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# **Spin Selective Imaging of Ground State Potassium Atoms**

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# Spin Selective Imaging of Ground State Potassium Atoms

Robin Eberhard

**Abstract**

Abstract

**Zusammenfassung**

Abstract



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# **1. Introduction**



## **2. Motivation**



Better head-line

### 3. Chopping

In the experiment, optical tweezers are used to generate two-dimensional arrays of single atoms. By using optical tweezers, each atom can be addressed individually and therefore parameters such as inter-atomic distances and trap depths can be adjusted freely. In order to load atoms into the optical tweezers, they have to undergo some cooling stages first. Being vaporized from a solid sample of  $^{39}\text{K}$ , the atoms move towards the center of a vacuum chamber through a Zeeman slower. The slower cools the atoms longitudinally, after which they are trapped and compressed in a magneto-optical trap (MOT). Atoms are already cooled inside the MOT, however the temperature limit is the doppler limit, therefore gray molasses and then a normal molasses is used in order to cool even further. When the atoms have reached their minimal temperature, they will be loaded into the spatial light modulator (SLM) tweezers. However, loading directly from the molasses proves difficult, due to the large light shifts of the D2 excited state, making it highly anti-trapped. To overcome this issue, trapping and cooling beams can be alternated [1]. By having the frequency of alternating the beams much larger than the trapping frequency, the atoms see an effective, averaged, trap. This way, they don't scatter near-resonant photons, effectively eliminating light shifts.

So far, alternating between molasses cooling and trapping light, called chopping, was achieved using an acousto-optical modulator (AOM). However, the switching speed in an AOM is limited by the speed of sound in the medium (here,  $\text{TeO}_2$  has  $4.2 \text{ mm } \mu\text{s}^{-1}$ ) and results in a chopping frequency of 1.4 MHz, governed by the AOM with the slowest rise time, which can be seen in Figure 3.1. By increasing the chopping frequency, the atoms will heat less during each trapping cycle. However, more importantly, as the atoms only see an averaged trap given by the duty cycle of the trapping beam, this means the relevant parameter for trapping is the average power per chopping cycle. This means, if the pulse shape during the chopping is better, more laser power can be used per tweezer. This in turn means, more tweezers can be deployed, as the average power increases when the pulse shape is more rectangular. Figure 3.1 shows how the pulse shape is limiting the average power during the cooling cycle as well as during trapping.

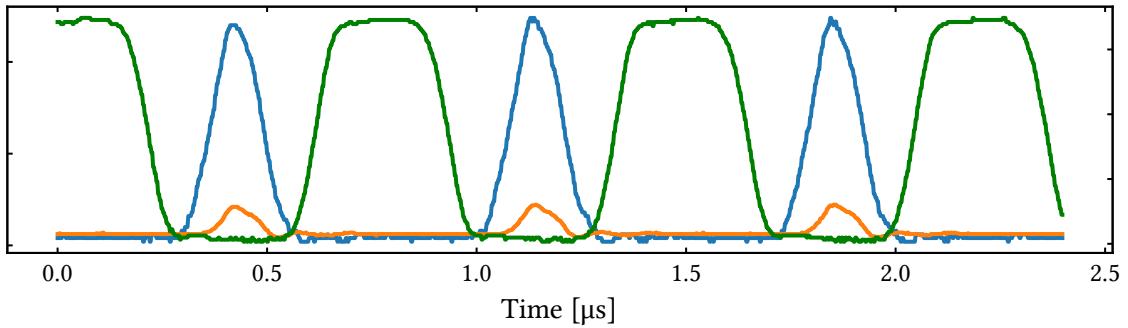


Figure 3.1.: Chopping in the experiment. Laser beams alternate between each other, with blue being the MOT cooler, orange the MOT repumper and green the SLM tweezer. The amplitude of the MOT beams is limited due to the risetime of the AOMs. The label on the y axis was omitted, since the MOT beams have been rescaled to be the same scale as the SLM tweezer.

Achieving larger duty cycles and higher chopping frequencies is possible by using electro-optical modulators (EOMs), which are not limited by acoustic waves. The optical medium is modulated using electric fields, and in fact, can be switched as fast as common condensators. Light entering the modulator will have its polarization turned, depending on the electric field that is applied. Therefore, in the following, polarization of electro-magnetic waves is discussed briefly, which is followed by the main effect governing the devices tested in this thesis — the pockels effect. The devices are then evaluated by filtering one polarization component and the rise times and extinction ratio measured. The new system will be able to switch with rise times on the order of nanoseconds, improving the current system by at least two orders of magnitude.

### 3.1. Theory on Polarization

Switching laser beams using EOMs means turning and filtering the polarization of the light. Therefore in the following is discussed the theory behind polarized monochromatic electromagnetic waves, leading to the pockels effect governing EOMs.

Polarization of electromagnetic waves is understood as the orientation of the wave in space, transverse to the direction of movement. In general, a wave travelling along the z-axis can be oriented somewhere in the x-y plane. Therefore, writing the electric field component of the light in this basis takes the following form:

$$\mathbf{E}(\mathbf{x}, t) = E_x \cos(kx - wt + \phi_x) \mathbf{e}_x + E_y \cos(ky - wt + \phi_y) \mathbf{e}_y. \quad (3.1)$$

Here,  $k$  and  $w$  refer to the wave number and frequency respectively. Depending on the amplitudes  $E_x$  and  $E_y$  and the phases  $\phi_x$  and  $\phi_y$ , the wave can be in different polarization states. If it is not possible to write the wave in this basis, the light is unpolarized. Otherwise, it is **linear**, when either one of the amplitudes  $E_x$  or  $E_y$  is zero or when the phase difference  $\Delta\phi = \phi_x - \phi_y$  evaluates to 0 or  $\pi$ . It is **circular**, when the phase difference  $\Delta\phi = \pm\pi/2$  and the amplitudes are the same,  $E_x = E_y$ . In any other case, the wave is **elliptically** polarized.

By changing the phases of the wave relative to each other therefore gives the ability to affect the polarization. Light traversing a medium will accumulate a phase shift, depending on the refractive index, which affects the speed of light in the medium. Therefore, media that have different refractive indices  $n_x, n_y$  along the two axes  $x$  and  $y$  means changing the relative phases of the wave:

$$\phi_x(z) = k_0 n_x z \quad (3.2)$$

$$\phi_y(z) = k_0 n_y z \quad (3.3)$$

where  $k_0$  is the free space wave vector of the light. Then a device that retards the phase difference  $\Delta\phi$  by  $\pi/2$ , which is a quarter of the wavelength, can change linearly polarized light to circularly polarized light (or vice-versa) and is therefore called a  $\lambda/4$  waveplate. Similarly, if the phase difference is changed by  $\Delta\phi = \pi$ , or a half wavelength, then we can turn linear polarization around a given axis or change the orientation of circularly polarized light. This is then called a  $\lambda/2$  waveplate. In the experiment, linearly polarized light will enter the EOM, which will act as a  $\lambda/2$  waveplate, turning the polarization by  $90^\circ$ , making it easy to filter unwanted polarization components and switching the light on and off.

## 3.2. Electro-optical modulators

Light travelling through a material generally has a speed smaller than the speed of light. This property of the material is the refractive index and is the ratio of the speed of light in the material to the speed of light in vacuum. Materials can change their refractive index by being exposed to an electric field, which in EOMs is generally a crystal connected to two

electrodes. There are two prominent electro-optical effects that need to be distinguished. If the refractive index changes linearly with the electric field, the effect is called Pockels effect and the EOM is called a pockels cell. The effect is discussed in the following and the pockels cells evaluated afterwards.

### 3.2.1. Pockels effect

As was motivated in the previous section, the goal of modulating light polarization is to change the relative refractive index of a medium in two axes. Following the argumentation from the book Fundamentals of Photonics [2], the pockels effect can be found by evaluating the refractive index with respect to the electric field applied to the modulator. Writing this as  $n(E)$  and applying a taylor expansion, we get the following expression:

$$n(E) = n_0 + \frac{dn}{dE}E + \mathcal{O}(E^2) \quad (3.4)$$

The pockels effect is the linear dependence of the refractive index to the electric field, therefore higher orders are neglected. The prefactor  $dn/dE$  can be found from the change of electric impermeability  $\Delta\eta$ , which is the ability of a material to be penetrated by an electromagnetic field. From

$$\eta = \frac{1}{n^2}, \quad (3.5)$$

we get

$$\Delta\eta = \frac{d\eta}{dn}\Delta n = -\frac{2}{n_0^3} \frac{dn}{dE}E = \mathfrak{r}E. \quad (3.6)$$

This results in the quantity  $\mathfrak{r} = -\frac{2}{n_0^3} \frac{dn}{dE}$ , which is called the Pockels coefficient given in units of  $\text{m V}^{-1}$ . It can be measured by evaluating the refractive index of the material:

$$n(E) = n_0 - \frac{1}{2}\mathfrak{r}n_0^3E. \quad (3.7)$$

As was seen in Equation 3.2, the refractive index directly affects the phase shift, which in turn changes the polarization of the light wave. Combining the results leads to an equation using parameters typically found in EOMs:

$$\phi = k_0 L n \quad (3.8)$$

$$= k_0 L n_0 - \frac{k_0}{2} L \mathfrak{r} n_0^3 E \quad (3.9)$$

$$= \phi_0 - \frac{k_0}{2} L \mathfrak{r} n_0^3 E \quad (3.10)$$

$$= \phi_0 - \frac{\pi}{\lambda_0} L \mathfrak{r} n_0^3 E \quad (3.11)$$

where the relation  $k_0 = 2\pi/\lambda_0$  of the wave number was used.

The pockels cells in this application act as dynamic wave retarders, therefore with the results from Section 3.1, we can tune the phase difference  $\Delta\phi = \phi_x - \phi_y$  along the axes  $x$  and  $y$  by applying an electric field. With the correct parameters, the phase difference lets the EOM act as a  $\lambda/2$  or  $\lambda/4$  waveplate. The following relations will help find the main formula governing pockels cells, resulting in the voltage that needs to be applied to the EOM in order to turn the polarization a given amount.

Labeling the refractive index in two dimensions as:

$$n_x(E) = n_{0,x} - \frac{1}{2} \mathfrak{r}_x n_{0,x}^3 E \quad (3.12)$$

$$n_y(E) = n_{0,y} - \frac{1}{2} \mathfrak{r}_y n_{0,y}^3 E \quad (3.13)$$

then the phase difference becomes:

$$\Delta\phi = \phi_{0,x} - \phi_{0,y} - \frac{\pi}{\lambda_0} E L \left( \mathfrak{r}_x n_x^3 - \mathfrak{r}_y n_y^3 \right) \quad (3.14)$$

$$\Delta\phi = \Delta\phi_0 - \frac{\pi}{\lambda_0} E L \left( \mathfrak{r}_x n_x^3 - \mathfrak{r}_y n_y^3 \right). \quad (3.15)$$

The next step is to replace the electric field by a voltage that can be applied to the pockels cell. For this, two electrodes are connected to the EOM, separated by a distance  $d$ . This gives the electric field as  $E = V/d$ . This quantity is replaced into Equation 3.17 and by realizing that the phase is unitless, all other prefactors of the voltage can be combined into one quantity, called the half-wave voltage  $V_\pi$ :

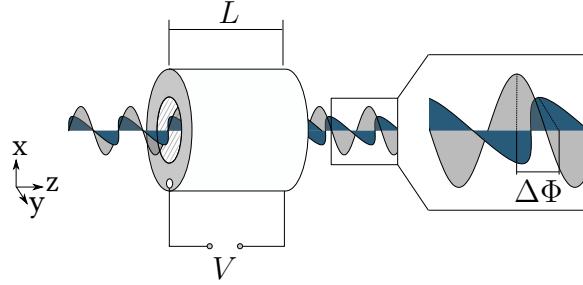


Figure 3.2.: Schematic view of light passing through an EOM of length  $L$ . The electrodes are positioned on the front and back side of the modulator, the same faces the light enters and exits. The light exiting the EOM has a relative phase shift  $\Delta\Phi$  depending on the change of refractive index due to the applied voltage  $V$ .

$$V_\pi = \frac{d}{L} \frac{\lambda_0}{\mathfrak{r}_x n_x^3 - \mathfrak{r}_y n_y^3}. \quad (3.16)$$

Thus, the phase difference can be rewritten as:

$$\Delta\phi = \Delta\phi_0 - \pi \frac{V}{V_\pi}. \quad (3.17)$$

With this it is clear, that applying the voltage  $V_\pi$ , the pockels cell will act as a lambda-half waveplate. A visual representation of the modulator and the light passing through it is given in Figure 3.2, highlighting the change in relative phase of the two components of the electro-magnetic wave.

We have seen, how applying a voltage to an electro-optical medium changes the refractive index and therefore affects the phase of an electromagnetic wave. By having two refractive indices in two axes, whose relative change depends on the applied voltage, it is therefore possible to modify the circularity and linearity of the polarization in an electro-optical modulator.

### 3.2.2. Driving a pockels cell

With an understanding of the pockels effect governing the EOMs tested in this thesis, it is now required to have electronics controlling voltages on the pockels cell. Having good electronics is important, as using pockels cells for switching of laser light means that rise

and fall times are a direct consequence of the switching electronics used to apply the respective voltages to the pockels cell. However, materials suitable for use as EOMs, such as  $\beta$ -bariumborate (BBO) and rubidium tanyl phosphate (RTP) have half-wave voltages in the kilovolt-regime, meaning not only does the hardware need to be able to handle high voltages, but it is also necessary to switch the voltages on a fast timescale. This will turn out to be on the order of nanoseconds for the drivers used here (by BME Bergmann).

The pockels cell drivers discussed in the following contain the switching electronics necessary to drive the EOMs. Moreover, it contains viewports for the laser light, such that the pockels cell can be integrated into the driver to not expose the high voltage to any parts of the experiment but the modulators. The driver has an input for the high voltage and option for watercooling in order to compensate temperature instabilities on the pockels cell. Furthermore, it contains four inputs, in order to have full control over the switching of the voltages. This means, the EOMs can be switched on and off by applying TTL signals to the inputs of the driver.

Therefore, it is necessary to understand the switching logic used inside the driver, in order to correctly drive the pockels cell and therefore turn the polarization of the light. Schematically, the driver is divided into the four switches mentioned above, that are controlled from the user: ON A, ON B, OFF A and OFF B. Two switches are connected to either side of the pockels cell, so A controls one electrode and B the other. Most importantly, the ON X and OFF X (X referring to either A or B) switches work exclusively, so sending a high to ON X will also send a low to OFF X and vice-versa. It is then possible to apply either a positive high voltage or a negative high voltage, depending on the state of the switches. For full identification of the circuit, which is given in Figure 3.3, the side containing the positive voltage information is called high side and similarly the side containing the negative voltage information is called low side. The figure shows switching logics for two different drives used in the experiment. These are named by the manufacturer as dpp-type and bpp-type.

A requirement for our experiment is to have the EOMs work consistently. This means it is preferable to only apply one type of voltage, because it can not be guaranteed that applying the same voltage with different polarity results in the same shift in polarization. This is due to the high fidelity of the pockels cell with respect to the input polarization and therefore highly depends on the alignment of the pockels cell. The diagram in Figure 3.4 shows pulses applied to the switches on the A and B side, necessary to only drive positive voltages to the pockels cell.

For the bpp-type driver, this is straightforward, as closing high side A and low side B gives

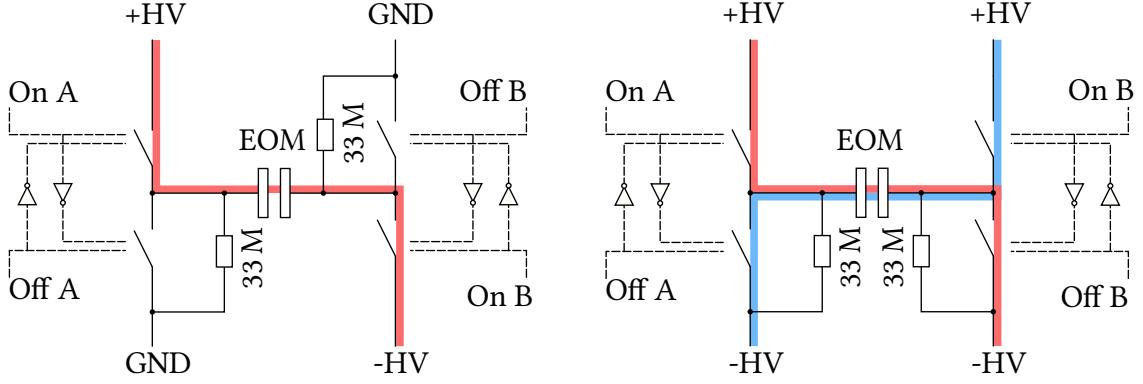


Figure 3.3.: Schematic of the high voltage switches used inside the bpp-type (left) and dpp-type (right) pockels cell driver from BME Bergmann. Not-Gates on both A and B sides ensure that there is always a potential over the pockels cell. The blue and red paths indicate the connection to apply a positive and negative voltage over the pockels cell respectively.

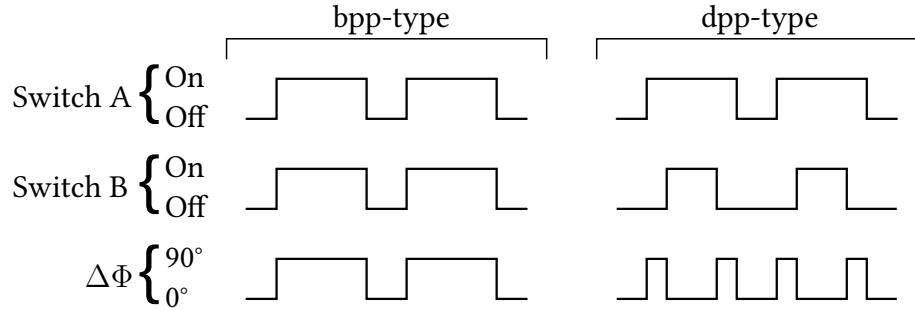


Figure 3.4.: Timing diagrams for the pockels cell drivers to turn the polarization of the EOM 90°. To get a positive high voltage from the bpp-type driver, the A and B side ON/OFF switches are flipped simultaneously. The dpp-type driver is more flexible, since it also allows negative voltages. The timings displayed here are an example to only apply positive voltages across the pockels cell.

a positive voltage across the EOM and the inverse connects ground to ground through the EOM, giving zero voltage. The dpp-type driver on the other hand, has high and low voltages on either side of the pockels cell. Therefore, the sequence that results in positive and then no voltage across the EOM is, to close high side A and low side B switch, resulting in a positive voltage across the EOM. Afterwards, connecting high side A and high side B gives the same voltage on either side of the pockels cell, resulting in a net zero voltage. After this point, low side B is closed again, giving the same state as before. In the timing diagram, the low side A switch would be closed at this point. It is possible to keep high side A closed the entire time, however it is recommended in the documentation to alternate both switches in order to relax their states.

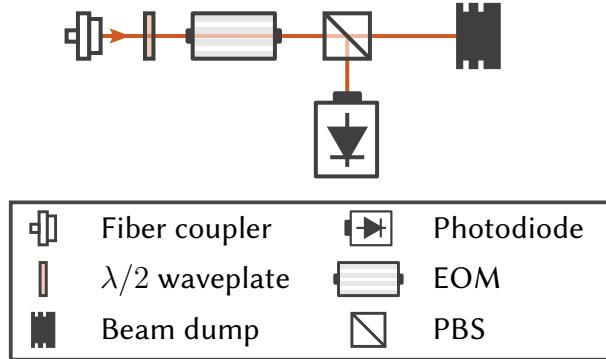


Figure 3.5.: The efficiency of the EOMs were evaluated by setting the polarization of the incoming light either horizontal or vertical using the waveplate. The pockels cell will then periodically turn the polarization 90°, which can be seen by measuring the voltage on the photodiode.

### 3.2.3. Evaluation of Leysop Pockels cells

In the following is discussed two pockels cells (from Leysop Ltd.). The EOMs in contrast to the AOMs in the current setup allow for longer duty cycles for the tweezer light. This means, the laser light needs to be switched on and off, which is achieved in pockels cells by exploiting the fact, that linearly polarized light can be filtered out. This is best achieved by placing a polarizing beam splitter (PBS) directly after the modulator as seen in Figure 3.5. This way, the setup can be configured such that applying no voltage means light passes through the beam splitter, while applying  $V_\pi$  means the light gets reflected 90° off the beam splitter, save for a fraction of light, given by the extinction ratio of the beam splitter (typically for the ones used in the experiment, the extinction ratio is about 200:1).

Two pockels cells were characterized by placing a photodiode on one end of the beam splitter. The EOMs are labeled by the material of their nonlinear crystal, RTP and BBO. Their characteristics are summarized in Table 3.2.3, where half wave voltage is given for 1064 nm light. Both EOMs are used in the chopping discussed earlier, where the RTP crystal will be used for the 770 nm. Consequently, BBO will be for the 1064 nm tweezer light.

The first measure is finding the rise and fall times of the EOMs. Light whose polarization component was filtered through the PBS arrives at the photodiode. For sufficiently high bandwidths on the photodiode and oscilloscope, the flanks of the signal are resolved and the rise time can be evaluated by fitting the function

$$f(x) = \frac{\text{high}}{1 + \exp(-x/\tau)} + \text{low}, \quad (3.18)$$

	RTP	BBO
Aperture (crystal dimensions)	3 mm	3 mm
Total crystal length (2 crystals)	30 mm	50 mm
Approximate half wave voltage (1064nm)	1.0 kV	2.8 kV
Peak damage threshold (1064nm, 1ns pulse)	$> 1 \text{ GW cm}^{-2}$	$> 1 \text{ GW cm}^{-2}$
Insertion loss	$< 2 \%$	$< 1.5 \%$

Table 3.1.: Characteristics of the two pockels cells with their respective non-linear crystal materials being RTP and BBO. The aperture, damage threshold and insertion loss are given for future reference.

where *high* and *low* refer to the high and low level of the signal respectively, which will come in useful later when evaluating the extinction ratio. The signals in Figure 3.6 were recorded for both EOMs, however from the low number of sampled points it is clear, that the oscilloscope used for the measurement is a limiting factor. Moreover, harmonics appear when the signal has risen to the upper level, indicating that the bandwidth of either the photodiode or the oscilloscope is too low. For this measurement, the oscilloscope (Teledyne Lecroy Wafesurfer 510) has a samplerate of  $10 \text{ GS s}^{-1}$  and a bandwidth of 1 GHz. The photodiode is a home-built model, whose bandwidth has not been evaluated as of yet. The fit can't be applied to the data, due to the low number of points, however an upper bound for the rise time can still be given by measuring the distance between the last point on the lower level and the first point on the upper level. For both crystals, this means that the rise time is at least a fraction of a microsecond. In contrast to the AOMs that are currently in use, this is already an improvement by at least one order of magnitude (see Figure 3.1).

The manufacturer of the pockels cell driver has done independent tests on the same EOMs used here. The data is available on their website [3] and they found rise times for RTP and BBO as 3 ns and 4 ns respectively, which would improve on the AOM setup by three orders of magnitude in rise times.

Moving on from the rise times, it is important to measure how much light is left when the light is supposed to be off, after filtering it from the PBS. The measure in question is the extinction ratio and is evaluated by the ratio of the *high* to the *low* level of the signal. Figure 3.7 shows signals taken for both crystals using the same setup as before. In order to correctly evaluate both levels, it is necessary to note that photodiodes are susceptible to

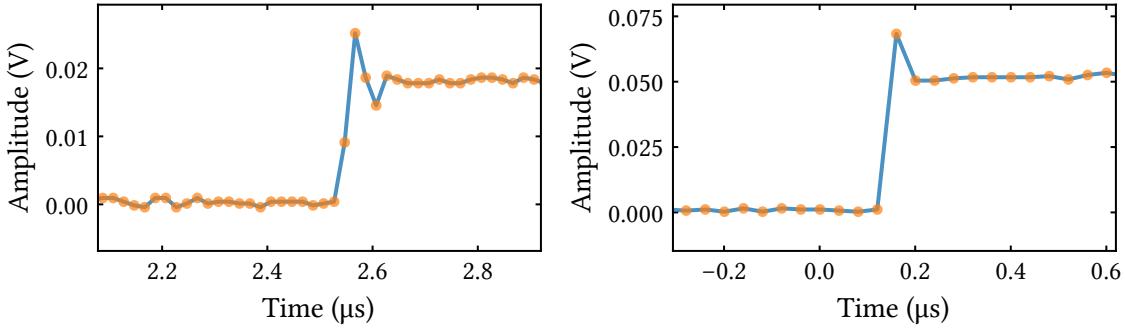


Figure 3.6.: The EOM was turned on, in order to measure rise times. However, the photodiode and oscilloscope both limit the measurement with their bandwidth and sampling rate. However, an approximation to the rise time can be given, by subtracting the last data point on the low level and the first level on the high level, giving at least a fraction of a microsecond for both EOM types.

dark noise, which is electrical noise falsely registered as light. This means a dark image was taken, with the laser beam off, and the mean of the dark image was subtracted from the signals used to evaluate the extinction ratio. The high and low levels are then found by selecting points of the respective level after it has stabilized, the ranges for which are given in Figure 3.7. Not considering the standard deviation on the dark level, already the standard deviation on the low level for both crystals is on the order of the mean, which makes it impossible to give an upper bound to the extinction ratio, the values for both are summarized in the following table.

	<i>upper</i>	$\sigma_{upper}$	<i>lower</i>	$\sigma_{lower}$	<i>upper/lower</i>
RTP	$1.9 \times 10^{-2}$	$6.2 \times 10^{-4}$	$3.7 \times 10^{-4}$	$5.2 \times 10^{-4}$	$5.1 \times 10^1$
BBO	$1.9 \times 10^{-2}$	$8.3 \times 10^{-4}$	$9.6 \times 10^{-4}$	$7.4 \times 10^{-4}$	$5.7 \times 10^1$

However, the lower bound is the mean of the level, which for RTP gives 51 : 1 and for BBO gives 57 : 1. The manufacturer provides an extinction ratio for the RTP crystal of > 200 : 1, however no value is given for BBO. This means, that our measurement is limited by the photodiode and in order to validate the value given by the manufacturer, it is necessary to reduce the dark noise for example by cooling the diode or alternatively, using a faster, low noise photodiode.

As the pockels cell will be used in the chopping, which currently has a frequency of 1.4 MHz, limits for the repetition rate of the EOMs were tested. During this process, it was noted

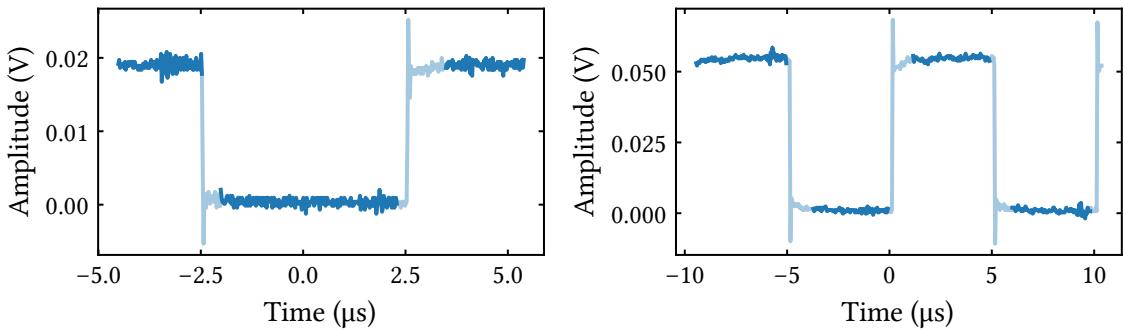


Figure 3.7.: Measurements of extinction ratio for RTP (left) and BBO (right). The highlighted values were used to find the high and low level, by taking their mean. However the uncertainty on the low level is too high to give a fair value on the extinction ratio.

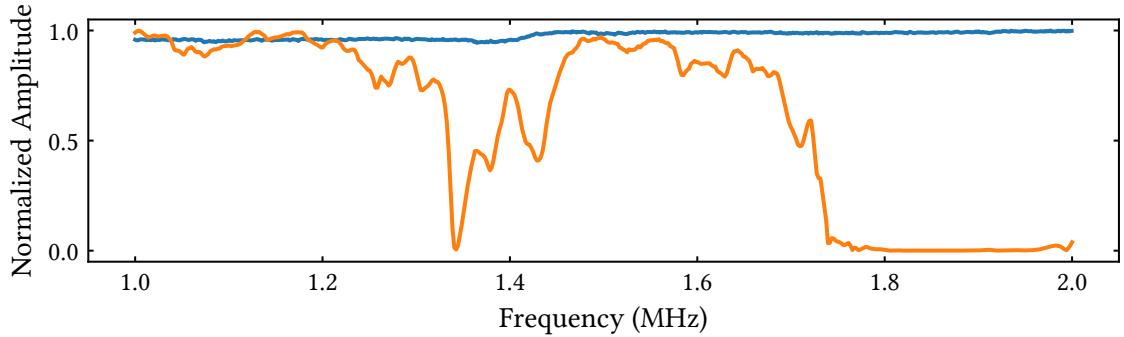


Figure 3.8.: Shown is the amplitude of a laser whose polarization was rotated by a pockels cell and then filtered using a polarizing beam splitter. The frequency is the repetition rate of the voltage placed into the EOM. The two materials are RTP (orange) BBO (blue). The curves are normalized to their maximum value.

that the amplitude of the signal from the pockels cell was inconsistent and in fact, changed depending on the repetition rate. This was most notable in the RTP crystal. To quantize this in more detail, a program was written, that ramped the repetition rate up in 60 s intervals, after which the resulting signal was recorded and the amplitude evaluated. This results in the diagram shown in Figure 3.8, however it needs to be noted, that alternating voltages were applied to the pockels cell, contrary to the argument before. This was found simply, because the behaviour was worse if only one type of voltage was applied. The diagram clearly shows resonant-like behaviour for RTP. This means, that in the future, the chopping will have to be done around 1.5 MHz, where the amplitude of the signal is close to the maximum and therefore loss of laser power is mostly only insertion loss into the EOM.

## 4. Sorting of atoms

### General idea and length

Tweezer arrays are especially suitable to study manybody systems, as arbitrary patterns can be configured, which is not possible when using laser lattices. Before atoms are trapped in tweezers, they are first cooled in optical molasses and are then loaded by making use of chopping. During loading, light assisted collisions result in parity projection of the atoms [4], which effectively heat pairs of atoms out of the trap. This leaves only sites occupied, that originally had odd number of atoms, resulting in a total occupation of 50% of atoms across the tweezer array. It is desired to have a fully occupied grid of atoms each run, however post-selection is unfeasible, as even on a  $3 \times 3$  grid of atoms, the chance of fully occupying the array is only  $0.5^9 = 0.2\%$ .

Consequently, the solution is to rearrange the atoms of the system, which is possible by using optical tweezers and has already been investigated in [5–7]. Initially, the atoms are loaded in SLM-tweezers. The atoms are then transferred into a new tweezer, which adiabatically moves them to new positions, while keeping the rest stationary. In this way, atoms are moved along pre-calculated paths to fill gaps of the pattern. In the following is discussed the sorting of atoms by using acousto-optical deflectors (AODs) as the device of choice for programmatically deflecting a laser beam. Using this device, the beam can be split up, generating tweezers, and also make the beams move along paths to rearrange the atoms into the new pattern.

### 4.1. Acousto-optically deflected tweezers

Being able to quickly change the position of a laser beam is the most fundamental prerequisite of sorting atoms. The process has to happen on short timescales compared to the lifetime of atoms and with high accuracy. In the following is discussed the process of light deflecting off a sound modulated crystal. By applying custom sound waves, it is possible to move a laser beam or split it into multiple beams. The optical element handling the

deflection is called an AOD and works very similar to an AOM. However, in an AOD, the first deflected order is stronger and higher orders are generally not visible.

After going through the theory of acousto-optical deflection, the AODs in question are discussed, following the setup of generating the tweezers needed for the rearrangement of the atoms.

#### 4.1.1. Acousto-optical effect

The acousto-optical effect describes the way optical waves deflect off sound waves in a solid medium, which is generally a crystal. This means, sound waves propagating the crystal modulate the positions of the atoms in the lattice, which in turn affects the refractive index on a macroscopic scale. If the sound wave is a planar wave, then the modulated refractive index is written as a function of position and time [2]:

$$n(x, t) = n - \Delta n_0 \cos(\Omega t - qx). \quad (4.1)$$

Using this relation, the next step is to calculate the deflection angle off the medium. In the following, a short summary is given, the detailed analysis can be found in [2]. Starting from the assumption, that the incident optical wave has a much higher frequency than the sound wave, then the light entering the medium will see the sound waves as stationary and the medium's crystalline shape is given by the sound wave.

Then, Bragg diffraction describes how light moves through the medium, which in turn is used to calculate how light is partially reflected when leaving the medium. To find this quantity, the medium is broken up into slices, off which the optical wave partly reflects, given by the Bragg diffraction. Each slice has a partial reflectance amplitude  $\Delta r$ , depending on the refractive index  $n$  and the angle of the incident optical beam with respect to the medium. The total reflectance amplitude  $r$  can then be found by integrating over all slices and will carry over the dependence on the angle. By maximizing this relation, it is then found, that the angle resulting in the maximum reflectance amplitude is given by the Bragg condition:

$$\sin \theta = \frac{\lambda_l}{2\lambda_s}, \quad (4.2)$$

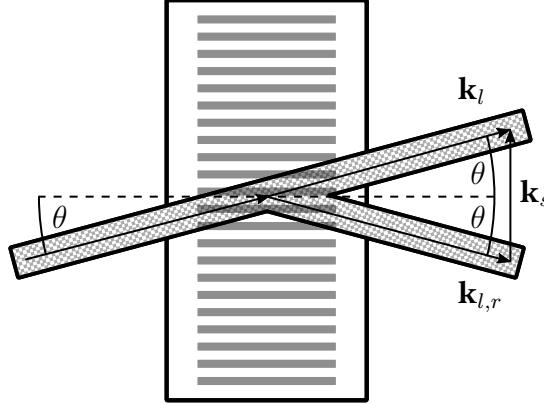


Figure 4.1.: Schematic operation of an AOD. Light waves travelling in direction  $\mathbf{k}_l$  are deflected off the sound waves with direction  $\mathbf{k}_s$ , resulting in a reflected beam  $\mathbf{k}_{l,r}$ . The optical waves is deflected under the Bragg condition, which can be calculated via the vector relation  $\mathbf{k}_{l,r} = \mathbf{k}_l + \mathbf{k}_s$ .

where  $\lambda_l$  and  $\lambda_s$  refer to the wavelength of the light and sound waves respectively.

The maximum of the reflectance amplitude with respect to the angle is very sharp, such that in general, we can say that only if the angle between the wave vectors of the optical wave  $\mathbf{k}_l$  and the sound wave  $\mathbf{k}_s$  matches the Bragg condition will there be a deflected beam. Thus, another way to arrive at the Bragg condition is by finding the trigonometric relation in Figure 4.1. Using

$$|\mathbf{k}_l| = |\mathbf{k}_{l,r}| = \frac{2\pi}{\lambda_l} \quad (4.3)$$

$$|\mathbf{k}_s| = \frac{2\pi}{\lambda_s}, \quad (4.4)$$

it follows directly, that

$$\sin \theta = \frac{|\mathbf{k}_s| / 2}{|\mathbf{k}_{l,r}|} = \frac{\lambda_l}{2\lambda_s}. \quad (4.5)$$

Using the acousto-optical effect in order to modify tweezer positions, it is necessary to break the dependence of the angle between incoming optical wave and acoustic wave, while keeping the dependence on the angle of the outgoing light. This is achieved by now modelling the sound wave as a gaussian distribution of planar waves. As such, there are waves travelling radially outwards from the origin of the sound. As a consequence of this, it will always be possible to fulfill the Bragg condition, no matter how the light enters the medium.

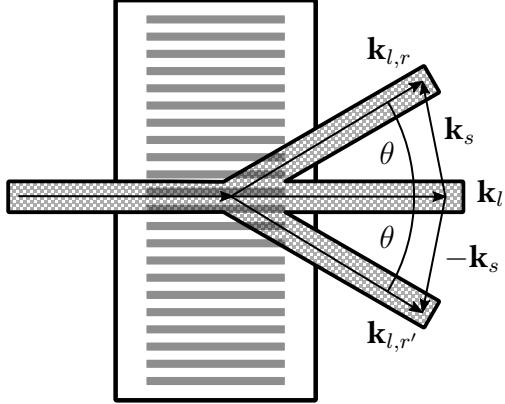


Figure 4.2.: Similar to Figure 4.1, light is deflected off sound waves in an acousto-optical medium. This time, the sound wave is modelled as a gaussian distribution of planar waves, such that besides the transmitted component, two more orders are deflected.

In Figure 4.2, an optical beam enters a medium straight and exits on a diffracted angle  $\pm\theta$ , given by the Bragg condition. Using again the trigonometric relations from Equation 4.5, the fact that there are acoustic waves travelling in opposing directions needs to be taken into account. In the approximation where the angle is small, the Bragg condition then simplifies to:

$$\theta_{\pm} \approx \sin \theta_{\pm} = \pm \frac{\lambda_l}{\lambda_s} = \pm \frac{f_s}{v} \lambda_l, \quad (4.6)$$

where the speed of light in the medium  $v$  needs to be taken into account.

This means, the angle of the first deflected orders from the AOD only depend on the wavelengths of the light wave  $\lambda_l$  and the sound wave  $\lambda_s$ , or in other terms, the angle of deflection can be tuned by changing the wavelength of the sound wave. As the deflector is driving with an RF-generator, this means, we will generally speak of the frequency and not the wavelength of the sound wave. Using the deflector for sorting, means blocking all orders, except the first deflected order. This way, a beam can be moved by driving a frequency ramp on the sound wave, thus changing the angle of the first deflected order. This means, the change of angle depending on the change in frequency of the sound wave is interesting and is then calculated as:

$$\Delta\theta_{\pm} = \pm \frac{\Delta f_s}{v} \lambda_l \quad (4.7)$$

Thus, all parameters required for manipulating the position of laser beam have been calculated, such that the tweezers can be operated for resorting. We have seen how optical light is deflected off sound waves in media and how that can be used to reposition laser beams and in the long run, move atoms along paths. When selecting AOD for an application, there are generally two modes available, that are normal mode and shear mode. In a normal mode AOM, the shape of the crystal viewed from the top, is rectangular, while a shear mode has its front and back sides cut at an angle. This means, sound waves won't be gaussian anymore, but instead be shear waves, meaning their velocity is slower. This is in general preferable, as we made the assumption, that the speed of the sound wave is much slower than the speed of the light wave, and thus this condition is reinforced. All in all, after having understood operation of AODs, the following chapter will discuss the setup in place for sorting the atoms.

#### **4.1.2. Preparation of the tweezers beams**

With the derivations from the previous chapter, it is possible to calculate the position of the laser beam, depending on the frequency of the sound wave propagating the AOD. However, the beam has to be prepared before entering the deflector, meaning its polarization has to be adjusted, as well as after the deflector, as the beam will pass an objective into the vacuum chamber. The following is discussed, as well as the configuration of AODs, in order to sort in two dimensions.

The deflectors ((AA DTSXY-400-800.860) from Pegasus optics) and their characteristics are given in Table 4.1.2. The AODs are driven by RF-frequencies, which map 1:1 to the frequency of the sound wave. In order to deflect in two dimensions, two deflectors are placed in series, which are turned by  $90^\circ$  with respect to each other. This way, the first order on the first AOD will extend e.g. into the x-axis, while the first order of the second AOD will then extend along the y-axis. Together, exiting the deflectors will be a  $2 \times 2$  grid of laser beams, which can be seen in Figure 4.3. These are the  $(x = 0, y = 0)$ ,  $(1, 0)$ ,  $(0, 1)$  and  $(1, 1)$  orders, however, only the  $(1, 1)$  order will be used, as this is the one that is deflected based on the sound wave placed into the AOD.

The details of the configuration and characterization of the devices used in the experiment are given in [8]. In Figure 4.4, the setup used to test the programming and homogeneity of the tweezers is drawn, where two laser beams are passing through the AOD configuration. This is due to two different things that are being studied, that both depend on movable

Central drive frequency at 795 nm	$(102 \pm 4)$ MHz
Bandwidth	36 MHz
Max optical power density	$5 \text{ W mm}^{-2}$
Max RF power	2 W
Laser beam diameter [ $D$ ]	$500 \mu\text{m} < D < 6 \text{ mm}$
Material (speed of sound)	TeO <sub>2</sub> ( $650 \text{ m s}^{-1}$ )
Scan angle	$(44 \text{ mrad})^2$

Table 4.1.: Properties of AA DTSXY-400-800.860 crossed AODs from Pegasus optics.

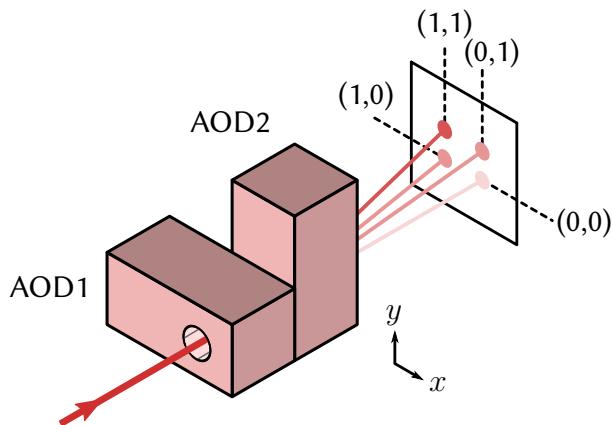


Figure 4.3.: Light passing through two AODs is deflected into a 2-dimensional grid. The colors refer to the optimized power going into the respective order, from lightest color being lowest power to darkest color being highest power. This way, the least amount of power goes into the (0,0) order and most into the (1,1) order.

optical tweezers. The first laser is used for the characterization in [8] and later sorting of atoms, as well as testing everything regarding the tweezers in the following and has a wavelength of 795 nm. The second effect is a spin-resolved imaging, which works by trapping a singular spin species and moving it around with a wavelength of 768 nm. This is further discussed in Chapter 5.

The intensity of laser beams is first stabilized, by measuring their power on a photodiode and using proportional-integral controllers to adjust the signal. They then pass a  $\lambda/2$  waveplate to further adjust the polarization, which in turn affects the efficiency of the AOD. The deflectors, which are connected to RF-synthesizers, then produce the  $2 \times 2$  grid of laser beams. Afterwards, a 75 mm lens, projecting the center of the AOD-array, extends the beam spatially until it is collimated on the 1000 mm lens. This sets the correct beam size in order for the objective to project the beam onto the atoms.

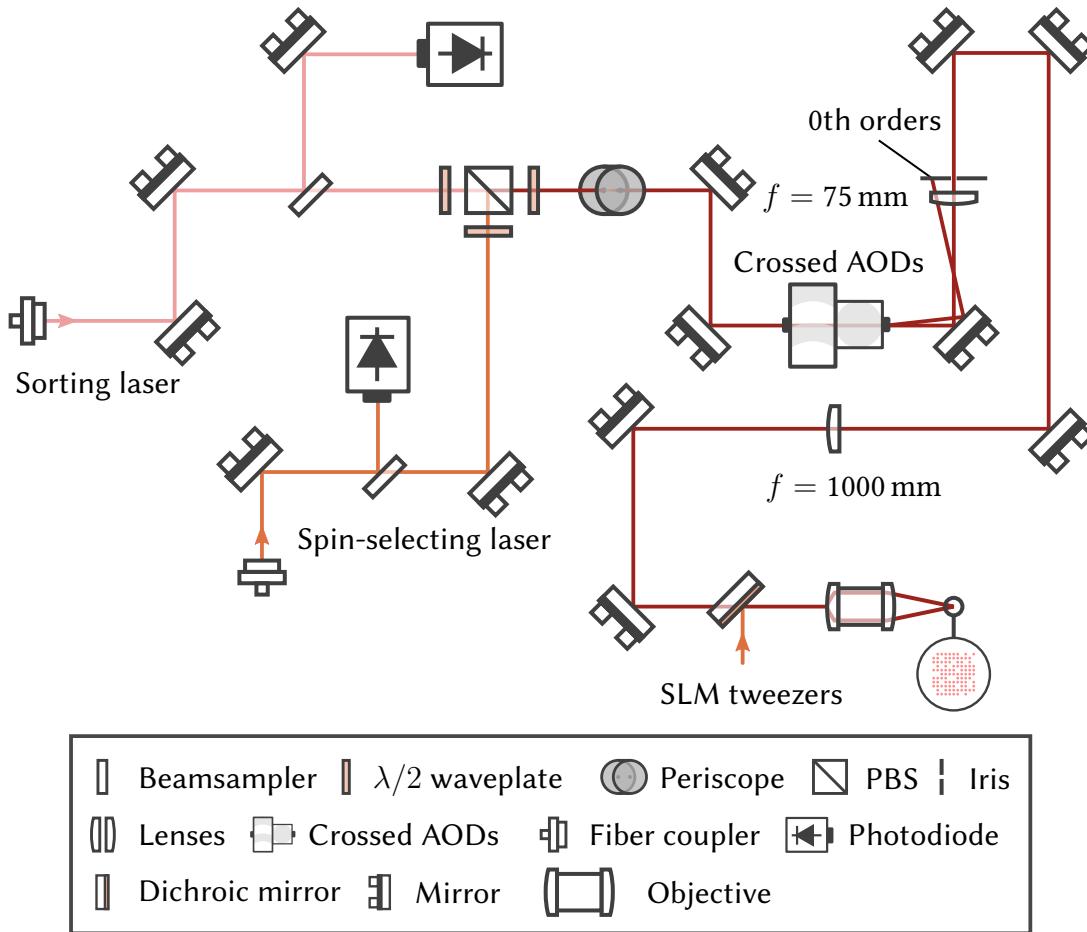


Figure 4.4.: Beam path to generate acousto-optically deflected tweezers. Two beams used for sorting and spin-resolved imaging are combined using a PBS. They pass the AOD after which the beam is shaped to match the objective into the experimental chamber.

#### 4.1.3. Moving tweezers

Now that the laser is in place, in order to move atoms, the question remains what frequencies to apply, in order to move the tweezers. From Equation 4.1.1, it is clear that any change in frequency results in a change on the output angle of the laser beam. This means, lasers can be moved by driving frequency ramps. In order to calculate the frequency ramp necessary, to move the tweezer by one grid point, the distance between the atoms needs to be mapped to the first collimating lens after the AOD, which is followed by a  $f = 1000$  mm lens. The objective in the experiment has an effective focal length of 33.18 mm, resulting in a magnification of  $M = \frac{1000}{33.18} = 30.14$ .

This means a distance  $x$ , appearing on the 75 mm lens, is projected into the AOD at an angle  $\tan \theta \approx \theta = x/75$  mm. With Equation 4.1.1, this results in a change of frequency on the AOD:

$$\Delta f = \frac{\Delta x}{75 \text{ mm}} \frac{v}{\lambda}, \quad (4.8)$$

given an optical laser wavelength of  $\lambda$ . Taking into account the magnification, this means a typical atomic distance of  $10 \mu\text{m}$ , requires a change in frequency of  $\Delta f = 3.6 \text{ kHz}$ .

## 4.2. Sorting algorithms

With the laser now passing through the crossed AODs and being shaped for the objective, it is time to rearrange the atoms for the experiment. To do so requires the knowledge about gaps in the pattern, which means when the atoms are loaded into the initial tweezers, an image is acquired. For this, the imaging beam is chopped together with the cooling, such that no atoms are lost in the process. From then on, atoms need to be moved along paths in order to fill the gaps. They can be lost, if the move is on the order of the scattering rate, as then the trap moves out of range while an atom is in the excited state. Generally speaking, the move needs to be as fast as possible, since heating effects discussed in Chapter 3 lead to  $1/e$  lifetimes on the order of 80 seconds. This in turn means, already 1.2% of atoms are lost after one second, or at least one atom in a  $10 \times 10$  grid.

Sorting the atoms as fast as possible in order to reach 100% filling means, finding paths that minimize the total sorting time. An obvious choice here would be using Dijkstra's algorithm, which is designed to find the minimal path between two points, in an arbitrary landscape. However, since the paths have to be calculated while the atoms are loaded, this means computation has to be taken into account as well. Since Dijkstra's algorithm scales with  $\mathcal{O}(n^4)$ , where  $n$  is the number of atoms, the question is, if there is a better solution of sorting the atoms. Indeed, some simplifications can be made, which can help find an algorithm that is both fast in calculation speed, as well as find fast sorting speeds. For one, we are operating on a rectangular grid and thus make the simplification to only move vertically or horizontally and not diagonally. Secondly, atoms that have started moving, stay in the tweezer until they arrive at their destination, and thus the tweezer does not suddenly jump to a new target. This is a sensible simplification, as an atom has to be transferred from the initial tweezer array to the moving tweezers (and back again when it arrives at the destination), which also takes up time. In the description of the algorithms, the grid is separated into a target and a reservoir region. This means we are trying to get a 100% filling in the target region, by moving atoms out of the reservoir region. Any atoms left in the reservoir after the sorting is finished, will be discarded. On the other hand, while

there are still holes in the target region, the algorithm will find a way to fill the gaps using atoms from the reservoir region.

Two algorithms are presented in the following, one is based on solving a pathfinding problem and moves one atom at a time. The other uses the feature of the AOD, that allows to work move several tweezers at once, by applying multiple RF frequencies, in order find a more parallelized approach.

### **4.2.1. Pathfinding**

The pathfinding problem is trying to find the shortest path between two points. For sorting of atoms, this means finding the shortest set of movements to relocate an atom from the reservoir region to an empty spot in the target region. The algorithm in described in the following was developed by Jan Werkmann<sup>1</sup> and is discussed in [9]. With the simplifications of above, atoms only move either horizontally or vertically. The algorithm will then find a path that first moves the full distance of the one dimension, then the full distance in the other, at which point the atom has arrived at its destination. This is a sensible approach, as that means only driving one frequency ramp per dimension, but does not change the total distance moved, since the atom won't move on diagonals. This way, there are only two possible paths every atom can take. The optimal path is then the one with the least amount of obstacles in it. Here, an obstacle is simply another atom. If there is one, it segmentizes the path, moving the atom out of the way and the initial atom into its place. An example path is shown in Figure 4.5.

### **4.2.2. Compression**

As was just discussed, the pathfinding algorithm moves atoms one by one. However, one might want to find a way to parallelize sorting, therefore decreasing the sorting time. By supplying an AOD with multiple RF-frequencies, it is possible to create multiple movable tweezers. One way to generate these multiple RF-frequencies, is by using a digitizer as an RF-synthesizer, by sampling a digital signal. The compression algorithm discussed here makes use of this in order to reduce the total time of the sorting, as well as having a lower computation time with respect to the pathfinding algorithm.

The compression algorithm works by picking a full line of atoms. It then moves the selected atoms along the line towards the target area, grid point by grid point. If an atom would

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<sup>1</sup><https://github.com/PhyNerd/GridRouting>

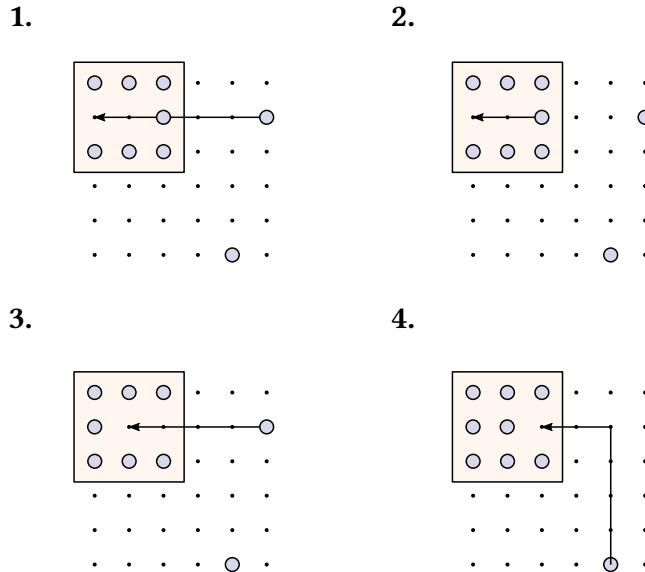


Figure 4.5.: Conceptual illustration of the pathfinding algorithm for resorting. The atom tries to move into a hole but has an obstacle (which is just another atom) in its way. The obstacle is first moved out of the way, after which the atom follows. The target area is then further filled with the remaining atom.

collide with an obstacle, that is, either another atom not currently inside an AOD tweezer, or the end of the target area, then that atom is transferred back to the initial tweezer grid, and not moved in the next step. This process is how in 4.6. When one line is finished moving according to this end condition, the next line is picked up and the process repeated. This is done first for all rows, then for all columns, and finally, all atoms are found in one corner of the grid. Doing it this way, effectively compresses all atoms in the grid into an area.

Due to the nature of the algorithm, there can still be holes in the target area when the sequence is finished. To overcome this problem, following the compression stage, the pathfinding algorithm will fill the final few gaps, whose runtime is favorable towards low hole numbers.

To further take advantage of the compression algorithm, a geometry is chosen, which has the target area in the center of the grid and the reservoir surrounding it, as seen in Figure 4.6. As the algorithm pushes the atoms into a corner, the grid can simply be split up into four sections. Then the moves for each section is individually calculated. Ending up with moves in the row-dimension and moves in the column-dimension for each section, they can then be merged together, if they operate on the same line, which is illustrated in Figure 4.7. As such, the sorting time of moving atoms into one corner is effectively the same as moving the atoms into the central area, by splitting it up into sections and merging the steps.

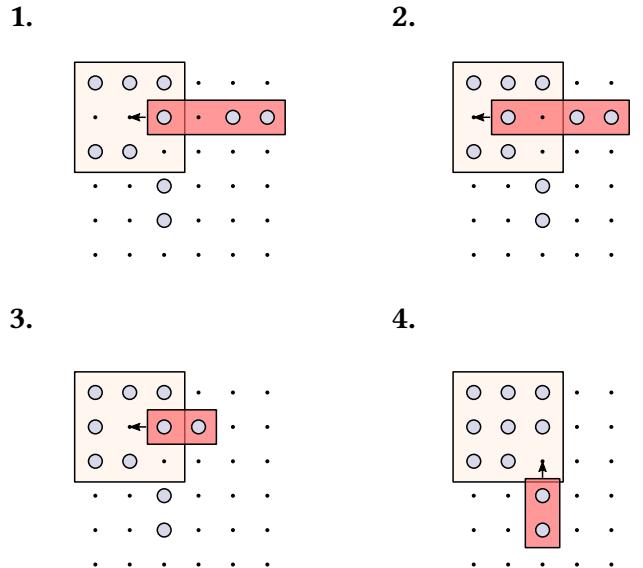


Figure 4.6.: Sorting atoms using the compression algorithm is done by selecting a full line of atoms. They are then moved towards the left edge. An atom that meets the edge is released before the others continue moving. When the steps for the rows have been completed, the same process follows for the columns.

### 4.2.3. Comparison of the two algorithms

As the pathfinding and compression algorithm are both solving the same sorting problem, it is necessary to see a performance comparison between the two. For this, the target area was chosen to be in the center, surrounded by the reservoir region. This gives a geometry, which has holes as close as possible to reservoir atoms, therefore giving a minimal number of movements for the pathfinding algorithm, while also making use of the performance gain that was highlighted in Section 4.2.2.

Relevant parameters that need to be compared, are the sorting and computation time, as they need to be much slower than the lifetime of the atoms. Atom loss can also occur, whenever the atoms are transferred from the initial tweezer grid to the AOD tweezer grid used for the sorting. This way, the number of transfers are also shown in the following. Simulations were performed, by populating the full grid with atoms with 50 % probability of occupying a grid point. Then each algorithm was run and relevant parameters recorded. Simulations were run for various grid sizes, while trying to keep the fraction of number of atoms in the target area  $N_{target}$  to the number of atoms in the reservoir area  $N_{reservoir}$  around  $\frac{N_{target}}{N_{reservoir}} \approx 0.65$ . This has to be compromised for low grid sizes, as the integer nature of grid points only allows natural numbers for reservoir sizes.

The results in Figure 4.8 show that the compression algorithm has a faster sorting and computation time, but has to transfer more atoms into the AOD tweezer grid. However, it

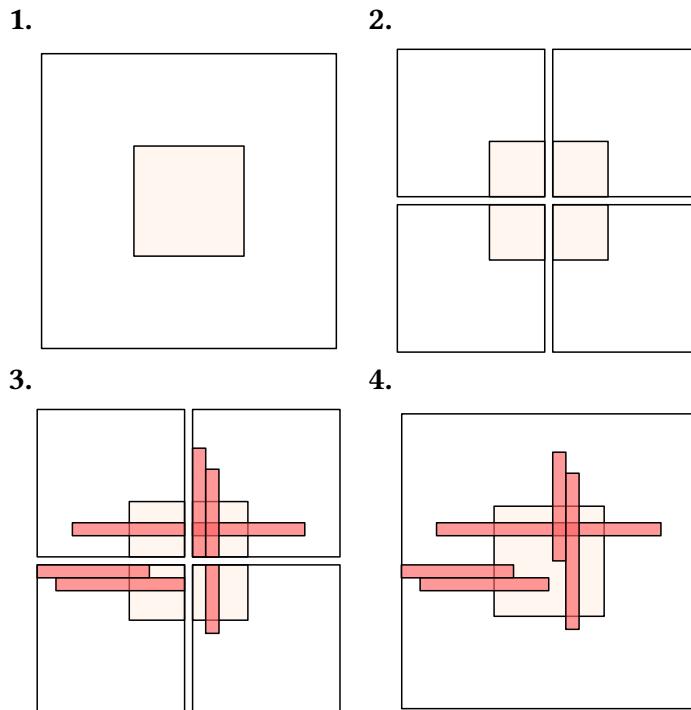


Figure 4.7.: Sequence of finding parallelized paths for the compression algorithm. Since it will always sort into a corner, the compression algorithm is split into four sections. The compression is run over each section, which finds the paths to move the atoms into a corner. In the last step, all paths that are in the same row or column, are combined and thus parallelized.

also shows that it scales better for increasing grid sizes. A polynomial fit is shown for the second half of the points, where the rounding issue is less present. The fit parameters are given in Table 4.2.3, from where it can be seen, that the compression algorithm scales more linearly than the pathfinding algorithm.

### 4.3. Driving an RF-synthesizer for arbitrary pattern generation

One of the most powerful aspects about AODs is the fact, that a superposition of sound waves results in a superposition of light waves in the output. This way, it is possible to generate a grid of tweezers, by supplying each AOD with one or more RF-frequencies. There are a multitude of ways to generate RF-frequencies, one way is using voltage controlled oscillators (VCOs), which can be simple LC-circuits. Using these, it is also possible to drive frequency ramps, however it is not possible to synthesize multiple frequencies from one VCO, meaning multiple it would be necessary to use multiple VCOs together. Therefore

Pathfinding		
	$N$	$a$
Resorting time	$1.3 \pm 1.7 \times 10^{-2}$	$5.8 \times 10^{-2} \pm 8.8 \times 10^{-3}$
Computation time	$1.8 \pm 8.9 \times 10^{-3}$	$4.8 \times 10^{-8} \pm 3.8 \times 10^{-9}$
Number of transfers	$1.4 \pm 1.8 \times 10^{-2}$	$5.7 \times 10^{-2} \pm 9.2 \times 10^{-3}$

Compression		
	$N$	$a$
Resorting time	$9.7 \times 10^{-1} \pm 1.7 \times 10^{-2}$	$3.6 \times 10^{-1} \pm 5.3 \times 10^{-2}$
Computation time	$1.6 \pm 3.1 \times 10^{-2}$	$9.0 \times 10^{-8} \pm 2.5 \times 10^{-8}$
Number of transfers	$9.5 \times 10^{-1} \pm 1.2 \times 10^{-2}$	$8.3 \times 10^{-1} \pm 8.6 \times 10^{-2}$

Table 4.2.: In order to compare the sorting algorithms against each other, simulations were run, which is shown in Figure 4.8. The log-log plot shows polynomial characteristics, such that the measurement was fitted by assuming  $f(x) = aN^m$ ,  $n$  being the atom number. The values for the fit are shown in this table, giving the result that the compression algorithm scales better in every aspect.

using this approach it is possible to sort the atoms one-by-one, however it is not possible to generate grid patterns.

To overcome this issue, we implement a digitizer card (M4i.6600-x8, Spectrum Instrumentation), whose specifications are summarized in Table 4.3.1. Doing so allows to sample arbitrary signals, for example sines, rectangles or even non-periodic ones. A digital-to-analog converter (DAC) on the board converts the sampled points into an analog signal, which can be passed into the AOD.

### 4.3.1. Functionality of the Spectrum driver

Communication with the card is provided through a low-level interface from the official drivers over a PCIe slot. In the following, two replay modes of the spectrum card are discussed, which are standard replay mode and sequence replay mode. In single replay mode, a signal is sent onto the card, which is played back a set number of times, from start to

Maximum sampling rate	$1.25 \text{ GS s}^{-1}$
Output level (at max sampling rate)	$\pm 4 \text{ V}$
Transfer speed PC to card	$2.8 \text{ GB s}^{-1}$
Memory	4 GB

Table 4.3.: Relevant parameters of the Spectrum M4i.6600-x8 card from the specifications given by the manufacturer.

finish. The sequence replay mode allows to upload sequences during initialization. It is then possible to play any arbitrary combination of the sequences one after another.

The functionality of the card depends on two factors: The layout of the memory, and the readout speed (the sampling rate) of the memory. In the following implementation, two output channels of the spectrum card are used. Doing so, the memory is formatted, such that two bytes of channel 1 data are followed by two bytes of channel 2 data as seen in Figure 4.9. Transferring data onto the memory then requires to fill a buffer, that is, memory on the computer running the driver, that has the same layout as the spectrum card's memory.

With this information, the structure of a program driving the digitizer card follows the format given in Table 4.3.1.

The maximum transfer speed for transferring data from the PC to the spectrum card is  $2.8 \text{ GB s}^{-1}$ , this means that it will always be preferable to move as few data as possible. Consequently, if possible, it is advantageous to use the sequence replay mode, as here, almost all data is already transferred in the initialization phase. All that is left to transfer, is the sequence the data pointer is following.

### 4.3.2. Limits of using the card in the experiment

There are some considerations to make when using a digitizer card as a driver for acousto-optical tweezers. The first one being, that the transfer of the data onto the card takes time and is given by the sampling rate. This means, that transferring data onto the card while atoms are loaded can be problematic, if the transfer time is on the order of the lifetime of the atoms, since that means that atoms are lost during this time. This can be solved by making use of the sequence replay mode, however to make use of this mode means that a large amount of memory needs to be available on the card.

In order to calculate the transfer time and memory usage, some assumptions need to be made. The assumptions and all necessary variables are summarized in Table 4.3.2. First of all, the central frequency of the AOD is approximately  $f_{AOD} = 100$  MHz. Therefore, in order to sample a sine at this frequency with at least 10 points per oscillation, means a sampling rate of at least  $1 \text{ GS s}^{-1}$ . For the M4i digitizer card, this means the next available setting is  $1.25 \text{ GS s}^{-1}$  and gives about 13 samples per oscillation. Being able to resolve the signal clearly, has the advantage to generate the frequency more accurately, therefore the 10 samples per oscillation is a good limit.

Now in order to find the time to transfer an atom adiabatically from the initial tweezer grid into the AOD tweezer grid (and back again), the relation  $\dot{w} > w^2$  needs to be fulfilled, where  $w$  is the trap frequency in transverse direction. In our case, this is on the order of 20 kHz and is fulfilled for a transfer time of  $t_{transfer} = 1$  ms. In order to calculate the moving time  $t_{move}$  for an atom from one grid point to another, the shape of the trap is considered, according to [10]. If the atom is accelerated in the first half of the movement, and decelerated in the second half of the movement, the total distance to transfer the atom is given as  $L = at_{move}^2$ . The maximal acceleration is found from the trap waist  $w = 1 \mu\text{m}$  and its radial frequency  $f_{rad} = 100$  kHz, as  $a_{max} \approx wf_{rad}^2 = 10^4 \text{ m s}^{-2}$ . This means, accelerating three orders of magnitude slower than the maximum allowed value of  $L = 10 \mu\text{m}$  results in a moving speed  $t_{move} = 1$  ms.

With the transfer time, moving time, and sampling rate in place, the size of one signal, in order to move and transfer an atom can be calculated as:

$$n_{points} = St = 1.25 \text{ GS s}^{-1} * 1 \text{ ms} = 1.25 \times 10^6 \quad (4.9)$$

$$M_{sig} = 2 \text{ B} * n_{points} = 2.5 \text{ MB}, \quad (4.10)$$

where 1 B is one byte and  $t = T_{move} = t_{transfer}$ . From the simulations of the algorithms in Figure 4.8, we see that assuming a  $10 \times 10$  grid, there are about 60 tweezer transfers and 40 movements for one sorting. This means 100 sequences need to be played per channel, which is  $n_{seq} = 200$  in total. Lastly, the memory for all signals needs to be aligned to a power of two. Therefore, from the transfer speed  $v_{transfer}$  in Table 4.3.1 follows the time it takes for one transfer  $t_{transfer}$ :

$$t_{transfer} = \lceil n_{seq} M_{sig} \rceil_2 v_{transfer} = 183 \text{ ms}, \quad (4.11)$$

where the symbol  $\lceil \dots \rceil_2$  refers to rounding up to the next power of two. These calculations set the limit for the single replay mode, however, in the sequence replay mode, the limiting factor is the memory it takes to store all possible sequences. The storage of the sequences already assumes knowledge of the composition of both channels. Therefore it is necessary to upload every relevant combination of signals for both channels. Working again with a  $10 \times 10$  grid of atoms, all relevant signals are found from the following table:

Signals on channel 1	Signals on channel 2	Usage
10 intensity ramps up	10 intensity ramps up	Transfer into AOD grid
10 intensity ramps down	10 intensity ramps down	Transfer out of AOD grid
9 frequency ramps up	10 constant frequencies	Move along x-axis
9 frequency ramps down	10 constant frequencies	Move along x-axis
10 constant frequencies	9 frequency ramps up	Move along y-axis
10 constant frequencies	9 frequency ramps down	Move along y-axis

Therefore, by multiplying the signals in the columns and then adding the rows, there are 560 combinations and  $n_{seq} = 560 * 2 = 1120$  signals to upload onto the card. Each having a size of  $M_{sig} = 2.5$  MB results in a required memory of  $M_{req} = 2.8$  GB. More generally, on a NxM grid, the number of sequences can be calculated via

$$n_{seq} = 2NM + 2N(M - 1) + 2(N - 1)M \quad (4.12)$$

and therefore the required memory is

$$M_{req} = 5 \text{ MB} n_{seq}. \quad (4.13)$$

With the calculations above, it is possible to apply the pathfinding sorting algorithm to the atoms in a timely manner. However for the compression algorithm, a much larger amount of signals needs to be sampled to cover all possible combinations. Considering, that two sides of the target area are sorting at the same time, and that slices of one row (or column) is selected at the same time, the number of sequences, in one channel, to move one row is

then given by

$$n_{seq, row} = \left( \sum_{N=1}^{M-1} N \right)^2 = \frac{1}{4}(M^2 - M)^2. \quad (4.14)$$

The square comes from the fact, that for every frequency ramp on one side, a frequency ramp on the other side of the target area needs to be matched. A similar relation (replacing  $M$  by  $N$ ) is found for the number of sequences for the columns. Then, taking into account, that the total number of sequences, considering that the channels aren't independent, is found by:

$$n_{seq} = M n_{seq, col} + N n_{seq, row}. \quad (4.15)$$

Taking then also into account, that after the compression phase follows a pathfinding phase, it is already easy to see, that the memory requirement would greatly exceed the available memory of 4 GB on the spectrum M4i on a  $10 \times 10$  grid.

This means, in order to use the compression algorithm, the sequences need to be sampled on-the-fly. This is in general slow, compared to the sorting time. However, it is possible to use parallelization of graphics processing units (GPUs). On a NVIDIA Geforce GTX 1080 Ti, 3584 cores are available, which can all sample part of a signal individually. This means for a sequence of 5 MB, about 1400 calculations are made in parallel. Assuming only rectangles are sampled, this gives one comparison per sampled value and one insertion (into an array). At a clock speed of 1480 MHz,[11] results in 1  $\mu$ s computation time, meaning only transfer speed from the GPU to the digitizer card is relevant. The transfer speed is then given from Table 4.3.1, adding 1.8 ms per move of one row (or column) of atoms.

Since one channel always has a fixed frequency, it is possible to use a VCO for this channel, meaning only half of the signals need to be sampled.

## 4.4. Conclusion and outlook

It was shown how crossed AODs are used, in order to generate movable tweezers. As loading of atoms can only guarantee 50% filling, the tweezers are then used to sort atoms into the gaps, in order to guarantee a perfectly occupied grid, as long as the sorting happens

faster than the lifetime of the atoms. Two different algorithms were discussed in order to move the atoms to their new locations, which are a pathfinding algorithm, moving single atoms and a compression algorithm, which is able to use parallelization, such that multiple atoms are moved at the same time. It was shown that this reduces computation and sorting time of the atoms. Lastly, it was explained how the signals are generated using a digitizer card and the memory requirement for both algorithms were stated. It was shown, that as long as the grid is small enough, the pathfinding algorithm can be used with the digitizer card, as it has a smaller memory footprint. However, for a grid size of  $12 \times 12$  already, the memory of the digitizer card (Spectrum M4i.6680-x8) is not sufficient, such that on-the-fly calculations are inevitable and the compression algorithm, with smaller computation time, can be used.

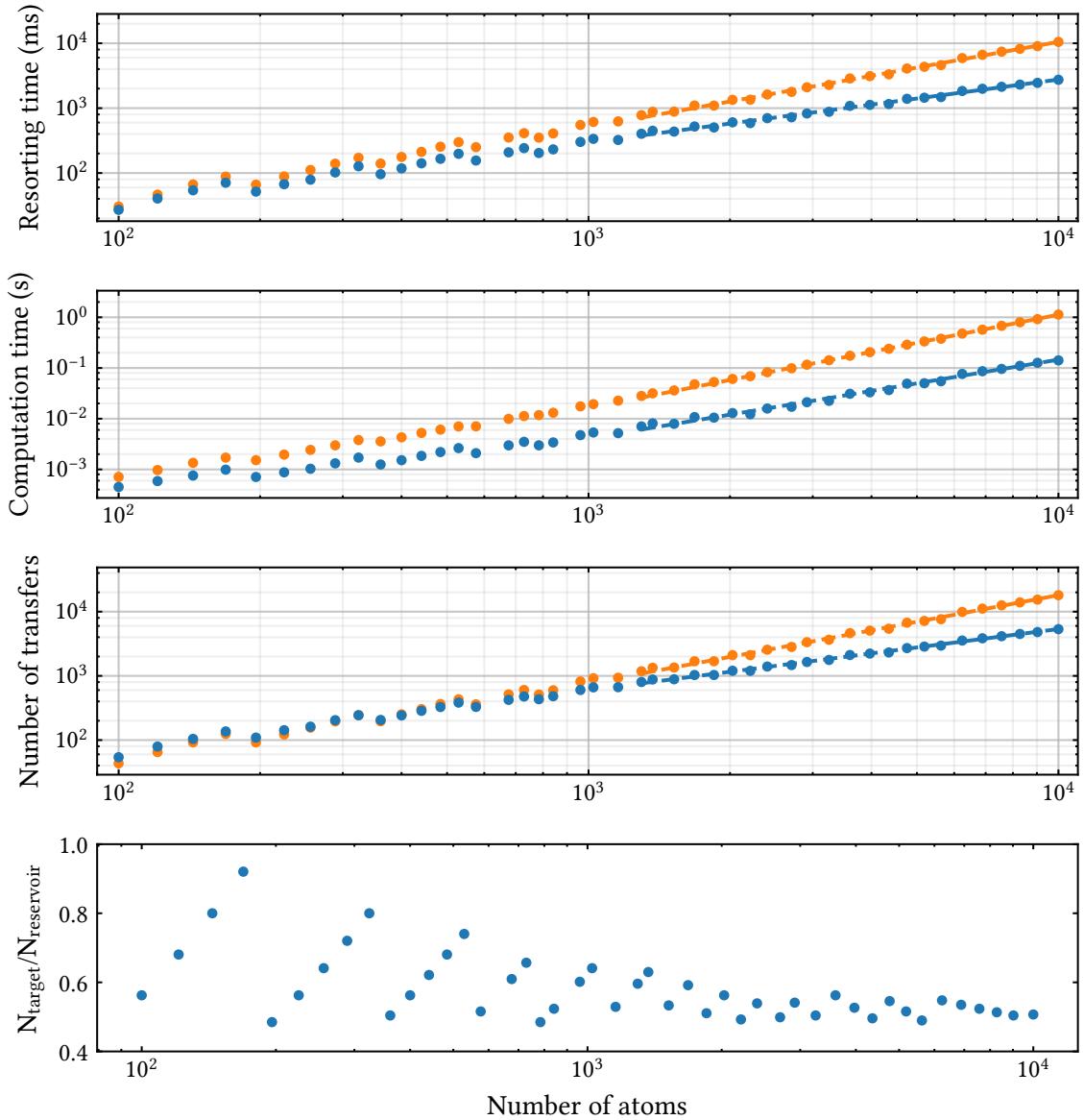


Figure 4.8.: Comparison of pathfinding algorithm (orange) and compression algorithm (blue) for sorting atoms into a target region. For each data point, 50 simulations were run and the mean of the result is shown. Standard deviation is on the size of the dots drawn and as such are not visible. The fraction of atoms in the target versus the reservoir area are shown in the last diagram. Since only integer values are allowed for the reservoir size, the fraction between the two sees a rounding effect. For this reason, the fit is only done for the upper half of the data points, where the effect is less pronounced. The values to the fit are given in Table 4.2.3.

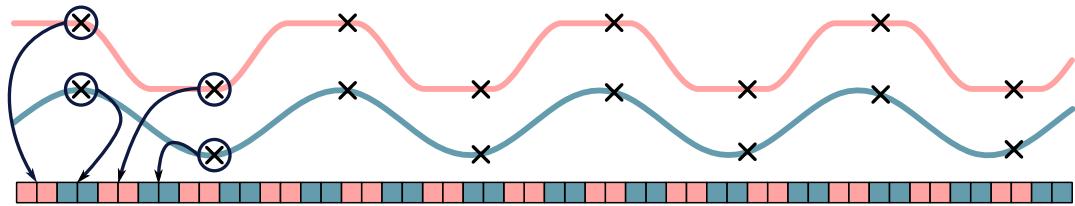


Figure 4.9.: Sampled data points are stored in a local buffer, which can then be transferred into the cards memory. The memory is effectively 1-dimensional, with two bytes for each sampled data point. Example signals are given for Channel 1 (red) and Channel 2 (blue). In the single replay mode, the data pointer will read from the first memory position until a given end point. In sequence replay mode, the data pointer will move forward, but can jump at any point based on user preference.

Single replay mode	
Initialization phase	<ul style="list-style-type: none"> <li>• Set sampling rate</li> <li>• Set replay mode to single replay mode</li> <li>• Allocate the buffer memory</li> </ul>
Main loop	<ul style="list-style-type: none"> <li>• Sample datapoints of the signal to play and move into the buffer</li> <li>• Transfer datapoints from the buffer to the card</li> <li>• Replay signal <math>N</math> times</li> </ul>
Sequence replay mode	
Initialization phase	<ul style="list-style-type: none"> <li>• Set sampling rate</li> <li>• Set replay mode to sequence replay mode</li> <li>• Sample signals to use in the sequence programmed later</li> <li>• Transfer signals onto the card</li> <li>• Allocate the buffer memory (will contain information about the sequence)</li> </ul>
Main loop	<ul style="list-style-type: none"> <li>• Fill buffer with information about which signals to play</li> <li>• Transfer buffer to the card</li> <li>• Play sequence</li> </ul>

Table 4.4.: Difference in programming when using either the single replay or the sequence replay mode of the Spectrum M4i card. In this case, it is instructive to see, that the single replay mode has an overhead during the main loop compared to the sequence replay mode, which has all sequences stored in memory already.

Variable	Used or assumed value
Sampling rate	1.25 GHz
Central AOD driving frequency	100 MHz
Adiabatic transfer time to new grid	1 ms
Adiabatic movement time to next grid point	1 ms
Grid size	$10 \times 10$
Number of tweezer transfers for sorting	60
Number of movements for sorting	40

Table 4.5.: Variables and assumptions used in the calculations for estimation of data transfer time and memory usage under the consideration of the experiment discussed in this thesis.

# 5. Spin-selective imaging

Being able to measure the spin of ground state potassium atoms in many-body quantum experiments gives insight into the full quantum state and thus being able to pinpoint the ground state on the Bloch sphere. In Rydberg dressing experiments [12, 13], the spin can be used in a Ramsey sequence, in order to measure correlations [14, 15]. This is, since the ground state atoms in a superposition of two spins, couple to the Rydberg state. In order to measure effects, such as Rydberg blockade, and the resulting correlations, the superposition state acquires a phase on the Bloch sphere, which needs to be evaluated. This is currently achieved, by doing a projection measurement by removing one component out of the system.

With the new approach, it is possible to evaluate the spin species, by transferring one spin component into a tweezer array. A spin-sensitive tweezer array is then moved, and thus the atoms having this spin component follow this dipole potential. This creates a separation, and by evaluating the geometry from a fluorescence image, it is thus possible to find how the tweezer arrays were previously occupied. Measuring the spins this way, also means the atoms will not heat out during the process, and therefore the system can be reassembled and reused for further investigation.

The following chapter will discuss the setup in question in more detail, as well as the wavelength in use, in order to have tweezers sensitive to only one spin component. The new laser system is explained in detail, which includes a cavity for frequency stabilization, and therefore stability of the laser is discussed.

## 5.1. Approaches

Measuring the spin means in our experiment, to take a fluorescence image of the two ground states  $F = 1$  and  $F = 2$ . However, during imaging, the spins are mixed, such that they can't be distinguished. As the experiment is using tweezers, this allows to move atoms, which was shown in 4. Therefore the approaches discussed in the following, both

work by separating the two spins spatially. However, this requires finding ways of being sensitive to one specific ground-state spin. Two viable approaches are discussed in the following. The first idea is using strong magnetic fields to increase the separation of the spin levels with the Zeeman effect. The second approach is using a state selective light shift, given by selecting a particular wavelength. This allows one spin component to be trapped, while the other will see no trapping effect. In both applications, the idea is to trap one spin state in its own trap and physically move it away from the other. By taking an image, it is then possible to map positions to spins and therefore find out which tweezers contained which spin species. Moving the spin-sensitive tweezers back into its original position, the initial system is reassembled and new measurements can be taken with more information.

### 5.1.1. Zeemann induced potential separation

In the previous paragraphs, it was highlighted how the spin levels are too close in energy space, to address them individually with optical lasers. However, by having a position dependent potential, that is different for each spin state, is enough to spatially separate them and thus there is no need of resonantly driving each spin. One way of achieving this, is by applying magnetic fields. In 1896, Pieter Zeeman wrote about how magnetic fields were affecting spectroscopy of atoms [16]. From this followed the Zeeman effect, which explains how spectral lines of atoms are split and shifted when applying magnetic fields. This can be calculated perturbatively [17], by modelling the atom as a magnetic dipole. In analaogue to the classic description of magnetic dipoles, this gives an energy  $V_M$  depending on the magnetic field  $\mathbf{B}$ :

$$V_M = -\mu \mathbf{B} \quad (5.1)$$

and is then the perturbation in the total Hamiltonian  $H = H_0 + V_M$ . The magnetic moment  $\mu$  contains contributions from nuclear and electron spin, which then give direction and length of the magnetic dipole. The energy associated with the perturbation evaluates to

$$E_z = B_z \mu_B (g_l m_l + g_s m_s). \quad (5.2)$$

It has contributions from the nuclear spin ( $g_l m_l$ ) and electron spin ( $g_s m_s$ ) and depends on the Bohr magneton  $\mu_B$ . The magnetic quantum numbers  $m_i, i \in \{l, s\}$  depend on the value of the associated quantum numbers, which are the orbital angular momentum  $L$  and electron angular momentum  $S$ , such that  $m_l \in \{-L, -L + 1, \dots, L - 1, L\}$  and  $s \in \{-S, -S + 1, \dots, S - 1, S\}$ . This means, not only is the hyperfine state shifted by the magnetic field, it is also split into more energy sublevels. However, a complete description of the energy shift, needs to integrate the shifts of the hyperfine levels, which has been done in the Breit-Rabi model [18].

Figure 5.1 gives an illustration of how the two spin components  $F = 1$  and  $F = 2$  in the potassium ground state are affected due to a magnetic field. Visible is a splitting of the spin-states into sublevels. In order to maximally separate the spin states, the  $F = 1$  spin would be pumped into the  $m_F = 1$  state, and consequently,  $F = 2$  into the  $m_F = 2$  state.

Using this, the idea is to create a position dependent trap for the two spin-states. To do this, we need to note, that from the figure, the  $F = 1, m_F = 1$  state has a negative slope, while the  $F = 2, m_F = 2$  state has a positive slope. This means, simply by generating a magnetic field ramp, the atoms in different spin states, will see a position dependent energy  $V_{mag}$ . Since the atoms are trapped inside optical tweezers, the potential given by the dipole force is:

$$V_{dip}(r) = -\frac{\pi c^2 \Gamma}{2w_0^3 \Delta} I(r), \quad (5.3)$$

where  $\Gamma$  is the line width of the transition, in this case the D2 line,  $\Delta$  the detuning,  $w_0$  the resonance frequency and  $I(r)$  the intensity of the laser beam. By applying the magnetic field gradient, the atoms see a total potential  $V$ :

$$V(r) = V_{dip}(r) + V_{mag}(B(r)), \quad (5.4)$$

where the position dependence was explicitly noted. This way, the potential minimum, which was originally just given by the dipole trap, is now shifted in the direction of the potential induced by the Zeeman effect. Thus, the two spin states will see different potentials, which are shifted in position space with respect to each other. However, numerical calculations of the potential minimum show that the shift is too small in order to spatially separate the atoms. For this, it is assumed, the atom is trapped on the D2-line and the

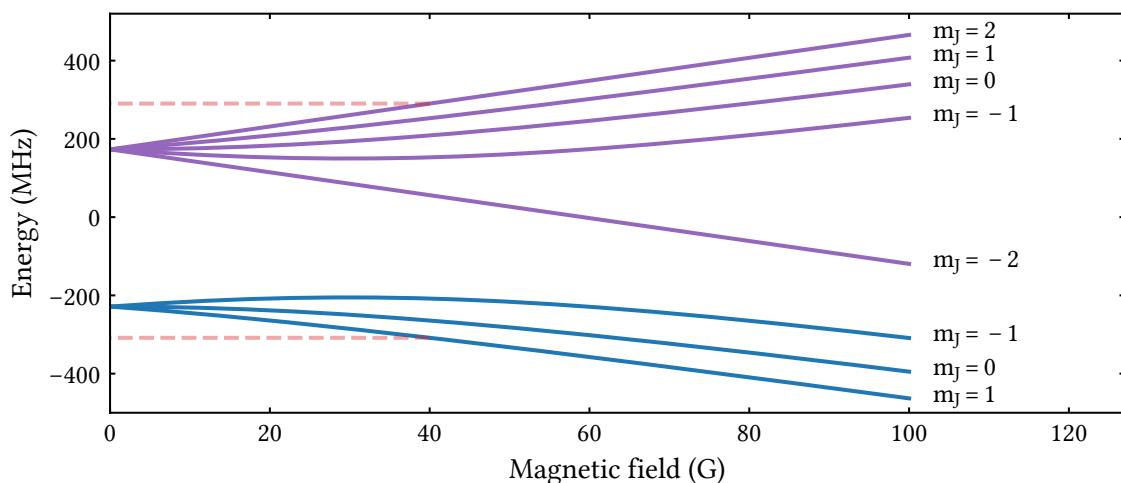


Figure 5.1.: The spectrum of ground state potassium is split into magnetic sublevels and shifted depending on a magnetic field applied to the atoms. Shown are two spin states  $F = 1$  in blue and  $F = 2$  in purple, relative to the ground state energy of  ${}^2\text{S}_{1/2}$ .

laser power is  $1 \mu\text{W}$ , where the spatial separation is favorable towards lower laser powers. Moreover, the magnetic field gradient is set to  $B(r) = 40 \text{ G cm}^{-1}$ . This gives a separation of  $\Delta x = 2.1 \text{ nm}$ . Given a beam waist of  $\omega = 1 \mu\text{m}$  and assuming the atoms have a temperature of  $20 \mu\text{K}$  means, at peak energy, the potential walls are separated by  $\Delta x_V = 1 \mu\text{m}$ . These results are further illustrated in Figure 5.2.

As such, given generous, but realistic experimental parameters, it is apparent, that this approach would only work for very high magnetic fields. From these calculations, given generous, but realistic parameters, we can conclude that this approach only works when very high magnetic fields are applied. From simulations, this means, applying a magnetic field slope of  $B = 4000 \text{ G cm}^{-1}$  in order to get a separation of  $0.2 \mu\text{m}$ . Luckily, there is another approach, which works by using only the light from frequency stable lasers, which is discussed in the following.

### 5.1.2. Utilization of state selective light shifts

The problem with the spin states being too close together still persists, however there is another effect that affects the energy of the spin states. Similar to the Zeeman effect, electrical fields also shift and split energy levels [19, 20]. Under the influence of modulated electrical fields, such as coherent laser light, the effect is called AC Stark shift or simply light shift.

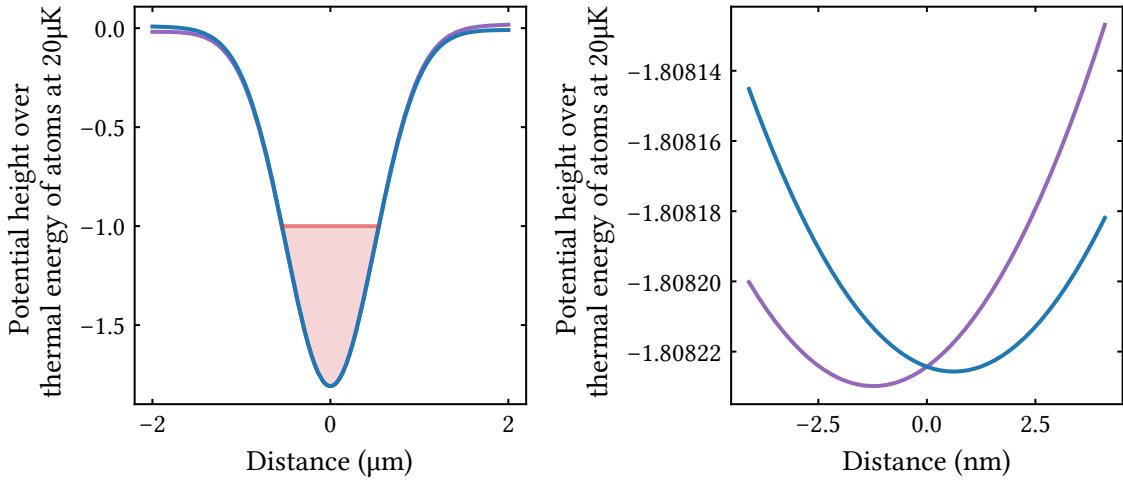


Figure 5.2.: Two spin species are subject to a dipole trap under the influence of a magnetic field gradient. The  $F = 1, m_F = 1$  and  $F = 2, m_F = 2$  states are colored in purple and blue respectively. The parameters for the trap are given in the text. Also shown is the energy of the atom as a red area. The zoomed in diagram on the right shows the separation of the two potentials, which is on the nanometer scale.

The shifts can be calculated by finding eigenenergies to the so-called Jaynes-Cummings Hamiltonian [21]. In it, the atom is described as a two-level system which has a resonance at  $w_a$ , as well as the being under the influence of a light field having a frequency  $w$ . Doing so, the Hamiltonian is written in three parts, containing the atomic resonance, light frequency and the interaction between both, resulting in:

$$H_{JC} = \hbar w_a \sigma^+ \sigma^- + \hbar w a^\dagger a + \hbar \frac{\Omega}{2} (a^\dagger \sigma^- + \sigma^+ a). \quad (5.5)$$

Here, the operators  $\sigma^+$ ,  $\sigma^-$  and  $a^\dagger, a$  refer to ladder operators of light and atomic levels respectively. The coupling strength is given by the vacuum Rabi frequency  $\Omega$ , which depends on the electric field of the light and its polarization, as well as the dipole moment of the atom. By solving the Hamiltonian, the energy of the states is a shift to the vacuum energy shifts, depending on the principal quantum number  $n$  and is given as:

$$E_{JC} = \hbar \left( n + \frac{1}{2} \right) w \pm \frac{\hbar}{2} \sqrt{\Omega_n^2 + (w_a - w)^2}. \quad (5.6)$$

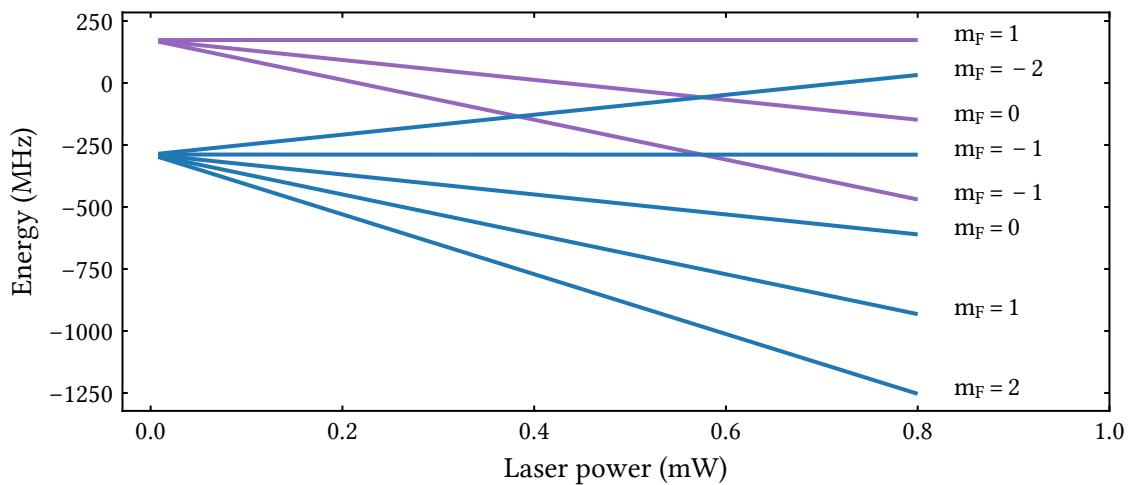


Figure 5.3.: The spin levels are split up due to the AC Stark shift from the laser illuminating the atoms. Shown are the ground states with  $F = 1$  in purple and  $F = 2$  in blue. The laser has a wavelength of 768.40 nm and positive circular polarization.

Here, the n-photon Rabi frequency is given as  $\Omega_n = \Omega\sqrt{n + 1}$ . With these relations, it is instructive to see, that the electric field of laser light, and therefore simply the presence of a light field, induces light shifts on the atoms. Figure 5.3 shows the light shifts for the two spin states,  $F = 1$  and  $F = 2$  for the potassium atoms in the experiment.

Due to the light shifts, the atoms see an induced potential, given by the energy of the state. Therefore, the two spins can be spatially separated, when one component sees a potential, where the other one does not. This is easy to see in Figure 5.4, where the light shifts for the two spin states are given as a function of wavelength of the laser for circularly polarized light. We can see, that at 768.40 nm, the  $F = 2$  state is trapped, while the  $F = 1$  component does not see a light shift, which makes the atom with this spin transparent to the light.

In the experiment then, the light is produced as optical tweezers and mapped over the initial grid. To transfer the atoms into the spin-selective tweezer, the resulting trap has to be much deeper than the initial tweezers. These have a power of  $\approx 15$  mW, but are highly detuned to the excited state on the D2 line at a wavelength of 1064 nm. Moreover, due to laser light having a bandwidth, the transparent atom might actually see a trap, therefore it needs to be verified, if that effect is non-negligible. Therefore, Figure 5.5 shows the trap depth of the spin-sensitive tweezer over the trap depth of the initial tweezer, for both spin-species, when also accounting for a laser bandwidth of 200 GHz. It turns out, that the bandwidth does not majorly affect the efficiency of not trapping the transparent state. Therefore, by using the AC-Stark shift, in order to shift atom levels is a viable approach in order to trap

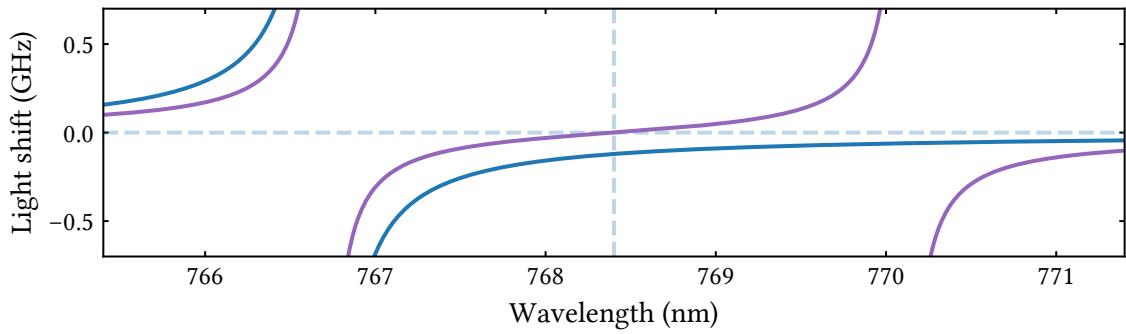


Figure 5.4.: The light shift of the  $F = 1, m_F = 1$  (purple) and  $F = 2, m_F = 2$  (blue) states is shown against wavelength for a laser power of 0.1 mW and positive circular polarization. At 768.40 nm, the  $F = 1$  component is transparent to the laser, therefore making it possible to trap only the  $F = 2$  state.

a single spin-component, allowing to image specific spin states.

## 5.2. Setup

We have seen, how light shifts can be used to trap a single spin species. Doing so, it is possible to spatially separate and image them onto a camera. However, it is necessary to have a stable laser at 768.40 nm. The following section highlights the steps in order to build such a laser system, which includes setting up a cavity and a Pound Drever Hall (PDH) lock, in order to frequency stabilize the system. The laser is then coupled into the same setup as in 4, allowing to generate acousto-optically, spin-sensitive tweezers, allowing to move the spin state in space.

### 5.2.1. Laser classification

The first step in building a stable laser source for spin-selective imaging, is having a laser to work with. This means, collimating light from a laser diode and forming a standing wave inside the laser cavity. The laser diode (Eagleyard EYP-RWE-02010-1500-SOT12-0000) used, is tunable in the range from 752 nm to 772 nm with a maximum power of 80 mW. Since the diode is also used as the active medium, the cavity simplifies to being just a mirror, that reflects back into the diode and transmits part of the light out of the laser casing.

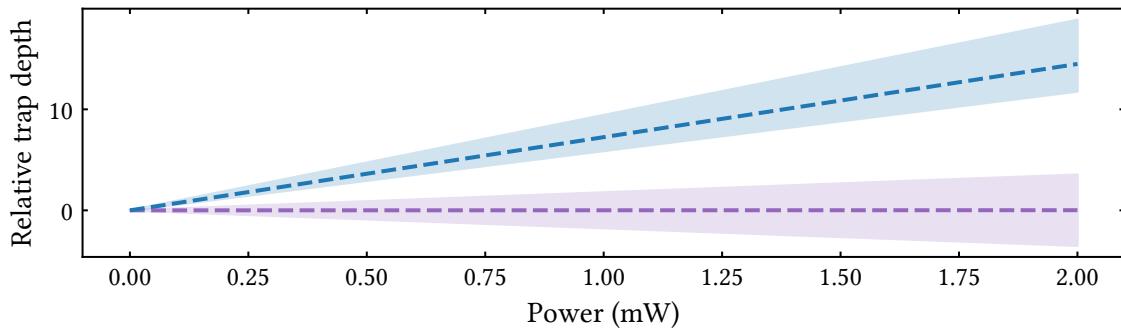


Figure 5.5.: Shown is the fraction of trap depths for the spin-tweezer and initial tweezers as a function of the spin-tweezer laser power. It is shown for the  $F = 1, m_F = 1$  (purple) and  $F = 2, m_F = 2$  (blue) state, to highlight that only one state is trapped. The colored area shows the effect of the laser bandwidth on the spin-tweezer, if a bandwidth of 200 GHz is assumed. Already at 2 mW power, the spin tweezer is more than 10 times deeper than the initial tweezer.

The light emitted from the laser device is then evaluated, based on the laser curve. This means, by increasing the current supplied to the laserdiode, there will be a point at which the power emitted from the cavity suddenly jumps. After that point, increasing the current on the laserdiode will increase the power in equal parts. This curve has been measured for the diode in question, verifying that the system is actually lasing, and is shown in Figure 5.6.

### 5.2.2. Beam setup of spin-selective laser

Now that there is a laser, the beam path in order to have a laser for spin-selective imaging can be set up. For this, two parts of the laser are split and coupled into fibers. One is used for monitoring of the wavelength, which will give an indication, if the frequency is currently locked or not. The second part will go to the cavity, allowing to actually perform the frequency stabilization. The full beam path is shown in Figure 5.7.

The main path will then be coupled into a fibre, going towards to AOD discussed previously. However, the beam needs to be turned on and off at certain times during the experiment, for this, it first passes through an AOM and finally a shutter to block any leftover stray light. As discussed previously, in 4.1.2, the light coming out of the fibre is then intensity stabilized and coupled into the AOD, which can be programmed to move the spin-sensitive tweezers.

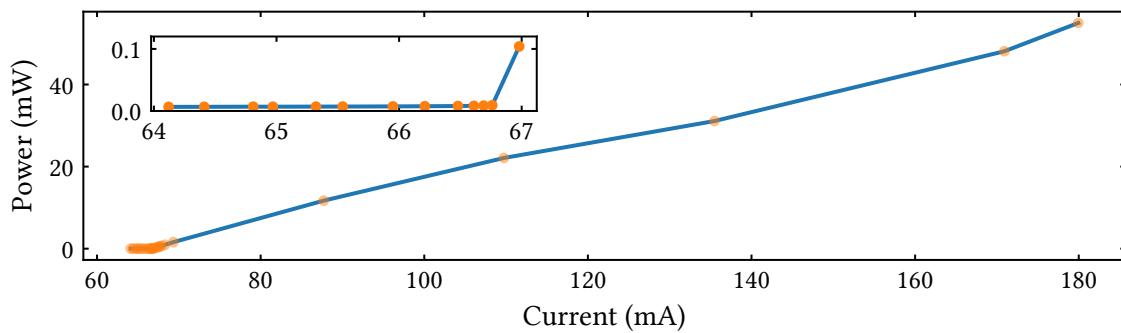


Figure 5.6.: Shown is the lasercurve for the home-built laser, driven with a Thorlabs LDC205C current controller. The power was measured using a Thorlabs PM100D power meter and the Thorlabs S121C sensor.

### 5.2.3. Cavity classification

The laser has been built and characterized and can be coupled into the AOD, in order to generate movable tweezer for spin-selective imaging. However, the process requires a stable frequency at 768.40 nm. As a matter of fact, not only are there resonances at 766.7 nm and 770.1 nm, this spin-selecting procedure works on the fact, that one spin state is completely transparent to the laser light, in terms of seeing a dipole potential. In order to have the laser emit a stable frequency, a piezo electronically controls the mirror inside the laser cavity. This way, the length of the cavity, and therefore the standing wave, can be adjusted in length. However, pressure and temperature can both affect the mirror, and therefore there needs to be a system in place, to compensate for these factors.

Therefore, it is necessary to have a device, that measures the instability, and feeds back a signal to the piezo. In order to do this, a part of the laser is split off and sent into a stable cavity. The light that has passed the cavity is measured using a photodiode and it is then possible to measure resonances of this cavity. When this is the case, a signal is generated, that is fed into the piezo, whenever the light on the photodiode is not on the resonance. This electronic signal is generated using the Pound Drever Hall locking method and has been used and described in the experiment before [22].

The stable cavity in place for locking the laser frequency is made from a ultra-low expansion (ULE) glass, that has two mirrors attached to it. The material is not explicitly necessary, however the full extent of this specific ULE couldn't be used anymore, as only one side has the mirror contacted, while the other mirror is glued. Therefore, due to the glue, this cavity is still prone to some wavelength drifts, induced by temperature expanding and compressing the material. This specific application can deal with these instabilities and therefore

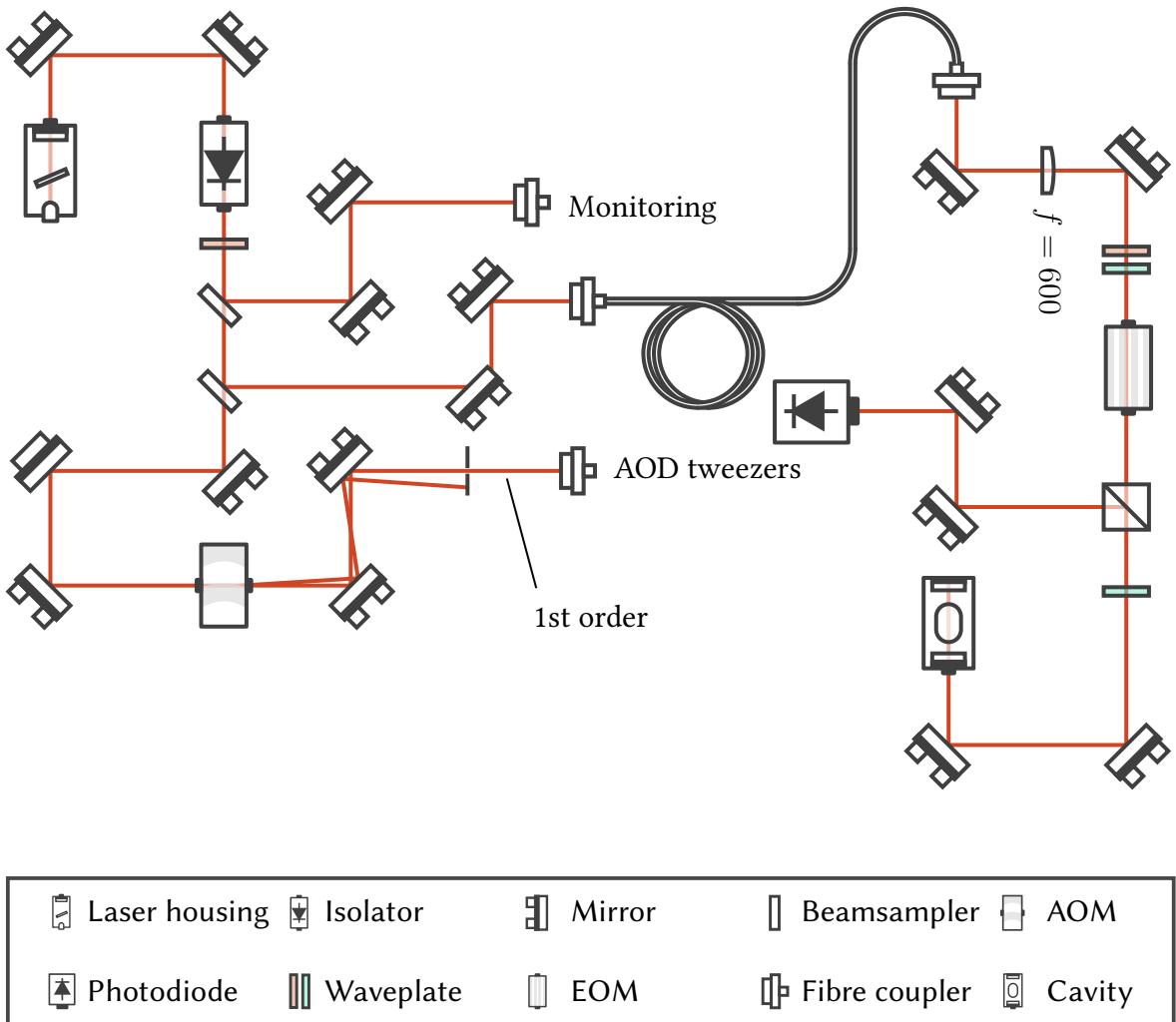


Figure 5.7.: Shown is the setup, in order to prepare the spin-sensitive tweezer for the experiment. The laser first passes an isolator, in order to protect the laser cavity from reflections. It is then split into two paths for monitoring and frequency stabilization. An AOD is used to switch the light on and off for the experiment.

the glass was recycled for this setup. In order to stabilize the cavity against temperature fluctuations, it rests in a copper housing. This copper housing further rests in a stainless steel container. This container is then evacuated with a vacuum pump, which stabilizes the cavity against pressure fluctuations. A picture of the cavity is given in Appendix A.

In order to quantize the stability this cavity can provide, the frequency drift is measured. However, at 768.40 nm, the frequency is in the hundreds of terahertz, which is difficult to measure conventionally. However, by superimposing a reference laser onto the spin-laser, that has a very stable frequency, it is possible to measure the beat mode. Mathematically, this means adding two sine-signals together:

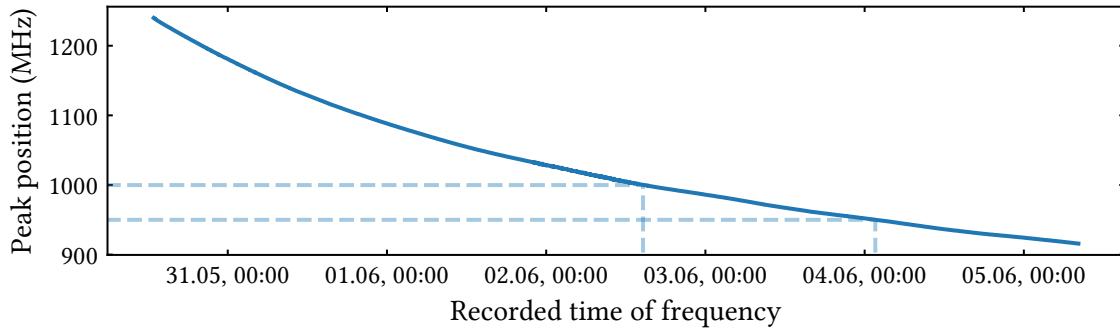


Figure 5.8.: The cavity drift was recorded over six days by doing a beat measurement with a reference laser. Horizontal lines show 50 MHz difference at the end of the measurement, where temperature and pressure has stabilized. From this it can be seen, that the drift is on the order of 33 MHz per day.

$$\sin(2\pi f_1 t) + \sin(2\pi f_2 t) = 2 \sin\left(\frac{f_1 + f_2}{2}t\right) \cos\left(\frac{f_1 - f_2}{2}t\right). \quad (5.7)$$

This relation turns two modulations, which have the frequencies added and subtracted. The first one still can't be resolved, however if the difference frequency is low enough, it is possible to see it on a spectrum analyzer. This means, the frequency of the "unstable" laser was first matched to the stable laser, such that the difference frequency was at least in the Megahertz regime. Then, it is possible to observe the drift of the cavity, which is the change in frequency with time. This usually happens due to temperature drifts affecting the cavity. The measurement was taken over several days and recorded as in Figure 5.8. Close to the end of the measurement, the drift was at a minimum of around 33 MHz per day, which is well within the limits, which can be verified with Figure 5.5.

With the cavity in place, all building blocks are there in order to separate spins of ground state potassium atoms. This means, the frequency stability given by the cavity locks the laser and makes it possible to position it close to the magic wavelength, where only one spin state sees a trap. By coupling the beam into the crossed AOD, each atom can be addressed and moved individually and an image of the spins can be acquired, while simultaneously keeping the atoms in the trap.



## **6. Conclusion**



## A. Cavity for frequency stability of spin-sensitive tweezer

A special cavity was built in order to stabilize the spin-sensitive tweezer against its frequency. The outer housing is made of stainless steel and can be evacuated using the flange in the back. The cavity is a ULE spacer, resting on a copper block, which should absorb most temperature instabilities. The spacer is surrounded by Viton rings, to prevent it from damage against direct contact with the copper block. Not visible are peek spacer between the copper block and steel casing, which isolate both parts from each other. A picture of the cavity is given below, in Figure A.1.

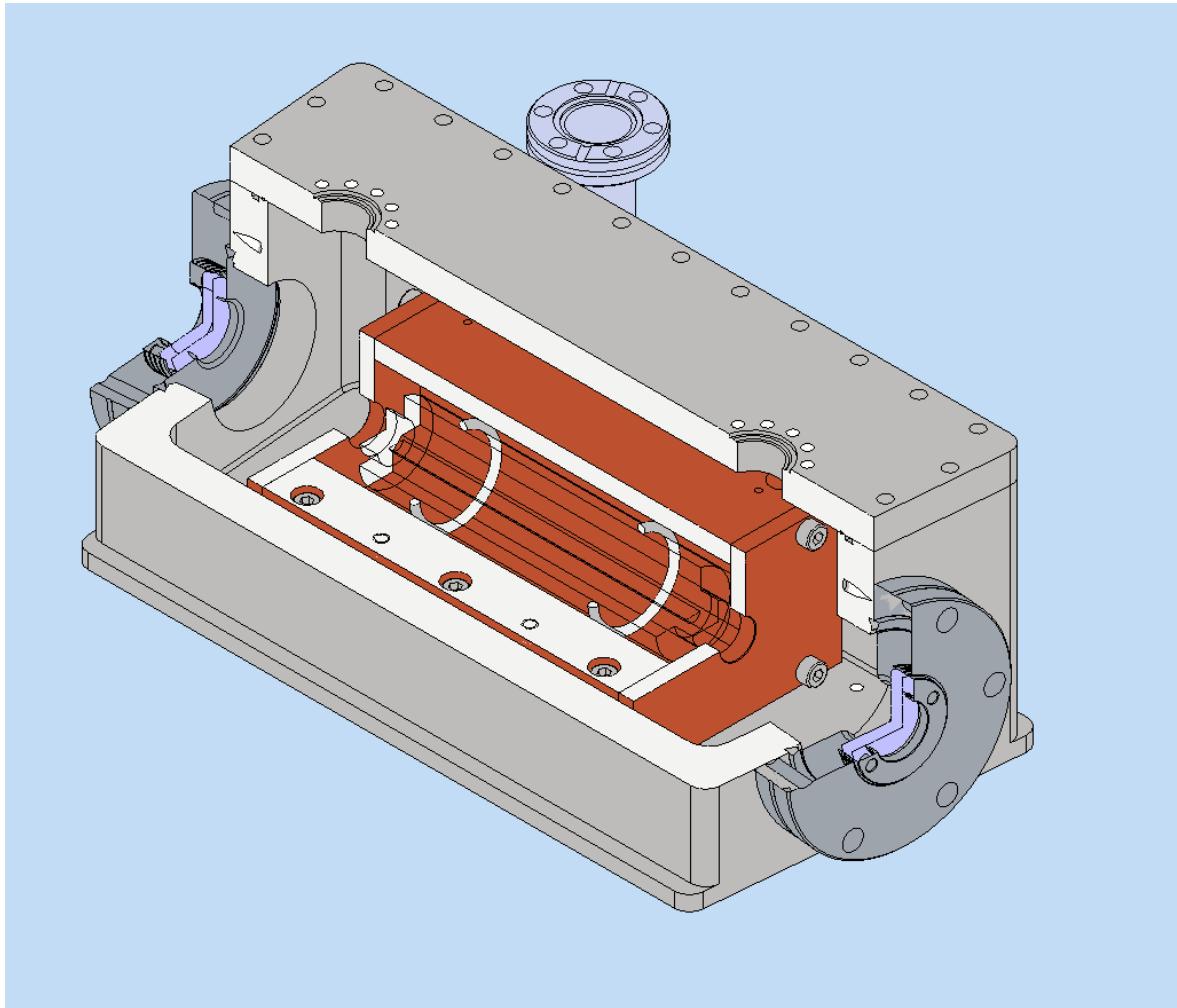


Figure A.1.: The cavity used for frequency locking the spins-sensitive tweezer.

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# **Statement of Authorship**

I herewith declare that this thesis was solely composed by myself and that it constitutes my own work unless otherwise acknowledged in the text. I confirm that any quotes, arguments or concepts developed by another author and all sources of information are referenced throughout the thesis. This work has not been accepted in any previous application for a degree.

Munich, October 16, 2020

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Signature