UvA-DARE (Digital Academic Repository)

Permanent magnetic atom chips

Barb, I.

Link to publication

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Chapter 5
Preparation and optimization of the cold cloud

The preparation of ultracold atomic samples for experiments in magnetic traps is a task involving multi-step cooling and trapping procedures. This chapter describes the techniques used to prepare the atom cloud before loading it in the chip magnetic trap. A crucial point of this transfer process is to match the size and position of the atomic cloud in the magneto optical trap (MOT) and in the magnetic trap (MT), so called ‘mode matching’, to obtain maximum transfer efficiency and to avoid heating. The experimental cycle starts with a mirror magneto optical trap (MMOT) where we collect and precool $^{87}$Rb atoms. We then compress the atoms in a compressed mirror MOT (CMMOT). This phase is followed by an optical pumping stage: pumping all trapped atoms into the $|F = 2, m_F = 2\rangle$ state. Then we trap the atoms magnetically using the external coils.

5.1 External coil mirror magneto-optical trap

The principal features of a MOT are its ability to simultaneously cool and trap atoms. It combines a fairly large trap depth, a relatively large capture velocity, and a weak sensitivity to disturbances concerning the directions of the laser beams and their polarization imperfections. A MOT is based on the spontaneous light force [78], i.e. the transfer of photon recoil momenta, $\hbar k_0$, to atoms, where $k_0 = 2\pi/\lambda_0$ is the wave vector of near-resonance laser light in vacuum. The configuration of the light fields is chosen such that this momentum transfer occurs in a preferential direction and in a succession of many absorption and spontaneous emission cycles. A central trapping force, based on a position-dependent Zeeman effect, is established in combination with a friction force that cools the atoms to a temperature close to the Doppler limit, $T_D = \hbar \Gamma / 2k_B$. For rubidium, with a transition linewidth $\Gamma / 2\pi = 6.1$ MHz, this limit is $T_D = 146$ $\mu$K. A schematic
Chapter 5. Preparation and optimization of the cold cloud

Figure 5.1: Configuration of the mirror magneto optical trap. An additional pair of counterpropagating laser beams, perpendicular to the drawing plane, is not shown.
representation of our realization of a MMOT is shown in Figure 5.1. We are using this scheme, with the chip used as a mirror. In this scheme the atoms do not experience any difference in the magneto-optical field if two laser beams from the standard six-beam MOT are replaced by a mirror [2].

The optical components of the MMOT are arranged in a way to maintain access to the vapor cell for other optics. Figure 5.2 shows the experimental MMOT setup built around the quartz cell. All four laser beams are derived from the 50 mW output of a polarization maintaining fiber. The fiber output is collimated with a snap-on fiber collimator (OFR, CFC-8-780) and a lens (Melles Griot, f = 300 mm, d = 50.8 mm). The lens diameter is chosen large enough to avoid diffraction fringes in the beam. The linear polarization of the light is adjusted with a half wave plate (\(\lambda/2\)) and a polarizing beam splitter (PBS) placed directly after the fiber output. Three polarizing beam splitters (PBS 2,3,4) in combination with half-wave plates (\(\lambda/2\)) divide the power equally over four beams. Two counter-propagating horizontal beams, coming from PBS 2 and 6, are steered upwards with two telescopes. The beams are then horizontally directed into the cell. The other two beams, split by PBS 4, are projected into the cuvette under a 45° angle of incidence (see Figs. 5.1 and 5.2). Before passing the cell, all beams are circularly polarized by quarter-wave plates (\(\lambda/4\)). The diaphragm before the first beam splitter facilitates the alignment of the beams with respect to the mirror surface, by means of observing the fluorescence of the narrowed beams in the rubidium vapor cell.

The repumping beam enters the system via the backside of a polarizing cube (PBS 5) and is superposed with one of the horizontal cooling beams. Its polarization is then changed by the half-wave plate and polarizing cube (PBS 6). The beams are as wide as possible, given by the one inch diameter of the optics used, so that a large capture region is covered. For the realization of the magnetic fields we use two MOT coils (see Figs. 3.6, 3.7) in the anti-Helmholtz configuration. These coils generate a gradient per unit current of 1.8 G cm\(^{-1}\) A\(^{-1}\). The trapping light of the MMOT is tuned 1.5 \(\Gamma\) to the red of the \(F_g = 2 \rightarrow F_e = 3\) cycling transition of the \(^{87}\text{Rb} D_2\)-line (see Figure 3.1). The atoms are trapped in \(F_g = 2\). Atoms that have decayed into \(F_g = 1\), are transferred back by the repumping laser, which is in resonance with the D1-line (\(F_g = 1 \rightarrow F_e = 2\)).

While loading the MMOT, the Rb dispenser is turned on for 5 seconds up to a current of 7 A. Using the high rubidium vapor pressure and loading times of \(\sim 10\) s, allows us to trap \(\sim 8\times10^7\) atoms in the MMOT. A fluorescence image of the MMOT is shown in Figure 5.3. After the rubidium vapor pressure in the cell reaches a steady state, we start to optimize the MMOT fluorescence power by aligning the laser beams, adjusting the bias magnetic fields, the magnetic field gradient and the cooling laser frequency. The optimized MMOT magnetic field gradient was found to be 16 G/cm. Since the MMOT fluorescence power is a function of both the atom number and the laser frequency detuning, optimizing the cooling laser frequency to maximize the MMOT fluorescence power does
not necessarily mean maximizing the atom number. Further optimization of the cooling laser frequency detuning is done by measuring the atom number with absorption imaging.

5.1.1 The chip-mirror MOT

The chip can not only be used as the mirror in the MMOT configuration, but also as the magnetic field source for creating the MOT. In the MMOT configuration, the 45° external coils can be replaced by a wire under the chip or in our case by magnetic structures. The magnetic field of the structures and a $y$-uniform bias magnetic field create a two-dimensional quadrupole magnetic field below the chip, as one can see in Figure 5.4. We can load the chip-mirror MOT in two ways: a) directly from the vacuum background and b) loading it from the normal MMOT configuration.

a) In the first approach, we adjust the bias field, in the $y$–direction, until we get a visible chip-mirror MOT. As soon as the chip-mirror MOT is observed and the bias field optimized, we optimize the cooling laser beams to make the cloud as bright as possible. The chip-mirror MOT is formed at $\sim 1.8$ mm below the chip surface. In this way we could trap $\sim 10^6$ atoms. This number is probably limited by the spatial extent of the quadrupole field, which limits the capture velocity as well as the incoming flux of atoms. The result of direct loading of the chip-mirror MOT from the background gas is shown in Figure 5.5.
5.1. External coil mirror magneto-optical trap

Figure 5.3: External coil MMOT - fluorescence image. The image was taken from straight below, looking vertically upwards. The two magnetic structures can also be seen.

Figure 5.4: Field of the chip using only a uniform bias field $B = -2 \text{ G} // y$ and an additional field along $z$ (field of the building) of 0.7 G. We see a quadrupole appear between the F structures.
Chapter 5. Preparation and optimization of the cold cloud

b) In the second approach, we load the chip-mirror MOT from the normal MMOT, by moving the cloud closer to the surface. This is done by ramping up an external bias and ramping down the current in the quadrupole coils. The final effect is that the quadrupole field is replaced with the field of the magnetic structures plus an external bias field. In order to see where the atoms move when we switch the external magnetic fields, we use fluorescence imaging. With this method we could trap $\sim 5 \times 10^6$ atoms in the chip-mirror MOT, which means that only $\sim 6\%$ of the atoms are transferred. As the loading efficiency is very low with both approaches we decided not to use the chip-mirror MOT to proceed further.

5.1.2 The compressed mirror-MOT

The next step after the MMOT is the compressed mirror MOT (CMMOT) [79, 80]. This consists of a MMOT with increased red detuning of the cooling laser and greatly reduced repumper laser power. The CMMOT has the effect of reducing radiation pressure in the trap and thus creating a denser cloud of atoms [81]. Reducing the repump power reduces the time the atoms spend in the state ($F = 2$) resonant with the trapping light. Increasing the detuning of the cooling light decreases the scattering rate and thus the absorption of re-radiated photons. The repump power is reduced from several mW to 130 $\mu$W. Simultaneously we detune the cooling laser to $\delta = 6 \Gamma$ (red to resonance). The magnetic field gradient is kept constant. We compress the atoms for about 5 ms. We adjust the alignment and the half-wave plates to control the power in the beams in order to overlap the CMMOT position with the MMOT as well as possible. The atoms are observed with a CCD camera, by absorption imaging, as described in Chapter 3 and section 5.1.3.

The CMMOT efficiently cools the atoms from 150 - 300 $\mu$K down to 70 $\mu$K by suppressing the light scattering with a further detuning of the cooling laser and a reduction of the repumping laser power. After the compression we are left with $\sim 50 \times 10^6$ atoms and a density of $\sim 5 \times 10^{16}$ m$^{-3}$. Therefore we encounter imaging problems of very dense clouds. This leads to a flattening of the intensity in the center of the gaussian profile.
5.1. External coil mirror magneto-optical trap

Figure 5.6: The absorption image of the CMMOT, truncated above a certain optical density. The center of the cloud has a flat top where the OD is saturated. The lower graph is a horizontal cut through the middle of the image. Image dimensions are 768×512 pixels, where one pixel corresponds to 13×13 µm².

5.1.3 Image analysis of dense clouds

For optically dense clouds the apparent atom number, as measured by absorption imaging, is easily underestimated. A major issue is probe light that cannot be absorbed by the atoms. In particular the probe light may contain spectrally broad frequency components [82] or modulation side bands. If the object is very dense and the absorption image is very dark, this nonresonant probe light yields spurious transmission so that the optical density appears truncated above a certain value, as one can see in Figure 5.6.

An additional source of error can be due to inhomogeneous broadening of the sample, or broadening due to a finite linewidth of the (resonant part of) probe laser. Inhomogeneous broadening is particularly important for imaging in magnetic fields (Zeeman broadening).

We can separate the probe light intensity into an off resonant “offset” part \(I_{\text{off}}\) and a resonant part \(I_r\), and modify Lambert-Beer’s absorption law accordingly. If the resonant part of the light is monochromatic, the absorption by an atomic sample, with a density distribution \(n_{3D}(x, y, z)\) can then be written:

\[
I(x, z) = I_{\text{off}}(x, z) + I_r(x, z)e^{-\sigma \int_{y} n_{3D} dy} = I_{\text{off}}(x, z) + I_r(x, z)e^{-\sigma n_{2D}} \tag{5.1}
\]

with \(\sigma = \sigma(\omega)\) the absorption cross section, and \(n_{2D}\) the column density. For unpolarized atoms in the \(F = 2\) ground hyperfine state, and a linearly polarized probe beam, the cross section is given by

\[
\sigma(\omega) = \frac{7}{15} \times \frac{3\lambda^2}{2\pi} \cdot \frac{1}{1 + 4\Delta^2/\Gamma^2} \tag{5.2}
\]
where $\Delta = \omega - \omega_0$ is the detuning from resonance. The factor $\frac{7}{15}$ comes from averaging the square Clebsch-Gordan coefficients of the $\Delta m_F = 0$ components for the $F = 2 \rightarrow F' = 3$ hyperfine transition of the $D_2$-line of $^{87}\text{Rb}$, see also appendix A, Figure A.1.

In the presence of broadening effects the frequency dependent cross-section will change in such a way that its spectrally integrated value remains invariant. Defining this value as the line strength,

$$S = \int \sigma(\omega) d\omega = \frac{7}{15} \cdot \frac{3 \lambda^2}{2\pi} \cdot \frac{\pi \Gamma}{2} = \frac{7}{20} \lambda^2 \Gamma$$

(5.3)

the line broadening can then be expressed by a normalized line shape function, $\sigma(\omega) \rightarrow S \, g(\omega)$, with $\int g \, d\omega = 1$.

The column density can thus be obtained by integrating over the full line shape, resulting in a value that is insensitive to the broadening mechanism:

$$\int_{-\infty}^{\infty} \sigma(\omega) n_{2D} d\omega = S \, n_{2D}$$

(5.4)

Finally, the atom number is obtained by a summation over all pixels of the camera image:

$$N = -\frac{d^2}{S} \sum_i \int_{-\infty}^{\infty} \ln \left[ \frac{I(i) - I_{\text{off}}(i)}{I_0(i) - I_{\text{off}}(i)} \right] d\omega$$

(5.5)

where $d^2$ is the area in the object plane that is imaged onto one camera pixel.

In the case of a naturally broadened absorption spectrum, which we assume for atoms in the MOT, the normalized line shape function is given by a Lorentzian:

$$g(\omega) = \frac{\Gamma}{\pi} \frac{1}{(\omega - \omega_0)^2 + (\Gamma/2)^2} = \frac{2\Gamma}{\pi} \frac{1}{4\Delta^2 + \Gamma^2}$$

(5.6)

with detuning $\Delta = \omega - \omega_0$.

In practice we have the problem of a high optical density in the CMOT. Due to a limited signal to noise ratio and the background signal, non-resonant parts of the spectrum, especially the modulation sidebands, are not absorbed and the true optical density becomes rather undefined. Instead of measuring the resonant optical density, we measure the full spectrum (scan the probe and take images at different detunings) and fit the following model function to the spectrum at each pixel:

$$I = I_{\text{off}} + I_0 \exp \left[ -\frac{7}{15} \times \frac{3 \lambda^2}{2\pi} \cdot \frac{n_{2D}}{1 + 4\Delta^2/\Gamma^2} \right]$$

(5.7)

where $I_{\text{off}}$ is the unabsorbed offset intensity. In order to account for some broadening by the laser line width, we still use a Lorentzian profile but leave the width $\Gamma$ as a free parameter. However, to reduce the error in the parameter estimation, we require the fit parameter $\Gamma$ and the $I_{\text{off}}$ to be constant over the whole image.
To manage the computational task of fitting the huge data set, we first use a small subset of pixels (representing both strong and weak absorption) to perform a single multi-dimensional fit. This allows us to fix the $\Gamma$ and $I_{\text{off}}$. We find $\Gamma = 8$ MHz, which accounts for the natural line width ($\sim 6$ MHz) and the laser line width. In addition we obtain a non-absorbed fraction $I_{\text{off}}/I_0 = 0.14$. In a second run, we fit the model function to every pixel with only $n_{2D}$ as a free parameter. The total atom number is found with Eq. (5.5).

5.1.4 Optical pumping

After the CMMOT phase, the gas is not spin polarized. Due to this only a part of the atoms would be trapped in the magnetic trap when the coils are switched on at this stage. In order to spin polarize the atoms, they are optically pumped into the state $|F = 2, m_F = 2\rangle$ with respect to the symmetry axis of the trap ($x$-direction). During optical pumping the quantization axis is defined by applying a magnetic guiding field of 1.8 G along the $x$-direction. For this purpose the MT coils are used. For the optical pumping one laser beam is applied also along the symmetry axis of the trap. The laser beam has $\sigma^+$ polarization with respect to the axis of quantization and is tuned to $F = 2 \rightarrow F' = 2$ transition. The atoms are excited to the $|5P_{3/2}, F = 2\rangle$ state by $\Delta m_F = +1$ transitions. From this state they decay spontaneously into both hyperfine ground states, from where they are re-excited by the lasers. After a few cycles, the atoms are pumped into the $|5S_{1/2}, F = 2, m_F = 2\rangle$ state. They stay in this state, as they do not interact. Since the polarized atoms become transparent to the pumping light, it is possible to optically pump the complete cloud, even if it is originally optically dense.

A long optical pumping time will not further increase the efficiency, but the cloud will be heated due to continuous scattering of light. In the experiment the optimum optical pumping time was found to be 200 $\mu$s. In order to produce this short light pulse the optical pumping beam is switched by means of an AOM. One laser beam is coupled in one of the horizontal beams through PBS 5 (see Figure 5.2) also along the symmetry axis of the trap. Atoms, which remain in the $|F = 2, m_F = 1\rangle$ state due to inefficient optical pumping, are not trapped in the magnetic potential. These atoms fall out of the magnetic trap within the first 150 ms of magnetic trapping, as the gradient in the magnetic potential is not strong enough to support them against the gravitational force.

The achieved efficiency of the optical pumping is about 60%, as $30 \times 10^6$ atoms are trapped in the magnetic trap, starting with $50 \times 10^6$ atoms in the CMMOT.

In Table 5.1 we list the used laser power, the magnetic field gradient and the time scales of the different stages: mirror-MOT, CMMOT, optical pumping and magnetic trapping. The atoms are now ready to be caught in the magnetic trap.
Table 5.1: Overview of the purposes and properties of the laser beams and magnetic fields used during the atom cloud optimisation and preparation.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Trapping/repump</th>
<th>Magnetic gradient</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOT</td>
<td>on/10mW</td>
<td>15 G/cm</td>
<td>10 sec</td>
</tr>
<tr>
<td>CMOT</td>
<td>on/50µW</td>
<td>30 G/cm</td>
<td>5 ms</td>
</tr>
<tr>
<td>Optical pumping</td>
<td>off/10mW</td>
<td>15 G/cm</td>
<td>200 µs</td>
</tr>
<tr>
<td>Magnetic trap</td>
<td>off/off</td>
<td>60 G/cm</td>
<td>500 ms</td>
</tr>
</tbody>
</table>

5.2 The Magnetic Trap

For loading the chip magnetic trap, we can follow two approaches. The first is directly from the chip-MMOT. With this method we could trap very few atoms in the chip magnetic trap because the optical pumping does not work very close to the chip, due to the presence of high magnetic field gradients. Due to this inconvenience we do not use this sequence to load the micro-trap.

The better way of loading is from the normal MMOT to an external coil magnetic trap followed by transport down to the chip micro-trap. After optical pumping the magnetic trap is switched on to capture the atoms. The current through the MT coils rises within 1 ms to its set value, 19.8 A, respectively -19.2 A. When ramping up the magnetic field, the center offset induces sloshing in the trap, which turns into thermal energy. We have to optimize the magnetic fields of the trap so that the cloud settles down in as short time as possible. This is achieved by shifting the symmetry axis of the magnetic quadrupole field in the vertical direction, which can be realized with the Big Coils and the MOT coils. We observe that even after adjusting the external magnetic fields, it takes about 100 to 150 ms for the cloud to settle down. We trap $30 \times 10^6$ atoms in the trap with a temperature of $\sim 90$ µK. The rise in temperature during the transfer is attributed to momentum diffusion due to photon scattering during optical pumping or to imperfections of the compensation of the gravitational shift. Due to gravity the minimum of the magnetic trapping potential is not at the same position as the minimum of the magnetic field.

5.2.1 Lifetime of the magnetically trapped atoms

The dominant loss of atoms from the magnetic trap is due to collisions with room temperature particles from the vacuum background. The total loss rate $\dot{N}$ due to the background collisions is independent of the density and proportional to the number of atoms in the trap. Thus, the number of trapped atoms decays exponentially as $N(t) = N(0)e^{-t/\tau_0}$, where $\tau_0 \propto 1/p$ is the trap life time and $p$ the background pressure. The life time was measured by repeatedly performing loading as described above, and measuring the atom number after a variable
Figure 5.7: Decay of the number of atoms in the magnetic trap, which can be attributed to background collisions. From the fit, based on an exponentially decaying background pressure (see text), we obtain an asymptotic trap lifetime of $\tau_0 \approx 15$ s, and a vacuum recovery time of $\tau_1 \approx 2$ s. The vacuum recovery takes place after switching off the rubidium dispenser.

trapping time. The atom number was measured by absorption imaging after switching off the trap. The resulting decay curve of the cloud is shown in Figure 5.7. We see relatively fast decay at early times changing into an exponential tail at later times. The enhanced decay at early times can be understood as a result of a recovering vacuum pressure after switching off the rubidium dispenser.

Assuming that the background pressure exponentially approaches its asymptotic value, $p(t) - p(\infty) \propto e^{-t/\tau_1}$, the number of trapped atoms is expected to decay according to $\dot{N}/N = -\frac{1}{\tau_0}(1 + a e^{-t/\tau_1})$, where $a = p(0)/p(\infty) - 1$ is the normalized excess pressure at $t = 0$. The expected decay curve is the solution to this differential equation,

$$ N(t) = N(0) \exp \left[ -\frac{t}{\tau_0} - \frac{a \tau_1}{\tau_0} \left( 1 - e^{-t/\tau_1} \right) \right] $$

(5.8)

Using this as a fitting function for the decay curve we obtain $\tau_0 = 15$ s for the asymptotic life time, and $\tau_1 = 2$ s for the pressure recovery time. The lifetime of the magnetic trap is long enough to allow for the transfer of the magnetically trapped atoms to the chip magnetic trap.

Apart from the collisions with the background gas, another loss mechanism that can reduce the lifetime in the quadrupole magnetic trap is scattering of resonant light impinging on the atoms. An atom absorbing a single photon has a large probability of falling back to an untrapped spin state and thus being ejected from the trap. In order to minimize this we place boxes made from opaque black cardboard panels on an aluminium frame around all the laser systems.

Majorana spin flips can also cause losses from magnetic quadrupole traps. This happens typically at low enough temperature when approaching Bose-Einstein
condensation. The solution is to load the atoms into a Ioffe-Pritchard trap as described in the next chapter.

5.3 Conclusions

In this chapter we present and compare three loading methods of the MOT: 1) directly from the background gas using the magnetic field of the external coils; 2) from the background gas using the magnetic field of the chip; and 3) a combination of the previous two methods, trapping the atoms first with the external coils and then transfer them to the magnetic field of the chip. The first method has been chosen to proceed further as the maximum atom number is achieved.

We optimized the loading of the magnetic trap by first compressing the MMOT for 5 ms and then optically pumping it for about 200 $\mu$s. By compressing the MMOT we reach a density $\sim 5 \times 10^{16}$ m$^{-3}$. After this we turn on the magnetic coils in order to magnetically trap the atoms. It takes about 100 to 150 ms for the cloud to settle down. We trap $30 \times 10^6$ atoms in the magnetic trap with a temperature of 90 $\mu$K.

The optimization steps for the MOT and the MT do not need to be repeated for future generations of atom-chips, as soon as the control timing has been determined. After a new chip is mounted inside the vacuum, we only need to redo the procedures from section 5.1 to find the right operating parameters. It is important that only a slight fine-tuning will be required, as the optimization steps can be very time consuming.