Evanescent-wave mirrors for cold atoms
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Experimental setup

A table-top ultra-high vacuum rubidium vapour cell has been built. Optical access to the vacuum system is achieved by use of a rectangular glass cell. Two techniques of vacuum sealing of such glass cells using either a knife-edged metal gasket or epoxy glue are discussed. In the vapour cell a magneto-optical trap is operated. With additional optical molasses, cooling provides samples of $\approx 10^7$ atoms at temperatures of $\approx 10 \mu K$. Frequency-stabilised diode lasers serve as trapping and cooling light sources. Their output is amplified by injection-locked single-mode diode lasers or, for high-power applications, tapered semiconductor gain elements. Real-time control of the experiment is achieved by a personal computer with an additional digital signal processor. Cold atoms are detected by imaging with a triggered digital frame-transfer CCD camera system.
3.1 Overview

An optical trapping scheme for atoms has to be realised in ultra-high vacuum (UHV) to avoid atom loss due to collisions with room temperature gas. Since the first demonstration, the magneto-optical trap (MOT) [33] has become a standard tool in atomic physics. Usually, a MOT provides a cloud of cold atoms after a single loading cycle. Alternatively, a slow continuous atomic beam is extracted [115,116]. In our experiments, a MOT with subsequent polarisation gradient cooling (PGC) [70] was used to prepare a cloud of atoms a few mm above an evanescent-wave atom mirror. We have chosen frequency-stabilised diode lasers to provide the various light frequencies required for the MOT, PGC, optical pumping, dipole trapping, and probing of atoms. Such devices are a low-cost and less maintenance demanding alternative to Ti:Sapphire laser systems. Their compactness permits to assemble a larger number of laser sources together with an UHV setup on a single table. The lasers consist of external grating diode lasers [117,118], the output of which is amplified by injection-locked diode lasers. The laser stabilisation schemes are based on frequency-modulation spectroscopy [119] and “Zeeman polarisation spectroscopy” [120–122]. The complexity of the experiments demands real-time computer control of experimental parameters. A digital signal processor is in charge of this task. Images of atoms bouncing on evanescent-wave mirrors were acquired with a digital CCD camera system.

In this chapter, the relevant properties of rubidium are discussed and the design of the table-top UHV rubidium vapour cell is described, in which our experiments were performed. A separate section is dedicated to the delicate issue of connecting and sealing glass cuvettes and window substrates to standard CF 40 and CF 16 Conflat™ steel knife-edge flanges. Also an overview of the used laser systems and the controlling computer hardware is given. In the last section, the MOT is described. The temperature of atom clouds, achieved by PGC, was determined by a time-of-flight method using falling atom clouds. The characterisation of one particular device, a tapered semiconductor amplifier, is given in Chap. 4.

3.2 Atomic species — rubidium

The experimental choice of an atomic species depends on physical properties including, (i) appropriate optical transition frequencies and the availability of laser sources operating on these frequencies, (ii) the atomic collisional properties and, (iii) the ease of handling in an UHV system.

(i) Optical transitions.— Optical cooling techniques require well separated optical transitions of sufficiently narrow natural linewidth, among which cycling (“closed”) transitions. Methods like PGC or velocity-selective coherent population trapping (VSCPT) [107] in “dark states” rely on optical pumping between magnetic sublevels or hyperfine states. The hyperfine-split D1 and D2 fine structure lines of alkali-metal atoms and the optical transitions of metastable noble gas atoms allow the use of dye lasers and Ti:Sapphire lasers with, wavelengths from the visible to
the near-infrared spectrum. With LNA lasers at 1083 nm also metastable helium became usable [123]. For an overview on common elements for laser cooling, see e.g. Ref. [12].

Well established in atomic physics are meanwhile stabilised diode laser systems, if providing sufficient optical output power together with spectral and spatial beam quality. The availability of the laser diodes is generally determined by commercial applications, e.g. for CD disk drives (785 nm wavelength), Nd:YAG laser pumping sources (808 nm), DVD drives (650 – 670 nm), or magnetometers for navigational systems using helium (1083 nm). Particularly, low-cost high-power laser diodes in the near infrared make rubidium an attractive choice, due to optical resonances at 780 nm and 795 nm wavelength.

(ii) Collisional properties.— In high density applications of cold atoms the s-wave scattering length is an important parameter, e.g. for evaporative cooling and for the properties of a Bose-Einstein condensate. For an overview of scattering lengths for various atomic species, see Ref. [63]. More specifically $^{87}\text{Rb}$, due to its suitable positive scattering length ($a \approx 109 a_0$), may be the most promising candidate to reach quantum degeneracy in a purely optical scheme, as envisaged in Chap. 2. Therefore we use this isotope in our experiments.

(iii) Handling in UHV.— A reliable and compact technical solution to handle rubidium atoms is a table-top UHV vapour cell setup, in which a MOT can be quickly and directly loaded from the room temperature vapour [124–126]. Rubidium can be used at convenient temperatures. For example, the (saturated) rubidium vapour pressure at room temperature is between $10^{-7} - 10^{-6}$ mbar and the melting point is $38.5^\circ \text{C}$ [127]. The natural abundance of the $^{87}\text{Rb}$ isotope is 27.9 %, next to 72.1 % of $^{85}\text{Rb}$. Some useful numbers for experiments with rubidium are listed in the Appendix A.1. The hyperfine level structure of the D1 (795 nm) and D2 (780 nm) line is shown in Fig. 3.7.

3.3 Ultra-high vacuum system

3.3.1 Requirements on a rubidium vapour cell

The used vapour cell is an UHV system which maintains a partial rubidium pressure of typically $10^{-8}$ mbar and a background gas pressure of $\lesssim 10^{-9}$ mbar. In an optical trap, light scattering will dominate the loss of trapped atoms, rather than background gas collisions. An experiment involving bouncing atoms from an evanescent-wave mirror typically lasts less than 100 ms, whereas the mean collision time of cold atoms with room temperature atoms from the vapour is $\sim 350$ ms (mean free path $\sim 100$ m). Experiments of longer duration, such as evaporative cooling of atoms towards BEC, require significantly better vacuum ($\lesssim 10^{-11}$ mbar). In these cases differentially pumped “double-MOT” systems [128] or bright beams of slow rubidium atoms [115,116] are employed to load a MOT in good vacuum with a sufficient number of atoms.
A vapour cell can be economically realised as a small stand-alone system using mostly commercial components. The very low rubidium consumption reduces maintenance tasks. For example, using 10 mg of rubidium in a reservoir, the operating time is limited by constructional changes on the system rather than by rubidium depletion. Due to vibrations, the use of turbo-molecular pumps located on a table together with stabilised lasers is undesirable. Therefore we employ ion pumps, though these pumps require care for shielding or compensating their stray magnetic fields. Usually it is sufficient to place an ion pump far enough away (\(\geq 0.5\) m) from the experimental region. However, this is at the cost of pumping speed and vacuum pressure.

In addition to vacuum specifications, also the optical properties of a vapour cell have to be considered. Experiments on evanescent-wave atom mirrors as discussed in this thesis, require a prism as the only optical component mounted inside the vacuum system. Nevertheless, optical access from various directions is needed to apply the numerous laser beams. The windows should be of laser optical quality and, if possible, antireflection coated. In the present system, an uncoated rectangular glass cell is used. Beside good optical access, a particular feature of such a cell is that magnetic field coils can closely approach the region of interest and hence can be small sized and of low power consumption. Since a glass cell is nonmagnetic, experiments are not perturbed by eddy currents caused by switching field coils.

### 3.3.2 Vapour cell setup

The vacuum system, shown in Fig. 3.1, consists of, (i) a lower UHV chamber, pumped by a 15 l/s ion pump and, (ii) an upper differentially pumped vapour cell connected to a glass cuvette and to a rubidium reservoir. The vapour cell is (optionally) pumped by a 8 l/s ion pump. The typical background pressure achieved in this system is \(\approx 10^{-9}\) mbar, after gentle bakeout up to 114\(^\circ\) C. The epoxy-glued glass cell used so far, did not allow warmer baking.

(i) **UHV section.** — The components of the UHV system are grouped in the horizontal plane at a 5-way CF 40 cross. The system is clamped to the optical table by aluminium mounts that can be water cooled, in order to protect the laser table during bakeout. An all-metal sealed valve (Granville-Phillips, gold-seal type 204) leads via bellows to a roughing turbo-molecular pump. When the valve is closed, the system is self-sustaining with an ion pump of 15 l/s (N\(_2\)) pumping speed (Varian, Vaclon Plus 20 StarCell with ferrite magnets). The achieved pressure can be monitored by an ionisation gauge in a range between \(10^{-12} - 10^{-3}\) mbar (Varian, type UHV-24p). A pressure below \(10^{-9}\) mbar might be possible by extending the system with a titanium sublimation pump or non-evaporative getter materials.

The UHV section is separated from the upper vapour cell section by a blank CF 40 copper gasket with a hole of 1.5 mm diameter. Differential pumping reduces the pumping speed in order to maintain the rubidium pressure in the vapour cell during experiments.
3.3 Ultra-high vacuum system

Figure 3.1: Vacuum system. Lower UHV section: ion pump (IP1), ion gauge (IG) and valve (⊗1) to roughing pump. Upper vapour cell section: rubidium reservoir (Rb, unmounted when photograph was taken) with valve (⊗2), and small ion pump (IP2, out of sight). A bypass valve (⊗3) connects the vapour cell and the UHV section. A diaphragm between the sections enables differential pumping. The closeup shows the $10 \times 10 \times 4 \text{ mm}^3$ right-angle BK7 glass prism used for the evanescent-wave mirror (Melles Griot, high precision prism, no. 01 PRB 009, cut to a width of 4 mm).
For pumping down from atmospheric pressure and during bakeout, an all-metal CF16 valve (Vacuum Generators, type ZCR 20R) is opened in a bypass from the 5-way cross to the vapour cell. The strong magnets of the ion pump are approximately 35 cm away from the prism. The ion pump manual specifies a stray magnetic field of $\lesssim 1.5$ G at a distance $\gtrsim 15$ cm from the pump.

(ii) Vapour cell section.— A hexagonal section with six CF 16 ports is mounted on top of the UHV section. It interconnects the cuvette, the rubidium reservoir and the pumping bypass. In addition, an in-line pair of custom-made optical viewports is mounted, that provides optical access for, e.g., time-of-flight diagnostics of falling atoms (if no prism is mounted). The horizontal tube of the bypass leads 40 cm away to a small 8 l/s ion pump (Varian, VaClOn with AlNiCo magnet). If necessary for stray field minimization and if the pump is not in use, the magnet can be removed. Together with the bypass, this pump assists in stabilising the rubidium vapour pressure or to reduce background gas pressure, respectively.

The rubidium reservoir is connected to the vapour cell by a short spacer tube and an all-metal valve. It consists of a flexible tube with a short intermediate bellows section. Before evacuating the system, a small cylindrical quartz ampule was inserted, containing a few milligram rubidium. When the final roughing pressure $\approx 10^{-6}$ mbar was established after bakeout, the ampule was broken by bending the bellows. When the pressure settled again, the system was sealed off from the roughing line and further pumped down by the ion pump. Commercial standard rubidium ampules can be used in the setup (Aldrich Chemical, 2 g. no. 38,599-9). However, a few milligram suffices to keep the system operable for years. For constructional changes, the reservoir can stay evacuated for a short time, avoiding a replacement of the ampule. Hence it is more economical (and more safely) to distil only a small amount of rubidium into custom reservoir ampules.

In case the ampule breaks too neatly, it might be necessary to keep the bellows bent to increase the rubidium diffusion out of the ampule. The reservoir is wrapped with a heating cord. When preparing experiments, the reservoir is gently baked with open valve until the desired vapour pressure in the cuvette is reached. (The saturated rubidium vapour pressure is, e.g., $\approx 10^{-5}$ mbar at 60°C.) It can be monitored by observing the fluorescence from a laser beam tuned to an optical resonance of rubidium. After cooling down the reservoir, the valve is kept open and adjusted to maintain a constant vapour pressure. Due to the differential pumping, the vapour pressure decays with a time constant of $\sim 30$ min if the reservoir is closed. Before inserting the differential pumping hole this was less than 5 min. It is difficult to estimate the rubidium diffusion and pumping speed for two reasons: First, the system has many bends and apertures. Second, rubidium is strongly sticking to surfaces. Since the surface-to-volume ratio is large, there is a delay of several hours in vapour pressure build-up when charging the system for the first time. One has to avoid saturating the entire system and, particularly, the cuvette by a rubidium droplet that slowly "creeps" through the system.
3.4 Optical access to the UHV system

It is worth mentioning two alternative techniques of charging a vapour cell with rubidium, taking less constructional and machining efforts: (i) commercial single-use quench-seal copper tubes as containment for the rubidium ampule and, (ii) a saturated dispenser compound that releases rubidium when heated by an electrical current (SAES Getters, type Rb/NF/3.4/12 FT10+10, 2.6 mg yield). The latter has the advantage that it offers cw and pulsed operation with short time constants $\sim$min, and may charge the vacuum system only locally with rubidium. A disadvantage are the electrical UHV feedthroughs and the limited rubidium load.

3.4 Optical access to the UHV system

In cooling and trapping experiments, laser-beam wavefronts must not be distorted by the UHV viewports. Also (stress-induced) birefringence of the viewports is undesirable, since it might perturb polarisation sensitive applications such as polarisation gradient cooling or “dark state” trapping. Furthermore, the vacuum sealing has to withstand common bakeout temperatures above 200\degree C. Commercial viewports are usually costly and have clear apertures that are significantly smaller than the Conflat flange counterpart. In order to achieve optical quality access from many directions, we have chosen a rectangular cuvette.

The first choice material was fused silica (“quartz glass”). It is available as laser-optical plate elements, that are welded in a baking process using glass weld powder at the connecting faces. The surface flatness is preserved locally in this process. A disadvantage is that no \textit{inside} antireflection (AR) coating can be applied. A pre-applied coating would be destroyed during welding, and the elongated geometry makes the application of an UHV compatible coating after welding impossible.

Such cuvettes are usually supplied with a “graded-seal” transition, with which the mismatch in the thermal expansion of the fused silica cuvette and an Invar steel flange is compensated. The graded seal consists of a succession of tubular segments that change gradually in composition from fused silica to Pyrex glass. Unfortunately, the minimal length of the graded seal is $>10$ cm, which may degrade the UHV in the cuvette. For our vacuum system, we have therefore extended an earlier reported window sealing technique [129] to seal a cuvette directly to a CF 40 flange.

In the following, our application of this technique to CF 16 viewports is discussed, and the CF 40 scheme is refined using spring-loaded knife-edge seals, that reduce stress on the glass substrate. Finally, a less complex preliminary solution based on an epoxy-glued “Optical Glass” cuvette is presented. Note that this cuvette, despite of modest bakeout temperatures, allowed for sufficient UHV to perform all experiments reported in this thesis (see also the photographs in Fig 3.1).
3.4.1 All-metal sealed optical quality UHV viewports

The viewport concept in Ref. [129] makes use of a standard 50 mm diameter laser window that is sealed to a CF 40 knife-edge flange. The substrate is pressed on a knife edge milled onto the outer surface of a common OFHC (copper) gasket ring. Under compression, the deforming copper knife edge seals the window with a leak tightness of $\lesssim 10^{-12}$ mbar l/s helium leakage, comparable with usual CF connections. We implemented this technique, to realise viewports also for CF 16 flanges. The maximisation of the clear aperture required custom-sized windows of 22 mm diameter and 6 mm thickness (Melles Griot, BK 7, AR/AR HEBBAR coating).

Fig. 3.2 shows a cross section and a frontal view of the viewport construction. A blank CF 16 flange was milled as a compression ring to clamp the window onto the copper seal. The ring has a circular overlap of 2 mm width with the window. Between them we use as a cushion a stack of 10 – 15 punched rings of aluminium foil. The clear aperture of the viewport is limited by the flange bore diameter and by the inner diameter of the gasket, both $\approx 16$ mm. The knife edge in the copper gasket is also shown in the figure. Tightening of the six (lubricated) bolts was done with a torque wrench uniformly and in small steps. A torque of 4.9 Nm provided good sealing without damage, whereas for 5.5 Nm we observed cracks in the AR coatings of the window. Also the copper gasket was significantly deformed due to a slight mismatch in the knife edge diameters. Compared to the CF 16 steel knife of 18.5 mm diameter, we used initially a slightly smaller diameter of 18.0 mm for the copper knife, in order to keep more space to the edge of the small glass substrate. Later we also used copper knives of 18.5 mm. The final sealing torque on the bolts was 3.9 Nm, similar to that in Ref. [129]. The copper knife was then compressed to a flat ring of 0.5 mm width, by a total loading force of $\approx 150$ kN from the 6 bolts, or $\approx 26$ kN/cm along the knife.

So far, three of our four windows withstood several bakeout cycles up to 200° C (max. 250° C). One window broke while being unmounted. Another window showed a slight edge damage by the compression ring but did not leak.
3.4 Optical access to the UHV system

3.4.2 All-metal sealed fused silica cell

The knife-edged Conflat seal.— In a first attempt, we adapted the knife-edged CF 40 gasket of the viewports also to a cuvette. Fused silica cuvettes were manufactured by Optiglass (England) and supplied by Starna Analytical Accessoires (Austria). They were made from 4 mm thick plates with a square outside width of 30 mm and lengths of 100 mm and 150 mm. The material is Spectrosil B from Thermal Syndicate. The cuvettes were molded each on a 15 mm thick ring disk substrate of 50 mm outer and 22 mm inner diameter. Particularly the lower (sealing) disk surface was polished.

Thus, the disk resembled a 50 mm dia. (CF 40) fused silica window. Here, the knife edge milled onto the copper gasket had a diameter of 42 mm, like a CF 40 steel knife. For a window, we achieved a good seal with a torque of 5 Nm on each of the 6 flange bolts, corresponding with 173 kN total load (13 kN/cm). Nevertheless, the disk-mounted cuvette did not withstand the compression clamp. Before vacuum sealing was achieved, the disk cracked at the corners of the cuvette, when the torque at the bolts was increased to about 3.4 Nm.

Therefore it seemed necessary to realise a seal using considerably less loading force on the disk than with an OFHC gasket. A possibility might be a softer gasket, e.g., made from nickel. However, nickel is ferromagnetic and therefore undesirable close to the experimental region.

The Helicoflex Δ spring-loaded seal.— With the single-side knife-edged gasket, most of the compression was needed to deform the bulk gasket material by the CF steel knife. Therefore, a double knife-edged gasket between two flat surfaces promised a stress reduction. A commercial solution is the Helicoflex Δ gasket (Le Carbone-Lorraine, type HNV 200 Δ (DN 25), spring Nimonic 90, lining aluminium/Inconel 600) [130]. The gasket consists of a toroidal lining made from the sealing material. It has tiny knife edges milled on the top and bottom circumference. Inside, as an elastic core, the torus contains a helical spring. This spring provides a homogenous compression all around the sealing circumference and avoids (torsion) stress on the sealed UHV components. A cross section of the Helicoflex Δ gasket is shown in Fig. 3.3 (not to scale). The helium leakage is specified as $<10^{-10}$ mbar l/s [130].

In the present setup, we have chosen an aluminium lining. Apart from the low costs, it offers advantageous properties in sealing our particular glass substrates. Aluminium is a ductile material: the knife edge is consumed under compression and requires less loading force compared to a nonductile material. Among other ductile materials like silver or copper, aluminium gaskets require less loading force, whereas the specified final compression is even larger. Note the distinction made here between "(linear) loading force" and "compression". The former is derived from applied torques when tightening flange bolts, the latter describes the visible geometrical deformation of the toroidal gasket and the knife edges. A large compression of the gasket promises accurate control during the sealing procedure. Aluminium gaskets require a Vickers hardness of the sealing surfaces of 65 only, in contrast to minimal
Experiment setup

Figure 3.3: All-metal UHV sealed fused silica cell.

100 – 120 for silver and copper. A disadvantage may be the maximum bakeout temperature of 280°C, which is, however, still above the attempted rating for our cuvettes. For detailed requirements on machining and finish of the sealed surfaces, see Ref. [130]. As an alternative to the Helicoflex gasket, also a metal wire seal might offer a solution. However, common wires from gold need significantly more loading force and, the softer indium does not allow larger bakeout temperatures than the epoxy-glued connection, discussed below.

Fig 3.3(a) shows a cross section and a top view of the sealed cuvette. This corresponds to the most recent construction. In order to provide a flat sealing surface, our workshop machined a CF 40 adapter to be connected to the hexagonal vapour cell section. This adapter accepts the Helicoflex gasket. The base of the cuvette assembly consists of a 50 mm diameter quartz disk of 20 mm thickness. In addition, between this disk and the rectangular cell, there is an intermediate quartz ring of 10 mm thickness, the outer diameter of which matches the 30 mm cross section of the cell. This assembly was clamped onto the Helicoflex by a combination of a stationary compression ring and a single compression nut, with a fine thread of 72 mm diameter and a pitch of 1.2 mm/turn. A thin ring of annealed aluminium forms a cushion between the compression ring and the quartz disk. A similar cushion, lubricated with MoS paste, serves as a sliding ring between compression ring and nut.

The 10 mm spacer ring was inserted to avoid focused stress at the cell corners. Standard DN 25 HelicoflexΔ gaskets were used. The inner and outer diameters are 30.4 mm and 40.2 mm, respectively. The torus cross section is 4.8 mm, with a nominal linear sealing load of 245 N/cm and a nominal compression of 0.9 mm. The load required to achieve sealing should thus be 100 times smaller than with the CF-sealed windows which were described in the previous section. The diameter of
the knife edges is 35.2 mm. The larger inner diameter of the compression ring causes
torsion stress in the quartz disk. Note that the choice of the standard DN 25 gasket
was motivated earlier by modifying an existing CF 40 flange rather than machining
a custom adapter to the vapour cell section.

The final construction was tested while mounted directly on top of the inlet of
the turbo-molecular pump. Sealing was achieved with a compression of 0.49 mm
(55% of the nominal one). The pressure reading from a Penning detector indicated
4.0 × 10^-8 mbar before bakeout. After a bakeout cycle up to 230°C, the pressure
settled at 1.8 × 10^-8 mbar, the same as when operating the terminated pump alone.
Our “consumption” of numerous gaskets reflects their quality. Under visual inspection
both used and freshly unpacked gaskets occasionally showed tiny scratches or
material faults in the aluminium knife-edges. In these cases sealing of the cuvette
was not achieved within the nominal compression. It is strongly recommended to
consume as many gaskets as necessary until sealing is achieved within the nominal
compression. In fact, a glance at the catalogues [130] indicates that these gaskets
are originally designed to seal reactor vessels rather than atomic vapour cells.

The actual two-disk cuvette was motivated by an unsuccessful attempt to use the
single-disk construction with a Helicoflex Δ gasket. The 15 mm thick single disk was
clamped on the gasket by 6 bolts of a modified CF 40 flange, similar to the viewport
construction. After sealing was achieved, the system was gently baked at 70°C.
Having cooled down slowly and after some hours of settling at room temperature, a
crack at one of the cuvette’s corners occurred, similar to the crack with the previously
used CF gasket. The reason was probably that the compression clamp finally made
a considerable wedge with the flange counterpart. The bolts had been tightened
evenly by observing the applied torque. This suggests that either the spring load
of the gasket was not constant along the circumference, or the torque readings
of the wrench were not reliable due to variable bolt friction. This is the reason
why we finally used a single screw terminal to control the compression rather than
controlling the linear load by individual bolts. Nevertheless, the latter concept has
been successfully realised by Dieckmann et al. [131], including bakeout above 250°C.
3.4.3 Epoxy-glued glass cell

We started experiments with an improvised glass cell, which we glued to a stainless steel rectangular platform, see Fig. 3.4. The low-vapour pressure epoxy resin was TorrSeal (Varian) which allows pressures down to $10^{-9}$ mbar and bakeout temperatures up to 120° C. The glass cuvette is a standard “Large Cell” from HELLMMA (Germany) and made from “Optical Glass” (B270-Superwite crane glass, from DESAG). The outside dimensions are $130 \times 42 \times 42$ mm$^3$ with a wall thickness of 4 mm.

The figure shows the rectangular stainless steel platform, that was welded to a tubular CF 40 flange. The epoxy resin forms a seam of triangular cross section along the bottom face of the cuvette. Thus, direct and polluting contact of the resin with the vacuum is kept small. The triangular steel edge is supported by a thin rim of steel. This proved to be necessary in order to allow the seal to relax from stress after bakeout. The resin seemed to soften at bakeout temperatures and to relax stress that has been induced by the thermal expansion mismatch of steel and glass. When cooling down after bakeout the resin hardens too quickly. In a first construction without any significant elasticity, this resin property caused the glass to break at several locations at the epoxy seam, some hours after cooling down to room temperature.

The ultimate pressure of $10^{-9}$ mbar was reached after bakeout of the system, during which we kept the resin temperature below 115° C. In fact, this pressure was permissible for the experiments reported in this thesis. Thus, the glued cell proved to be a low-cost, reliable concept, maybe even simpler and more robust than a cuvette that is assembled from loose glass plates as reported in Ref. [132]. Of course, it was not possible to apply an optical AR coating to the inner surfaces, neither did we apply any coating at the outside.
3.5 Semiconductor lasers for cooling and trapping

3.5.1 Requirements

There are three essential specifications of a laser system for atom-optical experiments, (i) frequency stability, (ii) optical output power and, (iii) beam quality, which are briefly discussed here, followed by a detailed description of our frequency stabilised diode lasers and injection-locked diode lasers.

(i) Frequency stability.— The laser linewidth must be smaller than the atomic transition linewidth. The frequency should also be stable on this scale. Using rubidium ($\Gamma/2\pi = 6.0$ MHz), this requirement is usually fulfilled with common laser sources. Frequency drift stability within 1 MHz is achieved by “locking” the laser to an atomic resonance using feedback from a reference spectroscopy signal [133]. Magneto-optical trapping and polarisation gradient cooling typically demand a laser detuning from the atomic resonance of a few times the transition linewidth $\Gamma$. Continuous and fast detuning control is achieved by frequency shifting acousto-optical modulators (AOM). Passive drift stability of the laser source is desirable when large detuning ($\delta \gg \Gamma$) is necessary and suitable references for locking are not available, e.g., when working with far off-resonance dipole potentials. In some applications also the spectral background has to be considered. In Chap. 4, the amplified spontaneous emission background (ASE) of a tapered amplifier system (TA) is discussed.

(ii) Output power.— In applications with near-resonance light, laser intensities of a few times the saturation intensity are usually sufficient, e.g. $I_0 = 1.67$ mW/cm$^2$ for the rubidium D2 line. A laser output of 15 mW allows operating a rubidium MOT with beam waists $\lesssim 5$ mm. Much more power is usually needed to realise optical dipole potentials. The trapping scheme envisaged in Chap. 2 requires intensities $\sim 10^6 I_0$. In this case, laser power constitutes the limiting factor to the spatial extension of the trapping potential.

(iii) Beam quality.— Most applications demand good beam quality and a well defined polarisation. For this reason single-mode optical fibres are used as spatial filters. In case of the TA system, such a fibre also provides spectral filtering of ASE background in the amplifier output.

3.5.2 Compact external grating diode lasers

A single-transverse-mode laser diode emits a diffraction-limited, elliptical beam. The emission linewidth of such a laser is typically several tens of MHz. The emitted centre frequency is determined by both the internal cavity formed by the reflective waveguide facets and the spectral gain profile. Between “mode hops”, it can be continuously tuned by means of operating temperature and injection current.

The most common technique to narrow the linewidth of a diode laser to below 100 kHz is optical feedback by the first diffraction order from a grating, see Fig. 3.5 (“external grating diode laser”, EGDL). The grating establishes an external cavity, while the specular reflection is coupled out. Simultaneous control of the grating angle
and distance, and of the diode current allows tuning and locking of the laser to a reference frequency [117,118]. In atomic physics this method provides a standard laser tool, reaching from the mid-infrared [134] to the red [135,136] and, recently, to the blue [137] range of the spectrum.

Spectroscopic applications usually demand a wide tuning range, free of mode-hops and covering various atomic or molecular resonances. A common realisation of an EGDL is the Littrow configuration (see e.g. Ref. [133]). The rotation axis of the grating is chosen such, that a change in feedback frequency $\Delta \omega$, due to a rotation $\Delta \alpha$, is matched with the grating displacement $\Delta l$, or $(\partial \omega / \partial \alpha) \Delta \alpha = (\partial \omega / \partial l) \Delta l$. Simultaneous modulation of the laser diode current provides continuous tuning over tens of GHz.

Efficient coupling of the laser output to a single-mode optical fibre requires the elliptical beam profile to be circularised. This is done immediately after the EGDL by a pair of anamorphic prisms. Since the Brewster effect assists in reducing reflection losses, the laser polarisation is first rotated to horizontal by means of a half-wave plate. The resulting circular beam typically has a waist of 0.5 mm ($1/e^2$ intensity radius). An EGDL demands good optical isolation against backreflections. In most situations an isolation of 30 dB is sufficient. However, if the EGDL is used as "master" oscillator to seed an amplifier or an injection-locked "slave" laser [138,139], 60 dB isolation may be required to prevent direct feedback to the master laser from the mode-matched slave output, see below.

An external cavity makes the system susceptible to vibrations and thermal drift. Various designs use compact realisations of the Littrow type to improve laser stability [135,140]. Other concepts put emphasis also on economical usage of commercial opto-mechanical components [141,142]. In the experiments reported in this thesis, our interest was in locking lasers to a single atomic resonance rather than a wide continuous tuning range. Hence, a very compact EGDL design was chosen, based on a stimulating idea from Poul Jessen [142]: the grating angle is preset manually with a
resolution $\sim 100$ MHz and kept fixed in experiments. Fine adjustment is performed by tuning the grating distance from the laser facet with a piezo actuator (PZT).

The construction of the laser head is shown in Fig. 3.6. A laser diode (TO-5 window package, 9 mm dia.) is mounted in a collimation lens tube (ThorLabs, type LT 230 B, $f = 4.5$ mm, N.A.=0.55). The beam can thus conveniently be collimated before the lens tube is mounted in the laser head. A gold coated holographic grating with 1800 lines/mm provides feedback to the laser diode (Carl Zeiss Jena, no. 263232-9451-325, $10 \times 10 \times 6$ mm$^3$). The feedback angle for 780 nm and 795 nm wavelength is $\alpha = 44.6^\circ$ and $45.7^\circ$, respectively. In a similar construction also gratings with 1200 lines/mm were used (Zeiss, no. 263232-9052-825). The feedback angle was there $\approx 19^\circ$. However, these gratings provided significantly less output power.
Both collimation package and grating are integrated in a single, milled block from copper-bronze. The rotational degrees of freedom for the grating are provided by a flexure construction. Adjustment of optical feedback (coarse vertical tilt) is achieved with a small screw using an Allan key. The feedback wavelength (horizontal tilt $\alpha$) is coarsely set with a screw also at the flexure mount, whereas fine adjustment is achieved using an additional double-stage flexure gear. Not shown in the drawing is an AD 590 temperature sensor, attached to the base of the laser head, close to a Peltier thermo-electric cooler (TEC). The small volume of the laser head allows relatively fast temperature control and provides good thermal drift stability to the external cavity. In particular, the flexure grating mount has better thermal conductance than a comparable spring-loaded construction using ball-bearings. The choice of copper-bronze (7% Sn) is a compromise between thermal and elastic properties [140]. The typical passive stability of this system is $\sim 100$ MHz per hour and limited by both thermal drift and drift of the PZT.

The laser head is mounted via the TEC on a brass heatsink that can be water cooled and also includes a compartment for laser current modulation circuitry. Vibrations from the optical table are damped by a polymer sheet underneath the heatsink (Edmund Scientific, Sorbothane). The laser head is shielded from surrounding airflow and from electro-magnetic noise by a metallised cap. This cap allows access to the fine adjustment gear.

The flexure gear.— In the drawing of the double-stage gear, the concentric pairs of large and small circles indicate the motion of parts from the gear, or the translations $d \rightarrow d'$ and $d' \rightarrow d''$, respectively. The total translation is 7:1. A single turn of the screw ($d = 0.5$ mm) results in a travel of $d'' = 70 \mu$m. The length change of the external cavity is $\Delta l \approx 0.3 \, d''$, or $20 \, \mu$m per turn of the screw. The frequency change of the cavity is $\approx 20$ GHz/$\mu$m. (With a cavity length of $\approx 20$ mm, the free spectral range is FSR$\approx 7.5$ GHz.) This resolution is sufficient to allow smooth manual presetting of the laser frequency. Essential is, that the user touches an actuator fixed to the bulk of the laser head rather than to the vibrationally sensitive grating holder.

The PZT stack actuator.— The grating is directly glued to a polymer-molded low-voltage PZT stack actuator (Piezomechanik, bare actuator type PST 150/7/7, travel 7 $\mu$m for 150 V). The length or frequency tuning of the cavity is given by $\approx 30$ nm/V, or $\approx 0.6$ MHz/mV, respectively. The only moving mass is that of the grating. This allows a faster response when tuning the cavity length as compared with a rotational grating mount. A prestressed PZT device in a tubular steel case has also been tested (PST 150/5/7/VS10), in first instance promising a more linear response. Unfortunately, the weight of the horizontally mounted grating bent the PZT. This resulted in friction with the steel case, causing an unreliable actuator response [Pickelmann, Piezomechanik, private communication].
3.5 Semiconductor lasers for cooling and trapping

Figure 3.7: Hyperfine structure of rubidium [143, 144].

(i) Near resonance cooling, probing and hyperfine pumping:

<table>
<thead>
<tr>
<th>Beam line</th>
<th>$F_g \rightarrow F_e$</th>
<th>Detuning</th>
<th>Fibre output</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) D2</td>
<td>2 → 3</td>
<td>0 - (±8) Γ</td>
<td>0 - 500 μW</td>
</tr>
<tr>
<td>(2) D2</td>
<td>2 → 2</td>
<td>0 - (±8) Γ</td>
<td>0 - 500 μW</td>
</tr>
<tr>
<td>(3) D2</td>
<td>2 → 3</td>
<td>(-10) - 0 Γ</td>
<td>20 mW</td>
</tr>
<tr>
<td>(4) D1</td>
<td>1 → 2</td>
<td>resonant</td>
<td>10 mW</td>
</tr>
</tbody>
</table>

(ii) Far off-resonance dipole potentials:

<table>
<thead>
<tr>
<th>Beam line</th>
<th>$F_g \rightarrow F_e$</th>
<th>Detuning</th>
<th>Fibre output</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5) D1</td>
<td>1 → 2</td>
<td>±2 nm</td>
<td>120 mW</td>
</tr>
<tr>
<td>(6) D2</td>
<td>2 → 3</td>
<td>±2 nm</td>
<td>200 mW</td>
</tr>
<tr>
<td>(7) D2</td>
<td>1 → 2</td>
<td>±2 nm</td>
<td>200 mW</td>
</tr>
</tbody>
</table>

Table 3.1: Laser frequencies used in experiments with $^{87}$Rb.
3.5.3 The laser park for atom-optical experiments

An experiment with rubidium requires various frequency-stabilised laser sources tuned to specific optical resonances of the considered isotope, here $^{87}$Rb. Fig. 3.7 shows the hyperfine energy levels of the rubidium D1 and D2 line. The optical transitions, labelled (1)–(7), indicate the corresponding laser frequencies in our setup of diode laser systems. The specific usage of the lasers is listed in Table 3.1. An overview of this setup is given in Fig. 3.8. It is specified essentially by two groups of lasers, (i) EGDL’s tuned close to a rubidium resonance, some of which are amplified by an “injection-locked” laser diode, and (ii) high-power tapered amplifiers used far off-resonance (see Chap. 4).

(i) Cooling, probing and optical hyperfine pumping.— The laser frequencies of the beams (1) – (3) are derived from an EGDL that is stabilised by feedback from a frequency modulation (FM) spectroscopy on rubidium. The EGDL serves as a master oscillator for an injection-locked slave diode laser (ILDL), providing the trapping and cooling light of beam (3). The laser diodes used for the EGDL’s were 60 mW single-spatial and -frequency mode laser diodes with a specified wavelength close to the D1 or D2 line (Hitachi, HL 7851 G98, selected 781 – 785 nm; Mitsubishi, ML 64114R, selected 788 – 793 nm). Recently also an 80 mW device became available (Sanyo, DL-7140-001, specified 785 nm).

The optical output power of our EGDL’s ranges between 5 – 30 mW after the isolator, depending on the used laser diode. A small fraction ($\sim 0.5$ mW) is split off to be used for spectroscopy. The lasing frequency mode of both master and slave can be permanently monitored by an optical spectrum analyser. The seeding beam from the master laser was inserted into the slave’s beam path by means of the accessible output polariser of a 30 dB optical isolator (Gsänger, single-stage type FR 780). Perturbing feedback from the slave to the master is thus prevented by this isolator, in addition to the 60 dB isolator directly after the EGDL. Mode matching of master and slave was achieved using identical beam collimation and circularising optics, see Fig. 3.5. If optimally aligned, a seeding input of 100 $\mu$W was sufficient to provide a stable locking range over $> 10^4$, as required to load a MOT and perform molasses cooling.

Fast and continuous frequency control of the beams (1) – (3) was achieved using acousto-optic modulators (AOM) in double-pass, see below. For the beams (1) and (2), the AOM also serves as a power modulator and a shutter.

**Figure 3.8:** The system of stabilised lasers and amplifiers (previous page). Injection-locked diode laser (ILDL), tapered amplifier (TA), half-wave plates (HW), optical spectrum analysers (SA), grating spectrometer (GS) and wavelength meter (WM). The frequency modulation (FM) and Zeeman polarisation (ZS) spectroscopy schemes are indicated symbolically (Rb). Frequency shifting AOM’s in double-pass are explained in detail below: lens (L), quarter-wave plate (QW), diaphragm (D), and mirror (M). The laser frequency $\omega_L$ is shifted by twice the RF frequency of the acoustic wave, $\omega_{RF}$. 
3.5 Semiconductor lasers for cooling and trapping

(i) Near-resonance cooling, probing, pumping

(ii) Far off-resonance dipole potentials

AOM frequency control:
The EGDL of beam (4) provides hyperfine repumping light to transfer atoms from $F_z = 1$ to $F_z = 2$, mainly for operating the MOT and cooling but also for specific probing techniques, see Chap. 7.

All beams were coupled to single-mode optical fibres, as indicated for beam (4). Coupling efficiencies were achieved, ranging between 70 – 85% for circularised beams of single-mode laser diodes, using compact fibre coupling ports, designed for beam input diameters between 0.9–1.8 mm (OFR, type PAF-X-5-780). These ports were used with standard fibre patchcords with angle-polished fibre connectors (type FC/APC). This avoids etalon effects from reflections at the fibre facets. The fibres were not polarisation conserving. However, twisting the fibres in loops and fixing them to the optical table provided arbitrary polarisation control of the output beam.

(ii) Far off-resonance dipole potentials.— High power output up to 200 mW from a single-mode fibre is achieved in two systems using tapered semiconductor amplifiers (TA). Only one scheme is sketched in Fig. 3.8. One system provides beam (5), the other provides the beams (6) and (7). The gain elements are each seeded by a well isolated EGDL. A detailed characterisation of these systems is given in the next chapter.

For near-resonance applications, the EGDL can be frequency stabilised by a Zeeman polarisation spectroscopy (ZS). A tunable frequency offset between ±500 MHz from the referenced atomic resonance is achieved using an AOM. For larger detunings, the EGDL remains unlocked and the frequency can be monitored by means of an optical spectrum analyser, a wavelength meter (Coherent, WaveMate), or a grating spectrometer (Ocean Optics, PC 2000).

Laser frequency tuning by acousto-optical modulators.— Laser frequencies are shifted using acousto-optic modulators in double-pass, also shown in Fig. 3.8. A lens (L) of focal length $f$ (between 10 – 20 cm) and a mirror (M) form a folded telescope. After the first passage of the AOM, the Bragg-deflected beam is retro-reflected and collimated again before passing the AOM a second time. All light but the selected diffraction order is blocked by a diaphragm (D). The polarisation of the retro-reflected beam has been turned by 90°, passing twice a quarter-wave plate. The light is coupled out by a polarising beam splitter cube. Using Bragg deflection in the first diffraction order, the light undergoes a net frequency shift of twice the RF modulation frequency $\omega_{RF}$, with no net deflection or frequency dependent displacement. This property is particularly important when shifting the frequency of the master laser in an injection-locking scheme or when coupling light to an optical fibre. Both cases require excellent directional beam stability.

A typical double-pass efficiency is 50% in first diffraction order. Higher orders are not practical due to their low efficiency. Our modulators have PbMoO$_4$ crystals and accept random polarisation [A.A. Opto-Electronique, type AA.SP.200/B100/A0.5-ir ($\omega_{RF} = 200 \pm 50$ MHz) and AA.MP.25-IR (110±30 MHz); Isomet, type 1205 C (80±15 MHz)]. It is recommended to use linear polarisations only, since birefringence of the crystal together with varying RF load may lead to severe thermal drift in the diffracted beam power.
In the laser setup of Fig. 3.8(i), AOM’s are used to derive the required frequencies from the master laser that is locked to the (bf) cross-over spectroscopy signal of the $F_g = 2 \rightarrow F_e = \{1,3\}$ transitions, see Fig. 3.9. The cross-over is centred between these transitions. Hence, a blue shift of 212 MHz realises the resonant probe (1) on the cycling transition $F_g = 2 \rightarrow F_e = 3$, using an AOM with 110 MHz specified centre frequency. By a red shift of 133 MHz, the depumping beam (2) on the open transition $F_g = 2 \rightarrow F_e = 2$ is realised. The injection-locked slave is supplied with a shifted seed beam, thus saving power from the slave for the experiment. Using an AOM with 80 MHz centre frequency, beam (4) is thus tuned $0 - 10 \Gamma$ to the red of the $F_g = 2 \rightarrow F_e = 3$ transition. The collimation of the (astigmatic) master laser beam was optimised for mode-matching the slave laser. This resulted in poor beam quality and thus poor AOM efficiencies in beam (1) and (2). In a later stage, a second injection-locked slave laser supplied these beams with more power and better beam quality.

When using an AOM as a switch or power modulator, “leakage” into the selected diffraction order reduces the extinction to typically 1 : 1000. Therefore we use also mechanical shutters. Power modulation with an extinction of 1 : 200 is obtained for beam (3) by an electro-optical modulator. [Gsänger, type LM0202 5WIR, aperture $3 \times 3 \text{ mm}^2$. We use also a version of the LM0202 5WIR with $5 \times 5 \text{ mm}^2$ aperture.]

### 3.5.4 Laser frequency stabilisation

The lasers were locked to rubidium resonances using Doppler-free saturation spectroscopy [133]. Rubidium is commonly used as a saturated vapour in spectroscopy cells at room temperature. Most spectroscopy schemes provide absorptive signals (“dips”), resolving the natural transition linewidth $\Gamma$. It is necessary to derive a dispersive signal with a zero-crossing as feedback to the laser. Three common techniques are:

- Frequency modulation (FM) of the laser creates RF sidebands [119]. A dispersive signal is obtained by mixing the spectroscopy signal with the local RF oscillator and adjusting the phase.

- Zeeman spectroscopy employs nondegenerate magnetic sublevels. “Dispersion” signals are electronically generated from oppositely frequency-shifted absorptive signals of orthogonal polarisations [120–122].

- Polarisation spectroscopy [133,145] probes the dispersion of the atomic species rather than the absorption, and a feedback signal is directly obtained. This can also be used in passive schemes, relying on purely optical feedback [146,147].

FM spectroscopy has an intrinsically large bandwidth providing fast feedback to the laser, with good distinction between neighbouring optical transitions. However, this technique is relatively complex due to RF electronics. More important, the FM sidebands imprinted onto the laser output may perturb the laser application. (This could be avoided by using an EOM to modulate only the light used for spectroscopy.)
We employ the FM technique therefore as a robust locking scheme for less sensitive tasks, such as the MOT, optical pumping or probing atoms. Zeeman spectroscopy is less demanding in electronics and optics equipment. We use it, with the far off-resonance lasers, were the moderate accuracy of the artificially dispersive locking signal is not an issue. In the following, a brief description of both methods is given.

**Frequency modulation spectroscopy.**— The FM scheme is shown in Fig. 3.9. The optical part is based on Doppler-free saturation spectroscopy: Light is split off from the output of an EGDL and sent in a first pass through a spectroscopy cell with rubidium vapour. If resonant within the Doppler-broadened absorption profiles, rubidium optical transitions are saturated. When the laser scans across a resonance, the retro-reflected beam probes these transitions. The Doppler effect cancels out on a resonance and an absorptive signal with a width ~ $\Gamma$ is recorded. Optimal retro-reflection, i.e. Doppler cancelling is achieved using a quarter-wave plate and a polarising beam splitter cube.

A *dispersive* signal is achieved by modulation of the diode laser current, $I$, with a local oscillator radio frequency, here $\omega_{RF} = 40$ MHz. This results in frequency sidebands, $\omega_L \pm \omega_{RF}$, next to the laser carrier, $\omega_L$, shown in the inset of the figure. Both sidebands beat with the carrier. If no spectral atomic feature is covered by any of these laser frequencies, the net beating cancels out, due to the opposite phase of the sidebands. The photodetector then receives no signal $\propto \omega_{RF}$. However, if one of the frequencies probes a resonance, the beating is out of balance and the photodetector detects an RF signal. (The detector is supplied with a RF bandpass filter.) By amplification of this signal, adjusting the phase, and mixing with a local oscillator, the dispersive (low frequency) signal for the laser lock is obtained and fed back to both, laser current and grating actuator. The grating feedback tackles down slow drifts of the laser using a longer integration time constant than the intrinsically fast current feedback.

Two exemplary FM spectra are plotted in the figure. For the (f) transition also the sidebands are resolved. Typical for this type of Doppler-free spectroscopy is the occurrence of so-called “cross-over” resonances, given the Doppler broadened absorption profiles of several resonances overlap. This is the case with room temperature rubidium vapour. The cross-over resonance of two transitions is located at the average transition frequency. (The spectra in the figure show that the overlap of the Doppler profiles is larger for the D2 line.) In our laser setup we locked the EGDL for the beams (1)–(3) to the (bf) cross-over.
Figure 3.9: Laser stabilisation by FM spectroscopy. **Scheme:** Half-wave plate (HW), double pass through a rubidium cell (Rb), outcoupling using a quarter-wave plate (QW) and a polarising cube, detection with a photodiode (PD). Inductive frequency modulation of the laser current $I$ using a RF oscillator. The photodiode signal is phase shifted ($\phi$) and mixed ($\otimes$) with the local oscillator (LO). The resulting dispersive DC signal is fed back to laser current and grating actuator (PZT). **Inset:** Laser carrier frequency $\omega_L$ and FM sidebands $\omega_L \pm \omega_{RF}$, spectral feature of natural linewidth $\Gamma$ at atomic resonance $\omega_0$. **Graphs:** FM signals of $^{87}$Rb (see Ref. [148]), labelling as in Ref. [143]. For comparison: absorption signals from a DC photodiode (thin curves).
**Figure 3.10:** Laser stabilisation by Zeeman spectroscopy. (a) Doppler-free saturation spectroscopy: rubidium cell (Rb) with axial magnetic field (B), quarter-wave plate (QW), polarising beam splitter cube, and photodetectors for $\sigma^+$ polarisation. (b) Exemplary Zeeman shift of magnetic sublevels: the resonance is blue (red) shifted for $\sigma^+$ ($\sigma^-$) polarised light. (c) Zeeman-shifted resonances of both circular polarisations. The dispersive signal obtained by subtraction.

**Zeeman spectroscopy.**— The scheme for this method is shown in Fig. 3.10 (see also Ref [148]). It uses the decomposition of linearly polarised light into circular polarisations, $\sigma^\pm$. In Doppler-free saturation spectroscopy, rubidium vapour is made birefringent by using the Zeeman shift of magnetic sublevels in an axial, homogeneous magnetic field. Therefore, the orthogonal circular polarisations encounter oppositely shifted resonances. Both polarisations are detected independently using a combination of a quarter-wave plate and a polarising cube as an analyser for the circular polarisation basis. A dispersive laser-lock signal is obtained electronically. This method requires an optical transition scheme with different $g$-factors, i.e. different Zeeman shifts in the ground and excited state sublevels. For example, for the D1-line $F_g = 1 \rightarrow F_e = 1$ transition this are $g_g = 9/4$ and $g_e = 3/2$, respectively.
3.6 Real-time experimental control

An atom-optical experiment constitutes a series of processes in quick succession, demanding real-time application of analogue and digital control signals. Data acquisition (DAQ) also requires precise triggering with μs-resolution. A typical experimental sequence consists of loading a MOT, cooling atoms in optical molasses, releasing them for bouncing on an evanescent-wave mirror and, finally, imaging them with a CCD camera. Laser beams must be switched on time scales of typically 0.1 ms. We employ a common personal computer (PC), that operates LabVIEW under Windows NT, to do both real-time control and data acquisition. This provides a flexible system with various software-controlled input and output channels. It can be configured for arbitrary time sequences. These tasks are performed by several hardware extension cards. In particular, a self-sustaining digital signal processor (DSP) performs the real-time control of digital output (trigger) channels, thus circumventing perturbing interrupts of the PC processor. Table 3.2 gives an overview on the various hardware components.

PC platform and DAQ hardware.— The system is based on a PC with Pentium II processor. An analogue output board (AT-AO-10) controls the modulation of AOM and EOM drivers. A general purpose DAQ board (MIO-16E-4) provides analogue inputs, which are used, e.g., to acquire photodetector signals for time-of-flight measurements. This board has additionally two waveform output channels and two general purpose counters. Therefore, it is also used as a versatile function and pulse generator. Two more slots of the PC are occupied by the DSP (DIO-128) and by the interface (ST-138) of a digital camera system.

The fluorescence of trapped atoms is permanently monitored by several analogue video cameras. These cheap surveillance cameras (Conrad Electronic) have no near-infrared blocking filters and are thus sensitive to the rubidium fluorescence. The video signals can be recorded by a framegrabber (FlashBus), e.g., for beam profiling tasks or assisting laser beam alignment in the UHV vapour cell. A grating spectrometer (PC2000) allows monitoring laser wavelengths. The framegrabber and the spectrometer are operated by a second PC.

Digital signal processor and LabVIEW user interface.— The main task of the DSP is to provide precise timing during the experiments. In a screen interface, the user fills in a time schedule of the experimental events. This record contains the possibly altered status of digital and analogue output ports for a given event, including the time of the event with 1 μs resolution for the DSP timer. Using a LabVIEW driver, the DSP loads the time table and the digital output record into its on-board memory. The analogue output record is buffered in the PC’s memory and handed over on request to the FIFO-buffered analogue output board by the DMA ("direct memory access") controller. All input and output channels are experimentally accessible through a front-end connector panel. One digital output of the DSP supplies a hardware event-update trigger to the analogue output board. Other digital outputs provide modulation signals for AOM/EOM drivers, magnetic
field coil current supplies and mechanical shutter drivers. CCD image capture and input of photodetector signals are triggered similarly. The DSP works independently from the PC. Thus, other LabVIEW routines can be used on the PC to acquire measurement data. The LabVIEW interface for the experiments discussed in this thesis was programmed in a simple and effective way, mainly using exemplary routines from the DSP driver library. Meanwhile, we use a commercially available program that has been developed by H. Alberda (AMOLF Institute, Amsterdam) and is very convenient in use, including also DAQ functions.

**CCD digital camera imaging system.**— An imaging system for (cold) atoms must have an accurate image capture trigger and a well defined exposure time. Mechanical shutters are usually too slow. Therefore we use a frame-transfer system (Princeton Instruments). Half of the CCD array is covered by a mask. After an exposure, the image is shifted within 1.6 ms under the mask to be shielded against further illumination and is read out. After shifting, the CCD is ready for another image capture. If masking a larger area of the sensor (1024 x 512 pixels in total), an even faster sequence of more than two image frames, although smaller in size, can be captured (cf. Refs. [149,150]). An advantage of the frame transfer for our experiments is, that the sensitive area can be kept “clean” (unexposed) by means of continuous line shifting, until ~2 ms before an image capture. This is particularly important, if an image is taken only a few ms after a strong (saturating) illumination source, e.g. an evanescent-wave, has been switched off.

Other important CCD specification are the spectral sensitivity, the pixel size, the pixel filling ratio, the pixel well depth (electron capacity), and the noise properties (dark current). These specifications are discussed in Ref. [151]. We may expect a strong background illumination while imaging optically trapped atoms. Therefore, the well depth of the pixels must be sufficiently deep (> 10^5 electron charges) to avoid saturation, and the resolution of signal digitisation should be at least 10 bits. It is also this expected background illumination why we don’t use an intensified imaging system.

There exist also “interline transfer” systems, which have read-out registers between adjacent pixel lines. This allows for even faster cleaning, shuttering and read out. However, the pixel filling ratio and the well depth of these CCD’s are low.

We use our CCD system with either a commercial 50 mm camera objective to capture fluorescence images of bouncing atoms (see Chap. 6) or with a relay telescope to do absorption imaging (see Chap. 7).
### Host system:

<table>
<thead>
<tr>
<th>Personal computer</th>
<th>Pentium II, 300 MHz, 256 MB RAM; Windows NT 4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Programming</td>
<td>LabVIEW 5.1, user interface by H. Alberda, AMOLF Institute, Amsterdam</td>
</tr>
</tbody>
</table>

### Experimental control:

<table>
<thead>
<tr>
<th>Real-time control, digital output</th>
<th>Viewpoint Software Solutions, DIO-128 (PCI-bus), Dynamic Digital I/O System, 64 inputs/64 outputs (128 inputs), timer 32 bit, resolution 1 μs; LabVIEW driver library</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogue output</td>
<td>National Instruments, AT-AO-10 (ISA-bus), 10 channels, resolution 12 bit, max. sampling 300 kS/s</td>
</tr>
</tbody>
</table>

### DAQ, imaging:

<table>
<thead>
<tr>
<th>Analogue input, counters, waveforms</th>
<th>National Instruments, MIO-16E-4 (PCI-bus), 16 single-ended (8 differential) analogue input channels, resolution 12 bit, max. sampling 300 kS/s, 2 general purpose counters (24 bit), 2 waveform analogue output channels (12 bit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital imaging</td>
<td>Princeton Instruments/Roper Scientific, TE/CCD-512 EFT frame transfer digital camera system, sensor EEV37, grade 1, 512 × 512 pixel, pixel size 15 × 15 μm, 100 % pixel filling, shift time 1.6 ms/frame, dark current 11 e−/pixels (@ − 40° C, fan cooled), NIR AR-coated vacuum window, no window on CCD; controller ST-138 (PCI-bus), A/D converter 12 bit (@ 1 MHz); WinView 32 imaging software, LabVIEW driver library</td>
</tr>
<tr>
<td>Video cameras</td>
<td>Conrad Electronic, b&amp;w miniature camera module, no. 19-27-75, tele-lens no. 11-65-32; EHD Physikalische Technik, KAM 08, b&amp;w 1/3&quot; CCD sensor</td>
</tr>
<tr>
<td>Framegrabbing</td>
<td>Integral Technologies, FlashBus BV Lite (PCI-bus)</td>
</tr>
</tbody>
</table>

### Laser diagnostics:

| Spectrometer | Ocean Optics, PC 2000, miniature PC-card fibre optic grating spectrometer (ISA-bus), grating no. 6, range 650 − 850 nm, entrance slit 10 μm, resolution 0.4 nm, accuracy 0.1 nm |

**Table 3.2:** (Computer) hardware for experimental control and data acquisition.
3.7 The magneto-optical trap

3.7.1 Trapping principle and molasses cooling

Since the first demonstration [33], the magneto-optical trap and optical molasses cooling have been topic of numerous experimental and theoretical investigations. For detailed information see, e.g., Refs. [11, 12, 70, 71]. Particular work on vapour-cell configurations has been reported in Refs. [124–126, 132].

The MOT is based on the spontaneous light force [2, 152, 153], i.e., the transfer of photon recoil momenta, $\hbar k_0$, to atoms, where $k_0 = 2\pi/\lambda_0$ is the vacuum wave vector of near-resonance laser light. The configuration of the light field is chosen such that this momentum transfer occurs with a preferential direction and in a succession of absorption and spontaneous emission cycles. A central trapping force is established in combination with a (velocity dependent) friction force that cools the atoms to a temperature close to the “Doppler limit”, $T_D = h\Gamma/2k_B$. For rubidium, with a transition linewidth $\Gamma/2\pi = 6.1$ MHz, this limit is $T_D = 146$ $\mu$K.

Sub-Doppler cooling schemes, such as polarisation gradient cooling in optical molasses, provide temperatures close the “recoil limit”, $T_R = (\hbar k_0)^2/Mk_B$. With the rubidium mass $M = 87$ amu, this is $T_R = 361$ nK. The corresponding photon recoil velocity is $v_{\text{rec}} = 5.88$ mm/s. (Some additional, useful numbers for rubidium are listed in the Appendix A.1).

Fig. 3.11(a) shows the principle of the MOT in a one-dimensional scheme. For convenience, a $J_g = 0 \rightarrow J_e = 1$ transition scheme is considered. In a magnetic field of constant gradient, $B(z) = bz$, the excited state sublevels, $m_e = \{0, \pm 1\}$, are Zeeman-shifted in a position dependent way by $\omega_Z(z, m_e) = m eg_e (\mu_B/\hbar)bz$. For simplicity, we assume a Landé factor $g_e = 1$. The counter-propagating laser beams are red detuned, $\delta = \omega_L - \omega_0 < 0$. The circular polarisations are assigned with respect to the $z$-axis, which is the atomic quantisation axis. The $+\sigma$-beam that travels to the right carries $+\hbar$ angular momentum, the $-\sigma$-beam that travels to the left carries $-\hbar$. However, when defining the polarisation state with respect to the propagation direction, and following the notation of Ref. [7], both beams are “left-circularly” polarised ($\mathcal{L}$): An observer facing the source sees the electric field vector in a counter-clockwise rotation. The Zeeman shift brings the red detuned light in resonance with the appropriate transition to a sublevel $m_a$, such that the atom is pushed towards $z = 0$. This establishes a central trapping force.

The cooling effect in the MOT configuration is based on the Doppler shift of the atomic resonance, $\omega_D(v) = -\hbar k_0 v$. Due to the red laser detuning, moving atoms are shifted into resonance with the counter-propagating laser ($\omega_D > 0$). Hence, a moving atom preferentially absorbs decelerating photons. This mechanism is called “Doppler cooling”. Note that it is effective also in the presence of the magnetic field gradient, thus enabling a combined spontaneous trapping and cooling force $\mathcal{F}$. This force can be written in terms of the scattering rate of an atom in the beams travelling to the right ($\mathcal{F}_+$) and to the left ($\mathcal{F}_-$), as shown in Fig. 3.11(a):

$$\mathcal{F}(z, v) = \mathcal{F}_+(z, v) + \mathcal{F}_-(z, v),$$  \hspace{1cm} (3.1)
3.7 The magneto-optical trap

Figure 3.11: The magneto-optical trap. (a) Simplified 1D two-level scheme with a red detuned laser, $\delta = \omega_L - \omega_0 < 0$. **Trapping:** The sublevels are Zeeman-shifted in a magnetic field gradient. An atom at a position $z$, preferentially absorbs resonant light that pushes the atom towards $z = 0$. **Doppler cooling:** An atom preferentially absorbs counter-propagating light that is Doppler-shifted into resonance. (b) 3D configuration of three counter-propagating beam pairs, $B_1$, $B_2$, and $B_3$ in the vapour cell. The mutual angle of $B_2$ and $B_3$ in the $yz$-plane is $70^\circ$. The opposing currents, $\pm I$, in the coils generate a quadrupole field gradient. The polarisation notation of right ($R$) and left ($L$) circular light visualises the symmetries of the configuration.

$$
F_{\pm}(z, v) = \pm \hbar k_0 \frac{I_L}{2I_0} \Gamma \frac{1}{4\delta_{\pm}^2(z, v)} + 1 + \frac{I_L}{I_0}.
$$

(3.2)

Here, $I_0$ is the saturation intensity for the atomic species, and $\delta_{\pm}(z, v)$ is the effective detuning including Zeeman and Doppler shift:

$$
\delta_{\pm}(z, v) = \delta \pm \frac{\mu_B}{\hbar} b z \pm k_0 v.
$$

(3.3)

Usually, a detuning of $|\delta| \sim \Gamma$ is applied and the magnetic field gradient is $b \sim 10 \text{ G/cm}$. In order to achieve temperatures close to the recoil temperature, we apply PGC in “$\sigma^+\sigma^-$” optical molasses. Comprehensive descriptions of the cooling process can be found in [11,12,70]. This technique is particularly useful here: when the magnetic field is switched off, the MOT laser configuration just results in the required “$\sigma^+\sigma^-$” polarisation scheme. Only laser intensities and detunings have to be adapted whilst switching. Note that there is no trapping force in the PGC configuration.
3.7.2 Experimental configuration

The 3-dimensional realisation of the MOT scheme is shown in Fig. 3.11(b). We use one horizontal (B1) and two diagonal (B2, B3) pairs of counter-propagating, circularly polarised, collimated laser beams. The horizontal $x$-direction is the axis of cylindrical symmetry of the magnetic field. The mutual angle of B2 and B3 in the $yz$-plane is $70^\circ$. This allows beam waists up to 5 mm ($1/e^2$ intensity radius) without significant clipping of the beams by the prism, given a MOT height larger than $\sim 5$ mm. In the following, before turning to the experimental performance of the MOT, (i) the optical setup and, (ii) the magnetic field coils are described.

(i) Optical setup.— The optical components for the MOT were arranged in a way to maintain access to the vapour cell for other optics. A schematic top view is shown in Fig. 3.12. The beam pairs B1, B2, and B3 are derived from a single Gaussian beam from a single-mode optical fibre. The fibre output was collimated to a waist of 4 mm by two achromatic lens doublets, L1 ($f = 50$ mm, dia. 30 mm) and L2 ($f = 300$ mm, dia. 40 mm). The lens diameters were chosen large enough to avoid diffraction fringes in the collimated beam. Two polarising cubes split off subsequently 1/3 and 1/2 of the power, thus preparing three beams of equal power. The linear polarisation for the splitting is adjusted by polarisation-controlling fibre loops (PCL) and a half-wave plate (HW). Optionally, a polariser is used directly after the fibre to keep the splitting ratio constant, despite thermal polarisation drifts of the fibre output. The cubes steer the beams B2 and B3 upwards at an angle of 35° with the optical table. The beams are then horizontally directed towards the upper mirrors (UM) of the trapping setup, shown in the photograph. These mirrors steer the beams downwards through the vapour cell under the same angle, 35°. The purpose of this construction is to use the (dielectric) mirrors exclusively either with normal or 45° incidence. Care was also taken to have only light in purely linear TE or TM polarisation being reflected under 45° incidence. This secures the polarisation of the reflected light to stay linear. Beam B1 passes the cell horizontally. Before passing the cell, all beams become circularly polarised by quarter-wave plates (QW). In retro-reflection, the initial helicity in each beam is restored by a second QW plate. The iris diaphragm (ID) before the beam splitters facilitates initial spatial alignment of the MOT beams by means of observing the fluorescence of the narrowed beams in the rubidium vapour cell. A repumping laser (RL) is coupled in by the second cube and is superposed with the the trapping beams B2 and B3.

The present retro-reflection concept suffers from an imbalance in the laser intensities, causing an imbalance in the light forces, for two reasons. First, the cloud of cold atoms in the MOT is optically dense. Hence, each retro-reflected beam carries a shadow in the centre. Particularly in molasses cooling this may increase the final temperature. To avoid this effect, six independent beams of equal intensity could be used. However, this requires more optical components and twice the laser power. A simpler solution is to apply a slight directional misalignment of the retro-reflected beams, in order to keep the cloud of atoms mostly out of the shadows.
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Figure 3.12: Optical scheme MOT. Top view in the drawing (not to scale): retro-reflected beam pairs (B1, B2, B3), trapping laser (TL), repumping laser (RL), optical fibre (OF), polarisation-controlling fibre loops (PCL), collimation lenses (L1, L2), iris diaphragm (ID), polarising beam splitting cubes (PB), half-wave plate (HW), upper and lower mirrors (UM, LM), quarter-wave plates (QW), opposing quadrupole field currents (±I). An “atom cloud” (black dot) and a glass prism are also indicated in the drawing.

The second imbalance stems from the uncoated UHV cuvette. While passing 4 glass surfaces, the beams suffer significant reflection losses. For example, in TM (TE) polarisation, the retro-reflected diagonal beams have 18\% (25\%) less power, when meeting the cold atoms in the MOT again. Obviously, also a prepared circular polarisation of the beams will become elliptical to a certain degree due to the different losses in TM and TE polarisation. The imbalance in optical power may be overcome by making the back-travelling beams slightly convergent, in order to increase the intensity at the place of cold atoms. Note, that with a cell made from fused silica (n = 1.45) the reduction in optical power would be different, namely 6.5\% (21\%) for TM (TE) polarisation. For details on the consequences of the beam imbalance on the performance of the MOT, see e.g. Ref. [154].
(ii) Magnetic field coils.— The magnetic quadrupole field gradient is provided by a pair of coils, placed in-axis with the horizontal trapping beam, B3. The currents, $\pm I$, oppose each other. This results in a magnetic field that increases approximately linearly with the distance from the centre. Along the symmetry axis, $r = (x, 0, 0)$, and close to the centre, the field is given by:

$$B(r) = bx.$$  \hspace{1cm} (3.4)  

$$b = \mu_0 N I \frac{3 R^2 d}{(R^2 + d^2)^{3/2}} \hat{x}. \hspace{1cm} (3.5)$$

where $N = 25$ is the number of turns per coil, made from 0.8 mm dia. copper wire. The wire is stacked in a square grid pattern such that the (average) coil radius is $R = 17$ mm. The distance between the coils is $2d = 57$ mm, being limited by the cuvette of 42 mm width. The resulting field gradient along the $x$-direction is calculated to be $|b(I)| = I \times 1.9$ G/cmA. The coils with an estimated inductance of each $\sim 25 \mu$H can be switched off by a power MOSFET (IRF 530) within 20 $\mu$s. After switching, the induction current is dissipated by a 4.7 $\Omega$ bypass resistor. The MOSFET switch was chosen with a breakdown voltage of 100 V to manage the induction voltage peak $\sim 50$ V without damage. Also visible in the photograph of Fig. 3.12 are connections for coolant flow through the coil mounts. However, since our MOT was not operated continuously over a longer period and the current usually was $I \lesssim 10$ A, no cooling has been required so far.

The source-free character of the magnetic field, $\nabla \cdot B = 0$, results in a field gradient twice as large along the symmetry $x$-axis as compared to the orthogonal $yz$-plane. Also the non-orthogonal crossing angle of the trapping beams in this plane together with intensity imbalances results in a reduced vertical trapping force. This may have caused the observed vertically elongated MOT shape of approximately 1:2 aspect ratio.

In order to compensate the earth magnetic field, usually $\sim 0.5$ G, and other stray fields at the location of the MOT, we mounted a cage-like frame of three coil pairs around the setup: 2 rectangular pairs (60 cm wide, 80 cm high) and 1 circular pair for the vertical axis (dia. 85 cm). Each pair consists of 80 turns of 0.8 mm dia. copper wires. The applied current ranged between $\pm 400$ mA, thus compensating indeed fields $\sim 0.5$ G.

### 3.7.3 Loading the MOT

The trapping light of the MOT is tuned 1.5$\Gamma$ to the red of the $F_g = 2 \rightarrow F_e = 3$ cycling transition of the $^{87}$Rb D2-line (see Fig. 3.7). The atoms that are off-resonantly excited to $F_e = \{1, 2\}$ and thus optically pumped into the $F_g = 1$ ground state, are transferred back by the repumping laser, which is in resonance with the D1-line ($F_g = 1 \rightarrow F_e = 2$). Typically, a power of 15 mW is distributed among the three trapping beam pairs. The intensity in the trap centre is $\sim 30 I_0$. 

The fluorescence of trapped atoms during MOT loading and molasses cooling was observed by a photodiode facing down from above the UHV cuvette. In order to capture light from a large solid angle, we used a lens ($f = 50$ mm, dia. = 50 mm) directly above the cuvette, and imaged the cloud on the photodiode. Fig. 3.13 shows a fluorescence signal, recorded when continuously cycling between MOT loading and molasses cooling. Note that the signal started here with a molasses period. The arrow at 0.8 s indicates the start of a MOT loading period, when the current in the quadrupole coils was switched on together with the trapping laser. The fluorescence signal at that moment stems from fluorescence of rubidium background vapour in both trapping and repumping light. The latter was applied permanently. After 2 s the number of trapped atoms saturates. By using slightly higher rubidium vapour pressure, also loading times $\sim 0.5$ s were achieved, which allows to increase the repetition rate of experiments. After loading the MOT, at 2.8 s, the magnetic field was switched off and the trapping light was changed into the molasses configuration by increasing the red detuning to $\delta = -10 \Gamma$ and by reducing the intensity to half the MOT intensity. Hence, the fluorescence signal abruptly gets weaker. The cloud diffusively expanded out of the detector’s field of view. After 1 s, the signal settled at the fluorescence from the background vapour (in the molasses light), and the cycle was repeated. Taking into account the solid angle covered by the detection scheme, we evaluated an atom number of $5 \times 10^7$ atoms in the MOT. The horizontal rms diameter of the MOT was approximately 0.5 mm.

**Figure 3.13:** Fluorescence of $^{87}\text{Rb}$ in MOT, molasses and background vapour.
3.7.4 Time-of-flight temperature measurement

In early experiments on laser cooling, the temperature of cold atom clouds was investigated by a "release & recapture" technique [155], with which the cooling light is switched off for a short ballistic expansion period of the released cloud after that only atoms in reach of the cooling light are recaptured and detected. The temperature is derived from the recaptured atom fraction. This method has been succeeded by the more accurate time-of-flight technique (TOF) [156], which we used also in our experiments. Various other techniques have been reported so far, e.g. using recoil-induced resonances [157] or imaging of ballistically expanding atom clouds [39].

The TOF technique makes also use of the ballistical expansion. During molasses cooling, the equilibrium temperature is established after a few ms. In order to release an atom cloud, we shutter the cooling laser mechanically after typically 4 ms of cooling. A significantly longer cooling time might lead to unfortunate diffusive atom loss. The falling atoms pass a thin sheet of resonant probe light below, and well separated from the cooling region. Either the fluorescence or the absorption is recorded as a function of time, see e.g. Fig. 5.2(a). The temperature is obtained by fitting a thermal Maxwell-Boltzmann velocity distribution to the recorded signal.

If the initial cloud size is known only approximately, the TOF method requires a fall height sufficiently large to make the cloud size negligible with respect to the thermal expansion during the fall time. In our setup, we can drop the atoms over a distance of 5 mm, which is sufficient to determine the temperature within 15% accuracy. The TOF method is also a simple way to investigate atoms bouncing on an atom mirror, see Chap. 5.

Fig. 3.14(a) shows TOF signals for two distinct height settings of the flat probe beam, 1.2 mm and 4.3 mm below the MOT. The origin of the time axis is the time when the mechanical shutter of the cooling light was closed. The signals were again recorded in fluorescence by means of a photodiode from above the vacuum cuvette, similar to the signal shown in Fig. 3.13. The probe had a waist of 0.4 mm vertical and 1.4 mm horizontal (1/e² radius). It was tuned close to resonance with the $F_g = 2 \rightarrow F_e = 3$ transition of the $^{87}$Rb D2-line.

For the fluorescence technique to be efficient also with small quantities of atoms, the probe must saturate the optical transition. In a travelling-wave probe beam, the atoms would be quickly accelerated by the recoils from absorbed photons. The atoms are therefore Doppler-shifted out of resonance and lost for longer recording of the TOF signal. In order to achieve a longer interaction time per atom, the probe was used in retro-reflection as a standing wave. The flat, horizontal probing section was formed by a cylindrical telescope with the focus of two cylindrical lenses ($f = 75$ mm) located below the MOT. An additional measure to enhance the interaction time was to choose a small red probe detuning $\sim \Gamma$, which converts the probe beam into a 1D molasses cooling configuration.
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Figure 3.14: Time-of-flight temperature measurement. (a) Fluorescence signals with probe beam 1.2 mm (○) and 4.3 mm (●) below the MOT. Solid lines are fits to a Maxwell-Boltzmann distribution. (b) Systematics of the temperature fit for various probe settings: fitted fall height vs. (relative) probe setting (○, with linear fit); fitted temperatures (●).

The fit of the distribution of an expanding and gravitationally accelerating cloud to the TOF signals assumes an Gaussian initial phase-space distribution in the vertical direction, \( \Phi_0(z_0, v_0, t_0) \), that corresponds to the optical molasses temperature [cf. Fig. 2.4(a)]:

\[
\Phi_0(z_0, v_0, t_0) = \frac{1}{2\pi \sigma_z \sigma_v} \exp \left[ -\frac{1}{2} \left( \frac{z_0}{\sigma_z} \right)^2 + \left( \frac{v_0}{\sigma_v(T)} \right)^2 \right],
\]

(3.6)

\[
\sigma_v(T) = \sqrt{\frac{k_B T}{M}}.
\]

(3.7)

The temperature is represented by the rms velocity spread \( \sigma_v \). The initial rms radius of the cloud is \( \sigma_z \). As atoms fall, the time-evolution of the distribution can be written by using transformed coordinates:

\[
z = z_0 + v_0 t + \frac{1}{2} gt^2, \quad v = v_0 + gt,
\]

(3.8)

\[
\iint dz dv \Phi(z, v, t) = \iint d z_0 dv_0 \Phi_0(z_0, v_0, t_0) \equiv 1.
\]

(3.9)

When the probe beam is approximated by a square intensity profile of thickness \( d \) and centred at the height \( z_p \), the signal recorded from atoms that pass the probe section is

\[
s(v, t) = \int_{z_p-d/2}^{z_p+d/2} \Phi(z, v, t) dz \approx \Phi(z_p, v, t) d.
\]

(3.10)
Integration over the velocity distribution leads to the TOF signal:

\[ S(t) = \int_{-\infty}^{+\infty} s(v, t) \, dv \]  
\[ \approx \frac{1}{\sqrt{2\pi} \sigma(t)} \, d \, \exp\left(-\frac{1}{2\sigma^2(t)} \left(\frac{1}{2} gt^2 - z_p\right)^2\right), \] 
\[ \sigma(t) = \sqrt{\sigma^2_z + \sigma^2_T(t^2)}. \]

The TOF signal is thus described by a Gaussian distribution, the rms width of which is growing in time. If \( z_p, \sigma_z, \) and \( d \) are known, the temperature \( T \) in \( \sigma(T) \) is the only parameter to fit the recorded signals to. Alternatively, \( z_p \) and \( \sigma_z \) can also be treated as fit parameters. Note that \( d \) appears as an overall amplitude scaling factor.

Fig. 3.14(b) shows temperature and fall height as obtained when fitting \( T, \ z_p, \sigma_z \) and the signal amplitude for various relative experimental probe height settings. The statistical errors in the temperatures are also shown. The statistical errors in the heights are small and not shown. Accurate knowledge of the fall height is not required to obtain a reliable temperature. This can be tested by fixing the height with a slightly different value and fitting again with the temperature as the only fit parameter. We find that the shift in the fitted temperature remains within the error margins.

The temperature fits suggest a small statistical error, \( T = 8.5(1) \mu K \). However, the uncertainty in the initial size of the molasses, \( \sigma_z \), causes a systematic error. Using \( \sigma_z \) also as a fit parameter resulted in \( \sigma_z \approx 0.55 \text{ mm} \). However, images recorded with a CCD camera suggested a value of 0.25 mm. When the \( \sigma_z = 0.25 \text{ mm} \) was used as a fixed parameter, the temperature fitted to \( \approx 12 \mu K \), since the contribution of thermal expansion in the expression \( S(t) \) was increased. It is obvious that a systematic error in \( \sigma_z \) is more severe for small fall heights, for which a falling cloud has little time to expand before being probed.

### 3.7.5 Molasses cooling and magnetic field compensation

The equilibrium temperature that is achieved in polarisation gradient cooling is expected to scale \( \propto I_L/\delta \) with the intensity and detuning of the cooling light [70]. In order to optimize the cooling process experimentally, we performed TOF temperature measurements for various settings of the cooling laser. Fig. 3.15(a) shows TOF signals that were recorded for various red detunings ranging from \( 1.2 - 8.3 \Gamma \) (see also Ref. [158]). In Fig. 3.15(b), the fitted temperatures are plotted vs. the inverse detuning. The inverse dependence on the detuning seems to be approximately fulfilled with our cooling setup. The linear dependence on the intensity, however, indicates an offset, see Fig. 3.15(c).
The lowest temperatures are achieved in molasses cooling when earth and other stray magnetic fields are compensated on the mG level. Note that the signals shown in Fig. 3.15 were recorded before any field compensation measure. Hence, the final temperatures were relatively high. The experimental region inside the UHV cell is not accessible for external field probes. In situ, one may investigate field dependent spectral properties of the atomic species using, e.g., electro-magnetically induced transparency (EIT) [159], i.e. the Hanle level-crossing effect [160]. Although these techniques are sensitive on the µG level, they require additional laser sources. As a simpler probe, we use the measured molasses temperature to optimize the field compensation [71], thus achieving temperatures as low as shown in Fig. 3.14. Experimentally, it proved to be also sufficient to observe the diffusion of atoms during molasses cooling and to maximize the diffusion time constant by means of the field compensation coils, see Fig. 3.13.