Permanent magnetic atom chips

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Chapter 3

Experimental setup

Experiments on atom chips involve a wide range of techniques and methods. They include laser cooling, magnetic trapping, optical detection, vacuum technology and many others. In designing our apparatus, we wanted a system that could deliver a large sample of cold atoms on the atom chip. In this chapter we will give a detailed description of the experimental components. The chapter is structured in six sections. We present the atomic species and the source, the vacuum setup, the laser setup and the magnetic coils followed by a discussion on the detection setup, the experimental control and the radio-frequency source.
3.1 The laser system

3.1.1 Atomic species - rubidium

The choice of the atomic species depends on physical properties like appropriate optical transition frequencies, the availability of laser sources on these frequencies, collisional properties and the ease of handling in an UHV system.

Optical cooling requires well separated optical transitions of linewidth among the cycling ('closed') transitions. 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 lasers with wavelength from the visible to the near-infrared spectrum. For an overview on common elements for laser cooling see e.g. [53].

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. More specifically $^{87}\text{Rb}$ is attractive due to its positive scattering length ($a \approx 109 \, a_0$).

The diagram of energy levels of $^{87}\text{Rb}$ isotope is shown in Figure 3.1. An extensive overview of the Rubidium properties can be found in [54].

Cooling and trapping is performed with laser light that is red detuned with respect to the $|5S_{1/2}, F = 2 \rangle \rightarrow |5P_{3/2}, F = 3 \rangle$ cycling transition of the D2 line. Light of another frequency originating from the same cooling laser is employed to optically pump the atoms into the $|5S_{1/2}, F = 2, m_F = 2 \rangle$ Zeeman state. The cooling laser also induces non-resonant excitation of the $|5P_{3/2}, F = 2 \rangle$ state, followed by decay to both the $F = 1$ and $F = 2$ hyperfine ground states. To prevent atoms from accumulating in the $F = 1$ state, another laser - the repumper - is used, tuned to $|5S_{1/2}, F = 1 \rangle \rightarrow |5P_{1/2}, F = 2 \rangle$ transition.

3.1.2 The laser setup

Developing the lasers with optical subsystems constitutes one of the most important parts in building an atom chip system. From the magneto-optical trap (MOT) to the final trap detection, precise and rapid control of laser frequencies and powers is required.

For the operation of a magneto optical trap (MOT) for $^{87}\text{Rb}$ one of the elementary ingredients is a well controlled laser. The $^{87}\text{Rb}$ D2 line ($5S_{1/2} \rightarrow 5P_{3/2}$) is the atomic transition that we use for this experiment. We need a laser system which has a small linewidth ($< 1$ MHz) compared to the natural linewidth $\Gamma = 2\pi \times 6.07$ MHz, stability to an atomic transition, high laser power, robust implementation and which is easy to handle. A free running laser will suffer from a changing frequency due to environmental effects. We have to employ a feedback loop to keep the laser at the desired atomic transition.

Nowadays there are three approaches to satisfy the above requirements. There are Ti:sapphire lasers, tapered amplifier systems and grating stabilized laser diodes. For the present experiment we have used a grating stabilized diode laser
3.1. The laser system

Figure 3.1: $^{87}$Rb energy level diagram
Figure 3.2: Antireflection coated quartz cell with two rubidium dispensers and the atom chip facing downward.
3.1. The laser system

(DL 100, Toptica) and a high power tunable diode laser (TEC-300-780-500 High Power External Cavity Diode Laser, Sacher).

In the following sections we will discuss the various requirements and the experimental implementation.

3.1.3 Frequency locked diode lasers

A free running laser diode has a typical linewidth of $\sim 50$ MHz, which is inadequate for laser cooling. However, there are several schemes to reduce the line-width. All approaches use frequency selective feedback elements. This can be an external cavity [55] or a grating [56]. The lasers we use have a grating as frequency selective element.

The diode laser is tuned by applying a voltage to the piezo element, onto which the grating is mounted. For the laser diodes itself, as their wavelength changes with temperature and current, we need to temperature stabilize the setup. For this we use a temperature controller, which controls a Peltier element. A PID (proportional integral derivative) feedback circuit in the temperature controller allows us to achieve the necessary temperature stability. In addition the current needs to be stable. Finally, the current controller allows us to add an external modulation to the current.

3.1.4 Laser stabilization and spectroscopy

A free running laser, without stabilization, will never stay at the specific atomic transition frequency. In order to stabilize the laser, we determine the frequency by means of Doppler free saturation spectroscopy. We used the D2 line of $^{87}\text{Rb}$ at 780.24 nm for this purpose. In order to stabilize the laser to the specific frequency, we have to provide a frequency dependent feedback to the laser. This error signal can be fed back to the current of the laser diode (the laser frequency changes with the current) and/or to the piezo (a change of the external cavity length also changes the frequency).

Figure 3.3 shows the basic setup for Doppler free saturation spectroscopy. The error signal is fed back to the piezo via locking electronics containing a PID circuit. When the laser is right on the atomic transition, the error signal is zero and the cavity length remains unchanged.

The described locking method allows us to stabilize our laser diodes exactly on the atomic transition. For trapping atoms in a magneto-optical trap (MOT), or for MOT compression it is necessary to be detuned by an adjustable amount $\delta$. This can be done with a double-pass acousto-optical modulator, at the cost of light power.
Chapter 3. Experimental setup

Figure 3.3: Laser stabilization by FM spectroscopy. Optical isolator (OI), half-wave plate (λ/2), double pass through a rubidium cell (Rb), outcoupling using a quarter-wave plate (λ/4), and a polarizing beam splitter (PBS), detection with a photodiode (PD). Inductive frequency modulation of the laser current I using a radio frequency (RF) oscillator. The photodiode signal is phase shifted (φ) and mixed (⨂) with a local oscillator (LO). The resulting dispersive DC signal is fed back to the laser current and grating actuator (PZT). Graphs: FM error signals for $^{87}\text{Rb}$.
Table 3.1: Laser frequencies used in experiments with $^{87}$Rb

<table>
<thead>
<tr>
<th>Laser beams</th>
<th>Line</th>
<th>Atomic transition</th>
<th>Purpose</th>
<th>Detuning</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>D2</td>
<td>$F=2 \rightarrow F=3$</td>
<td>MOT, CMOT</td>
<td>(-10 - 0) $\Gamma$</td>
<td>20 mW</td>
</tr>
<tr>
<td>(2)</td>
<td>D2</td>
<td>$F=2 \rightarrow F=2$</td>
<td>Optical pumping</td>
<td>0 - (± 8 $\Gamma$)</td>
<td>0-500 $\mu$W</td>
</tr>
<tr>
<td>(3)</td>
<td>D2</td>
<td>$F=2 \rightarrow F=3$</td>
<td>Imaging</td>
<td>0 - (± 8 $\Gamma$)</td>
<td>0-500 $\mu$W</td>
</tr>
<tr>
<td>(4)</td>
<td>D1</td>
<td>$F=1 \rightarrow F=2$</td>
<td>Repumping</td>
<td>Resonant</td>
<td>6 mW</td>
</tr>
</tbody>
</table>

3.1.5 Experimental implementation

Table 3.1 gives an overview of the needed light frequencies and the atomic transitions we stabilize the appropriate lasers to. The labels (1)-(4), correspond to the lasers beams as shown in Figure 3.4.

The cooling, pumping and probing laser

The light for cooling, optical pumping and probing is all provided by the same laser - the Tiger, which is commercially available at Sacher-Lasertechnik. Figure 3.4 shows the beam path used in the experiment. The frequency of this laser is stabilized by feedback by means of frequency modulation (FM) spectroscopy in a rubidium vapor cell. The optical output power of the Tiger is about 400 mW after the optical isolator of 60 dB. A small fraction ($\sim 1.5$ mW) is diverted for Doppler absorption spectroscopy. The spectroscopy setup is also shown in Figure 3.4.

Fast and continuous frequency control of the beams (1) and (2) is achieved using acousto-optic modulators (AOM) in double-path. The double-path AOM configuration with a mirror at one of the focal planes of the lens L1 (f=150 mm, Thorlabs achromatic doublet) compensates for the change of beam direction when changing the AOM RF frequency. So 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 double passed $\lambda/4$ wave plate changes the polarization of the master laser from horizontal to vertical so that the master laser beam can be totally reflected by the polarizing beam splitter (PBS). In addition to frequency shifting, the AOMs are also used for fast switching of the optical power. When using an AOM as a power switch, "leakage" into the selected diffraction order limits the extinction to typically 1:1000. Therefore we use also mechanical shutters (Uniblitz LS2T2, 2 mm aperture) to switch the cooling laser on or off. Power modulation with an extinction of 1:200 is obtained for beam (3) by an electro-optic modulator (Gsänger, type LM 0202 5W IR, aperture $3\times3$ mm$^2$).

As mentioned before, the frequencies of the lasers are shifted using acousto-optic modulators, one in double-pass for the cooling beams (AOM1) and one in single pass for the optical pumping beam (AOM2). The typical double-pass
Figure 3.4: Schematic overview of the laser setup. PBS: polarizing beam splitter, L: lens, PD: photodiode, M: mirror, OI: optical isolator, EOM: electro-optic modulator, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate, D: diaphragm, AOM: acousto-optic modulator, PMF: polarizing maintaining optical fiber, Rb: cell with rubidium vapor.
efficiency is 50\% in first diffraction order. Our modulators have PbMoO$_4$ crystals (*Isomet*, type 1205C, 80±15 MHz and *AA Opto-Electronique*, type AA.MP.25-IR, 110±30 MHz).

**The repumper laser**

The repumping laser is a commercial laser, DL100 from *Toptica*, with a low power laser diode, 795 nm wavelength, and delivers about 40 mW. It is locked on-resonance to the transition from $F_g=1$ to $F_e=2$, as shown in Figure 3.4. An EOM provides rapid control of the laser power. After the EOM the repumping laser is coupled into a single mode PM fiber that directs the light to the atom-chip system. The power of the repumping laser at the fiber output is about 6 mW.

### 3.2 Ultra-high vacuum system

The vacuum system, like the laser system, has to fulfill a couple of demands, like a good pressure ($<10^{-11}$ mbar) and a good optical access to the trapped atoms.

Figure 3.5 shows the complete setup. In the following we will discuss the most important parts of the vacuum system. As experimental chamber we have chosen a quartz cell, 40 x 40 x 70 mm$^3$ (outer sizes), with a wall thickness of 4 mm. The windows are antireflection coated on the outside. The cell is connected through a glass graded seal, 100 mm long, to a stainless steel CF 40 flange (*Hellma*, UK).

Besides the optical access, an attractive feature of such a cell is that the magnetic field coils can be mounted close to the region of interest. Since a quartz cell is not magnetic and not conducting, experiments are not perturbed by eddy currents caused by switching field coils.

The main chamber is mounted at a 45° angle with respect to the optical table. It consists of a 6-way cross custom made chamber, 2 X CF63 inline and 4 X CF40. An all-metal sealed valve (*Granville-Phillips*, gold-seal type 204) leads via bellows to a roughing turbo-molecular pump that has been used while baking the setup. When the valve is closed, the system is self-sustaining with an ion pump of 75 l/s pumping speed (*Varian*, Vadon Plus 75 StarCell). The achieved pressure can be monitored by an ionization gauge in a range between $10^{-12}$-$10^{-3}$ mbar (*Varian* type UHV-24p NBA). A pressure of $4 \times 10^{-11}$ mbar is reached by adding to the system a titanium sublimation pump (*Varian*, TSP filament cartridge CF 40).

The experimental chamber is separated from the rest of the vacuum setup by a UHV gate valve with a Viton seal bonnet, (manually operated, *VAT*, series 108). This gate valve is used when there is a replacement in the experimental chamber. The ion pump is placed at $\sim$ 45 cm from the main chamber so that the stray magnetic field created by its magnets is almost zero (0.01 G).

One port of the 6-cross chamber houses the chip mount, the baking lamp and the rubidium source, which are alkali metal dispensers (*SAES Getters*), described
Figure 3.5: Vacuum setup - the 6-way cross chamber, ion pump (IP), ion gauge (IG), quartz cell, titanium sublimation pump (TSP), electrical feedthrough, gate valve, vacuum compatible windows, all-metal sealed valve.
3.2. Ultra-high vacuum system

<table>
<thead>
<tr>
<th>component</th>
<th>temperature limit (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold valve</td>
<td></td>
</tr>
<tr>
<td>open</td>
<td>450</td>
</tr>
<tr>
<td>closed</td>
<td>250</td>
</tr>
<tr>
<td>gate valve</td>
<td>200</td>
</tr>
<tr>
<td>ion pump</td>
<td></td>
</tr>
<tr>
<td>without magnets</td>
<td>550</td>
</tr>
<tr>
<td>with magnets</td>
<td>250</td>
</tr>
<tr>
<td>ion gauge</td>
<td>450</td>
</tr>
<tr>
<td>electric feedthroughs</td>
<td></td>
</tr>
<tr>
<td>feedthrough</td>
<td>450</td>
</tr>
<tr>
<td>connector</td>
<td>125</td>
</tr>
<tr>
<td>glass-to-metal seals</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 3.2: Temperature limit of vacuum components

in more detail in section 2.2.2. By running a current through the dispensers, Rb vapor is released. For baking the vacuum we use halogen lamps inside the vacuum. We have two of these lamps in two places of the vacuum which are enough to bake these parts up to 180 °C.

3.2.1 Construction, pump-down and bake-out

Before the construction of the vacuum system, all components except the ion pump and the cell, are degreased and cleaned in an ultrasonic bath and rinsed with methanol. Once built, we pump down and bake out the system using a grease and oil-free turbo pump. The permanently attached ion pump is off during the entire bake-out.

In Table 3.2 we list some of the temperature limits of the components. We also outgas the dispensers and the TSP filaments during the bake since these contain large amounts of embedded impurity gases that would outgas during use and compromise the operating pressure. After the initial rough pump-down we outgas the TSP filaments by slowly increasing current through each: 30 A for 10 minutes, 40 A for 15 min and finally a ramp up to 55 A over 1 min, followed by a quick ramp down of the current. Next, we outgas each of the alkali metal dispenser. We slowly ramp up the current, and at the end we keep it on at 4.5 A for 5 minutes. During this process the dispenser glows visibly.

Now we describe the full system bake-out. We heat the system with halogen lamps placed inside the vacuum, and at some places with heater tapes. We are careful not to overlap tapes because the generated heat can burn the tapes. At all temperature-sensitive joints and components (e.g. magnets, glass-metal seals) we place thermocouples to monitor bake temperatures. The entire system is then wrapped in layers of aluminium foil to isolate the heat and spread it equal on the
vacuum surface.

We begin the bake by ramping up the current in the lamps and the heater tapes over 8 - 12 hours to minimize the thermal shock of the vacuum components and moderate the initial outgassing that could overwhelm the roughing pumps. We also run 20 A through one TSP filament to heat the vacuum in that part. The system is baked near the maximum allowable temperature for 48 hours. We then cool the ion pump over 6 hours, after which we close the system from the roughing pump and then turn on the main ion pump. Finally, we cool the entire system down over 8 hours, observing steadily decreasing pump currents (pressure). The entire bake out takes 90 hours to complete. Afterwards the pump registers zero current, and the ion gauge indicates a pressure of \( \sim 4 \times 10^{-11} \text{ mbar} \).

### 3.2.2 Rubidium dispenser

Rubidium dispensers are widely used as compact atom sources in atomic research [57, 7, 58]. In the dispenser, rubidium atoms are released from a metal reservoir when heated by an electric current. After the current is switched off and the dispenser cools down, it stops dispensing. The rubidium dispenser is a commercial product from *Saes Getters*, RB/NF/ 3.4/12 FT10+10. It is a metal strip in which rubidium is present in a small container that contains a mixture of rubidium chromates \((\text{Rb}_2\text{CrO}_4)\) and a reducing agent. The dispensers are 1.2 cm long and contain roughly 2.8 mg/cm of rubidium. A more detailed description on how to handle these dispensers in atomic physics experiments is presented in [59].

The equilibrium Rb vapor pressure is determined by the amount of current passing through the dispenser. We placed two dispenser strips in the glass cell. The dispensers are shaded by the return wires so that hot atoms emerging from it do not collide with atoms trapped in the MOT, as can be seen in Figure 3.2. The dispenser is connected to an electric feedthrough using kapton isolated copper wires. The lead wires are mounted close together to minimize the stray magnetic field. During the loading of the MOT, a current of 7 A runs through the dispenser for 8 seconds. After loading we switch off the current so that the vacuum pressure stabilizes to the original value \( 5 \times 10^{-11} \text{ mbar} \), and wait 10 s before we go to the next step, the compressed MOT, described in Chapter 5.

### 3.3 Magnetic field coils

For cooling and trapping of atoms, coherent light and a magnetic field gradient are needed. The magnetic quadrupole field gradient is provided by a pair of coils, placed in an anti-Helmholtz configuration. This results in a magnetic field that increases approximately linearly with the distance from the center. Along the symmetry axis, \( \mathbf{r} = (x,0,0) \), and close to the center, the field is given by:
3.3. Magnetic field coils

Figure 3.6: Magnetic field coils. The coils are wound on water cooled square tubes.

\[ B(\mathbf{x}) = b \times \hat{\mathbf{x}} \]  
\[ b = \mu_0 NI \frac{3R^2d}{(R^2 + d^2)^{3/2}} \]

where \( N \) is the number of turns per coil, \( R \) the radius of the coil, \( d \) the distance between the two coils, and \( \mu_0 \) the permeability of free space.

This external magnetic field is also used to manipulate the cold atoms. Therefore, the coils play an important role in the entire atom-chip system. The magnetic field coils configuration used in this setup is shown in Figures 3.6 and 3.7. It consists of six individual coils which can be controlled independently. The current through all of these coils can be reversed, so that we can create uniform magnetic fields as well as quadrupoles. All the coils are water cooled and isolated from each other. They are mounted all together as a compact block, around the UHV quartz cell, as shown in figure 3.7.

The coils have 70 windings, made from 0.8 mm diameter high-temperature-resistant copper wire, which is stacked in a square grid pattern that has a water cooled tube under it for good thermal contact. A thermal compound (Stycast 2850FT) is placed between the windings for better cooling. This also gives a very rigid and solid coil, with a high mechanical strength. The coils are so designed that they are placed at a minimum distance to the cell. Their specifications are given in Table 3.3 and Figure 3.8. The coils that are the smallest and the closest
Chapter 3. Experimental setup

Section 3.4 Imaging

3.4.1 The optics

The detection setup must be versatile enough to enable the detection of clouds ranging in size from several millimeters to several microns. The schematic outline of the detection optics is presented in Figure 3.9 and the probing light path can
Figure 3.8: Dimensions of the coil pair. a: average width; b: average height; \( \Delta \): coil thickness in the coil plane; d: separation of the two coils; t: thickness of a single coil.

Table 3.3: Specifications of the coils.

<table>
<thead>
<tr>
<th></th>
<th>MT coil</th>
<th>MOT coil</th>
<th>Big coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a \times b ) (mm)</td>
<td>66 \times 86</td>
<td>102 \times 106</td>
<td>120 \times 142</td>
</tr>
<tr>
<td>( \Delta ) (mm)</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>t (mm)</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>d (mm)</td>
<td>50</td>
<td>24</td>
<td>68</td>
</tr>
<tr>
<td>N (turns per coil)</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>R (resistance) (Ω, per coil, 20°C)</td>
<td>0.76</td>
<td>1.04</td>
<td>1.3</td>
</tr>
<tr>
<td>L (inductance) (mH, per coil)</td>
<td>0.7</td>
<td>1.04</td>
<td>1.4</td>
</tr>
<tr>
<td>Field at the center (G/A) per pair</td>
<td>12</td>
<td>11.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Gradients (G/cm/A) per pair</td>
<td>3</td>
<td>1.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>
be seen in Fig. 3.4.

Figure 3.9: Schematic outline of the detection system.

The shadow of the sample in the resonant laser beam is magnified by a telescope and imaged onto a CCD array. The telescope is made out of two achromatic lenses of 75 mm and 150 mm focal length (Melles Griot). The image device is a cooled CCD camera (Princeton Instruments, model MicroMAX:512BFT). The controller of the camera gives a 16-bit analogue-to-digital conversion. The camera pixel size is 13×13 µm². A feature of this camera is the ability to operate in a so called ‘frame transfer’ mode, so there is no need for a shutter. In this mode only a part of the chip is exposed to the light, while the rest of the chip is used as a storage area. One can thus take a burst of images at high speed (limited only by the array shift time) and read them out later.

During the alignment of the magneto-optical trap (MOT) two additional video cameras are used: a 1/3″ interline CCD (Sony) ‘finger’ camera which looks directly at the chip surface from the optical table upwards and a CCD machine vision camera (CM-50 EHD imaging GmbH, Costar). These two cameras are used to optimize the mirror MOT (MMOT) position. After the MMOT is located at the center of the chip, we adjust the laser beams to optimize the number of trapped atoms by looking at the images of the CCD MicroMAX camera.

3.4.2 Imaging techniques

Generally speaking imaging techniques can be divided into three classes. The first class is the imaging of light sources, for example the fluorescence of atoms in a MOT. The second class is absorption imaging, which is a standard way of imaging atoms in situations where fluorescence imaging is not applicable. The third and most complex class are phase-contrast imaging techniques. These techniques make use of spatial variations in the refractive index that are caused by the sample. For our measurements we use the first two techniques.

Imaging in non-uniform magnetic fields

The use of permanent magnets require us to image the atoms in a non-uniform magnetic field. The obstacle to overcome is the magnetic field gradient, which
### 3.4. Imaging

Table 3.4: Possible transitions with different probe beam polarizations.

<table>
<thead>
<tr>
<th>Propagation direction</th>
<th>Polarization</th>
<th>Transitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>Right circular</td>
<td>$\sigma^+$</td>
</tr>
<tr>
<td>Parallel</td>
<td>Left circular</td>
<td>$\sigma^-$</td>
</tr>
<tr>
<td>Parallel</td>
<td>Linear</td>
<td>$\sigma^+, \sigma^-$</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>Circular</td>
<td>$\sigma^+, \sigma^-, \pi$</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>Linear along quantization axes</td>
<td>$\pi$</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>Linear $\perp$ to quantization field</td>
<td>$\sigma^+, \sigma^-$</td>
</tr>
</tbody>
</table>

causes a spatially varying energy shift due to the Zeeman effect. Therefore, we cannot apply light which is resonant with the entire cloud and so we detune the probe laser. Due to this we also change the probe polarization to linear and perpendicular to the magnetic field. Table 3.4 lists the possible transitions for the various probe beam propagation directions and polarizations.

Naively, one might expect that at maximum only half of the light could be absorbed, because one thinks of linear light as an equal amount of $\sigma^+$ and $\sigma^-$ light. However in the atoms frame these two polarizations are not the correct basis and are actually coupled. Absorption of this type is known as the Voigt effect. In fact all of the light can be absorbed by the atoms, and the only effect of the direction of the polarization is to reduce the line strength by a factor of 2 [57]. It is possible for a magnetic field with a component transverse to the light propagation direction to cause a differential absorption along the axes parallel and perpendicular to the direction of the field. The optical rotation effect is dependent on the angle between the electric field vector of the light and the transverse magnetic field component [60].

**Focusing the image**

We focus the image onto the CCD by imaging a small cloud (few times our image resolution) with low density. We first make sure that the probe light is on resonance. Above and below the optical resonance frequency the real part of the index of refraction of a gas is nonzero, so that light will not only be absorb but also refracted (‘lensed’). With the probe laser on resonance, we adjust the position of the last lens along the imaging axis. The focus of the image is at the minimum cloud width. We focus the image by looking at the axial cloud width.

**Pixel calibration**

The pixel size was experimentally calibrated to be $7.00 \pm 0.01 \text{\mu m}$ by comparing the known size of the chip structures with the size we observe with the camera.
3.4.3 Imaging sequence and analysis

To take an absorption image at the end of an experimental cycle, a sequence of events is defined. The main method of detection of the atomic clouds in our experiment is imaging the absorption profile produced by the cloud in a resonant laser beam. The used light is resonant with the $F = 2 \rightarrow F = 3$ transition and is spatially filtered by an optical single mode fiber. A pulse of 10 ms gives an adequate signal-to-noise ratio. We found that switching on the repumper light before imaging is sufficient to bring all the atoms into the resonant state.

After collimation, the probe beam passes horizontally along the radial direction of the magnetic Ioffe trap ($y$-direction), through the UHV quartz cell, which contains the atomic cloud. To avoid saturation effects the maximum intensity of the absorption beam is $50 \mu W/cm^2$. The optical setup used for absorption imaging of the atomic cloud is shown in Figure 3.9.

In order to avoid blurring of the images, the exposure time is 150 $\mu s$. To extract density profiles from the CCD images three images are taken in the following way: first an absorption image $I_{\text{abs}}(x, z)$ of the cloud is taken, then a second, so called 'flat field', $I_{\text{ff}}(x, z)$ image is taken with the same probe beam but without atoms. Afterwards, a third image is taken to record the background field $I_{\text{bg}}(x, z)$ without atomic cloud and without detection beam. The correct intensity ratio is then obtained by first subtracting the background image before normalizing the absorption image to the flat field image as

$$
\frac{I(x, z)}{I_0(x, z)} = \frac{I_{\text{abs}}(x, z) - I_{\text{bg}}(x, z)}{I_{\text{ff}}(x, z) - I_{\text{bg}}(x, z)}
$$

(3.3)

The images are immediately transferred to a computer and analyzed by a LabVIEW application which processes and displays the resulting absorption image. The convenient realtime visualization of the data is very valuable to quickly detect failures when they occur during operation of the experiment.

3.5 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 $\mu$s-resolution. A typical experimental sequence consists of loading the MOT, cooling the atoms in CMOT, trapping them magnetically 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 XP, 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. 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.

3.5.1 Digital signal processor and LabVIEW user interface

The main task of the DSP (Digital signal processor) is to provide precise timing during the experiment. In a screen interface, the user fills in the 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 of 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 the AOM/EOM drivers, the magnetic field coil current supplies and the mechanical shutter drivers. The CCD image capture and the input of the photodetector signals are triggered similarly. The DSP works independently from the PC. Thus, other LabVIEW routines can be used on the PC to acquire and process measurement data.

We use a commercially available program that has been developed by H. Alberda (FOM – Institute AMOLF, Amsterdam) and adapted to our purposes.

3.6 The radio frequency source

The rf-signal needed for evaporative cooling is generated by a frequency synthesizer (Agilent, model 33120A). The frequency ramp is performed using the internal linear sweep of the generator. The signal amplitude is set under (analog) computer control using a 60 dB variable attenuator. At the output of the attenuator the signal can be switched by a mechanical relay with a switching time faster than one millisecond. The signal is then amplified by 43 dB to yield a maximum power of 20W into 50 Ω. For this we use an rf-power amplifier (Amplifier Research, model 25A250A).

The amplifier is connected to an rf-antenna located next to the quartz cell at a distance of 3 cm from the trap center. The direction of the oscillatory magnetic field in the central region of the trap is perpendicular to the stationary bias magnetic field.

The rf-antenna is a coil with two separate loops, with a diameter of 4.5 cm, and is made of copper wire with a thickness of 1 mm. The diameter of the coil preserves good optical access. The number of windings (n = 4) was chosen to
achieve the largest magnetic field at the upper edge of the frequency band. An identical coil, used as a pick-up coil, is mounted directly onto the antenna. The signal received from this coil is connected to a 50Ω input of a spectrum analyzer. In this way the power delivered to the antenna can be monitored.