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Laser cooling, trapping and spectroscopy of calcium isotopes

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Chapter 3

Experimental setup

The original goal of the Al⁴¹Catraz setup was to separate ⁴¹Ca from the other calcium isotopes and to trap and detect ⁴¹Ca atoms. The setup described in this chapter is capable of trapping all the stable isotopes of calcium from ⁴⁰Ca to ⁴⁸Ca separately.

Figure 3.1 shows a schematic picture of the setup. In summary, the setup works as follows. Calcium atoms are evaporated from the oven and are entering the Zeeman slower. Here, by means of a counter propagating laser, atoms are decelerated to a velocity of about 50-100 m/s. The Zeeman slower was designed to slow down atoms with velocities up to 1000 m/s. After the Zeeman slower, the atoms proceed towards the optical deflection stage. At this point, the desired isotope is deflected over an angle of 30° towards the Magneto Optical Trap (MOT). In this MOT, atoms are trapped and detected by measuring their fluorescence.

The setup is mounted on an optical table, measuring 3 by 1.2 meter. The laser systems used in the experiment are placed on a separate optical table measuring 2.4 by 1.2 meter. Because the laser systems are sensitive to dust, a flow box with air filter is installed above this table and plastic curtains are mounted around the table, thus creating a slight over pressure above the laser table. Mounting racks are installed above and below the tables to provide room for all kinds of equipment like power supplies and electronics.

3.1 Vacuum system

The vacuum system consists of three sections that can be separated from each other by two gate valves. One valve is placed between the deflection chamber and the trapping chamber and the other one is placed between the second oven and the deflection chamber. The latter is closed during normal operation of the setup. This way a more or less separated section is formed where spectroscopy experiments are performed. Each of the sections is pumped by an ion getter pump (the pumps for the two larger sections have a capacity of 100 l/s, the pump for the smaller one has a pumping speed of 30

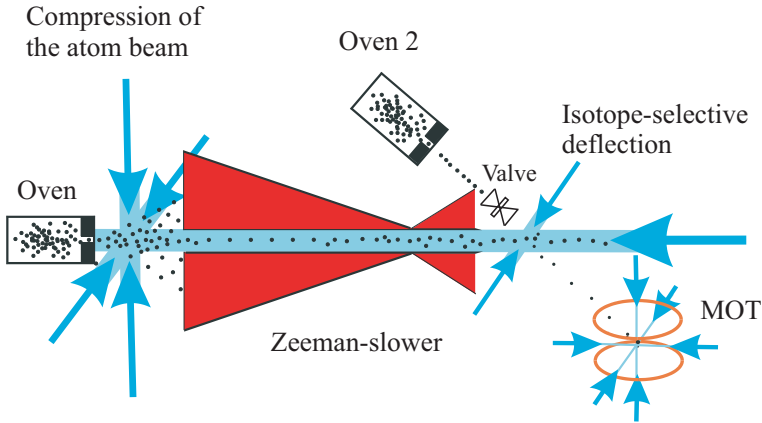


Figure 3.1: Schematic overview of the setup.

1/s), and can be connected to an external pump system via an angle valve for roughing and venting purposes. The base pressure in the vacuum system is $1 - 3 \times 10^{-9}$ mbar. The pressure can rise into the 8×10^{-9} mbar range when the oven is operated at high temperatures.

3.2 Light source

Laser light with a wavelength of 423 nm is needed to excite the $^1S_0 - ^1P_1$ transition of calcium, which is used for laser cooling, trapping and spectroscopy. For this wavelength a diode laser system is used. Laser diodes are relatively cheap and easy to handle. However, they are not available for every desired wavelength. Unfortunately, in the case of 423 nm light, diodes are not widely available. To produce 423 nm light, the light from a 846 nm diode is frequency doubled using Second Harmonic Generation (SHG) [61, 62]. Free running laser diodes usually have a broad emission linewidth (> 10 MHz). The output wavelength is in this case determined by the current through the diode and the temperature of the diode. In order to obtain a narrow emission linewidth (< 1 MHz), one has to apply optical feedback. In this case, this is done with a Littrow geometry [63, 64], using a Littrow grating. In this geometry, light from the diode is sent onto a Littrow grating and the first diffracted order is fed back into the diode. The diode now lases on a pseudo-external cavity that consists of the back facet of the diode laser and the diffraction grating. The use of a Littrow grating provides the possibility to fine-tune the frequency by controlling the tilting of the grating with respect to the laser beam produced by the diode. The fine tuning of the tilting of this grating is done using a piezo transducer.

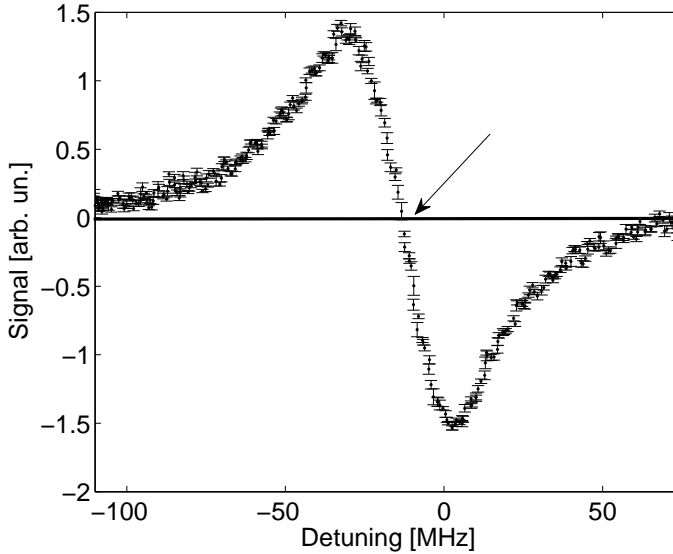


Figure 3.2: *LiPS spectrum used for frequency stabilization. The arrow indicates the zero-crossing, used as the actual locking point of the laser. Note that the frequency axis is not absolutely calibrated.*

3.2.1 423 nm Laser

The laser system used to provide the experiment with blue 423 nm light is a commercially available TA-SHG 110 Diode Laser System, manufactured by Toptica Photonics AG, Germany. It consists of an laser diode with an extended cavity, in a Littrow setup, producing approximately 50 mW of 846 nm light. This light is sent into a tapered amplifier, that amplifies this with approximately a factor of ten and a doubling cavity, finally producing 100 to 150 mW of laser light in the desired 423 nm wavelength.

The heart of the doubling cavity is the Lithium Triborate (LBO) crystal, which is a SHG crystal. The crystal itself is in the centre of a bow tie ring geometry. One of the four mirrors in this cavity is mounted on a piezo transducer (PZT), making the total length of the cavity adjustable to match the wavelength of the diode laser. To stabilize the doubling cavity to the diode laser, the Pound Drever stabilization technique [65,66] is used to create an error signal (PDD110) that is fed into a PID controller (PID100) that controls the piezo element in the doubling cavity. The temperature of the diode, tapered amplifier and doubling crystal are controlled using separate DTC110 temperature controls.

The control units for the grating-PZT voltage (SC 110) and the diode current (DC 110) are equipped with modulation inputs to which external signals can be connected.

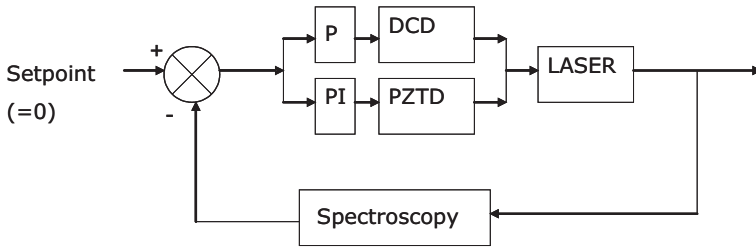


Figure 3.3: The frequency stabilization control loop. DCD: diode current driver (DC110). PZTD: PZT voltage driver (SC 110).

In our case we use those for frequency stabilization of the laser (cf. next section). Another feature of the laser system is the so called feed forward amplification: a signal proportional to the PZT driver voltage is fed into the current driver modulation input. If now the PZT voltage is changed, the diode current is slightly changed as well and this way mode hops can be eliminated over a rather wide frequency range. We measured mode hop free tuning ranges of about 16 GHz.

3.2.2 Frequency Stabilization of the Laser

Since the frequency of the light emitted by diode lasers tends to drift it is very important to frequency stabilize (or lock) the diode laser. In our case, we reference the laser directly to the atomic transition of interest for cooling and trapping purposes. In our setup, we adopted our newly developed LiPS spectroscopy scheme (cf. Chapter 4 and Mollema et al. [67]), which directly produces dispersive-like signals. As can be seen in Figure 3.2 the signal obtained from LiPS has a so called zero-crossing, the point where the signal changes sign. This particular feature makes the signal very suitable to use in a control loop, as depicted in Figure 3.3. In this control loop, the LiPS signal is compared with a setpoint (usually 0) to produce a so called error signal. The error signal is fed into a parallel control system consisting of a proportional (P) and a proportional/integrating (PI) amplifier. The P-amplifier output is connected to the current controller of the diode and serves to take care of laser frequency changes on a very small time scale. The PI-amplifier output is connected to the PZT controller that controls the grating-PZT and eventually the tilting of the grating. This part of the control system takes care of the long term frequency drifts of the laser. Acousto optical modulators (AOMs) are used to shift the frequency of the light used for the spectroscopy such that the laser can be locked at the desired frequency for the isotope of interest.

3.3 Optical lay-out

An overview of the optical lay-out of the experiment is given in Figure 3.4. It is pointed out that this lay-out gives the general configuration when atoms are trapped. For several

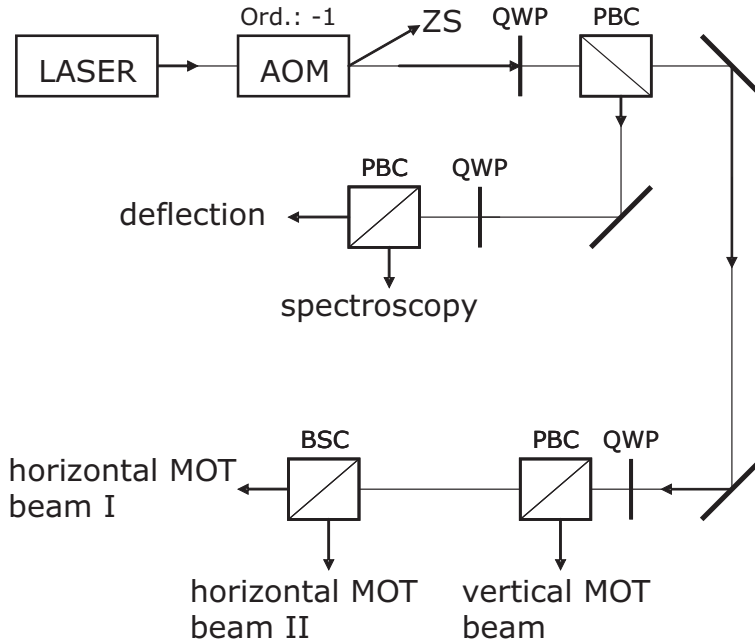


Figure 3.4: *Optical lay-out of the experiment. AOM: acousto-optical modulator, QWP: quarter wave plate, PBC: polarizing beamsplitter cube, BSC: Beamsplitter cube (non-polarizing), ZS: Zeeman slower.*

other experiments the lay-out of the experiment was altered. A common tool to divide the optical power of the laser beam is a combination of a $\lambda/4$ wave plate (QWP) and a polarizing beamsplitter cube (PBC), which together form a variable beam splitter setup.

In order to operate the setup at different frequencies (which is needed to trap different isotopes) the frequency of the light used to frequency stabilize the laser by means of LiPS needs to be shifted. The setup used for that is schematically depicted in Figure 3.5. The double passed AOM (DPAOM) operates on the -1st order, while from the single pass AOM either the -1st, 0th or 2nd order is selected, depending whether either ^{43}Ca , ^{42}Ca or ^{40}Ca is to be cooled and trapped.

3.3.1 Acousto optical modulators

AOMs are used at several places in the setup to shift the frequency of the laser light (see Ref. [68] for a discussion on the principles and applications of acousto optical modulation). For our experiments 3 types of AOMs are available. The Isomet 1250C-848 and the Brimrose EF-200-100-423 have a central shift frequency of 200 MHz and a bandwidth of 100 MHz. The Brimrose EF-400-100-423 has a central shift frequency of 400

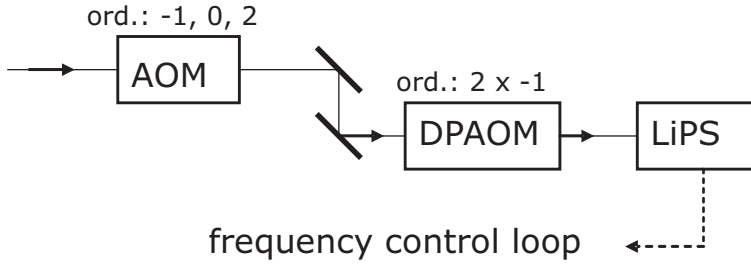


Figure 3.5: Schematic drawing of the frequency shift and spectroscopy setup. AOM: acousto-optical modulator; DPAOM: double passed AOM.

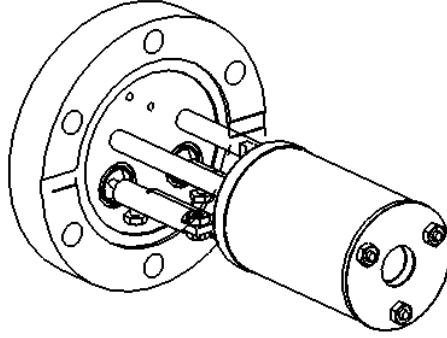
MHz and a bandwidth of 100 MHz. These types of AOMs typically consume between 0.5 and 1 W of RF power. The RF signal is either provided by a signal generator (in our case either a Hewlett-Packard 8657B or a Rohde-Schwarz SML 01) together with a RF amplifier (Mini-Circuits ZHL-1A) or directly from an AOM driver (Isomet D325) comprising a voltage controlled oscillator (VCO) and a variable amplifier circuit. The AOM driver is equipped with a frequency monitor output which is used to measure the produced frequency using a frequency counter (Hameg Universalzähler HM 8021-3).

3.4 Oven

The AlCatraz experiment uses two similar ovens to produce an atomic beam of calcium. One (oven 1) is used to produce the atoms that will eventually be cooled and trapped and the other one (oven 2) is used to produce an atomic beam for spectroscopy purposes. The design of both ovens used to evaporate Ca is adapted from the design of an oven used by the Time and Frequency group of the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany [20], and is nowadays within KVI also used for Na and Ba experiments [6, 69].

The central part of the oven is the crucible made of heat resisting stainless steel (AISI 310/DIN 1.4841). The crucible can be filled with calcium pellets (Goodfellow Cambridge LTD.). A thermocouple is attached to the crucible to measure its temperature. The crucible of oven 2 has an exit channel of 1 mm diameter and 10 mm length. Oven 1 has some 25 of these channels. The crucible is surrounded by a ceramic cylinder, holding a tantalum wire that is thread back and forth through thin holes in the ceramic cylinder to provide uniform heating. The whole oven setup is mounted on a CF35 flange which has feedthroughs for the thermocouple and the heater current. The oven is surrounded by a tantalum heat shield. The temperature of the oven is regulated using a PID controller. The temperature of oven 1 usually does not exceed 450 °C. Oven 2 is usually heated to 600 °C.

We can make a rough estimation of the atomic beam flux. According to Kittel and Kroemer [70] the flux through a channel of length L and diameter d is given by

Figure 3.6: *The calcium oven.*

$\Phi = n \cdot S$ where the conductance of the exit channel

$$S = \frac{2k_B T d^3}{3m v_s L} \quad (3.1)$$

and

$$n = \frac{P}{k_B T} \quad (3.2)$$

in which k_B is Boltzmann's constant, T is the temperature, m the mass of the atom and P the pressure. The average velocity is

$$v_s = \frac{2}{\sqrt{\pi}} \sqrt{\frac{2k_B T}{m}} \quad (3.3)$$

if the gas in the oven has a Maxwell-Boltzmann distribution. The typical vapor pressure for calcium at 400°C is 4.4×10^{-6} Torr [71]. From this formula we find an estimated total flux of 2.5×10^{13} atoms/s for 25 channels.

3.5 Zeeman slower

In order to increase the number of atoms that can be captured by the MOT, the atomic beam evaporated by the oven needs to be decelerated. For this purpose a Zeeman slower is used (see also Refs. [20, 72]). The design of the Zeeman slower is shown in Figure 3.7. The main coil is wound on a 75 cm long water-cooled tube which has an inner diameter of 86 mm, a maximum outer diameter of 110 mm. The coil is water-cooled at the outside too. To ensure a smooth magnetic field there are 51 winding layers and the

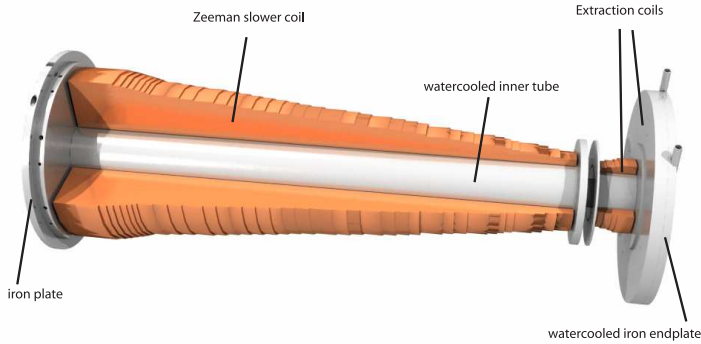


Figure 3.7: *The Zeeman slower design.*

windings are far from the central axis. The total length of the copper wire used in the Zeeman slower is 2450 meter.

An iron plate at the beginning of the Zeeman slower minimizes the size of the coil and the electrical power required. Moreover the plate ensures that the magnetic field in between the oven and the Zeeman slower is low. The extraction coil at the end of the Zeeman slower is placed between two iron plates, one of which is water cooled, to get a steep field gradient at the end of the Zeeman slower and also to minimize the size of the extraction coil.

3.6 Magneto optical trap

After being slowed down by the Zeeman slower and being deflected by the deflection section, the atoms eventually are trapped in the magneto optical trap. The MOT consists of three pairs of counter propagating, circularly polarized laser beams and a quadrupole magnetic field. This magnetic field is created by two coils in anti-Helmholz configuration. The design of the MOT chamber is shown in figure 3.8.

The coils have an inner diameter of 43 mm, an outer diameter of 125 mm, a thickness of 22 mm and consist of 902 windings each. The wire used has a diameter of 1 mm. The distance between the two coils is 56 mm.

With a current of 3 A through each of the coils, the field gradients were, within a radius of 1 cm around the trap centre, measured to be 0.5 T/m (5×10^1 G/cm) in the midplane between and parallel to the coils (the xy -plane) and 1 T/m (1×10^2 G/cm) on the axis through the coils (the z -axis) [72]. So as a function of coil current, the gradient is roughly 17 G/cm/A and 33 G/cm/A for the mid plane and the axis respectively.

The electrical power consumed is ~ 105 W, for which air cooling turns out to be sufficient. Cooling ribs have been attached to the copper container in which the coils

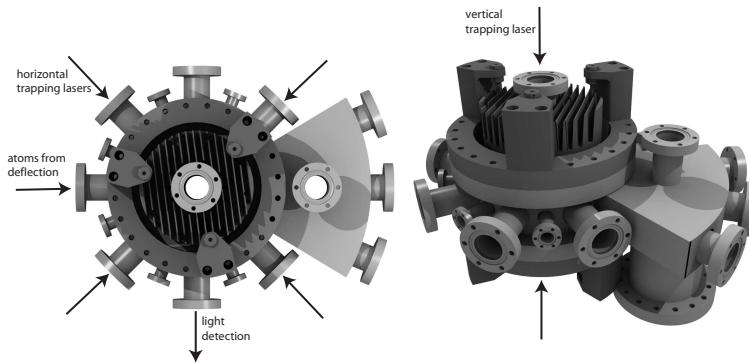


Figure 3.8: Top and side view of the MOT chamber.

are placed, and small fans provide air cooling of these ribs. A triangular extension has been made on the side of the chamber to ensure a good access to the ion pump, which is connected via a CF60 extension tube to the bottom of the triangular expansion. A hole in the optical table enables us to place the ion pump underneath the table. The chamber itself is mounted on an aluminum support structure on the optical table.

3.7 Detection system and data-acquisition

3.7.1 Lens system

The lens system used to collect the fluorescence from trapped atoms in the MOT that is to be detected by the PMT (photon multiplier tube), see Fig. 3.9, consists of two parts: one inside the MOT vacuum chamber and the other outside the vacuum. The part outside the vacuum consists of two lenses and a pinhole, together constituting a spatial filter, and has the option of mounting a neutral density filter (NDF) or a bandpass filter. The optical system is mounted inside a light tight box. The position of one of the lenses and the position of the pinhole can be controlled from outside the box. The photon detector, discussed in more detail later on, is screwed into this box at the back. The entrance side of the detector box is mounted to a CF40 viewport of the vacuum chamber using a light tight connection. The part inside the vacuum is a lens system based on a design by W. Alt [73]. A key parameter of this lens system is the so called Numerical Aperture (NA), defined as

$$\text{NA} = \sin \theta \quad (3.4)$$

where θ is the half-angle of the maximum cone of light that can enter the lens system. Our system has an NA of 0.29. The corresponding solid angle Ω is given as

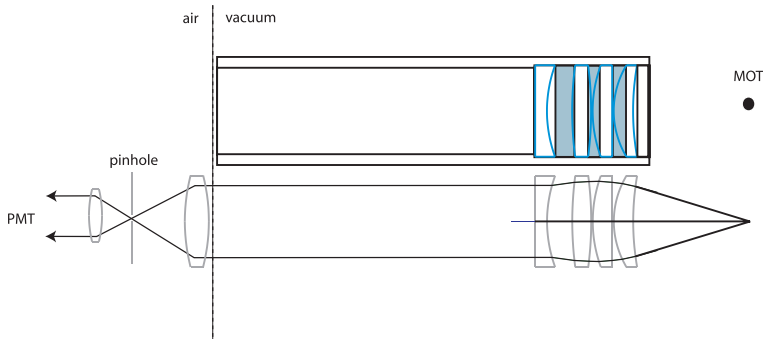


Figure 3.9: The imaging system.

$$\Omega = 2\pi(1 - \cos \theta). \quad (3.5)$$

So the fraction of the total solid angle ($\Omega/4\pi$) which is covered by the system is $\Omega_f = 0.021$. The transmission T_l of the total lens system including the vacuum window was measured to be 0.69.

3.7.2 PMT unit

The photons are detected with a Hamamatsu PMT unit (H7360-02), comprising the PMT itself, a high speed photon counting circuit and a high voltage power supply. The sensitivity for this device at 420 nm is specified by the manufacturer to be $4.4 \times 10^5 \text{ s}^{-1} \text{ pW}^{-1}$. Since the energy per photon at 423 nm is 2.93 eV ($4.69 \times 10^{-19} \text{ J}$) it takes $1 \times 10^{-12} / 4.69 \times 10^{-19} = 2.13 \times 10^6$ photons per second to obtain 1 pW of optical power. So 2.13×10^6 photons per second arriving at the detector yield a count rate of $4.4 \times 10^5 \text{ s}^{-1}$. Therefore the quantum efficiency Q is 0.21.

3.7.3 Determining the number of trapped atoms

The total optical power produced by the MOT cloud P_{MOT} is given by

$$P_{MOT} = \Gamma_p N E_p \quad (3.6)$$

where N is the number of atoms in the trap, E_p is the energy per photon and Γ_p is the scattering rate, given as

$$\Gamma_p = \frac{s_0 \Gamma / 2}{1 + s_0 + (2\delta / \Gamma)^2} \quad (3.7)$$

where Γ is the natural linewidth of the transition, defined as $\Gamma = 1/\tau$, where τ is the life time of the upper state or the transition. δ is the detuning of the laser light with respect to the transition frequency. s_0 is the saturation parameter, defined as $s_0 = I/I_s$, where I is the laser intensity and I_s the saturation intensity. The count rate S measured by the detector can be written as

$$S = \Omega_f Q T_l N \Gamma_p \quad (3.8)$$

where the count rate is expressed in Hz. So for the number of atoms N we arrive at

$$N = \frac{S}{\Omega_f Q T_l \Gamma_p} = \frac{S}{\Omega_f Q T_l} \frac{1 + s_0 + (2\delta/\Gamma)^2}{s_0 \Gamma/2} = \frac{S}{3.0 \times 10^{-3}} \frac{1 + s_0 + (2\delta/\Gamma)^2}{s_0 \Gamma/2} \quad (3.9)$$

Since the PMT can only detect up to about 1×10^7 counts per second, the maximum number of atoms it can detect at moderate trap laser intensities before getting saturated is in the order of 600. In order to be able to deal with a higher number of atoms, a NDF can be mounted in front of the PMT. The ones used in this experiment (Newport FSR-OD200 and FSR-OD300) have Optical Densities (ODs) of 2.0 and 3.0 respectively at 546.1 nm. At 423 nm, the optical densities were measured to be 2.2 and 3.4. The optical density is defined via the transmission T as $T = 10^{-\text{OD}}$. So if a NDF is used during the measurement, Q in Eq. 3.9 should be replaced by QT . When using a NDF with $\text{OD} = 3.4$, the maximum number of atoms that can be detected is about 1.5×10^6 .

3.7.4 PMT Data acquisition system

The pulses produced by the PMT are registered using a FAST ComTec MCA-3FADC multi channel analyzer PCI-card in multi scalar mode. Typical dwell times used are 2 to 4 ms. The spectra recorded with the card can directly be saved on the hard disk of the measurement PC hosting the card. The output of the PMT is, via a Dual Sum and Invert (ORTEC 433A) and a Constant Fraction Discriminator (ORTEC 463) also connected to a rate meter (ORTEC 449-2) for alignment optimization purposes.

3.7.5 CCD camera

To measure the density distribution and the waist of the MOT cloud, a SONY XCD-SX900 CCD camera with a zoom lens is used. The camera is placed in the mid-plane of the MOT, opposite to the PMT system. The camera can be connected to the measurement PC using the IEEE 1394 (FireWire) interface. The camera is controlled and read out using the National Instrument measurement and acquisition explorer (NI MAX) or a LabView application. CCD files are usually saved in PNG format which can easily be processed using Matlab.

