Feshbach resonances in 40K

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Chapter 3

Experimental setup

3.1 Introduction

In this chapter the experimental setup is described. The experiments are done using the apparatus designed and developed for mixtures of ultracold $^6$Li and $^{40}$K. At the time this apparatus was devised there were no other experiments on this specific mixture. Additionally, the scattering properties between the atomic species were not yet known, so the design had to make allowances for possible slow thermalization between the species. Recently the groups in Munich, in Innsbruck, at the MIT and in Paris have also built experiments for $^6$Li and $^{40}$K. The group in Munich [Tag06] included $^{87}$Rb as a third atomic species in their setup to ensure efficient cooling. $^{87}$Rb had been brought to degeneracy previously together with both $^{40}$K [Roa02, Ino04] and $^6$Li [Sil05], after the interspecies scattering lengths had been determined [Fer02, Sil05]. In the group in Innsbruck an all-optical approach was chosen, resulting in large numbers of $^6$Li and low numbers of $^{40}$K. In that experiment efficient thermalization of the sample is ensured by evaporating on the high-field side of a Feshbach resonance in lithium at 834G [Wil08, Spi09]. The potassium is kept in the lowest hyperfine state and is sympathetically cooled by the lithium. In the group at the MIT the bosonic isotope $^{41}$K is used as a coolant [Wu11]. The group in Paris chose an approach similar to ours [Rid11b, Rid11a], relying on the thermalization between $^6$Li and $^{40}$K.

We decided on a setup which combines magnetic and optical trapping. A magnetic trap can be efficiently loaded from a magneto-optical trap (MOT) and provides large atom numbers [Ono00, Sta07]. An optical dipole trap has the advantage that all hyperfine states can be trapped and the trapping potential is identical for all states of one atomic species. Loading the dipole trap from a magnetic trap requires less optical power and a smaller trapping volume than loading it directly from a MOT. Two aspects of the design make the cold atoms easily (optically) accessible: firstly we use an optically plugged magnetic trap [Dav95a] instead of a more commonly used Ioffe-Pritchard type trap [Pri83]. Secondly the optical dipole trap is employed as optical tweezers to transport the atoms [Gus01] to a science cell where the experiments are done. In many cold atom experiments magnetic transport is employed instead, in which a cascade of coils or moving coils are used to transfer the atoms [Gre01]. The science cell is a quartz cell offering good optical access with a small working distance for the
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Producing samples of ultracold atoms requires a vacuum system, lasers tuned close to the transition frequencies of the atoms, a magnetic trap, an off-resonant optical dipole trap or a combination of both to cool the gas close to degeneracy.

Much of the experimental setup has already been described in detail in the thesis of T.G. Tiecke [Tie09a]. The present chapter summarizes the experimental setup putting emphasis on added components and the parts essential for the experiments described in this thesis. In section 3.2 the vacuum system is described, the laser system is covered in section 3.3 and the magneto-optical trap in section 3.4. In section 3.5 the optically plugged magnetic trap is explained including its fast switching electronics. Our optical dipole trap and the feedback circuit with large dynamic range used to stabilize its intensity are presented in section 3.6. The coils used to produce homogeneous and stable magnetic fields for Feshbach measurements are covered in section 3.7. The experimental sequence, the preparation and detection of the Zeeman states and the calibration of the Feshbach coils are described in Chapter 4.

3.2 Vacuum system

The vacuum system is shown in Fig. 3.1 and Fig. 3.2. It consists of four parts: a stainless steel chamber (labelled (c) in Fig. 3.1) where the initial cooling and trapping is done, a two-dimensional MOT (2D-MOT) source for lithium (h), a 2D-MOT source for potassium (a) and a small quartz cell as a science cell (d).

The stainless steel chamber (Kimball Physics Inc., MCF800-SO2000800-A) in the middle is used for the MOT, magnetic trapping, evaporation and the loading of the optical trap. The chamber is cylindrical and has eight CF40 ports on the mantle (labelled 1–8 in Fig. 3.1) and CF160 ports on top and bottom. Two of the CF40 ports (numbered 1 and 5) are taken up by the 2D-MOTS. Another four (numbered 2, 4, 6 and 8) are used for MOT beams. Of the remaining two, one (7) is used as an input port for the dipole trap, the plug beam and the horizontal imaging light. The last port (3) hosts the science cell. All vacuum windows are uncoated and of optical quality. In the big ports on the top and bottom of the chamber uncoated quartz windows with a diameter of 113 mm protrude bucket-like into the steel chamber. The windows are connected to CF150 re-entry flanges with a non-magnetic glass-to-metal seal (Vacom). The coils employed for the magneto-optical trap (MOT) and the magnetic trap are placed close to the windows. The re-entry flanges were chosen to ensure a small distance between the coil centres (see Fig. 3.7). The two MOT beams for the vertical direction enter the chamber through the hollow core of the coils.

Connected to the main vacuum chamber via a four-way cross is a titanium sublimation pump (Leybold, V150) and via a 60 cm long tube of diameter 2 1/2 inch (labelled (e) in Fig. 3.1) a 55 l/s ion pump (Varian, Vacion Plus 55 Starcell). The current reading of the ion pump controller (Varian, Midivac) is below the detection limit ($1 \times 10^{-7}$ A), corresponding to a pressure $P < 6 \times 10^{-10}$ mbar. As an indicator of the vacuum quality we use the lifetime of the atoms in the optical dipole trap ($\approx 40$ s). A T-piece just before the ion pump allows the connection of a turbo pump through an all-metal valve (Varian, 951-5027).

Probably due to residual argon in the system the ion pump needs an occasional
bake-out. The argon saturates the ion pump and reduces the ultimate vacuum. In the experiment it is then noticeable that the lifetime of the atoms in the optical dipole trap shortens to \( \approx 15 \text{s} \). A bake-out of the ion pump was necessary every 6 – 9 months. Argon was introduced into the system during the first bake-out of the vacuum system [Tie09a] and has since then been pumped by the ion pump through the differential pumping section connecting the \(^{40}\text{K}\) 2D-MOT to the main chamber. When a bake-out of the ion pump is necessary, it is heated to just below 400 \(^\circ\text{C}\) for several hours while a turbo-molecular pump disposes of the gas load. As the ion pump is cooling down, the titanium sublimation pump connected to the main chamber is run for about one minute at 50 A, after degassing it at 25 A.

The lithium 2D-MOT is pumped by a 401/s ion pump (Varian, Vacion Plus 40 Starcell) and another titanium sublimation pump (Leybold, V150)(h). This titanium pump was never used since the initial bake-out and the ion pump shows no load when the lithium oven is heated. This confirms the reputation of alkalis as efficient getters in high-vacuum applications. The lithium 2D-MOT can be separated from the rest of the vacuum system with a gate valve (Leybold, UHV 28699).

Attached to the main chamber via a glass-to-metal transition is the quartz science cell with a length of 42 mm and a 12.7 mm\(^2\) cross-sectional area produced by Techglass Inc. (in Aurora, Colorado, USA). The science cell allows for excellent optical access. Coils designed to produce a highly homogeneous magnetic field to measure Feshbach resonances are built around the science cell (see section 3.7).

The potassium 2D-MOT cell is custom-made of glass by Techglass. A four-way cross with optical quality windows (diameter 30 mm) provides access for the four 2D-
MOT beams cooling the atoms in radial direction (see Fig. 3.5 and Fig. 3.6). The cell is connected via a glass-to-metal transition to a CF40 flange. A differential pumping section of 23 mm length and 2 mm diameter connects the 2D-MOT to the main chamber. Mounted in front of the differential pumping tube is a gold mirror with a 2 mm hole in its centre. A distance of 2 mm between the back of the mirror and the differential pumping tube ensures efficient pumping between the two surfaces. The gold mirror can be used to reflect a probe beam or a one-dimensional optical molasses beam. Opposing the mirror on the other end of the 2D-MOT cell is a fifth optical quality window which is used for probe, cooling and push beams along the axis of the 2D-MOT.

Connected to the side of the 2D-MOT cell is a glass tube of 13 mm diameter leading via a T-piece to a break-seal ampule containing $^{40}$K-enriched potassium. The glass tube ends via a glass-to-metal transition and bellows in a CF16 flange. The flange was initially intended to pump the 2D-MOT cell but was never used during the baking and remains sealed with a valve [Tie09a]. As a source for the $^{40}$K we use KCl enriched to an abundance of 6% $^{40}$K (Trace Science International). The distillation into the break-seal ampule was done by Techglass. To achieve the necessary vapour pressure in the 2D-MOT, the entire cell is heated with heater tape and insulated with aluminium foil.

To complete the description of the vacuum system, it is mentioned that we have built the first realisation of a 2D-MOT for lithium. It is fed by an effusive oven and results in an output flux up to $3 \times 10^9$/s. Lithium reacts with glass, therefore we chose a stainless steel chamber for the lithium 2D-MOT. The windows admitting the MOT light are under a 45° angle to the main axis of the lithium beam emitted from the oven, so the lithium cannot reach the windows under normal operation. The lithium
3.3 Laser system

All manipulation of $^{40}$K with light is done on the D2 line, where we call the transition $|^2S_{1/2}, F = 9/2\rangle \rightarrow |^2P_{3/2}, F = 11/2\rangle$ the *trap transition* and the $|^2S_{1/2}, F = 7/2\rangle \rightarrow |^2P_{3/2}, F = 9/2\rangle$ is referred to as the *repump transition* (see Fig. 3.3). Light with frequencies tuned close to those transitions we refer to as trap and repump light respectively. In contrast to many other alkali isotopes, $^{40}$K has a sufficiently small hyperfine splitting in the ground state ($\Delta E_{hf} = 1285.79$ MHz) to allow for the use of an acousto-optical modulator (AOM) to bridge the frequency difference.

One master laser (Toptica DLX110) is stabilized in frequency. The output power (350 mW) is split into several beams, which are shifted by AOMs to the proper frequencies for the beams to trap, repump and image the atoms. To have sufficient power, the trap and repump light is amplified by tapered amplifiers. In Fig. 3.4 the simpli-
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The repump frequency is generated by shifting the master frequency by 1143 MHz with an AOM from Brimrose (GPF-1240-200-766). All other frequencies used to manipulate the $^{40}\text{K}$ are obtained using AOMs by Isomet.

The DLX110 laser is stabilized to a polarization Zeeman spectroscopy. We lock the laser to the unresolved $|S_{1/2}, F = 1\rangle \rightarrow |P_{3/2}\rangle$ transition in $^{39}\text{K}$. Light from the master laser is brought via a polarization-maintaining fibre to a separate optical table and its frequency is shifted by -260 MHz with an AOM by Crystal Technologies. The linearly polarized light ($\approx 200 \mu\text{W}$) passes through a heated vapour cell ($\approx 40^\circ\text{C}$) filled with potassium in natural abundance. A partial reflector ($R = 10\%$) reduces the power in the retro-reflected beam such that the two beams form a pump-probe setup of a Doppler-free saturation spectroscopy [Lev74, Bir74]. The vapour cell is placed in a homogeneous magnetic field of a few Gauss. The field is parallel to the light, resulting in $\sigma^+$ and $\sigma^-$ transitions ($\Delta m_F = \pm 1$), being the allowed optical transitions. The $\sigma^+$ and $\sigma^-$ transitions are shifted in frequency due to the Zeeman shift and differ in strength due to different Clebsch-Gordon coefficients. By placing a quarter waveplate and a polarizing cube in the path of the probe beam as shown in Fig. 3.4, the two circular polarizations can be split and detected separately by photodiodes (OPT101P-ND). By electronically subtracting the two photodiode signals a dispersive signal to lock the laser is retrieved. Two different stages stabilize the laser: one fast loop (bandwidth $\approx 4 \text{ kHz}$) feeds back to the diode current of the master laser and one slower loop (bandwidth $\approx 1 \text{ Hz}$) feeds back to the piezo-electric actuator controlling the grating position in the DLX110. The slow loop compensates for thermal drifts whereas the current feedback ensures short term stability.

The light for the trap and the repump beams is amplified by tapered amplifiers (Eagleyard, EYP-TPA-0765-01500-3006-CMT03-0000). The amplifier chips are mounted in a home-built aluminium housing, which we designed to ensure that thermal effects do not alter the position and consequently the injection of the amplifier. The main feature is that the chip is mounted such that any thermal expansion results in a minute rotation around the optical axis rather than a displacement. This rotation preserves the injection of the laser beam in the amplifier chip and ensures constant power output. The temperature of the chip mount is stabilized with two thermo-electric Peltier elements (Eureca Meßtechnik, TEC 1H-30-30-44/80-BS). The chip mount is electrically insulated from the aluminium housing by studs made from PEEK (polyether ether ketone), a plastic with high tensile strength and small mechanical relaxation. The collimation lenses on both sides of the chip are also mounted on holders made from PEEK. The threads on the lens holders are tightly fitted into the aluminium housing; for collimation the holder is simply wound in or out using a wrench. The design of the mount and its thermal behaviour is described in some detail in [Koo07].

The tapered amplifier for the repump light is injected with 8 mW and emits 200 mW. The temperature is stabilized to 31 $^\circ\text{C}$ by a temperature controller (Thorlabs, TED 200C). The current through the chip (1.7 A) is supplied by a home-built power supply. The tapered amplifier for the trap light has both temperature and current (2 A) stabilized by a laser controller (Sacher, Pilot 2000). It runs at 25 $^\circ\text{C}$, is injected with 47 mW and emits 767 mW. Both tapered amplifiers only required re-adjustment of the injection when the optical path before the amplifiers changed. The collimation has stayed stable. The coupling efficiency into optical fibres is about 50\%.
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Figure 3.4: Optical setup of the laser system for $^{40}$K. The Toptica DLX110 serves as the master laser. Light for the trap and repump transitions is amplified by tapered amplifiers (TA). The spectroscopy setup is located on a separate table. Beam shaping and folding optics have been omitted from this schematic.
3.4 Magneto-optical trapping

In a magneto-optical trap (MOT) neutral atoms are cooled by the absorption and re-emission of light and trapped in a steep magnetic gradient. The cooling mechanism works due to radiation pressure from three orthogonal pairs of counter-propagating beams \cite{Raa87, Met07}. Depending on the number of levels in the atomic spectrum and the lifetimes and transition probabilities of the excited states, several optical transitions need to be driven by light. Successive absorption of light on a so-called cycle transition, enables the cooling. To achieve this in alkalis, two frequencies are needed: a trap (or cool) and a repump frequency. An atom moving towards the light beam is in resonance due to the Doppler effect when the laser frequency is red detuned by several linewidths $\Gamma$. Additionally the magnetic field gradient causes a spatially varying Zeeman shift of the transition frequencies and restricts the allowed optical transitions. If the counter-propagating beams have $\sigma^+$ and $\sigma^-$ polarization, a moving atom will always be closer to being resonant with the light beam pushing the atom to the centre of the trap. Effectively the atoms are pushed to the centre of the trap where the magnetic field vanishes \cite{Met99}.

For the magneto-optical trapping of $^{40}\text{K}$ the trap laser is red detuned by $6\Gamma$ from the $|2S_{1/2}, F = 9/2\rangle \rightarrow |2P_{3/2}, F = 11/2\rangle$ transition. The repump light is detuned by $2\Gamma$ from the $|2S_{1/2}, F = 7/2\rangle \rightarrow |2P_{3/2}, F = 9/2\rangle$ transition. The detuning is chosen to be identical for the two- and the three-dimensional MOT (3D-MOT).

3.4.1 Two-dimensional MOT for $^{40}\text{K}$

As sources for cold atoms, we employ a two-dimensional magneto-optical trap (2D-MOT). A great variety of sources for cold atoms have been developed over the years. For potassium custom-made dispensers are used alone \cite{WI97, DeM99b}, or in combination with light-induced atomic desorption (LIAD) \cite{Goz93}, as demonstrated in \cite{Kle06} using UV light. The resulting short vacuum lifetimes of using dispensers can be somewhat improved \cite{Moo05, Gri05} but the shortest loading times and highest atom numbers so far have been achieved with beam-loaded MOTs. The highest loading rates for different atomic species have been achieved with a Zeeman slower \cite{Lis99, Slo05, Sta05}. However, the design of a Zeeman slower requires substantial engineering, especially when recycling schemes or multiple species are used.

Compared to a Zeeman slower a 2D-MOT has the advantages that it is a compact setup, it does not allow hot atoms into the main chamber and it makes most efficient use of the atoms. Furthermore there are no stray magnetic fields close to the main MOT. Especially in the case of potassium the high price of enriched potassium is an argument to use a 2D-MOT. The 2D-MOT is a two-dimensional realisation of a MOT. The circularly polarized light beams are applied from four (not six) directions in space and the magnetic gradient is also two-dimensional as shown in Fig. 3.5. The two-dimensional quadrupole field is zero along the symmetry axis. The MOT beams drive cold atoms towards this axis. Along the axial direction there is no confinement by magnetic fields. A push beam is used to push the atoms through the differential pumping tube into the capture region of the 3D-MOT in the centre of the main chamber (see section 3.2). Some designs for 2D-MOTs employ an additional cooling beam
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opposing the push beam creating a one-dimensional optical molasses [Die98, Cha06, Rid11b]; others are purely two-dimensional [Sch02]. For potassium 2D-MOTs are used in Hamburg [Osp06b], Florence [Cat06] and Paris [Rid11b].

As described in section 3.2 we use two separate 2D-MOTs for the two species, the one for lithium is described in detail in [Tie09b]. Our source for the potassium is a break-seal ampule, which was opened with a glass-encapsulated magnet also included in the glass cell (see Fig. 3.6, Fig. 3.5 and Sec. 3.2). The glass cell of the 2D-MOT is heated to about 50°C to increase the vapour pressure. Two sets of permanent magnets provide the magnetic quadrupole field. The magnets are made of Nd₂Fe₁₄B (Eclipse magnets, N750-RB) and their magnetisation has been measured to be 8.8(1) × 10⁵ A/m [Koo07]. Each set consists of two magnets separated by 12 mm. A single magnet has the dimensions 25 × 10 × 3 mm. Effectively the two magnets then form a 62 mm long magnetic dipole. The two magnet sets are each placed 35 mm away from the axis of the cell and together form a radial gradient of 20 G/cm. We use 120 mW trap light and 40 mW repump light per beam. The beams are retro-reflected (see Fig. 3.5) and have a 1/e-diameter of 18 mm. For an improved loading of the 3D-MOT we employ a push beam, which is aligned along the axis of the 2D-MOT. The push beam consists of 2.6 mW of trap light detuned only by 2Γ from the trap transition. With this 2D-MOT we achieve loading rates in the 3D-MOT of 3 × 10⁸/s. This is over an order of magnitude more than reported from Hamburg [OS06]. Recently the group in Paris [Rid11b] achieved 3D-MOT loading rates of 1.4 × 10⁹/s using larger and more intense 2D-MOT and 3D-MOT beams, and an additional molasses beam in the symmetry axis.
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Figure 3.6: The 2D-MOT chamber for $^{40}$K is a custom-made glass cell. A side arm leads to the potassium reservoir and a valve. In the foreground the glass-encapsulated magnet, which was used to break the potassium ampule, is visible.

3.4.2 Three-dimensional MOT

The three-dimensional magneto-optical trap (3D-MOT) was designed and optimized as a dual system for lithium and potassium. All waveplates, polarization cubes and mirrors are therefore dichroic. The six 3D-MOT beams, three orthogonal pairs of counter-propagating beams, are all derived from a single beam, which consists of trap and repump light. The beam is split into six using $\lambda/2$ waveplates and polarizing cubes. To produce circular polarization we use quarter waveplates custom-made by Casix for the wavelengths 670 nm and 767 nm. They have a diameter of 18 mm, which is about the $1/e$ diameter of the MOT beams. The trap light has $P = 10$ mW per beam, corresponding to an intensity of $I = 2.3I_s$, where $I_s$ is the saturation intensity (see Appendix A). Although the polarizing cubes are suitable for both the lithium and the potassium wavelengths, the reflection angle differs slightly for the two. When aligning the MOT optics, care has to be taken to minimise the impact of this effect.

For the loading of the MOT we make use of a dark spot MOT [Ket93]. This results in high atom numbers and a high density. For the dark spot MOT the repump light in all the MOT beams is switched off and a separate beam is used. This separate beam of repump light (3.4 mW) is sent through a plate with a dark spot in the middle. The beam is then split into two counter-propagating beams and imaged onto the centre of the MOT. At the center of the MOT the intensity of the repump light is reduced to $2\%$ compared to the intensity in the surrounding area. The image of the dark spot has a diameter of $\approx 3$ mm at the center of the MOT. The dark spot is also favourable for the suppression of light-induced collisions between the lithium and potassium when performing experiments on the mixture [Tie09a].

The magnetic quadrupole field for the MOT is produced by the same coils as used for the magnetic trap (for a more detailed description see Sec. 3.5.1), and has a gradient of 14 G/cm. The push beam from the 2D-MOT is directed at the center of trap produced by these coils. This impedes the loading of the 3D-MOT and pushes on the atom cloud. To prevent this and optimize the loading, shim coils produce another few Gauss to shift the atom cloud away from the path of the push beam. The shim coils consist each of several loops of ribbon cable wound around the main vacuum chamber. The
individual wires of the cable are connected in series resulting in 80 windings per coil. There are four shim coils in total: two coils to shift the MOT up or down, positioned around the top MOT coil, and two coils positioned orthogonal to the MOT coils and orthogonal to each other. The shim coils can produce up to 10 G. They are powered by Delta Elektronika (ES030-5) power supplies. The current can be switched quickly to dummy loads using MOSFETs. In 16 s we load up to a total of $2 \times 10^9$ atoms in the 3D-MOT. For large atom numbers the temperature of the MOT is $T = 190 \, \mu \text{K}$. Sub-Doppler MOT temperatures were reached with $40 \, \text{K}$ by [Cat98, Mod99], but these results concern lower MOT densities.

After the MOT loading the MOT parameters are modified briefly to increase the phase-space density before loading into the magnetic trap. In 10 ms the magnetic field gradient is ramped up to 44 G/cm and the shim coils shift the MOT to optimize the magnetic trap loading. Following this compression stage, the atoms are optically pumped into low-field seeking states. Optical pumping light resonant with the $|2S_1/2, F = 9/2\rangle \rightarrow |2P_3/2, F = 9/2\rangle$ transition is applied to the atoms for 60 $\mu$s at an intensity of about $1.4I_s$. During the optical pumping step, repump light from all six directions prevents population of the $|2S_1/2, F = 7/2\rangle$ manifold. The bright repump light has $P = 1.5 \, \text{mW}$ per beam, corresponding to an intensity of $I = 0.3I_s$ and is not attenuated by a dark spot in the centre.

An offset field of 3.6 G along the direction of the optical pumping beam is provided by one of the shim coils. The optical pumping has been optimized to achieve a mixture of atoms in the $F = 9/2, m_F = 9/2, 7/2$ and $5/2$ states. About 60% of the atoms in the MOT are then recaptured in the magnetic trap. A higher efficiency can be achieved [Tie09a], but this yields much more atoms in the fully-streched state $m_F = 9/2$. However, to achieve thermalization in the magnetic trap, a mixture of atoms in different spin states is necessary.

### 3.5 Optically plugged magnetic trap

For the magnetic trapping we employ an optically plugged magnetic trap. It is a combination of a magnetic field supplied by two coils and a blue-detuned laser focused in the center of the magnetic trap as an optical plug. The coils create a linear quadrupole trap with zero magnetic field at the centre. Near the zero crossing of the magnetic field the atoms can undergo spin-flips to untrapped states and be lost from the trap. These so-called Majorana losses [Maj32] become more pronounced the colder and therefore closer to the trap centre the atoms get. The dipole force exerted by the blue detuned laser repels the atoms from the centre of the trap and prevents Majorana losses. This method has been used to produce the first Bose-Einstein condensate at MIT in 1995 [Dav95a]. The idea of the optical plug was later abandoned in favour of magnetic traps with an offset field. The advantage of the optically plugged trap is that it allows to make use of a linear trap with its favourable evaporation properties and it saves space, which would be needed for an additional coil or Ioffe bars to produce the offset field. When evaporating in a linear trap the volume decreases faster than in a harmonic trap, thus increasing the phase space density faster [Bag87, Dav95b]. Only recently other groups have started again employing an optically plugged trap to produce large Bose-Einstein condensates [Nai05, Heo11] or ultracold Fermi clouds [Wu11].
Figure 3.7: Schematic of the cut through the vacuum chamber showing the MOT coils and the water-cooling. The shim coils are wound around the main chamber and are used as trim coils for the MOT loading and optical pumping. Only two of the four shim coils are shown in the schematic. The antennas consist of simple wire loops.

### 3.5.1 Magnetic Trap

The magnetic trap is formed by the two MOT coils with their centres separated by about 110 mm. The coils are developed for the use in loudspeakers and fabricated out of a Kapton insulated copper tape (Canatron, CT 7419). The copper tape has a 25×0.25 mm cross-section and Kapton insulation on both sides. Each coil has 76 windings resulting in a coil with 45 mm outer radius and 17.5 mm inner radius. The coils are glued to slit copper plates, which are water-cooled. The copper tape ensures a high current density. With a current of 100 A a magnetic gradient of $B' = 176$ G/cm along the $z$-direction is created. The absolute value of the magnetic field is $B(x, y, z) = (B'/2)\sqrt{x^2 + y^2 + 4z^2}$. The symmetry axis is in $z$-direction as indicated in Figs. 3.7 and 3.2. The inductance of the coils is 365 $\mu$H. Each coil is mounted close to the CF150 windows protruding into the main chamber.

The magnetic field has to be switched off entirely by the time an image of the atoms is taken. Residual fields would shift the resonance frequency of the atoms and distort the number of detected atoms. According to Faraday’s law fast switching of magnetic fields induces a high voltage, which can drive an induced current creating a magnetic field opposing the initial one. To prevent this a special switch is employed. The switch was constructed following the example of [Aub05], described in detail in [Stu04]. In one switch box several features are included: four IGBT switches (Semikron, SKM100GB123D) disconnect the coils from the power supply within 600 ns. The induced voltage spike is absorbed by stacks of transient voltage suppressor diodes (TVS, ST SM15T39A). A current of 100 A then switches off within 100 $\mu$s.
Figure 3.8: Simplified circuit diagram of the MOT coil switch. The grey arrows indicate the direction of the current. Analogue and TTL signals control the various functions of the switch. Apart from optical decouplers, insulators and other means to protect the involved parts, also the filters to prevent ringing of the current after switch on have been omitted in this schematic.

For a fast switch-on to a high current a pre-charged capacitor (8 µF) is switched into the circuit with a thyristor (CS35/1200). The switch-on time is limited by a filter to 50 A/µs to protect the thyristor. The switch box also includes two relays (Stancor, 586-914), which allow to change between a gradient and a homogeneous field. All operations of the switch box are controlled by analogue signals (0-10V) and TTL pulses. The steering signals are decoupled by insulation amplifiers from the control circuit to protect the computer control from high voltages. For a simplified schematic see Fig. 3.8

However using tape to make a coil has two major flaws: a thermal gradient within the coil, with the thereby caused magnetic inhomogeneities and instabilities, and eddy currents within the tape. The coil is only cooled from one side, resulting in a thermal gradient from top to bottom. This gradient gives rise to a gradient in resistance and therefore in current density in each winding. The stability of the magnetic field in strength and position is limited by the thermalization of the coils. In particular the position of the magnetic field zero with respect to the position of the optical plug depends on an identical rate of thermalization for both coils, which cannot be assumed. It is difficult to achieve optimal thermal contact between coil and cooling plate. The Kapton insulation of the tape is not coated onto the copper but attached in the form of a 50 µm thick adhesive tape. The Kapton tape protrudes on the top and bottom
of the coil. We have improved this by milling off the Kapton and placing 0.2 mm thick electric insulation pads between cooling plate and the coils. The thick pads were necessary because the contact surface is not entirely flat. However, the insulation limits the thermal conductance between the coils and cooling plates.

The heating of the MOT coils results in a decreased atom number if the coils run for longer than usual (for example when measuring the lifetime in the magnetic trap). For a normal experimental cycle where the atoms are transferred from the magnetic trap to the dipole trap after 23 s and a new measurement starts about every minute, the temperature varies about 8° C. When running 100 A through the coils, they heat up by about 35° C within 2 minutes. In addition the tape coils have the disadvantage that the switching-off induces eddy currents within the copper tape of the coils, which can persist for a couple of milliseconds. The current only produces a small field, orthogonal to the dipole created by the coil itself. In practice a shift of the resonance frequency for the imaging is not noticeable any longer after 2 ms time-of-flight. We do not recommend the use of copper tape with a large aspect ratio for coils in a magnetic trap.

3.5.2 Optical plug

The coils create a linear quadrupole trap with zero magnetic field at the centre. To prevent Majorana losses at the zero-crossing we focus 9 W of 532 nm laser light as an optical plug in the centre of the trap. It is essential that the beam profile of the plug laser is a Gaussian transverse electro-magnetic mode (TEM\(_{00}\)). Dust on the optics or thermal lensing in an AOM can lead to a doughnut shaped mode (TEM\(_{01}\)), which makes the optical plug less efficient. To avoid this problem we have replaced the AOM, which was initially used to switch off the plug, by a high power shutter (nmLaser Products Inc., LST4WBK2-D123). The shutter does not close sufficiently fast to be able to image the cloud in the main chamber after release from the magnetic trap. For alignment purposes it is best to leave the plug switched-on during time of flight. The imaging of the atoms then allows for qualitative measurements. All quantitative measurements are done releasing the atoms from the optical dipole trap with the optical plug switched off.

As illustrated in Fig. 3.9 the beam mode and focus shape is monitored with a CCD camera placed in the focus of the reflection from the beamsplitter which combines the optical plug and the optical dipole trap just in front of the vacuum chamber. The passage through the beamsplitter introduces astigmatism to the plug beam profile, displacing the two foci by about 2.2 mm. The average waist of the beam is \( w = 16 \mu m \). The light for this optical plug is provided by a 10 W Verdi (Coherent).

When running a high current through the MOT coils for times longer than 30 s, for instance when measuring the vacuum lifetime in the main chamber, the coils heat up noticeably and this affects the number of trapped atoms. This can be attributed to the thermalization of the coils. When heating up, the position of the magnetic field zero changes such that the alignment of the optical plug is not optimal any more and Majorana losses are not sufficiently suppressed. The alignment of the plug beam itself is stable, we only have to adjust it every 4–6 weeks during normal operation.
3.6 Optical dipole trap

The cold atom cloud is loaded into an optical dipole trap (ODT) and transported into the science cell by moving the focus of the trap. The cold atoms are transferred from the magnetic trap after the evaporation (see Sec. 4.1 for more details). In an optical dipole trap (ODT) the dipole force exerted by the laser light on the atoms is directed to regions of high intensity if the light is red-detuned to the atomic transitions [Ash70, Chu86]. The dipole force depends on the intensity and detuning as described in Appendix A and is identical for all hyperfine states.

The light for the ODT is provided by a 1065 nm fibre laser (YLD-5-LP, IPG Photonics). The intensity noise $\Delta I/I$ of the fibre laser is at its lowest when the laser is set to high output powers (5 W). Therefore we do not control the trap depth via the output power of the fibre laser but with a high-power AOM (Crystal Technology, 3080-197) set to 80 MHz. The AOM shows no signs of drift or heating. The ODT is formed by focussing up to 1.62 W of laser light $^\dagger$ to a waist of $w_0 = 20 \mu m$. The resulting trapping potential has, according to the expression [A.9] in Appendix A, a maximum depth of 345 $\mu$K for 40K. At full beam power the harmonic trapping frequencies are, according to Eq. [A.12], $\omega_r = 2\pi \times 4.27$ kHz in the radial and $\omega_a = 2\pi \times 51$ Hz in the axial direction.

$^\dagger$The power of the beam is 1.9 W before passing four more optical elements. Assuming 4% loss at each surface results in 1.62 W laser power in the chamber.

Figure 3.9: A dichroic beamsplitter combines the optical plug and optical trap beams. A small percentage of the plug light is reflected on a CCD camera to detect the beam quality and the focal size. The position of the translation stage is controlled using an additional laser. The polarization of the light is normal to the plane of this figure.
3. Experimental setup

As illustrated in Fig. 3.9, we transport the cold non-degenerate cloud of atoms by means of optical tweezers to the science cell. This method has first been used by [Gus01]. A $f = 100 \text{ mm}$ lens, producing the focus for the ODT, is mounted on a linear air-born translation stage (Leuven Air Bearings, LAB-LS). The translation stage is moved by a geared DC motor (Maxon Motor, 118751) via a grooved belt. The motor is steered by a motion controller (Maxon Epos 24/5) that gets its commands from an encoder (HEDL5540). The focussing lens ($f = 100 \text{ mm}$) can be moved over 22 cm with the translation stage. A 1:1 telescope installed behind the focussing lens images the focus to its position in the vacuum chamber. The telescope preserves both the numerical aperture and the focus shape during the transport to ensure constant trapping frequencies.

The starting position of the translation stage is kept constant by a feedback loop using the power level on a photodiode as input. A laser beam is aligned on a knife edge positioned on the translation stage. The power of the light passing the knife edge is measured using the photodiode. As soon as the stage reaches its homing position, the motor is stopped. The reproducibility of the focus position after the transport is $\sigma_r = 1 \mu m$ in the radial and $\sigma_a = 40 \mu m$ in the axial direction [Tie09a]. Both deviations are much smaller than the typical diameter of the cloud in radial ($d_r \approx 10 \mu m$) and axial ($d_a \approx 1 \text{ mm}$) direction. When transporting the cold atom cloud to the science cell and back, the atom number is not reduced within the experimental error for the typical vacuum lifetime of 40 s. We transport a thermal cloud in the 345 $\mu K$ deep ODT and do not detect significant heating due to the transport.

Just before entering the main chamber the dipole trap beam is overlapped with the optical plug beam using a dichroic beamsplitter (CVI laser, BSR-15-1940) as shown in Fig. 3.9. The dipole trap beam is reflected by the beamsplitter, so the focus is not influenced by the beamsplitter contrary to the optical plug. This ensures a uniform trapping frequency in the radial direction. To increase the trap depth allowing for higher atom numbers we plan to include another laser to form a crossed-dipole trap in the science cell.

3.6.1 Intensity stabilization of the fibre laser

Intensity fluctuations of the ODT laser lead to heating and loss of trapped atoms [Sav97]. The heating and subsequent atom loss is most severe when reaching low trap depths [Geh98]. When evaporating the cold atom cloud by lowering the trap depth, high atomic densities can not be reached reproducibly if the intensity of the dipole trap is fluctuating. When evaporating from the optical trap (see Sec. 4.1), we lower the power typically down to 5% of the full power. An intensity stabilization for the dipole trap has to have a large enough dynamic range to be still effective at low intensities. Additionally, an AOM has non-linear deflection efficiency. The deflected optical power increases logarithmically with the driving radio-frequency. When optimizing evaporation ramps, a linear response of the output power to the control signal is convenient.

At full laser power the noise spectrum of the fibre laser shows peaks of 10 dBm at 100 Hz and 300 Hz, we detected no other noise peaks up to the detector limit of 3.5 GHz. To realize an intensity stabilization with a feedback loop we detect light of the fibre laser leaking through a mirror in its path (see Fig. 3.9). This mirror has to be chosen
3.6. Optical dipole trap

Figure 3.10: Schematic of the components used to control the diffraction power and frequency of the AOM for the ODT. The circuit for the intensity stabilization is shown in Fig. 3.11. All parts marked with * are manufactured by Mini-Circuits.

with care: the main polarization leaking through the mirror has to match the desired polarization of the dipole trap, otherwise the feedback will even increase intensity noise as it stabilizes on the minority polarization. The polarization leaking through a mirror depends on its orientation relative to the beam and its polarization [Hec90]. Although the light from the fibre laser is linearly polarized, the AOM and mirrors (not all shown in Fig. 3.9) modify the polarizations of the beam [Ekl75]. A Glan-Thompson polarizer (Thorlabs, GTH10/M) with a high extinction ratio (10⁵:1) in the beam path after the AOM filters out the minority polarization. The light leaking through the sampling mirror is detected with a high speed photodiode (Thorlabs, DET110) with 20 ns rise time. The signal of the photodiode is compared to a reference voltage (power control voltage in Figs. 3.10 and 3.11) with a differential amplifier. The difference signal is integrated, rectified and amplified with a logarithmic amplifier as depicted in Fig. 3.11.† The circuit contains several potentiometers and fixed value resistors, which need to be set depending on the specific rf-amplifier and AOM used. These resistors ensure the linear response of the optical power deflected by the AOM to the power control voltage supplied by the main experiment control.

As illustrated in Fig. 3.10, the frequency for the AOM is set by a voltage controlled oscillator (VCO) (Mini-Circuits, ZOS-100) attenuated by 7 dB. We use the AOM at a fixed frequency of 80 MHz. The rf-amplification circuit for the AOM was set up using a ZX73-2500 (Mini-Circuits) voltage variable attenuator (VVatt). The output of the VVatt is split into two (Mini-Circuits, ZSCJ2-2-1), one half of the signal is used as a monitor output and the other is amplified by a ZHL-03 (Mini-Circuits) amplifier and sent to the AOM. The output power of the VVatt is controlled by the feedback signal generated by the intensity stabilization circuit.

In the intensity stabilization circuit in Fig. 3.11 the analogue and manual switches and an additional amplification of the power control voltage allow for an operation of the AOM without the stabilization. The analogue switches (AD7512DIJ) are controlled by triggers from the main experiment control (see Sec. 3.9). Monitor outputs give out the photodiode signal, the error signal and the feedback signal controlling the radio frequency power going to the AOM. Followers (not shown in Fig. 3.11) built with LF353 amplifiers provide buffered output for the monitor signals. All other amplifiers used for the circuit are of the type AD844AN. The whole circuit has been constructed such that ground loops and radio frequency noise from other equipment have minimal influence.

†We acknowledge support from the group of I. Bloch for details of the electronics design.
To protect the radio frequency amplifier from damage a load detector (not shown in 3.11) allows an output to the amplifier only when an AOM is connected.

To test the intensity stabilization we modulated the output power of a test laser diode at different frequencies and measured the attenuation of the modulation of the optical output power due to the lock. Up to 300 Hz the modulation is attenuated by 25 dB. That is sufficient to reduce the intensity noise of the fibre laser. When testing the lock with the fibre laser, we do not detect any noise peaks. The white noise of the fibre laser is reduced by 10 dB by the lock.

3.7 Feshbach coils

In the field of cold atoms Feshbach resonances have proven to be a powerful tool to manipulate atoms and vary their interaction strength. To make use of Feshbach resonances the magnetic field has to be set to values where the resonances occur. The position and widths of the Feshbach resonances differ for the different atomic species used, so the requirements on stability, homogeneity and strength of the magnetic field are different for each system. For the $^6$Li- $^{40}$K case, first experiments and calculations [Wil08, Tie10b] showed that many of the Feshbach resonances are located below 500 G and are narrower than 1 G. High precision, stability and homogeneity of the magnetic field over the whole sample of cold atoms is thus required to be able to make use of these Feshbach resonances.

To achieve high homogeneity, the coils for the Feshbach field are arranged in Helmholtz configuration. Both coils are wound on a mount manufactured from a single piece of brass to ensure and maintain the correct distance of the coils. The outer diameter of the coils is 158 mm. The brass housing is slit to prevent eddy currents. The slit itself has been refilled using glass-fibre. The brass mount is water-cooled and its overall volume is minimised to prevent eddy currents and provide good optical access. To ensure high field homogeneity and thermal stability we chose to employ many windings per coil and relatively little current. Each coil has 126 windings and is made of copper wire (Romal bv) with a rectangular ($3 \times 2$ mm) cross-section. The different layers of the coil are then easier to position during the winding procedure. The rectangular cross-section also increases the overall current density $j$ and homogeneity compared to a wire with circular cross-section. The two coils are identical except for the helicity of corresponding layers.

Around the origin of the two coils, where the cold atoms are located, the overall current density is then antisymmetric:

$$\vec{j}(\vec{r}) = -\vec{j}(-\vec{r})$$

Deviations from perfect homogeneity around the origin due to finite size effects, the changing of layers of the wire and the leads to the coils cancel each other in all odd orders. The windings of the coil proceed around the mount as a true helix. The transitions between layers do not occur stepwise but continuously over a whole winding. Spacers made from glass-fibre ensure the correct positioning of the individual windings and the coil is glued with epoxy (Stycast, 1266). The design and construction of the Feshbach coils is described in more detail in [Tie09a].
Figure 3.11: Simplified schematic of the circuit for the stabilization of the ODT intensity. Not shown are the load detector, the stabilized power supplies, followers for the output signals and various filters. The potentiometers and in certain circumstances other resistors need to be adapted to the specific combination of the rf-amplifier used for the AOM and the AOM to ensure an overall linear response.
Figure 3.12: Schematic of the Feshbach coils and the additional coils for fast sweeps and Stern-Gerlach experiments. The position of the trim coils is indicated, the coils are omitted from the schematic. The mount is made of a single piece of brass and is water-cooled. Holes drilled in the mount offer good optical access to the science cell in the middle.

Mounted inside the Feshbach coils are coils to allow for fast sweeps, coils to trim residual field curvatures and a coil to apply a gradient for Stern-Gerlach experiments. The fast sweep coils have a diameter of 21 mm, and 10 windings. The used copper foil (Alphacore, Laminax B-series) has a $3.175 \times 0.254$ mm cross-section and a 25.4 $\mu$m thick Kapton insulation coated onto one side. The fast sweep coils are mounted in Helmholtz configuration around the science cell. Like the Feshbach coils these coils are set up in an antisymmetric way. The trim coils have a diameter of 74 mm, 15 windings, and they are glued 50 mm from the centre (see Fig. 3.12). The copper wire has a diameter of 1 mm. The coil for the Stern-Gerlach experiments (see 4.4) is located about 1 cm away from the centre of the science cell, has 56 windings, a radius of 15.5 mm and a wire diameter of 0.5 mm. The Stern-Gerlach coil is glued with epoxy (Stycast, 1266) and has a 10 k$\Omega$ temperature resistor (RS, 484-0149) attached to it.

The magnetic field homogeneity was determined using a XEN-1200 field probe with a resolution of 3.5 mG up to 100 G. The remaining inhomogeneities were fitted to a polynomial expansion in the $z$-direction (for more details see [Tie09a]). The main coils have an inhomogeneity in the first order of $B'/B_0 = 1.5 \times 10^{-6}/$mm, the relative overall homogeneity is better than $10^{-5}$. The fast sweep coils are in first order less homogeneous ($B'/B_0 = 4 \times 10^{-4}$/mm) than the big coils. However, considering the low fields in the sweep coils, the absolute homogeneity of the two coils is comparable.
The thermal stability of the Feshbach coils has been simulated and the maximum temperature of the coils has been measured to fluctuate less than 0.1 °C within two hours [Tie09a]. The fluctuation is determined by the drift of the cooling water temperature in the laboratory.

Apart from a high field stability and homogeneity the Feshbach coils also have to allow for fast sweeping and switching of the field to be able to manipulate the atoms. The main Feshbach coils are powered by a Danfysik (Model 858) power supply. The power supply is specified to a stability of ±1 ppm for 30 min. It delivers up to 25 A. The programming via RS232 is limited to 2 A/s (≈ 35 G/s). To shorten the time the field in the Feshbach coils takes for switch-on and -off, we employ a switch and a dummy resistor. At the beginning of each experimental cycle (described in detail in Chapter 4), the current is programmed to the desired value and switched to run through a resistive load, matched to the resistance of the Feshbach coils. The ≈ 50 s, which elapse during the experimental cycle until the Feshbach coils are needed, are sufficient to stabilize the current running through the dummy load. At the beginning of the Feshbach experiment two MOSFETs (BUZ 344) switch from the dummy load to the Feshbach coils. The current through the coils then reaches its set value within a few hundred milliseconds (see Sec. 4.3). For a fast switch-off, the MOSFETs switch back to the dummy load while transient voltage suppressors absorb the induced voltage spike. Once the current is running through the dummy load again, the power supply is programmed to zero current output.

The fast sweep coils are powered by a Delta Elektronika (ES075-2) supply. Combined with a homebuilt transistor regulation, linear sweeps up to 40 G/ms with a field stability of less than $10^{-5}$ can be achieved.

### 3.8 Imaging systems

The means to detect the number of atoms and their temperature and distribution is imaging. We employ three different methods: fluorescence imaging at low field and absorption imaging in low and high field. The imaging is done by detecting the (near) resonant light on a CCD camera.

#### 3.8.1 Cameras and optical setup

As shown in Fig. 3.13 four cameras in total are used for the imaging. Two of these (Sony, SX90) are used for the separate imaging of lithium and potassium and can image on the horizontal axis both in the science cell and in the main chamber. The lenses for the two horizontal imaging paths are on flippable mounts to switch between the two imaging positions. The other two cameras provide images in the vertical direction in the main chamber (Sony, X710) and the science cell (Apogee, U13). The effective pixel size at the location of the atomic sample has been calibrated for all cameras as described in [Tie09a]. The effective pixel sizes at the sample of the Sony (SX90) cameras including the telescopes are 3.60 μm when imaging in the science cell and 3.67 μm when imaging in the main chamber. The time elapsing between taking the absorption and the reference image is limited by the readout time. For the Sony cameras this takes 500 ms. The Apogee has an effective pixel size of 3.94 μm when using a ×4 microscope.
Figure 3.13: Schematic of the imaging systems in (a) the main chamber and (b) the science cell. The lenses with \( f = 200 \) and \( 250 \text{mm} \) can be flipped in and out of the optical path. For the vertical imaging with the Apogee camera in the science cell a \( \times 4 \) microscope objective is used.

The resonant imaging light is derived from the master laser by a double-pass through an AOM (see Fig. 3.4) and split into two beams which are each coupled into polarization maintaining fibres (Schäfter + Kirchhoff, PMC-630-4.5NA011-3-APC). With dichroic beamsplitters the imaging light for lithium is combined with the light for potassium (not shown in Fig. 3.4). The output of the first fibre is used for the imaging in horizontal direction. The light is linearly polarized. The second fibre can be connected either to a collimator at the science cell or at the main chamber. This light is used for the imaging in vertical direction and is \( \sigma^+ \) polarized by a waveplate. The circular polarized light can be used for imaging both in low and high magnetic field. The linear polarization is only used for low field imaging.
3.8. Imaging systems

3.8.2 Fluorescence imaging

For fluorescence imaging in the main chamber we irradiate the atoms with near resonant light using the MOT beams and the light scatters in all directions. The MOT beams are under an angle to the imaging path, so only scattered photons and no photons of the MOT beams are detected by the CCD camera. A trapped atom in the MOT can scatter many photons without being lost from the trap. This allows for long exposure times of the camera and thus a good signal to noise ratio. This imaging method is used to characterise the MOT, the magnetic trap and to optimize the magnetic trap capture efficiency. We only used it for relative measurements, which do not require calibration of the signal. The characterization of the lithium 2D-MOT-source in [Tie09b] was also done using fluorescence imaging.

3.8.3 Absorption imaging

For absorption imaging a low intensity resonant light pulse passes through the cloud of atoms onto the camera. In areas where there are atoms, the light is absorbed and the image shows a shadow of the atomic sample. In this thesis all absorption images were taken after release of the atoms from a trap after variable times of expansion. In ballistic expansion only a few photons can be scattered per atom as atomic motion and photon recoil can blur the image. In addition to the resonant light a pulse of repump light is switched on when imaging to prevent a population of dark states. In the main chamber the repump light is part of the MOT beams, therefore under a 45° angle to the imaging beam and in two counter-propagating beams. In the science cell the repump light is back reflected and under an angle of ≈ 30° to the imaging path. During the imaging pulse the atoms absorb photons from the imaging beam and re-scatter them in all directions. For a resonant light pulse of duration $\Delta t$ with low intensity, i.e. the saturation parameter $s_0 = I/I_s \ll 1$, the number of photons $N_p$ scattered is given by

$$N_p = \frac{1}{2}s_0\Gamma\Delta t,$$

with $\Gamma$ being the natural linewidth of the optical transition [Met99]. The recoil from the absorbed photons shifts the atoms out of resonance due to the Doppler effect. The frequency shift is given by $\omega_D = v_{\text{rec}}kN_p$, with the wavevector $k$ of the light and the recoil velocity $v_{\text{rec}} = \hbar k/m$. The re-emission moves the atoms in random directions resulting in a blurring of the cloud’s image. The atoms are then on average displaced in the transverse direction by $r_{\text{rms}} = v_{\text{rec}}\Delta t\sqrt{N_p/3}$ [Jof93]. For potassium we use intensities for the imaging pulses with saturation parameter $s_0 = 0.4$ and a pulse length of $\Delta t = 100\mu$s, resulting in a displacement by $r_{\text{rms}} = 9\mu$m and a frequency shift of $\omega_D = 0.4\Gamma$.

To obtain a signal from the CCD camera three images need to be recorded. After every absorption image taken with intensity $I_{\text{abs}}$, two images of the optical field are taken. One as a reference with imaging light $I_{\text{ref}}$ and one without imaging light with intensity $I_{\text{bg}}$ as background. The signal is then: $I(x, y)/I_0(x, y) = (I_{\text{abs}} - I_{\text{bg}})/(I_{\text{ref}} - I_{\text{bg}})$. For the Sony cameras we found that the background image $I_{\text{bg}}$ can be neglected, and it is not used in the analysis of the data. The intensity distribution is used to calculate the column density of the atomic distribution using the Lambert-Beer law:

$$\frac{I(x, y)}{I_0(x, y)} = \exp(-OD) = \exp(-\sigma n(x, y)),$$
3. Experimental setup

Figure 3.14: With rising magnetic field the detuning from the zero field imaging transition $|^2S_{1/2}, F = 9/2\rangle \rightarrow |^2P_{3/2}, F = 11/2\rangle$ changes. Shown are the frequencies for $\sigma^-$ transitions $m_F = -9/2 \rightarrow m_F' = -11/2$ (full line) to $m_F = 5/2 \rightarrow m_F' = 3/2$ (long dashes). For magnetic fields higher than 55 G, the different transitions are separated by more than the linewidth $\Gamma$ and the $m_F$ states can be imaged individually.

with the optical density $OD$, the column density along the imaging beam axis $n(x, y) = \int dz n(x, y, z)$ and the atomic absorption cross-section of the atoms

$$\sigma = \kappa \frac{3\lambda^2}{2\pi} \frac{1}{1 + (2\delta/\Gamma)^2}.$$  

Here $\delta$ is the detuning from the atomic resonance and $\kappa$ a transition dependent coefficient. For the transition $|^2S_{1/2}, F = 9/2\rangle \rightarrow |^2P_{3/2}, F = 11/2\rangle$ and linear polarized light $\kappa = 2/5$, for circular polarized it is $\kappa = 1$ [Tie09a].

3.8.4 HIGH-FIELD IMAGING

The ability to image in high field is vital if switching-off times of the magnetic fields are slower than the dynamics of the cold atom cloud. Atoms can be lost from the cloud or become invisible to the imaging light under conditions where molecules are formed as a result of sweeping through a Feshbach resonance during the switch-off. In non-zero magnetic field the different Zeeman states are not described by just one set of quantum numbers but by a combination of different sets. Transitions which are closed transitions at zero field cease to be closed at higher magnetic fields. In addition, the transition probabilities change with magnetic field. The imaging transitions have to be chosen carefully depending on the specific magnetic field and the state which has to be imaged. The transition probabilities of $^{40}\text{K}$ in dependence of the magnetic field are described in more detail in C.2. For atoms in the states $|^2S_{1/2}, F = 9/2, m_F = -9/2, \cdots, 5/2\rangle$ $\sigma^-$ transitions to the states $|^2P_{3/2}, F' = 11/2, m_F' = -11/2, \cdots, 3/2\rangle$ are allowed. As shown in Fig. 3.14 with rising magnetic field the atomic transition frequencies change by a considerable amount.

\[\text{For convenience the low-field labelling of the states is used.}\]
To be able to adapt to these changes, we stabilize the frequency of the high-field imaging laser with a frequency offset lock. The lock is based on the fact that a beat signal of two laser frequencies accumulates a frequency-dependent phase-shift when propagating through coaxial cable. The time delay introduced by the cable is frequency independent, so the phase shift is only proportional to the beat frequency and a feedback signal to stabilize a laser can be derived [Sch99]. The high-field imaging laser itself is a grating stabilized external cavity diode laser (ECDL), built after a scheme by [Ric95]. The diode used is an anti-reflection coated diode (Eagleyard, EYP-RWE-0790-04000-0750-SOTO1) and the grating is a holographic grating (Thorlabs, GH13-18U) optimized for the ultra-violet to prevent a high power density within the cavity.

Reference light with frequency $\nu_{\text{ref}}$ is superimposed with the light of the high-field imaging laser with frequency $\nu_{\text{hfi}}$. Both beams are matched in power (about 95 $\mu$W in each beam) and polarization and coupled into a single mode polarization maintaining fibre. The resulting beat note $\Delta \nu = \nu_{\text{ref}} - \nu_{\text{hfi}} = 266$ MHz of the two beams is detected by a fibre coupled fast photodiode (Thorlabs, DET02AFC) with a bandwidth of 1.2 GHz.

In Fig. 3.15 it is shown how the beat signal is processed electronically to obtain a lock signal. To retrieve a feedback signal for the stabilization of the high-field imaging laser, the signal of the photodiode (level $\approx -32$ dBm) is first amplified by 20 dB (Mini-Circuits, ZFL-500). In a second step the signal is mixed (Mini-Circuits, ZFM2000+) with the reference frequency $\nu_{\text{vco}} = 320$ MHz from a voltage controlled oscillator (Mini-Circuits, ZOS400). The signal now contains the frequency components $\nu_{\text{vco}} - \Delta \nu, \nu_{\text{vco}} + \Delta \nu, \nu_{\text{vco}}$ and also higher orders and combinations of those frequencies (see Fig. 3.16).

The signal is split into two, one part is for control purposes, the other part is amplified once more by 20 dB and then divided by another splitter (Mini-Circuits, ZSCJ-2-1). One part is delayed by $l = 4.5$ m of coaxial radio-frequency cable, resulting in a time delay of $\tau = l/c_g \approx 22.5$ ns where the group velocity $c_g$ of the signal is about 2/3 of the speed of light. Both signals are recombined on a phase detector (Mini-Circuits, ZRPD-1). The output voltage $U_{\text{err}}$ of the phase detector varies with the cosine of the phase shift $\phi$ acquired in the coax cable. The phase shift depends...
3. Experimental setup

Figure 3.16: Spectrum of the mixed beat signal showing the signal used for locking at $\nu_{\text{vco}} - \Delta \nu$, the beat frequency of the two lasers $\Delta \nu$, the frequency of the voltage controlled oscillator $\nu_{\text{vco}}$ and higher orders and other combinations of those frequencies.

only on the mixed signal and the time delay between the paths: $\phi = 2\pi(\nu_{\text{vco}} - \Delta \nu)\tau$. One of the zero crossings of the output signal $U_{\text{err}}$ is used as a locking point for the feedback for the high-field imaging laser. The spacing of the zero crossings depends on $1/\tau$ and the position can be set with the frequency $\nu_{\text{vco}}$. For a wider capture range and a higher locking stability a shorter coax cable can be used. The length of the coax cable was chosen to achieve a high resolution and a narrow laser bandwidth.

The output of the phase detector is sent through a low pass filter (Mini-Circuits, BLP1.9) with cut-off frequency at 1.9 MHz. The error signal $U_{\text{err}}$ then feeds back into two separate servo loops: a slow loop (\leq 1 kHz) feeding back to the piezo-electric actuator (Thorlabs, AE0505D08F) setting the length of the cavity of the high-field imaging ECDL and a fast control (bandwidth \approx 1 MHz) to feed back to the current running through the laser diode.

The linewidth of the stabilized high-field imaging laser is estimated by recording the beat signal $\Delta \nu$ of the two lasers. The output of the photodiode is fed into a spectrum analyser. The data of the spectrum analyser is read out to an oscilloscope using the x-y-outputs, averaged 4 times and rescaled to dBm as read from the spectrum analyser. The read-out via the oscilloscope adds electronic noise so a direct conversion to a linear scale introduces big errors. The data is thus first smoothed before rescaling and fitting. The video filter setting of 1 MHz contributes to the linewidth. The data, converted to a linear scale, is shown in Fig. 3.17.

The beat signal of two lasers can be described as the convolution of two Lorentz functions – if no broadening due to e.g. electronic noise occurs. Electronic noise is certainly added to the beat-signal by the spectrum analyser. The locking circuit might also contribute noise. Assuming a Gaussian distribution of the noise, the measured beat-signal is a convolution of Lorentz and Gauss functions, which is a Voigt function. The fit with a Voigt function results in a width of 1.2 MHz for the Gauss part and 0.45 MHz for the Lorentz part of the function. The widths $w_i$ of two Gaussian distributions convolute to $(w_1^2 + w_2^2)^{1/2}$, for a Lorentz distribution it is $w_1 + w_2$. Without exact knowledge of the sources of broadening of the signal 1 MHz is an upper estimate.
3.9 Computer control and analysis

The whole experiment is controlled by one desktop computer running on the operating system Windows XP. This computer addresses all analogue and digital outputs and accesses the cameras. A laptop computer, also running on Windows XP, is used to control the stepper motor for the optical transport as described in Sec. 3.6. The laptop is also used to view and analyse the data from the CCD camera monitoring the focus size and shape of the dipole trap and the plug beam.

The main computer reads out the cameras and saves the images to the network. The analysis of the measurements is done on a computer running on Linux (Fedora Core 6). For the analysis we use open-source software. We made this choice because most drivers for cards and cameras are more easily available for Windows and our control program was developed for Windows (see 3.9.1). Using open-source software makes the analysis more portable and compatible. With a Linux operation system it is also comparatively easy to make use of remote processing or use and write bash scripts.

3.9.1 Control program and hardware

The hardware for the computer control was chosen to accommodate the laboratory control system as developed by T. Meyrath and F. Schreck (a detailed description and manuals can be found online: [Mey02]). We did not entirely reproduce their system and did not include analogue inputs and radio-frequency synthesizers.
3. Experimental setup

Our control includes at the moment 80 digital and 40 analogue outputs and an interface to DDS evaluation boards. The digital outputs are compatible with TTL and can drive 50Ω loads. The analogue outputs can each drive a current up to 250mA and are programmable between -10 and +10 V. A 32-bit National Instruments Digital I/O card (NI6533) interfaces between the output bus and the controlling computer. More details on the used hardware can be found in [Tie09a].

Apart from the outputs mentioned above, the main control computer also uses various protocols to address other devices used in the experiment. The cameras used mostly for the imaging (Sony X710 and SX90) are read out using FireWire. The fibre laser and the Danfysik power supply are programmed via RS232. USB is used for one of the DDS systems and the Apogee camera. An oscilloscope (Fluke, PM3394B) and a multimeter (Tulby Thandar, 1906) can be read out via GPIB.

3.9.2 Software

As mentioned in Sec. 3.9, the control software is based on the control system described in [Mey02]. The program uses Visual C++ functions which provide access to all outputs. In a graphical user interface (GUI) the defined variables can be set and measurement routines can be called. Whenever the measurement routine is called the program is executed twice. In the first run the system is prepared and external devices are pre-set. In the second run the digital outputs are switched, the analogue outputs are set to the programmed voltage and external devices such as the cameras and the optical transport are controlled in a synchronized manner. The time resolution between the different output commands is 3µs. As mentioned above, we have not implemented any input channels; the cameras are read out using home-written software which is called by the control program. The programs are written in Visual C++ and make use of drivers for the cameras. All cameras get their triggers via digital outputs from the main control program. The same holds for the optical transport: the Maxon motor controller is steered by a separate program running on the laptop. The endpoint and the sinusoidal trajectory are controlled by the separate program but the triggers to start and end the transport are given by the main program.

With each experimental run images are taken. The images are acquired and saved in PGM (Portable Gray Map) format. First they are saved to a local hard drive and then transferred together with files containing the experimental parameters to a network drive. The analysis is then done using software written in GNU C++ running on the Linux computer. A dynamic library offers various routines to fit one- and two-dimensional distributions to the PGM images. The library can either be called from a GUI written in Python 2.5.1 or from command lines in a bash program or shell. For more details about the used software see [Tie09a].

3.10 Sources for radio and microwave frequency

To manipulate the $^{40}$K atoms many different frequencies are necessary: for laser cooling and imaging the light has to be shifted by 50–250 MHz, the evaporation and the repump
laser require frequencies in the GHz range and the state manipulation described in Sec. 4.2 works at frequencies in both ranges.

The frequencies for the optical transitions require a frequency stability \(< 1\, \text{MHz}\), smaller than the linewidth (\(\Gamma = 6.03\, \text{MHz}\)). This stability can easily be achieved with voltage controlled oscillators (VCOs). We use VCOs from the ZOS-series manufactured by Mini-Circuits for most of our AOMs. Voltage variable attenuators (Mini-Circuits, ZX73-2500+) regulate the power and Mini-Circuits amplifiers ZHL-3A-S (for \(\nu < 150\, \text{MHz}\)) and ZHL-2-S (for \(\nu < 150\, \text{MHz}\)) produce the power required, which is up to \(\approx 1\, \text{W}\).

The only AOM where we do not use a VCO is the Brimrose AOM that shifts the light to obtain repump light (see Sec. 3.3). The frequency needed there is 1.1GHz. A VCO with the required frequency stability would have to have voltage drifts of the steering voltage lower than 1mV, which is hard to achieve. For the repump AOM we employ a DDS (AD9956) as frequency source. The power is amplified by a 2W amplifier (Hughes, 700-1400MHz).

\subsection{3.10.1 DDS systems}

There are two different types of direct digital synthesis (DDS) systems in use in our experiment. The first system consists of three AD9956 (Analog Devices) DDS chips mounted together with a VCO and a loop filter on evaluation boards. The boards are programmed via USB and updated and synchronized to the experiment with triggers from the digital output boards. Each VCO is phase-locked to a DDS chip. The available output frequencies are then 0.9–1.35GHz from two of the boards and 200–300MHz from the third board. The other DDS system is based on four AD9858 (Analog Devices) DDS chips mounted on evaluation boards. These chips can be programmed in parallel via the main bus system. The DDS frequency can then be changed every 15\(\mu\)s with a 32-bit accuracy. Again VCOs are phase-locked to the DDS chips. The output frequencies of this system are 1–1.3GHz from one output and 0-400MHz from the three other outputs. Both DDS systems give out frequencies with a linewidth less than 100Hz. More details on the used clocks, VCOs and more detailed circuitry of the DDS systems can be found in \cite{Tie09a}.

\subsection{3.10.2 Amplification and switching}

All the frequencies for the evaporation and state manipulation from the DDS require additional amplification. Figure 3.18 shows a schematic of amplification stages and the switching to the right antennas. All powers are regulated by voltage variable attenuators (Mini-Circuits, ZX73-2500+) and the signals from the DDS boards can be directed to one of the two outputs of a switch (Mini-Circuits, ZASWA-2-500R+).

The frequency for the hyperfine manipulation is derived from a AD9858 DDS chip. A switch is used to direct the frequency to the main chamber or the science cell. The frequency for evaporation on the hyperfine transition (1.2GHz) in the main chamber is amplified with a 1W (Mini-Circuits, ZHL-2-12) and then with a 15W (RSE, PA15-23) amplifier. The power is sent via a bi-directional coupler and a triple-stub tuner to the antenna. The antenna is a single loop of unshielded BNC cable and has strong
resonances. The triple-stub tuner is tuned to achieve a flat frequency response in the range 1.1–1.3 GHz.

When the other output of the switch is in use, the microwave power is increased first by 12.8 dB (Mini-Circuits, ZX60-3018G) and then sent through a 30 W (Downeast, 2330PATV) amplifier and a circulator to the antenna. In the science cell this frequency range is used for the clean out of undesired Zeeman states and for the calibration of the magnetic field as described in Chapter 4. The bi-directional coupler and the circulator protect the amplifiers from the power being reflected back by the antenna.

The lower frequency range from 0–400 MHz is used for the preparation of the proper Zeeman states and for field calibration in the science cell. Here the output from the AD9858 DDS chip can be switched to a 50 Ω terminator to prevent noise. For both the use in the main chamber and the science cell the radio frequency is amplified by the same 4 W (Mini-Circuits, TIA-1000-R18) amplifier. The switching between the two antennas is done with a relay. There is no circulator or coupler in this path as the amplifier is protected against back-reflected power.

The antennas for the radio and microwave frequencies consist of simple wire loops. The antennas for the microwave have one winding and the ones for the radio frequency have seven. For more detailed specifications of the used antennas and the setup for the lithium antennas see Table 3.3 in [Tie09a].