node}}}{(I_{\text{max},1} + I_{\text{max},2})/2} \quad (2.17)$$

where I_{node} is the intensity at the nodal plane, and $I_{\text{max},1/2}$ is the intensity at the two maxima. For the experiment to work, the darkness has to be on the per mill level. The repulsive laser that creates the 2D channel increases the chemical potential with respects to the reservoirs. If the nodal region is too bright, and therefore the chemical potential too high, the atoms will

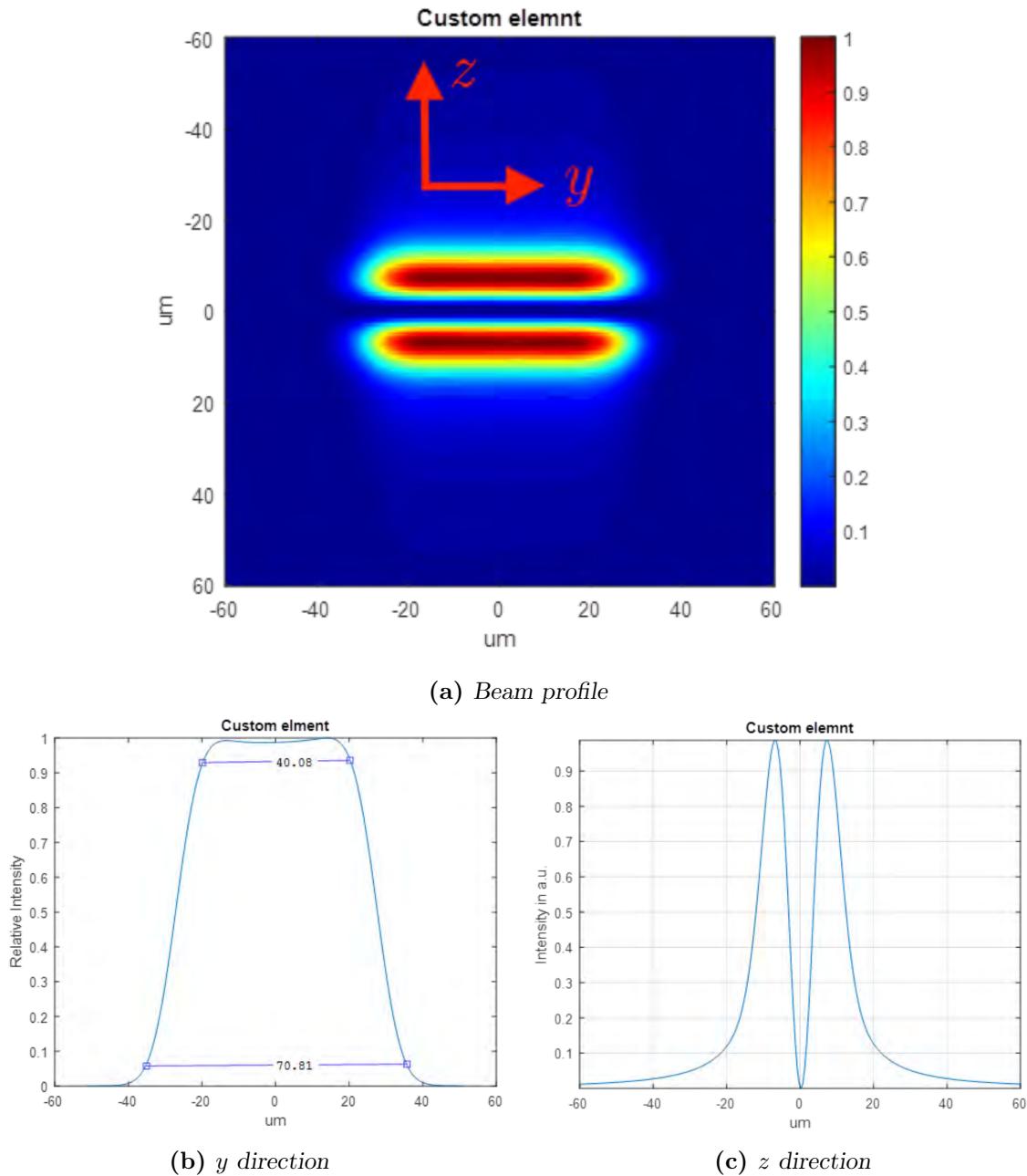


Figure 2.3: Customized phase plate. In the y direction, the intensity follows a "top hat" profile, characterized by a Gaussian ramping up, a flat region, and a symmetric ramping down. In the z direction, the intensity follows the same profile of a $0 - \pi$ phase plate. The image was provided by Holoor, the manufacturing company.

not be able to pass through the channel, and the transport will be suppressed. According to Krinner's work, for a $0 - \pi$ phase plate and typical powers of 1.3 W, a darkness of one per mill increases the chemical potential by 70 nK, and the transport is not suppressed.

In order to freeze-out the z dimension, the trapping frequency must be high enough. If we approximate the trapping potential in the neighbour of the nodal plane with a second order polynomial

$$U(z) = \frac{1}{2}m\omega_z^2 z^2 + \mathcal{O}(z^4) \quad (2.18)$$

we require the trapping energy $\hbar\omega_z$ to be higher than the following energy scales:

- Fermi energy $E_F \approx 600 \text{ nK} = 12.5 \text{ kHz}$
- Binding energy, estimated to be smaller than the 20% of the Fermi energy $E_B \approx 120 \text{ nK} = 2.5 \text{ kHz}$
- Temperature $T \approx 60 \text{ nK} = 1.3 \text{ kHz}$

Therefore, the phase plate was ordered to have a trapping frequency of at least $\omega_z/2\pi = 30 \text{ kHz}$, much larger than all the other energy scales.

The final goal of using this phase plate is to have a central region as dark and as uniform as possible. The darkness can be evaluated computing D as explained above in Eq. (2.17). The uniformity of the potential depends on two things: the intensity variation in the central region and the trapping frequency variation. We can understand it by thinking again at the assumption we made for the potential. Assuming that the potential is approximately harmonic, we can write as

$$U(y, z) = \frac{1}{2}mz^2\omega_z^2(y) + U_0(y) \quad (2.19)$$

where we have explicitly indicated the dependency of ω_z and U_0 on y . Assuming the atoms are in the ground state, they will feel an effective potential dependent on y

$$U(y) = \frac{1}{2}\hbar\omega_z(y) + U_0(y) \quad (2.20)$$

What we want to minimize is then the variation of $U(y)$ along y , which will depend both on the variation of $\omega_z(y)$ and of $U_0(y)$.

Chapter 3

Characterization of the phase plate

The final goal of this project was to have a complete characterization of the phase plate that we received from the company. We knew its expected behaviour, namely the creation of a top hat potential with the characteristics described in Section 2.2.2. However, it was important to test it to see how it behaved in reality.

3.1 Building the experimental setup

3.1.1 Imaging system

In order to characterize the phase plate, the first step was to set up an imaging system. This was necessary to acquire images of the final intensity distribution. Since the expected dimensions of the intensity distribution were of the order of $10\text{ }\mu\text{m}$, a magnification system was assembled. The imaging system was composed of a microscope objective, which magnified the beam, and by a camera. The distance between the two was kept constant by fixing them on a cage. The objective could be moved in the horizontal (y) and vertical (z) direction by turning two micrometers. The whole system (objective and camera) was mounted on a linear translation stage. The stage could be moved along the x direction to focus the image. A sketch of the setup is shown in Fig. 3.1.

In order to use the imaging system to take measurements, it had to be calibrated. For the calibration, a laser beam was sent onto a target like the one shown in Fig. 3.2a and imaged. From the image shown in Fig. 3.2b, it was possible to calculate the magnifying power of the imaging system. The lines were measured to be separated by $413(2)\text{ }\mu\text{m}$. Knowing that on the target the separation was $1/55\text{ mm}$, we found a magnifying power of $22.7(1)$.

3.1.2 Test with the $0 - \pi$ phase plate

Before characterizing the top hat phase plate, the setup was tested on the $0 - \pi$ phase plate currently used in the experiment. The laser beam coming from a fiber was collimated with a lens. Then, the beam was expanded in the z direction by a telescope made of two cylindrical lenses ($f = -40/150\text{ mm}$). The expansion of the beam helped achieve higher trapping

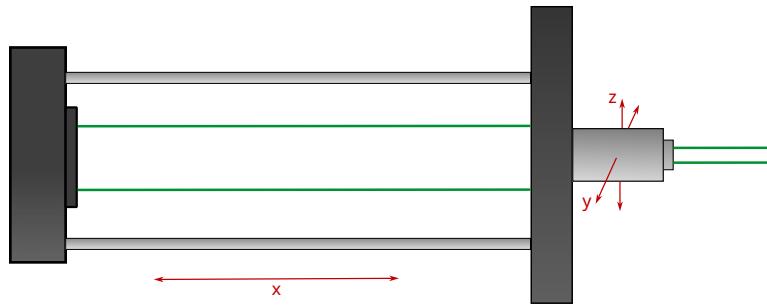


Figure 3.1: Imaging system. A microscope objective magnifies the image and a CCD camera acquires it. The objective can be moved in the y and z direction with two micrometers. The whole system can be moved in the x direction to focus the image.

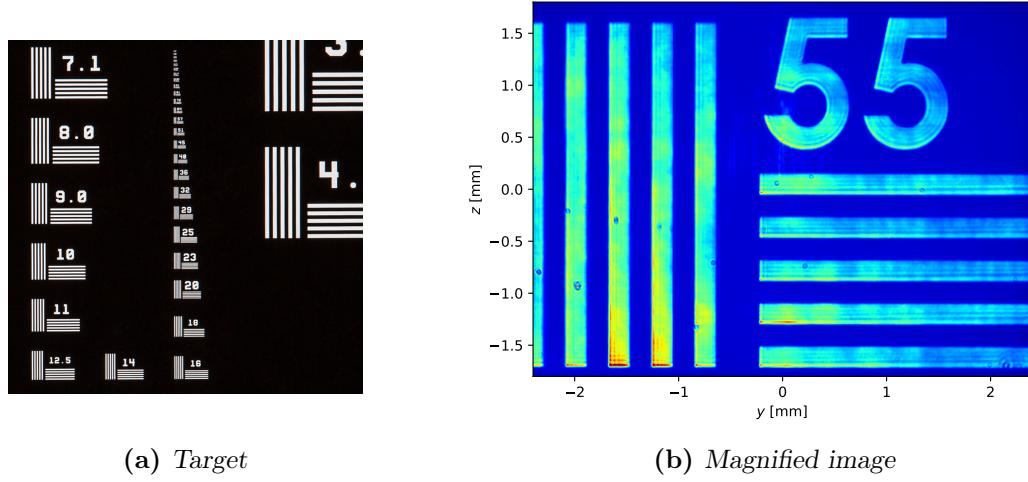


Figure 3.2: Calibration of the imaging system. On the left, an example of a target similar to the one used in the experiment. On the right, the magnified image of a portion of the target. The number 55 means that the target has 55 lines / mm.

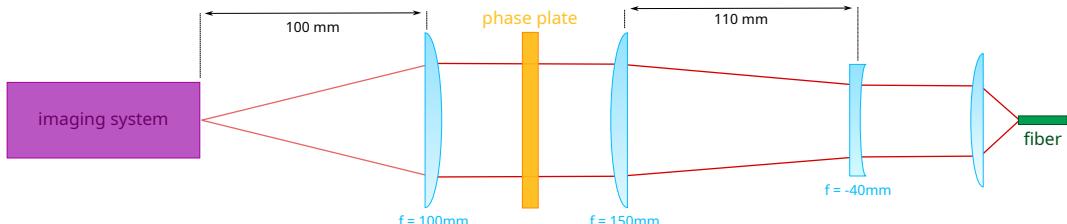


Figure 3.3: Setup for the test of the $0 - \pi$ phase plate. The beam coming from the fiber is collimated by a single lens, then expanded by two cylindrical lenses and sent to the phase plate. After the phase plate, an $f = 100$ mm lens is placed and the result is imaged at the focal plane of the last lens. The two cylindrical lenses and the phase plate are mounted on a rotation mount.

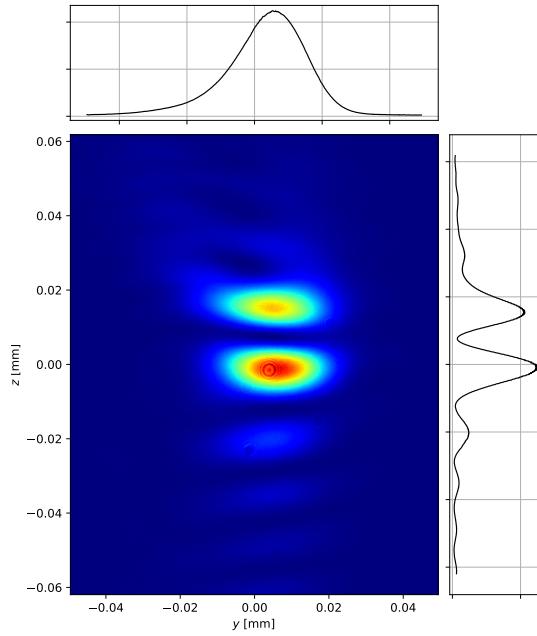


Figure 3.4: Intensity distribution after the $0 - \pi$ phase plate. The size shown on the axis is the real size of the beam. The plots on the right and on top of the image show the integrated sum of the intensity along the respective axes.

frequencies. The beam was then directed to the phase plate and to a $f = 100$ mm lens. The two cylindrical lenses and the phase plate were mounted on a rotation mount, to allow the alignment of their axis. The result was imaged by the imaging system at the focal plane of the last lens. The focus was adjusted by moving the imaging system along the x direction. A sketch of this setup is shown in Fig. 3.3.

In order to get good results, it was important that the two cylindrical lenses and the phase plate axes were aligned. To align them, the beam was observed at short and long distances. Acting on the first lens, the beam was rotated in such a way that, when observed at a short distance, its axis was vertical. The same alignment was then performed acting on the second cylindrical lens and looking at the beam at a longer distance. The procedure was repeated, “walking” the beam, until the two lenses were aligned. The collimation of the beam was ensured by using a shear plate. Finally, the phase plate was aligned rotating its axis in such a way that it was parallel to the beam axis.

The final result is shown in Fig. 3.4. The result resembles the expected TEM_{01} mode shown in Fig. 2.2b, but it is clear that it could be optimized, making it more symmetric. In particular, the alignment of the whole setup could have been improved. However, since the characterization of the $0 - \pi$ phase plate was not the goal of the project, the alignment was not refined. Nonetheless, this test was useful to gain familiarity with how phase plates work

and with the optics involved in the setup.

3.1.3 Shaping the input beam

It had already been reported in Schmidt's work that the most crucial parameter to make the phase plate work is the beam diameter [14]. The phase plate was ordered for a diameter of 6 mm, so this is the first thing we tried to achieve.

Single collimating lens + $\times 2$ telescope

Initially we tried to collimate the beam coming from the fiber with a single lens, chosen to produce a 3 mm beam. Expanding the beam with a $\times 2$ telescope, composed of a $f = 50$ mm and a $f = 100$ mm achromatic lenses placed 150 mm apart, we expected a final beam with a diameter of 6 mm. We first tried to collimate the beam with a 15.3 mm C260-TME-A lens (Fig. 3.5a), but the beam was smaller than 3 mm. Then we tried two 18.4 mm lens (Figs. 3.5b and 3.5c). The diameter of the former (C280-TMD-A) was too small (≈ 3 mm), and produced a beam with many aberrations; the latter, with a larger diameter, seemed to solve the problem. The beam was then magnified by the telescope, resulting in the picture shown in Fig. 3.5d.

Given the bad result, we decided to try with a different configuration.

Schäfter-Kirchhoff collimator + $\times 3$ telescope

In the second configuration, we collimated the beam with a Schäfter-Kirchhoff collimator (60FC-4-M12-10, $f = 12$ mm). The collimator was expected to produce a beam with a diameter of ≈ 2 mm, which therefore required a $\times 3$ telescope. The telescope was assembled using a -50 mm lens and a 150 mm lens. Both lenses were achromatic lenses. The use of a concave and a convex lens, beside reducing aberrations, allowed to keep the setup more compact. The beams before and after the telescope are shown in Figs. 3.6a and 3.6b.

In Fig. 3.6c it is also shown the profile of the beam after being shaped by the phase plate in combination with a 100 mm lens. It is clear that, despite the general features of the top hat distribution being present, the intensity distribution is very different from the expected one. In particular the top and bottom light sheets seem to be curved around the centre.

Single collimating lens

To improve the previous result, we tried to reduce the aberrations using a single achromatic lens to collimate the beam directly to the desired size. In particular, we tried two different lenses: TRH254-040-A-ML ($f = 40$ mm) and MG 01LAO785 ($f = 37.5$ mm). The results are shown in Fig. 3.7. Also with this configuration, the result was disappointing, since the beam deviated a lot from the expected Gaussian profile.

Schäfter-Kirchhoff collimator

Since we were not able to achieve good results only with the optics we had in the lab, we decided to order a collimator with the desired features. In particular, we ordered a Schäfter-Kirchhoff 60FC-L-4-M35-26 collimator, specifically designed to collimate large beams. In

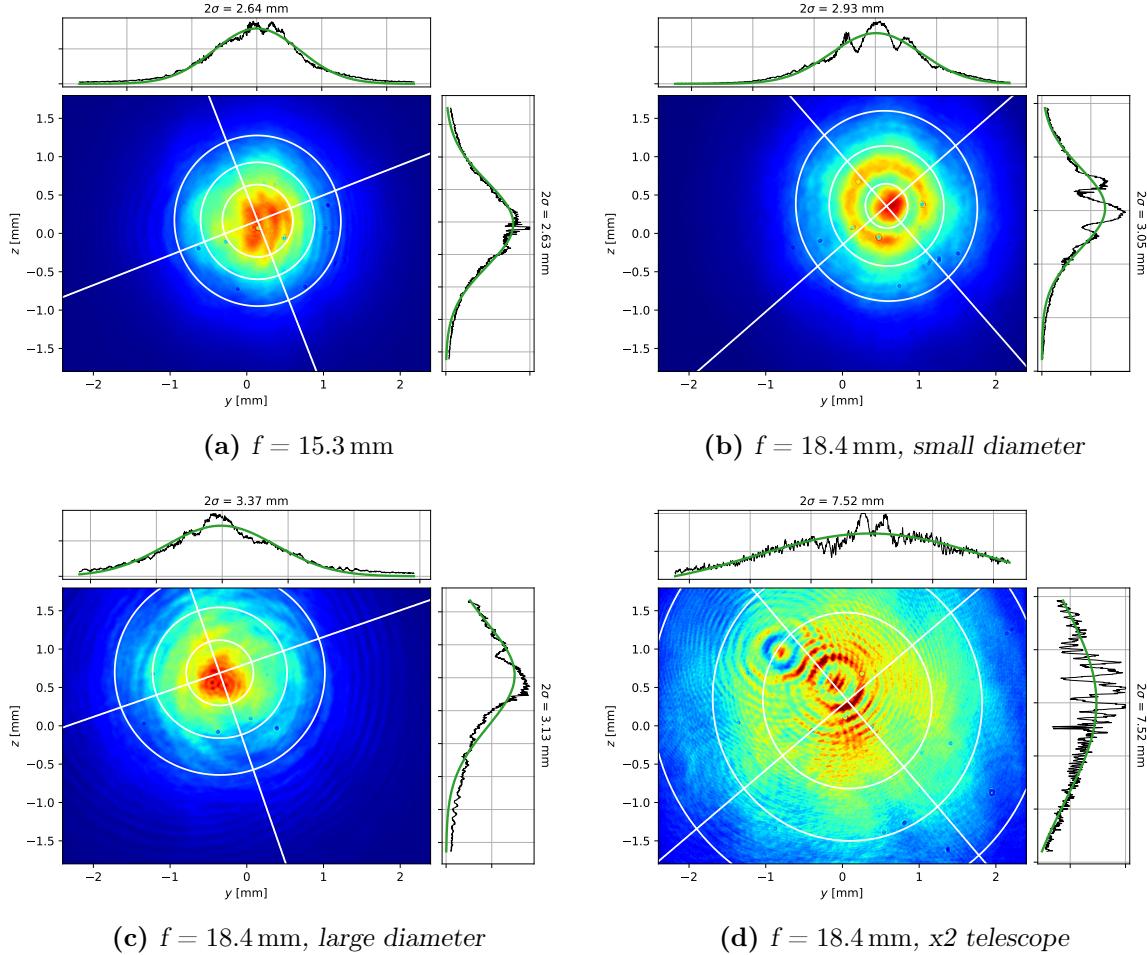


Figure 3.5: Beam collimation with a single lens. The focal length of each lens is indicated below the respective figure. In figure (b) and (c) the lenses have the same focal length but different diameter. In figure (d) the beam is magnified with a $\times 2$ telescope.

Fig. 3.8 we show the beam and the result after shaping it with the phase plate and a 100 mm lens. Surprisingly, the result was even worse than the previous ones. Placing the phase plate in the far field with respect to the collimator did not change the result appreciably. Also trying to reduce the aberrations by adding a 1:1 telescope with a pinhole in between did not have any noticeable effects.

Schäfter-Kirchhoff collimator + $\times 3$ telescope with varying size

Since even in the (theoretically) best configuration, i.e. using a collimator designed to produce a beam of the desired size, the result was far from optimal, we thought that the problem may have resided in the beam size itself. Therefore, we decided to investigate the influence of the beam diameter on the result more systematically. To do so, we went back to the

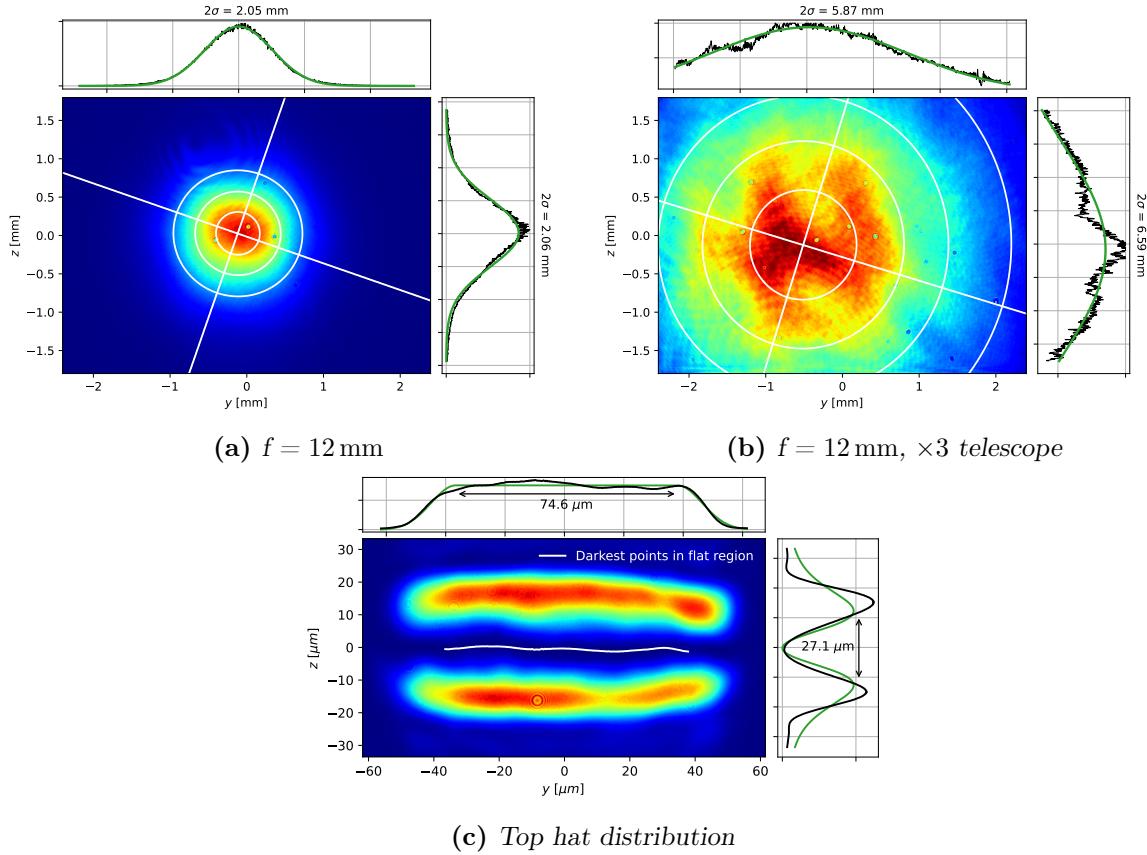


Figure 3.6: Beam collimation with a 12 mm Schäfter-Kirchhoff collimator, magnified with a $\times 3$ telescope ((a) and (b)). The meaning of the fits in (c) are explained Section 3.2.1.

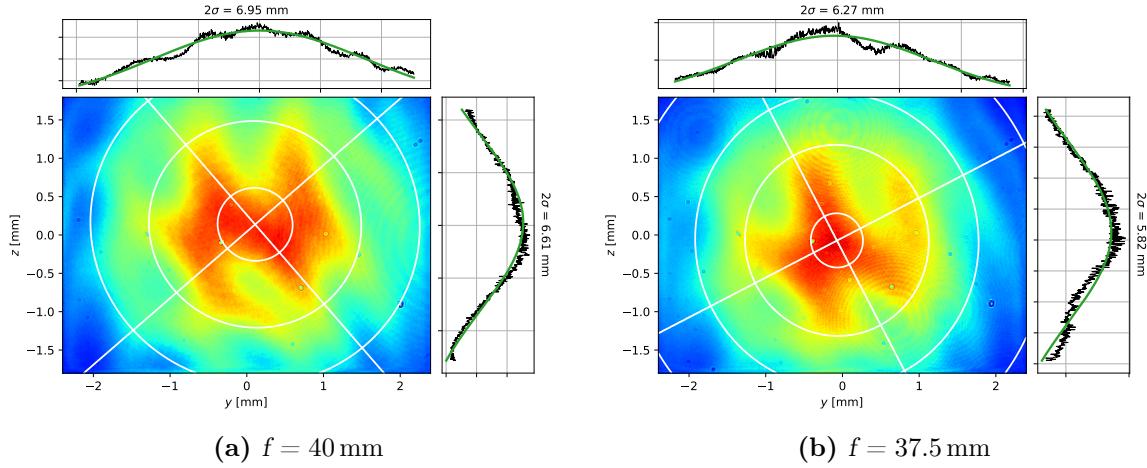


Figure 3.7: Beam collimation with a single lens.

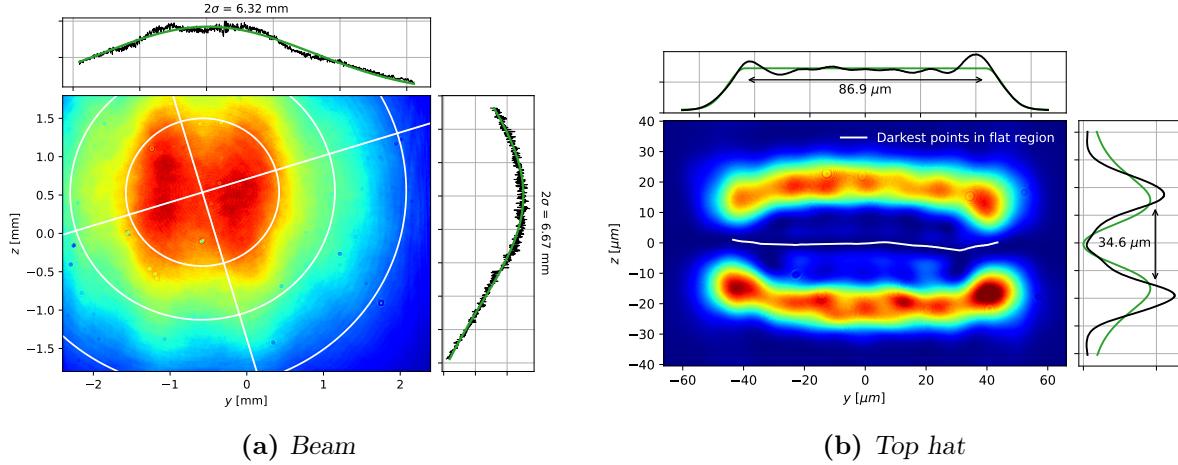


Figure 3.8: Beam collimation with a Schäfter-Kirchhoff 35 mm collimator. The first image shows the beam after the collimator. The second image shows the top hat distribution generated by the phase plate together with a 100 mm lens. The meaning of the fits in (b) are explained Section 3.2.1.

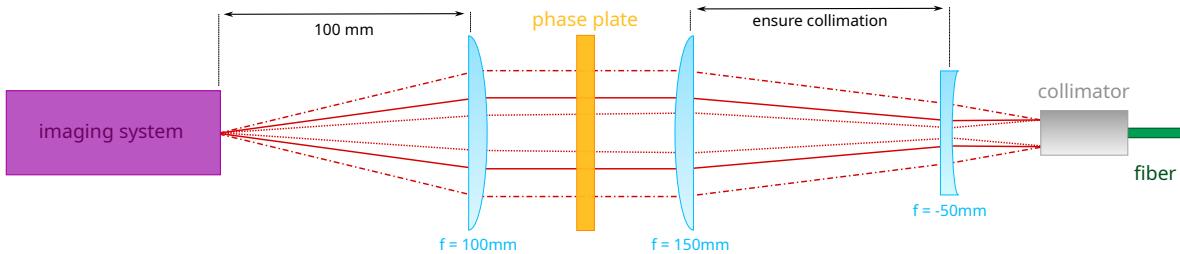


Figure 3.9: Setup f for the test of the top hat phase plate for various beam sizes. The beam coming from the fiber is (not perfectly) collimated by a Schäfter-Kirchhoff collimator, then expanded and collimated by two lenses and sent to the phase plate. After the phase plate, an $f = 100$ mm lens is placed and the result is imagined at the focal plane of the last lens.

configuration with the Schäfter-Kirchhoff 12 mm collimator and the $\times 3$ telescope, with which we had obtained the best result so far.

To vary the size of the beam, instead of using the collimator in its usual way, we manually adjusted it to produce a non-collimated beam. A diverging (converging) beam directed to the telescope produced a final beam larger (smaller) than a collimated one. Moving the second lens of the telescope back and forth, it was possible to re-collimate the beam. In this way, we could vary the size of the beam keeping it collimated at the phase plate position. A sketch of this configuration is shown in Fig. 3.9

The results, for three different sizes of the beam, are collected in Fig. 3.10. From the figures, it is clear that the dimension of the beam has a big influence on the result. Even changes of fractions of a millimetre produce great differences in the final result. In particular, it is interesting to observe that for large beams we recognize the behaviour observed in all the previous configurations, i.e. a curvature of the two light sheets around the centre. On the

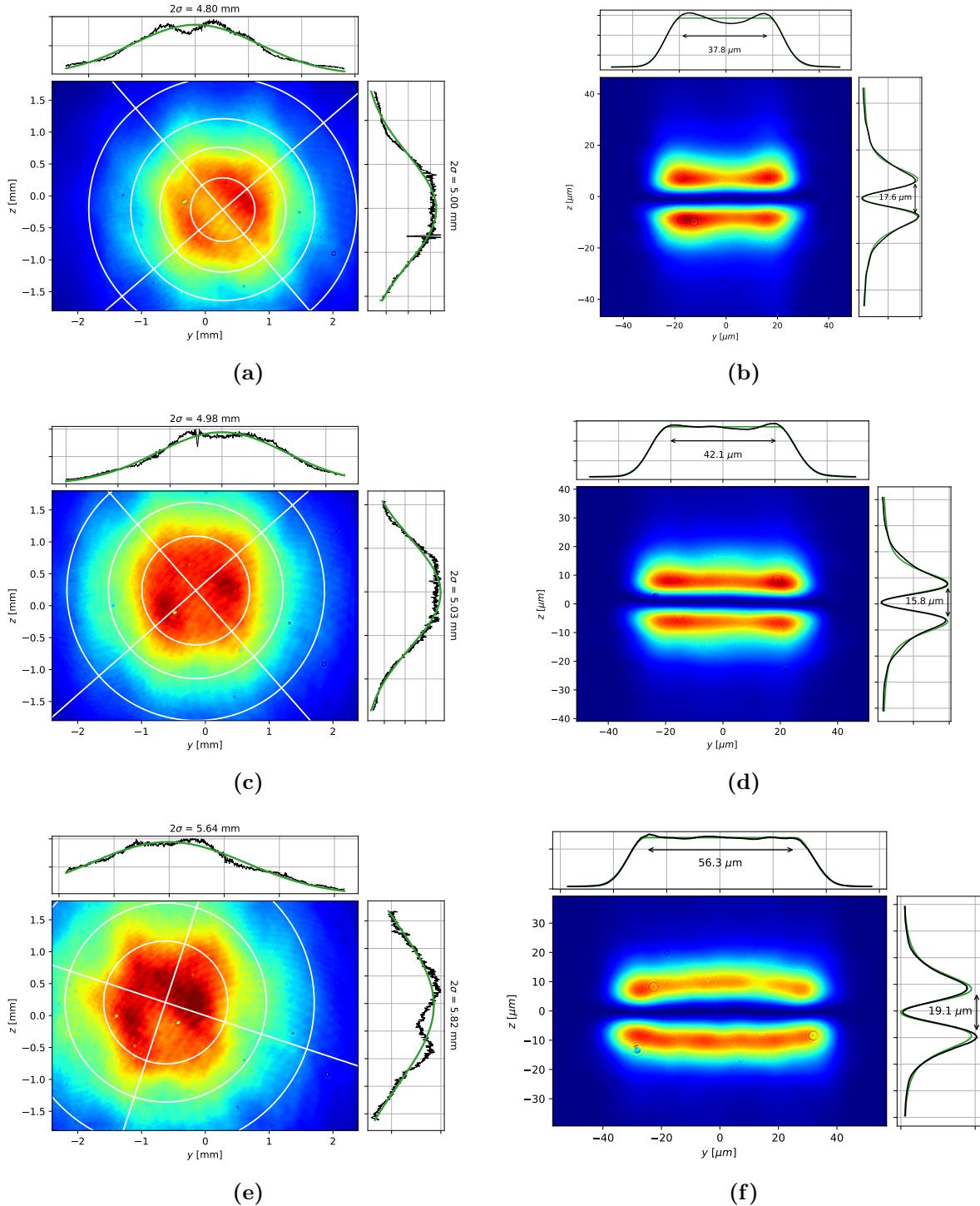


Figure 3.10: Beam and top hat distribution for different beam sizes. Every row shows a beam on the left and its respective top hat distribution on the right. The results were obtained with the 12 mm collimator and together with the $\times 3$ telescope. The meaning of the fits on the top hat images are explained Section 3.2.1.

other hand, small beams produce an uneven intensity distribution along the y axis, with peaks at the border of the flat region. A good compromise seems to be found for a beam of ≈ 5 mm. This explains the bad results obtained before, since we were using much larger beams, even if the size was similar to the specifications given by the manufacturing company.

3.2 Characterization

Having found a good beam size which we could aim for, we decided to assemble a telescope that would give us approximately the desired size, and use it to fully characterize the phase plate. For the characterization of the phase plate we decided to keep using the Schäfter-Kirchhoff 12 mm collimator, but instead of expanding the beam with a $\times 3$ telescope, we used a $\times 2.4$ one. With this setup, we expected a beam with a diameter of ≈ 4.8 mm, size for which we had previously found a good result. The telescope was built with a -50 mm and a 120 mm achromatic lenses.

For a complete characterization of the phase plate, it was necessary to analyse its behaviour for different beam sizes and different distances from the focus. It was important to look at the light sheet at different distances from the focus because, despite the focal point being in principle well-defined, finding it was non-trivial. Moreover, we did not know if for our goals a non-perfectly focused beam may have been better than a focused one.

3.2.1 Methods

Before presenting the results, we offer a brief overview of the methods used to characterize the phase plate. The goal was to define a couple of quantities that would tell us how “good” was a result compared to another one, allowing us to find the best possible configuration.

Intensity normalization

For every combination of beam size and distance from the focus, two pictures were taken: a normal (non-saturated) picture and a saturated picture. The non-saturated picture gave us information on the intensity distribution of the whole light sheet. The saturated picture allowed us to increase the dynamic range of the image in the dark central region, increasing the precision of the measurements. To saturate the picture, we increased the exposure time. Taking note of both the exposure time of the saturated picture and of the non-saturated one, it was possible to “normalize” the saturated picture as

$$I_s^{\text{norm}} = \frac{\tau_{\text{ns}}}{\tau_s} I_s \quad (3.1)$$

where $\tau_{\text{ns/s}}$ are respectively the exposure time of the non-saturated and saturated pictures, I_s the intensity measured by the camera for the saturated picture and I_s^{norm} the normalized intensity.

For both pictures, the absolute intensity I_{abs} was found scaling the intensity measured by the camera I_{rel} (already normalized for the saturated image) by a factor given by the power

of the laser P divided by the total power measured by the camera

$$I_{\text{abs}}(y, z) = P \frac{I_{\text{rel}}(y, z)}{\int dy' dz' I_{\text{rel}}(y', z')} \quad (3.2)$$

For all the following calculations, we assumed to have a laser with a power P of 1 W.

Global behaviour

The expected intensity distribution generated by the phase plate $I(y, z) = I_{\text{th}}(y)I_{0\pi}(z)$ is given by a top hat distribution $I_{\text{th}}(y)$ in the y direction and by a $0 - \pi$ distribution $I_{0\pi}(z)$ in the z direction. The top hat distribution is defined as

$$I_{\text{th}}(y) \propto \begin{cases} \exp \left[- \left(\frac{|y| - w_F}{w_R} \right)^2 \right] & |y| > w_F \\ 1 & |y| \leq w_F \end{cases} \quad (3.3)$$

where we have defined $2w_F$ as the length of the flat region and w_R as the length of the ramp-up. The $0 - \pi$ distribution is given by (cf. Kircher's thesis [12])

$$I_{0\pi}(z) \propto \text{erfi} \left[\frac{z}{w_e} \right]^2 \exp \left[-2 \left(\frac{z}{w_e} \right)^2 \right] \quad (3.4)$$

where $\text{erfi}(z) = -i \text{erf}(iz)$ is the imaginary error function and w_e an appropriate length scale. It is possible to notice that the erfi distribution has two peaks distanced by $2w_e$.

Since the two variable (y, z) of the intensity distribution $I(y, z)$ are theoretically independent, we can gain some first information looking at the integrated distribution of the intensity along the two axis

$$I_z(y) = \int dz' I(y, z') \quad (3.5)$$

$$I_y(z) = \int dy' I(y', z) \quad (3.6)$$

and fitting the respective distributions $I_{\text{th}}(y)$ and $I_{0\pi}(z)$. This is what was done, for example, in Fig. 3.10d, for which we have found a flat region length $2w_F$ of 42.1 μm and an erfi distribution with the two peaks distanced by $2w_e = 19.1 \mu\text{m}$.

The integrated intensity $I_z(y)$ could also be used to calculate a first quantity useful to quantify the "flatness" of the top hat, the so-called peak-to-peak (P2P). The P2P is simply defined as the minimum intensity in the flat region divided by the maximum

$$\text{P2P} = \min_y(I_z(y)) / \max_y(I_z(y)) \quad |y| < w_F \quad (3.7)$$

The closer the P2P is to one, the flatter the top hat distribution is.

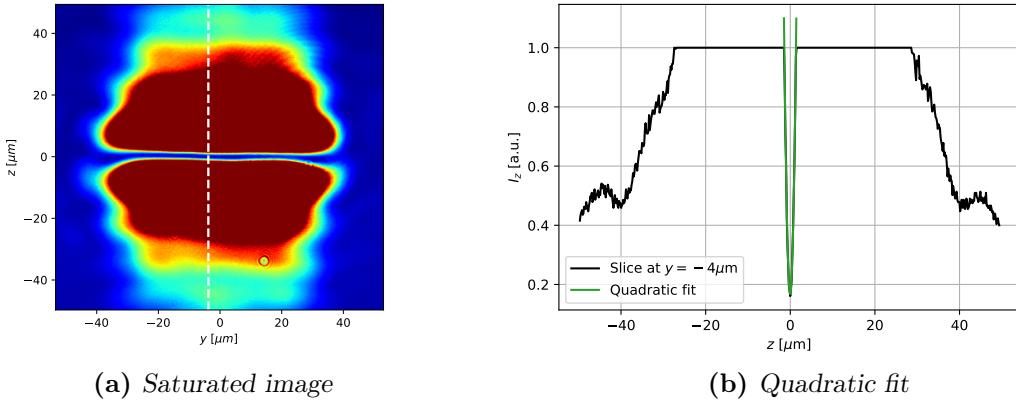


Figure 3.11: Example of the quadratic fit of a slice of a saturated image. The slice is taken at $y = -4 \mu\text{m}$.

Local behaviour

Even if the previous analysis gives us a good understanding of the global characteristics of the intensity distribution, it fails to be precise about the exact behaviour at the point we are mostly interested in: the central region. Since the atoms will be trapped in this region, ideally in a 2D space, they will only feel the local potential near $z = 0$. It is therefore important to characterize this region with more precision.

We have already mentioned in Section 2.2.3 that three important quantities for the characterization of the phase plate are the darkness $D(y)$, defined in Eq. (2.17), the trapping frequency $\omega_z(y)$, defined in Eq. (2.18), and the effective potential $U(y)$, defined in Eq. (2.20). If these three quantities are evaluated for every y , their mean and their variation will give us information on the darkness of the region, on the strength of the trapping potential and on the uniformity of the potential.

To compute these quantities, using the saturated picture, we fitted a parabola in the z direction for every y . We then used the fitted coefficients to compute the trapping frequency, the darkness and the effective potential. An example of a fit is shown in Fig. 3.11.

3.2.2 Results

Pictures were collected for different beam sizes and different distances from the focus. In total, seven beams with diameters between $\approx 4.8 \mu\text{m}$ and $\approx 5.5 \mu\text{m}$ were considered. For every beam size, seven pictures at seven different distances from the focus were taken. Between every picture, the imaging system was moved by $50 \mu\text{m}$. We defined the focused image as the one where the peaks found by integrating the intensity along the y direction were the closest. In practice, after fitting the $0 - \pi$ distribution $I_{0\pi}$ to $I_y(z)$, we chose the image for which w_e was minimized (see Eq. (3.4) in Section 3.2.1). An overview of the results is shown in Fig. 3.12.

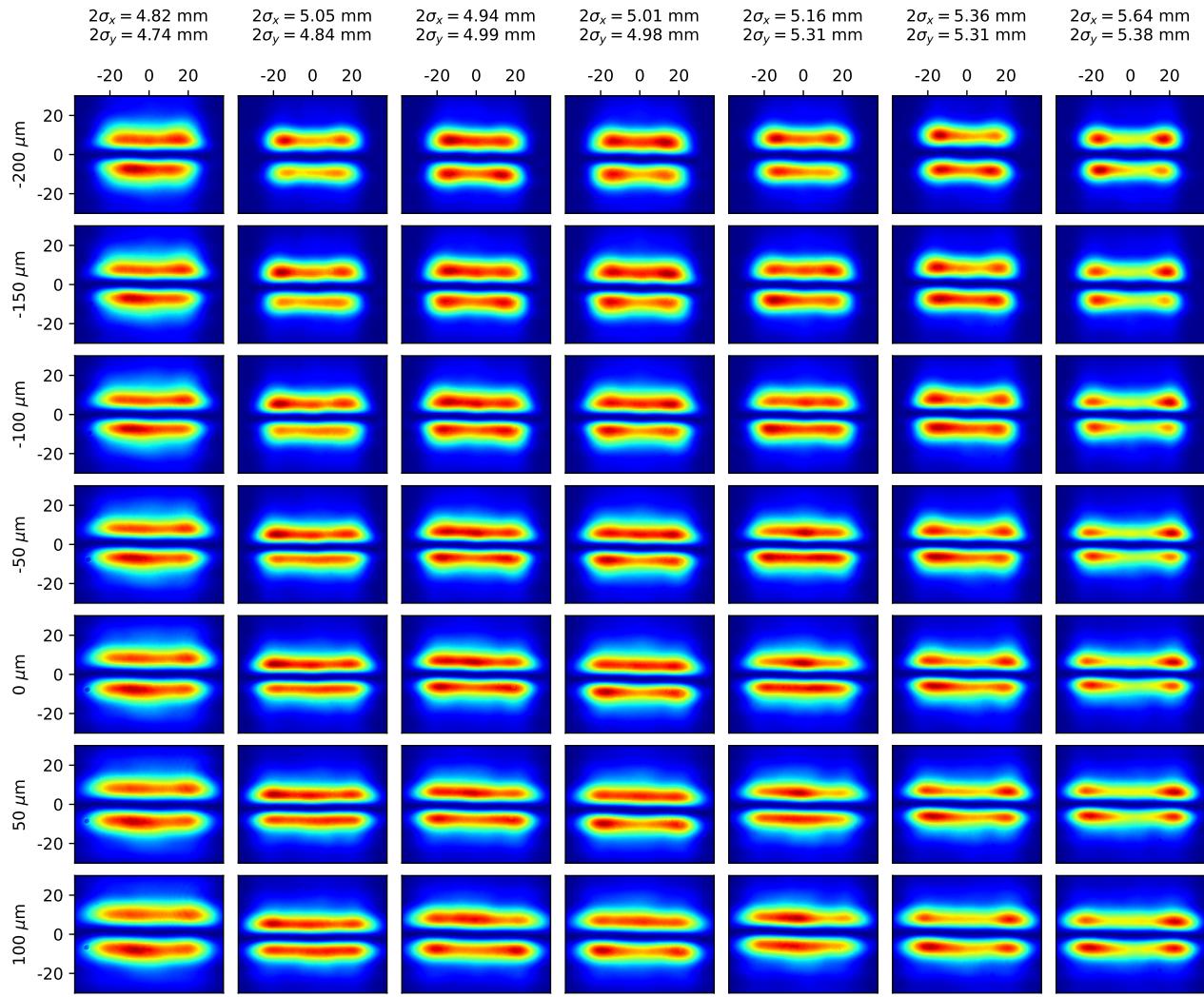


Figure 3.12: Overview of the intensity distribution generated by beams of different diameters and at different focal points. The diameter of the beam along its two main axes are shown on top, while the distance from the focus is indicated on the left. The dimensions of the pictures, shown on the axes, are expressed in micrometers.

Analysis along the focus

We first present an analysis of the result of the phase plate modulation at different distances from the focus. Below, we discuss the case of the light sheet generated by a beam with a diameter of 5 mm (third column in Fig. 3.12). An overview of the results is shown in Fig. 3.13.

First, we computed the characteristic sizes of the light sheets, namely the length of the flat region $2w_F$ and the distance between the peaks $2w_e$. The result is shown in Fig. 3.13a. We notice that the peak distance is minimized for a particular position of the imaging system, which we identified as the focus. On the other hand, the length of the flat region seems to grow linearly while moving along the focus. Then we shifted our attention to the trapping frequency ω_z and its relative variation along the y direction $\Delta\omega_z/\omega_z$. The result, shown in Fig. 3.13b, confirms that the focus is well-defined, since at that point ω_z is maximal and its variation minimal. We also computed the average darkness D , shown in Fig. 3.13d. From the plot, we notice that the darkness increases along the focus. This means that the closer to the phase plate we look, the darker the central region is.

To evaluate the uniformity of the light sheet, we computed three parameters. The first is the P2P, defined before in Eq. (3.7) and plotted in Fig. 3.13c. We notice that it seems to grow, approaching one, while moving away from the focus. This would indicate an intensity distribution that gets more uniform far from the focal point. Another way to look at the uniformity of the distribution is to look at the position of the darkest point in the central region. These points are shown in Fig. 3.13e as a white line for the focused image. The standard variation Δz_D of their z coordinate, calculated along the y direction, is reported in Fig. 3.13c, scaled by w_e . We notice that the uniformity evaluated in this way has an opposite behaviour compared to the P2P. In fact, the further we move away from the focus in the direction that maximizes the P2P, the more the vertical position of the darkest points varies. This implies that the atoms would not move in a straight line, but they would follow an irregular path. The third parameter used to evaluate the uniformity of the light sheet is the difference ΔU between the highest and the lowest effective potential felt by the atoms in the flat region, as defined in Eq. (2.20). Surprisingly, this difference has a maximum at the focal point. It is also interesting to notice that it has an order of magnitude of 5 μK , not negligible compared to the energies involved in our system. An example of the trend of U and ω_z along the y direction for the focused image is also presented in Fig. 3.13f.

Analysis of the focused images

After analysing the behaviour of the phase plate at different distances from the focus, we shifted our attention to the influence of the beam size. For this, we only considered focused images (fifth row of Fig. 3.12). For these images, we computed the same quantities as above. The results are shown in Fig. 3.14.

The characteristic dimensions of the light sheet w_F and w_e can be observed in Fig. 3.14a. We notice that the length of the flat region increases with the diameter of the beam, going from a minimum of around 30 μm for a beam of 4.8 mm to a maximum of around 45 μm for a beam of 5.5 mm. This size should be compared with an expected width of 40 μm for a beam of 6 mm. On the other hand, the distance between the two peaks in the z direction shows an

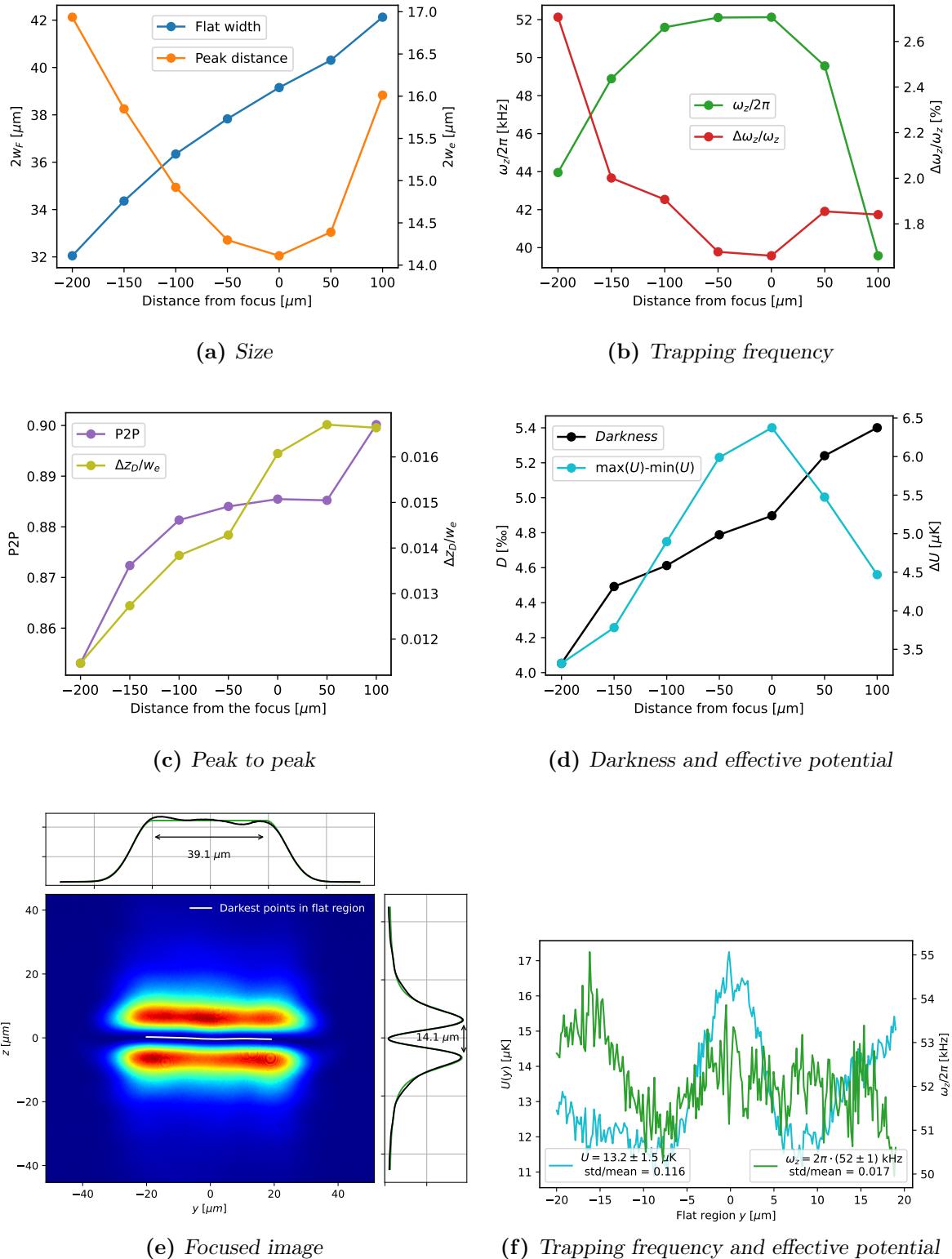


Figure 3.13: Analysis of the images across the focus for a beam with a diameter of 5.0 mm. The images (a)-(d) show the dependency of various parameters on the distance from the focus. Picture (e) shows the focused image and picture (f) the variation of the trapping frequency and the effective potential along the y direction for the focused imagesetter.

opposite behaviour, decreasing with the increase of the beam diameter.

The behaviour of the trapping frequency, shown in Fig. 3.14b, also shows a clear dependence on the beam diameter. We notice that both its mean value ω_z and its relative variation $\Delta\omega_z/\omega_z$ increase for bigger beams. Moreover, we observe that for all the tested diameters ω_z is above $2\pi \cdot 45$ kHz, therefore enough to trap the atoms in a 2D space. The dependence of the average darkness D is reported in Fig. 3.14d. In this case, we do not observe a clear relation between the two. For all the beams, we measure a darkness of the order of 4-5 %. This suggests that to optimize the darkness the alignment of the setup is more important than the size of the beam.

The uniformity of the light sheet could be evaluated looking at the P2P, at the variation of the position of the darkest points Δz_D and at the difference ΔU . The first two parameters clearly show a higher flatness for smaller beams, with a smaller variation $\Delta z_D/w_e$ and a P2P closer to one. This is also in agreement with what was observed for the trapping frequency, whose variation was smaller for smaller beams. The data for the potential difference ΔU is less clear, but still compatible with the same conclusions. In particular, we notice that the potential variation is of the order of $10 \mu\text{K}$, so not negligible if compared to the energies involved in the system.

3.2.3 Additional considerations (appendix?)

Below, we present some smaller findings that have proven to be relevant during the characterization process. It may be useful to take them into account when trying to build and align the final setup.

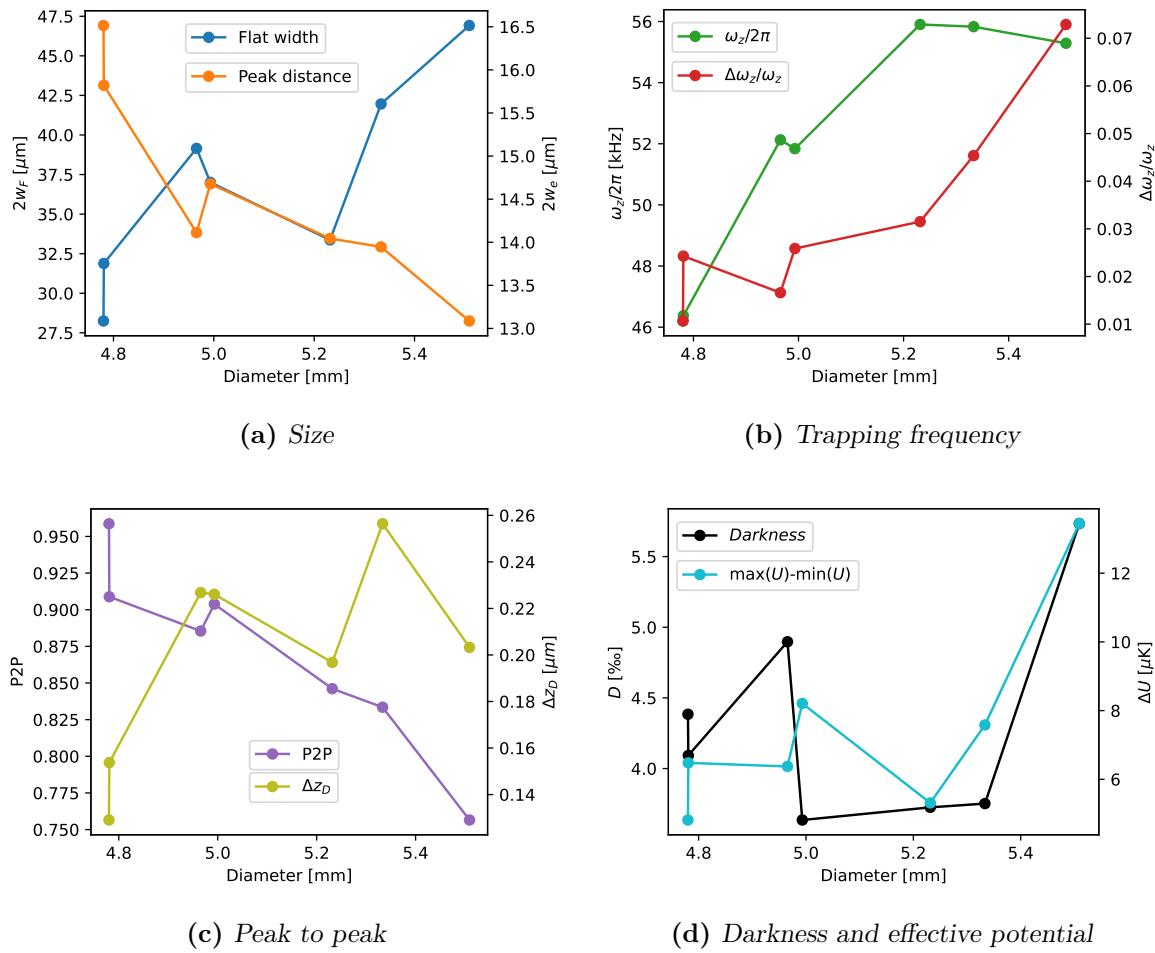
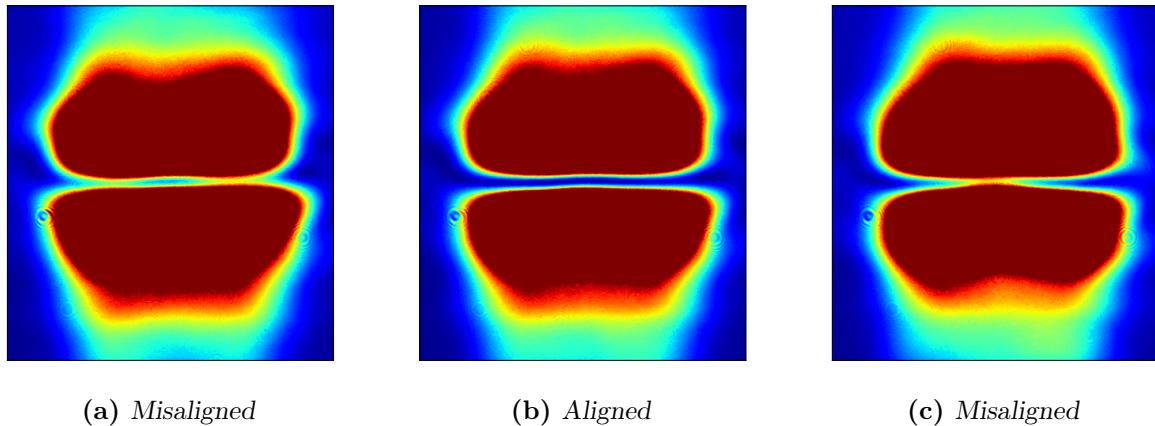
Alignment of the phase plate

In order to characterize the phase plate, the setup had to be correctly aligned. The most important alignment procedure was assuring that the beam hit the centre of the phase plate, in particular in the vertical direction. An incorrect alignment resulted in a central region with bright areas, that would suppress the transport of the atoms.

To align the phase plate, the intensity distribution was observed with a camera set with a long exposure time. Most of the points of the resulting image were saturated, but not the ones in the central region. Acting on a screw that moves the phase plate vertically, it is possible to optimize the darkness in the central region. An example of aligned and misaligned phase plates is presented in Fig. 3.15.

Singlet or achromatic focusing lens

It was found that the quality of the focusing lens placed after the phase plate is essential for the final result. In particular, we compared the use of a singlet lens and of an achromatic lens. Both lenses had the same focal length of 100 mm and the beam incident on the phase was also the same. The result is displayed in Fig. 3.16. It is clear that the use of an achromatic lens greatly improves the result. The intensity distribution obtained with the achromatic lens is more uniform ($\text{P2P} = 0.86$), compared to the one generated by the singlet lens ($\text{P2P} = 0.76$).

**Figure 3.14:** Analysis of the focused images for different sizes of the input beam.**Figure 3.15:** The vertical alignment of the phase plate is performed looking a saturated picture and optimizing the darkness at the centre.

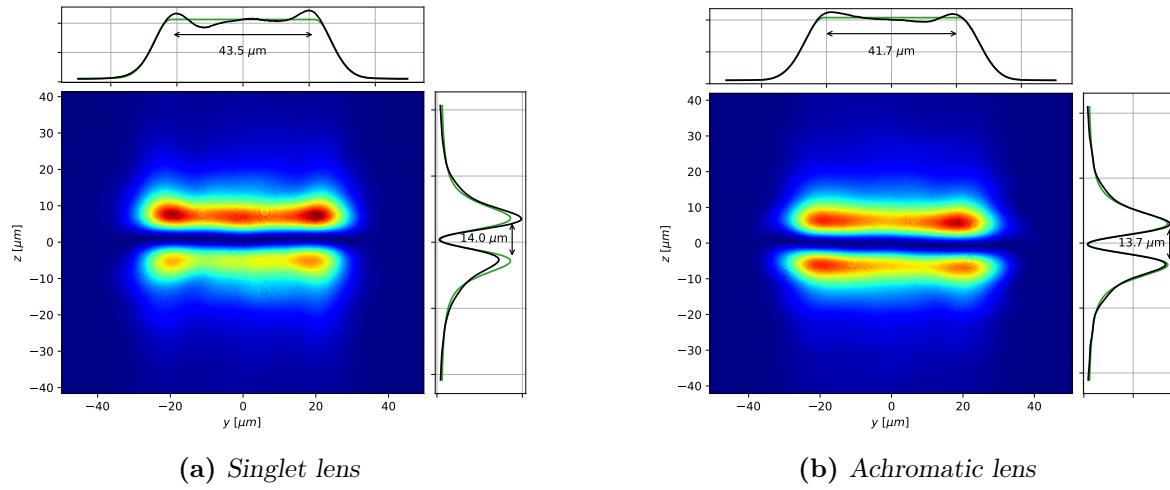


Figure 3.16: Intensity distribution for the same beam, but using two different lenses after the phase plate. The first lens (a) is a singlet lens and the second (b) an achromatic lens.

Use of a pinhole in the telescope

In order to try to reduce the aberrations introduced by the telescope, the usage of a pinhole placed between the two lenses was investigated for small and large beams. In Fig. 3.17 we present the result for the $-50/150$ telescope. It is important to notice that since the first lens is a diverging lens, the pinhole is almost completely open, and in fact partially “cuts” the beam. However, even in this unusual configuration, the pinhole seems to have an effect. In particular, as it can be observed from the figures, the use of the pinhole reduces spherical aberrations and contributes improving the final result, especially for larger beams. On the other hand, for beams close to the desired size (around 5 mm), it does not seem to have a huge impact on the final intensity distribution.

Fixing the horizontal dark line

In Section 3.2.1 it was explained how we computed the quantities used to characterize the phase plate. In particular, for quantities like the trapping frequency or the darkness, we fitted a parabola along the z direction for every point in the y direction, and extracted the dependency of the parameters on y (e.g. $\omega_z(y)$, $D(y)$...). For this process, the parabolic function used in the fit had three free parameters, namely the three coefficients of a second order polynomial. This means that the vertex of the parabola was allowed to have an arbitrary height (used to compute the darkness D) and position (used to compute Δz_D).

Another possible approach is to fix the z position of the vertex z_D , and fit a function with only two free parameters. In this case, it is logical to set z_D to the position of the minimum of the integrated intensity $I_y(z)$, found fitting the distribution $I_{\text{th}}(z)$ (cf. Section 3.2.1). The result is shown in Fig. 3.18. We notice that the irregularity of the intensity is moved from a variation in the z coordinate of the minima to a bigger variation of the trapping frequency and effective potential along the y direction. In particular, both the trapping frequency and

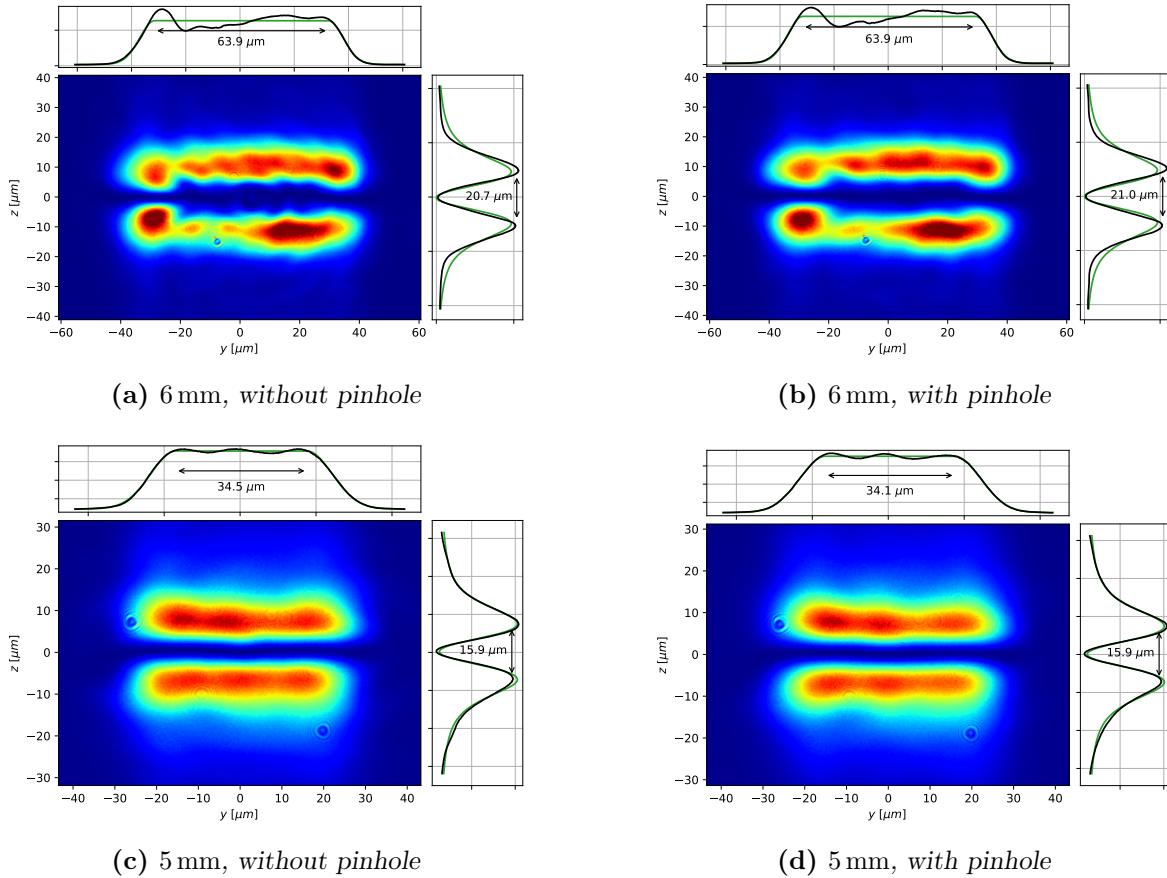


Figure 3.17: Influence of the use of a pinhole in the telescope $-50/150$ for two beam sizes.

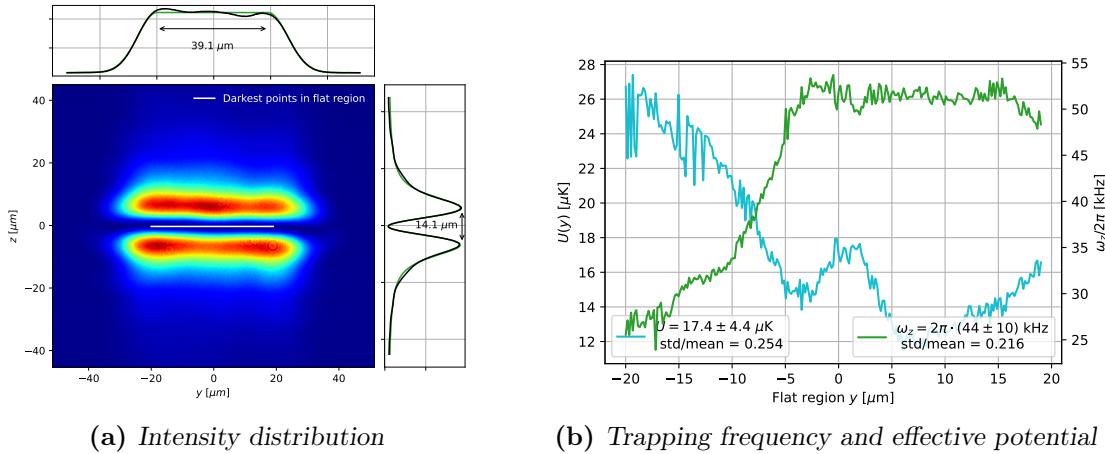


Figure 3.18: Analysis of the focused image for a 5 mm beam keeping the coordinate of the position of the dark central region fixed. The result should be compared to Figs. 3.13e and 3.13f.

the effective potential show variations larger than a factor of two (between 25 and 50 kHz for ω_z and between 12 and 26 μK for U). We consider this method inferior to the one described above, since in reality the atoms would move in the region of lower potential, so following an irregular path, rather than in a straight line.

Chapter 4

Conclusions

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