Laser stabilization and frequency modulation for trapped-ion experiments

Michael Matter
Supervisor: Florian Leupold
Semester project at Trapped Ion Quantum Information group

July 16, 2014

Abstract

A laser locking system and an acuosto-optical modulator are installed. This paper focuses on the setup procedure and outlines functionality and theoretical background. The setups are designed to prepare lasers to conduct quantum information experiments on trapped-ion systems. To test the setup, an experiment is designed to see if different energy level transitions can be driven with light of different polarization. The experiment was successfully conducted.

Contents

1 Introduction

Trapped-ion systems are used to conduct quantum simulations and are promising candidates for quantum computing. The ions are held in place by an electromagnetic field, which forms a potential well. Optical fields are used to manipulate the ions. By laser cooling, the ions temperature is lowered such that the electromagnetic field can hold them in the trap. If sufficiently cold their motion and electronic states follow a pure quantum mechanical description. Lasers are then used to initialize different electron energy levels and manipulate them. For those operations, stable lasers at exact frequencies are needed. One method to stabilize a laser is to lock it to a optical reference cavity. Frequency tuning of the laser can be achieved by guiding the beam trough an acousto-optic modulator (AOM).

In this report, the relevant physical properties of a cavity and the functionality of a Pound-Driver-Hall (PDH) scheme are described, as well as the

setup procedure of a laser locking apparatus. An 846 nm laser was stabilized by locking it to a cavity in a PDH scheme. The setup is described such that a physics student without previous experience of setting up optical equipment can comprehend the procedure. The same was done for an AOM setup of a 397 nm laser. First the functionality and second the setup is described.

The laser coming from this AOM setup was used to conduct an experiment on the ion. The beam was guided on the ion and its polarization was controlled. Different polarization directions of the light drive different energy level transitions. An experiment to demonstrate this effect was successfully conducted.

This laser locking method and similar AOM setups are already used in the trapped-ion quantum information lab at ETH Zurich. The fulfilled tasks in the framework of this semester project are needed to conduct the planned and further experiments in this research group.

2 Laser frequency stabilization

2.1 Cavity physics

A cavity is an essential part of a PDH locking scheme. Therefore the central aspects of a cavity are briefly described. A cavity is basically made up of two mirrors facing each other. If a light beam at a wavelength λ that equals a multiple integer of the distance L between the mirrors,

$$2L = n\lambda \tag{1}$$

standing wave modes can build up. The distance between two such modes in the frequency domain is called the free spectral range $\Delta\nu_{\text{fsr}} = c/2L$, where c is the speed of light.
Using the reflection r and transmission coefficients t of the mirrors, one can calculate the intensity of the reflection and transmission of the cavity. The reflection $F(\omega)$ of the cavity as a function of the frequency ω of the incident light beam for a loss less cavity is (see [2], p.422).

$$F(\omega) = \frac{E_{\text{ref}}}{E_{\text{inc}}} = \frac{r(\mathrm{e}^{i\omega/\Delta\nu_{\text{fsr}}} - 1)}{1 - r^2\mathrm{e}^{i\omega/\Delta\nu_{\text{fsr}}}} \tag{2}$$

The squared absolute value of $F(\omega)$, which describes the reflected intensity, is plotted in Fig. 1.

For this setup, we consider a half-symmetric resonator, where the first mirror in direction of the incident light is flat ($R_1 = \infty$) and the second mirror has a radius of curvature R_2. For the resonance to be stable inside the cavity, the beam has to retrace itself after one round trip. The Gaussian beam has to fit exactly in the cavity, meaning that the waist of the beam is at the position of the flat mirror and the curvature of the wave front of the beam at the position of the second mirror has to fit the curvature of this mirror. If the beam is well adjusted to the mirrors according to those conditions, the resonance corresponds to the zeroth Gaussian mode. If the adjustment is slightly off, other modes can be observed, for example with a camera. Therefore, looking at the intensity cross-section is a good method for the calibration. The length of the cavity can be adjusted by piezoelectric elements. When the laser is locked, the wavelength of the laser can be regulated by changing the length of the cavity. [1][2]

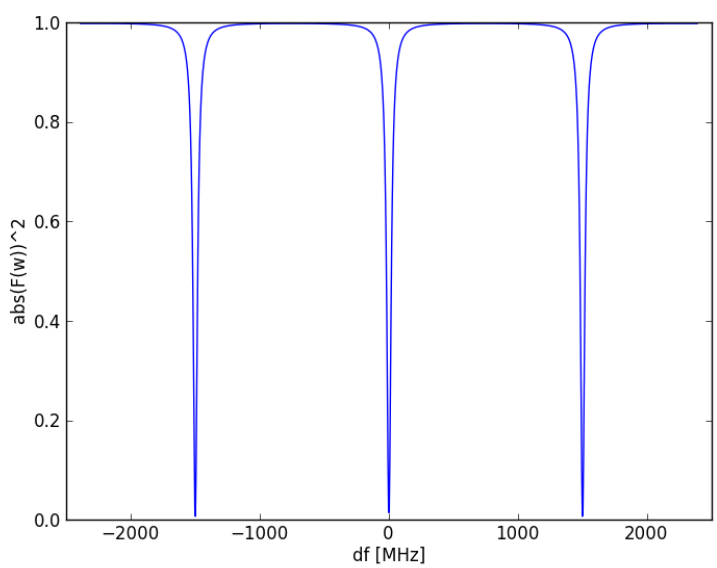


Figure 1: The squared absolute value of the reflection of the cavity for r=0.96 and $\Delta\nu_{\text{fsr}}$=1500 MHz, where $df = f_{\text{res}} - \frac{\omega}{2\pi}$

2.2 PDH Locking

The idea behind Pound-Driver-Hall laser stabilization is that one looks at the reflection of the cavity. If the laser is at the right frequency no light is reflected. The problem is to figure out which direction one has to correct the laser if it is not at the right frequency. The trick is to modulate sidebands on the laser, which are far off resonance with the reference cavity. The frequency spectrum of the beam consists of two sideband frequencies equally spaced around the carrier frequency. The intensity of the carrier is much higher than that of the sidebands. Measuring the reflection of the cavity with a high-frequency photodiode and mixing it with the sideband generation signal yields an error signal, which can be used for locking the laser. The PDH scheme is shown in Fig. 2. A polarizing beam splitter (PBS) is used to channel the reflection of the cavity to the photo diode (PD). The sideband modulation is generated by a voltage controlled oscillator (VCO). This signal is sent by a bias tee input directly on the laser, which yields the sidebands. This signal from the VCO is then mixed with the signal from the PD. The VCO and the mixer are implemented in the KILL-Box (Keitch Integrated Laser-lock Box). This gives an error signal ϵ of the form: (see [1])

$$\epsilon = -2\sqrt{P_C P_S} Im(F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)), \tag{3}$$

where P_C is the power of the carrier, P_S the power of the sideband and Ω the modulation frequency. The important part of the error signal is that it changes sign at the cavity resonance, which is needed for locking (Fig. 3). This error signal is fed through a low-pass filter in a proportional-integral-derivative controller (PID), which generates the locking signal for the laser. This PID controller is implemented in the EVIL-Box (Electronically Variable Interactive Lock Box.)[4]

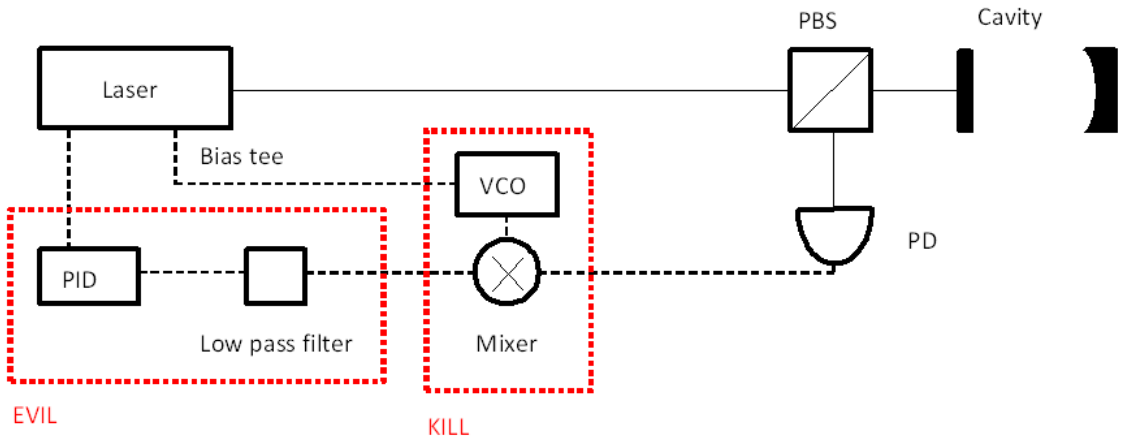


Figure 2: PDH scheme. The continuous line represents the laser path and the dashed lines represent signal paths.

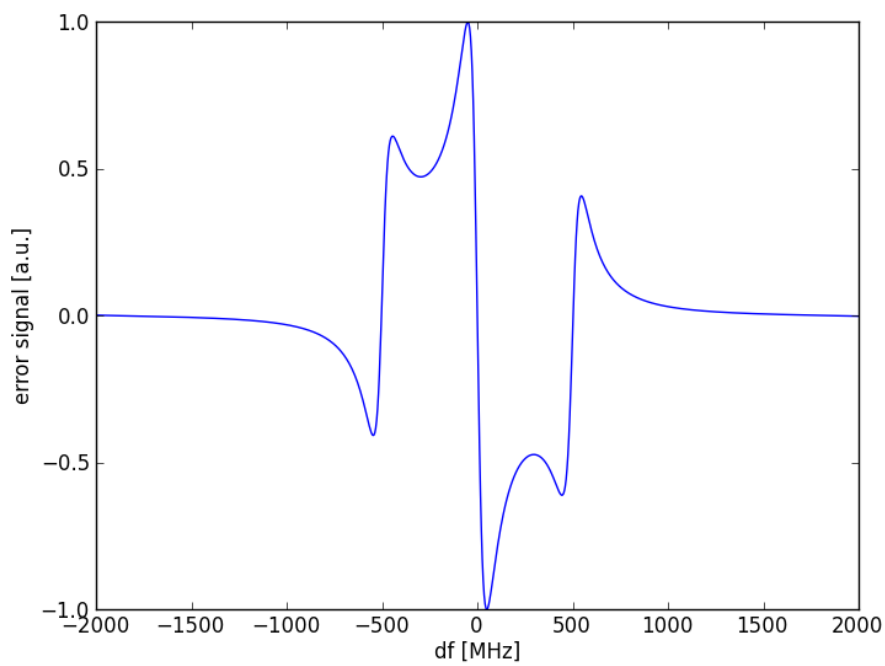


Figure 3: Simulated error signal, plottet against $df = f_{\text{res}} - \frac{\omega}{2\pi}$.

2.3 Setup and installation

The laser needs to go into the cavity and its reflection to the PD. Therefore it has to pass the PBS the first time and get deflected on the way back (Fig. 4). The incident light is vertically polarized and is turned to horizontal polarization by a half-wave plate. The PBS transmits horizontally polarized light. After the PBS, a quarter-wave plate is installed to turn the polarization into circular polarization. After the reflection in the cavity the beam passes the quarter wave plate again, which makes its polarization vertical and therefore the light gets deflected by the beam splitter into the PD.

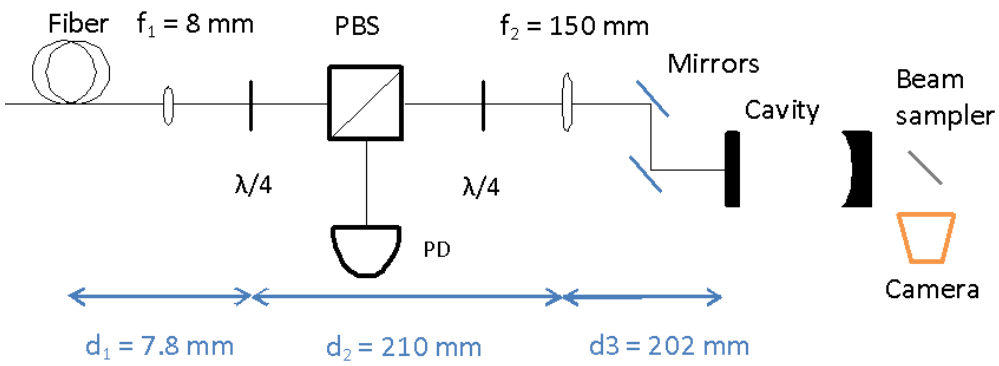


Figure 4: Setup of the cavity

The difficult task is to fit the laser exactly into the cavity. The light used to lock the laser comes out of a single-mode glass fiber and can therefore be regarded as a Gaussian beam. Two mirrors are needed to adjust the direction and position of the beam and two lenses are needed to fit the waist of the beam to the cavity as described in the theory. The path between the fiber and the cavity can be described by ray transfer matrices. The mean field diameter of the beam, when leaving the fiber is approximately 6.25 µm and the required beam waist at the position of the flat mirror is 54 µm. Inserting the positions of the two lenses (one close to the fiber with a focal length of 8 mm and one with a focal length of 150 mm)as degrees of freedom into the ray transfer matrices and solving for the required beam diameter and waist position yields possible solutions for the lenses as specified in Fig. 4. The described optical setup was installed with the two lenses approximately placed according to the calculations.

First the mirrors were adjusted such that the beam enters the cavity. A photo diode and a camera where placed behind the cavity to observe the transmission, which is very helpful during the setup. Then the cavity was scanned. This means that the piezoelectric element of the cavity was connected to a sawtooth wave voltage source, such that the cavity changes its length. The mirrors are tuned until resonance peaks can be observed on the photo diode behind the cavity. The position of the lenses must be adjusted until the light in the cavity corresponds to the zeroth Gaussian mode. This is done by looking at the camera and changing the position of the lens, which is close to the fiber, and keep adjusting the mirrors, until the image on the camera behind the cavity shows a homogeneous round spot of light (Fig. 5). The PD behind the cavity should show a single peak at every point where the resonance condition (Eq. 1) is fulfilled and all other modes should be suppressed. The distance between two peaks in the frequency space is the free spectral range and is proportional to a voltage change of 240 Volts on the piezo element (Fig. 6).

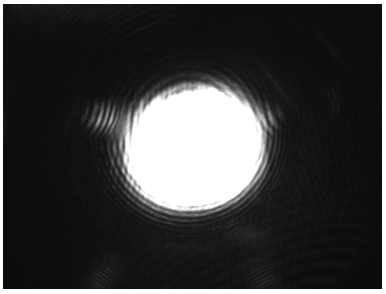
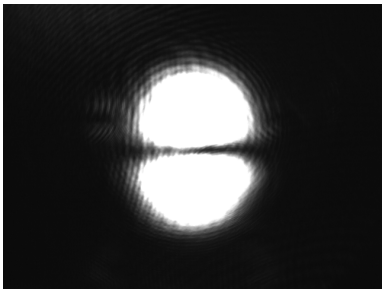
a)  **b)** 

Figure 5: Camera image of the intensity crossection of the transmission through the cavity. a) Shows the zeroth Gaussian mode. b) Shows the first Gaussian mode if the vertical axis of one of the mirrors is slightly off.

Then the rest of the PDH scheme was connected. On the photo diode behind the cavity the modulated sidebands could now be observed and the KILL-Box yields the error signal (Fig.7). The EVIL-Box automatically evaluates the error signal. The PID gains are chosen by trial and error such that the laser is stabilized.

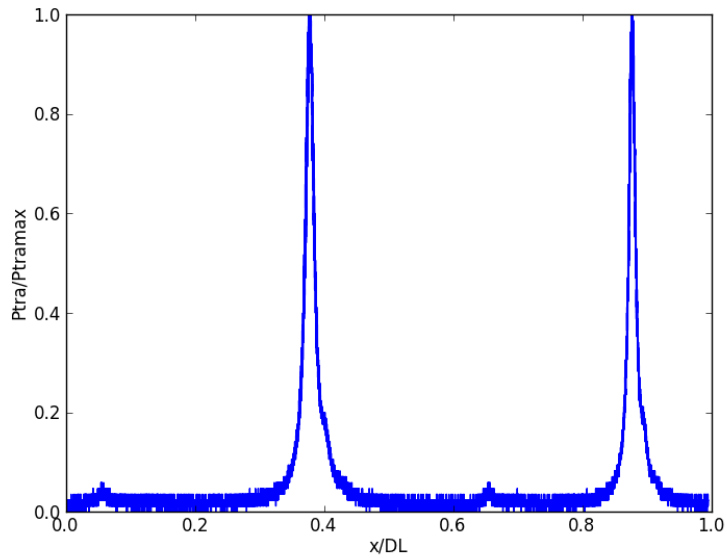


Figure 6: PD measurement of the normalized transmission though the cavity, while the cavity was scanned. DL is the scanning distance, Ptra the transmitted power though the cavity and Ptramax its maximum value. The scanning distance DL was induced by a voltage difference of 490 Volts on the piezo element. The free spectral range is proportional to a voltage change of 240 Volts.

2.4 Results

The laser was successfully locked to the cavity. The locking scheme was tested by disturbing the laser, for example by clapping. When disturbed, the correction signal from the EVIL-Box could be observed to swing away from zero and stabilizing the laser frequency. When the length of the cavity was changed, the frequency of the laser followed, such that the resonance remained in place. The frequency of the laser can now be tuned by changing the cavity length.

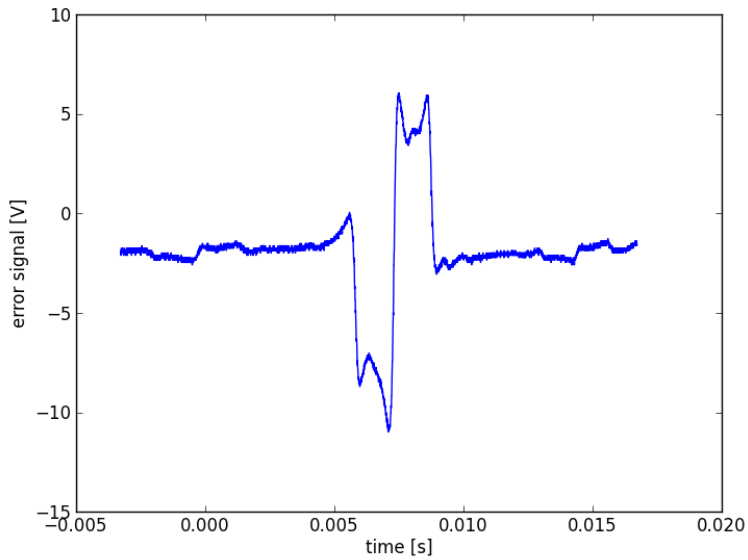


Figure 7: The error signal generated by the KILL-Box.

3 AOM

3.1 Bragg reflection on a sound field

An acusto-optic modulator can be used to turn a laser beam on and off and to modulate the frequency of the light in a range of 80 MHz. An AOM is built up of an optically transparent medium, in this case a crystal, and a speaker. When an RF-frequency acoustic wave propagates through this crystal, a periodic change in the refractive index occurs due to the sound wave. This periodic variation produces a grating, which causes Bragg reflection for an incident laser beam at the Bragg angle θ_B.

$$\theta_B = \frac{\lambda}{2\Lambda}, \tag{4}$$

where λ is the wavelength of the light and Λ is the wavelength of the sound wave. While the optical beam crosses the acoustic wave a Doppler shift by an amount equal to the acoustic frequency occurs. If the laser beam enters the crystal at the Bragg angle in the same direction as the sound wave, the optical frequency is down-shifted. This is called the minus first order. In the

opposite direction it is up-shifted and called the plus first order(Fig. 8). [3]

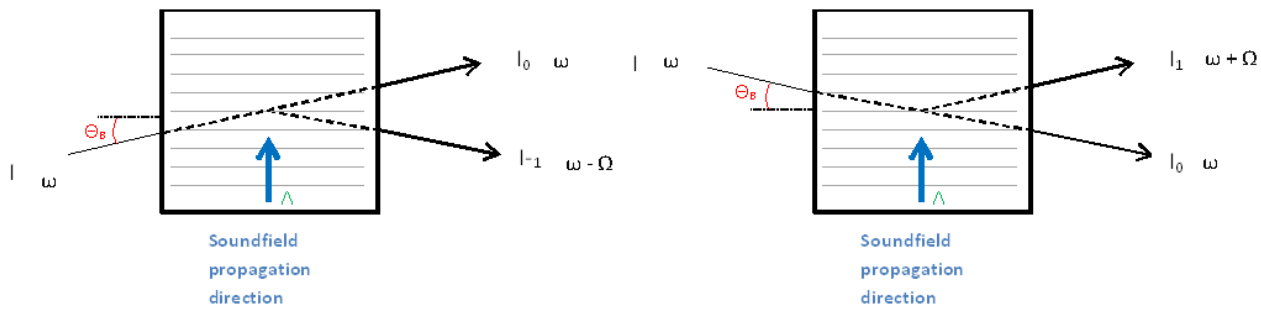


Figure 8: Frequency shifting in an AOM

3.2 Setup and installation

The AOM is needed to modulate the frequency of the light. The problem is, that by changing the frequency of the soundfield the reflection angle of the light changes too. After the AOM the light needs to go into a fiber to transport it to the Ion, but coupling into a fiber is not possible if the angle of the light after the AOM is variable. To get around this problem the beam is guided trough the AOM twice (Fig. 9). The initial beam goes into the AOM. One part of the light gets deflected, called minus first order (-1). The part, which passes the AOM without deflection is called the zeroth order (0). The zeroth order is blocked after the AOM. A lens and a reflector are placed behind the AOM, such that the AOM and the reflector are both a focal distance of the lens away. The minus first order passes the AOM a second time at the same place and the same angle in the horizontal plane, but in the other direction. This way the (-1,-1) beam is always parallel to the incoming light, regardless of the reflection angle. To get the outgoing beam away of the incident beam, the reflector changes the height of the beam and after the lens therefore the angle of the beam in the vertical plane. Now one can separate the outgoing beam with a mirror, which is low enough to let the incident beam pass and high enough to deflect the outgoing. Because the beam goes twice through the AOM the modulation range is doubled. Light can only pass the AOM setup if the AOM is turned on, because the zeroth

order is blocked. Therefore the AOM can be used as a switch for the laser.

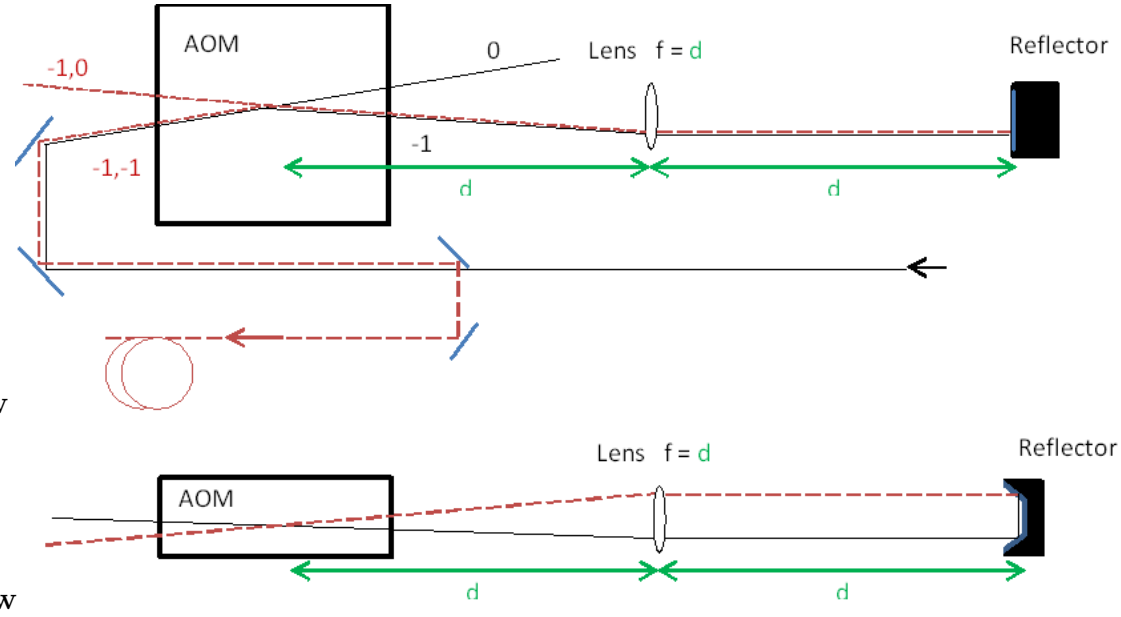


Figure 9: Setup scheme of the AOM. The incident beam is solid and the beam going to the ion is dashed. A lens with a focal length of 150 mm is placed such that the AOM and the reflector are in its focal plane. The numbers next to the beams describe their orders of reflection.

3.3 Result

The light got deflected by the AOM in the expected direction and the beam could actually be blocked by turning the AOM off. Therefore the setup seems to work properly.

4 Experiment on the ion

4.1 Energy levels

The Calcium ion is trapped under an electronic chip, which is placed in a helium cooled cryostat. It moves inside a potential well, that is generated by this chip. The ion's electron configuration corresponds to different energy levels. If light with an energy, which equals a difference between the energy

levels, shines on the ion, the ion absorbs photons of the light beam and it oscillates between those energy levels. To avoid the ion heating up and loosing it, this means that it leaves the potential well, it must be cooled. This is done by laser cooling.

An electron in the $4P_{1/2}$ level has a high probability for spontaneous emission of a photon and falling down to the $4S_{1/2}$. It can also fall down to the $4D_{3/2}$ level, but this is less likely. If both lasers (397 nm and 866 nm) are on, the spontaneously emitted photon can be observed with a camera. If one of the lasers for example the 866 nm is turned off, the ion goes dark, because the electron will be stuck at the $4D_{3/2}$ level.

4.2 Experiment

If a magnetic field is applied on the ion trap in the direction of the 397 nm laser propagation the energy levels of the ion split up in $m_J = \pm 1/2$ states, due to the Zeeman effect. Light with a polarization, which is linear and parallel to the B-field, is called π polarized and circular polarized light is called $\sigma^{\pm}$, plus and minus indicating the direction of rotation. σ polarized light can change the spin orbit interaction part of the energy level ($\sigma^{\pm}$: $\Delta m_J = \pm 1/2$), but π polarized light cannot (π: $\Delta m_J = 0$). Therefore if the 397 nm laser polarization is in a pure σ state (either σ^+ or σ^-, no linear combination of both), the ion should go dark, because the electron will be stuck in one of the states of $4S_{\pm 1/2}$(Fig. 10).

4.3 Setup

The laser coming from the AOM by a fiber needs to hit the ion. This is a similar problem as getting the laser into the cavity. Two lenses and two mirrors are needed to get the beam at the right place with the right beam diameter. The beam should be focused at the ion. Additionally a polarization filter and a quarter wave plate are placed in the path, such that the polarization of the beam can be adjusted as needed for the described experiment. The positions of the lenses are calculated by ray transfer matrices. To do the adjustments of the lens, the beam is deflected by an additional mirror, such that it does not enter the cryostat. A beam diameter measurement device is placed at the distance, where the ion would be without the mirror. Now the position of the lenses are adjusted to minimize the beam diameter at this position. Then the additional mirror is removed. The next step is to adjust

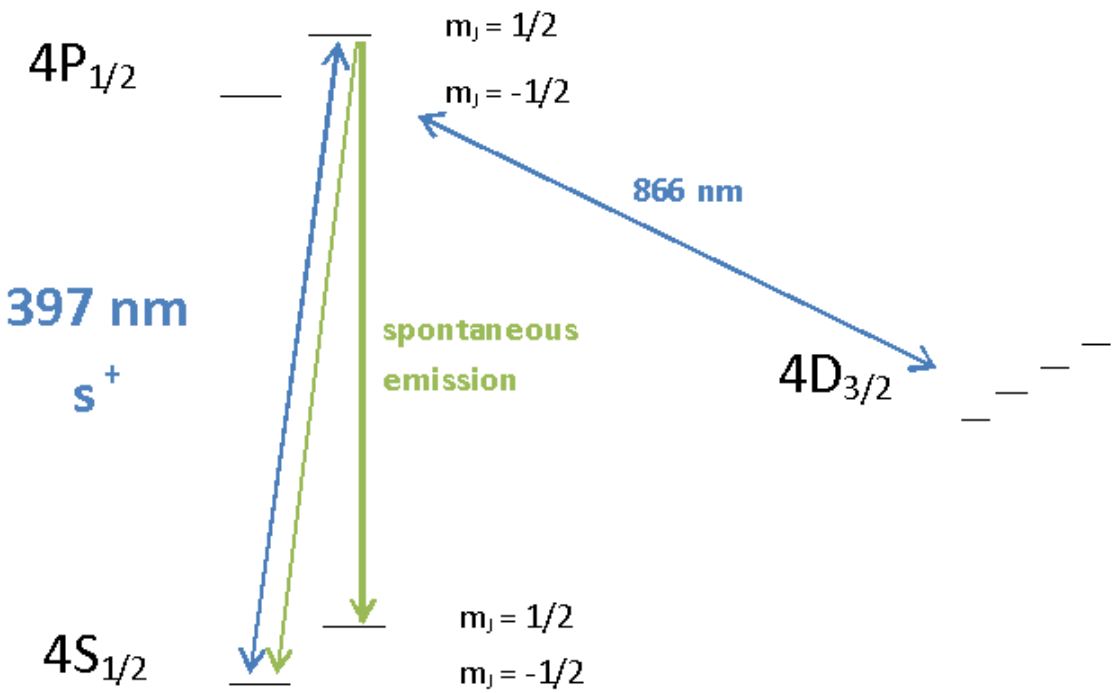


Figure 10: Situation of the experiment: If the 397 nm laser is purely σ^+ polarized, the electron will end up in the $4S_{1/2}$ m_J=1/2 state.

the mirrors such that the beam hits the ion. The chip is surrounded by a cooper case with apertures on the side. The mirrors are tuned until the beam is aligned with the apertures, passes the chip and leaves the cryostat on the other side. The camera, which is used to look at the ion, can be focused on the chip. This is used to continue the adjustment of the beam position. One can observe scattered light if the beam hits the chip. Then the beam is slightly tilted downwards, where the ion should be. When the beam hits the ion, the ion should emit photons, because the ion gets excited to the $4P_{1/2}$ and falls back to the $4S_{1/2}$. The emitted photons are detected by a camera and photo multiplier tube. The incident lasers are pulsed. First a phase of 200 µs is used for laser cooling. Then a short phase of 20 µs where the 397 nm laser has only σ polarization is used to make sure that the electron is in the desired state. During a time of 400 µs, where again the 397 nm laser

has only σ polarization, the emitted photons, that reach the photo multiplier tube are counted. These counts are done for different rotation angels of the quarter wave plate.

4.4 Result

The photons detected in the multiplier tube for different rotation angles of the quarter wave plate is shown in Fig. 11. If the quarter wave plate turns the 397 nm laser into a pure σ plus or minus state the counts are suppressed, because the electron is stuck in one of the $4S_{\pm 1/2}$ states. If the quarter wave plate is turned such that the polarization is $1/2(\sigma^+ + \sigma^-)$ the electron can be excited from both $4S_{\pm 1/2}$ states and the counts reach a maximum. The minima and maxima are expected to be 90° apart. For the displayed data this is not the case. The two peaks are approximately 100° apart and the two minima 80°. This can be explained by double reflection at the cryostate window.

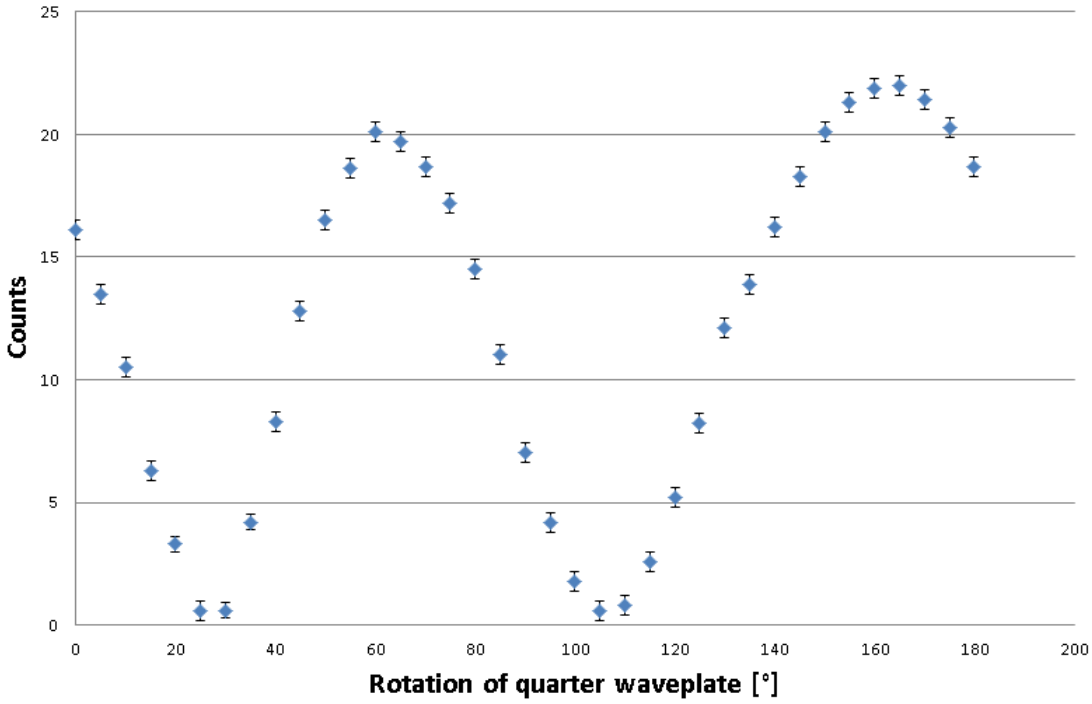


Figure 11: Photons detected in the multiplier tube for different rotation angles of the quarter wave plate. The error bars indicate the standard deviation of the count measurements.

5 Conclusion

The polarization experiment was successfully conducted. This shows also that the AOM setup works properly, since only with the frequency shift of the AOM the required frequency to drive the energy level transitions can be adjusted. The stabilization of the 846 nm laser was also successful. Therefore the goals of this semester project were achieved and the important parts for preparing the lasers, as needed in this lab, were understood and installed. The installed equipment is now used to conduct further experiments with the ions.

The assigned tasks were instructive and the gained experience from working in a professional laboratory was very valuable.

References

[1] E. Hecht *Optics*, 4th edition, Addison Wesley, 2002, p. 416 ff.

[2] A.E. Siegmann *Lasers*, Unversity Science Books,1986

[3] W.R. Klein, and B.D. Cook *Unified Approach to Ultrasonic Light Diffraction*, IEEE Transaction on Sonic and Ultrasonics, Vol. SU-14, July 1967, pp. 123-134

[4] F. Leupold *Cavity Basics and PDH Locking*, ETH Zrich, December 2013