Bose-Einstein condensation with high atom number in a deep magnetic trap

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Chapter 5

Magneto-optical trap with high atom number

This chapter describes how the atomic beam source, which has been introduced in the previous chapter, is used to load the ultra-high vacuum magneto-optical trap (MOT). This is done with the goal to take benefit of the high beam flux and to achieve a high atom number after a short loading time. The measured atomic beam flux is compared to the measurements of the trap loading. It is demonstrated that the effective loading flux can be improved by avoiding loss from the atomic beam due to fluorescence light originating from the magneto-optically trapped cloud. After loading polarization gradient cooling is used to cool the cloud to a temperature below the Doppler limit, which is 144 μK for rubidium. Further, it is described how the temperature of the atomic cloud after sub-doppler cooling was minimized for the case of a large atom number.

5.1 Experimental setup

In Figure 5.1 the experimental setup is shown, which is build around the two glass cells of the vacuum system as described in Section 3.2. The lower half shows the magnetic field coils and the laser beams for the atomic beam source, which is described in Chapter 4. In the upper half the setup with the magnetic trap (compare Figure 2.3) and the laser beams for the MOT are depicted. Furthermore, the laser beam used for absorption imaging of the cloud and the CCD screen are indicated.

For the realization of the MOT the two pinch coils of the magnetic trap are used with the currents flowing in opposite directions. These coils generate a gradient per unit current of 0.73 G cm⁻¹ A⁻¹ for the spherical quadrupole field along the z-direction. A gradient of 29 G/cm is used during the loading phase of the MOT. Six independent laser beams, which are red detuned by 30 MHz with respect to the trapping transition, create the light fields of the MOT. The 1/e²-radius of the laser beams is 8.1 mm, so that a large capture region is covered. This is necessary as the Gaussian half width of the atomic
FIGURE 5.1: Setup used for laser cooling and magnetic trapping: In the lower part the atomic beam source is shown. The atoms are recaptured from the atomic beam into a magneto-optical trap made of six laser beams and two pinch coils. The atomic cloud is at the same location loaded into the magnetic trap, which is made of the Ioffe, pinch, and compensation coils.
loading beam at the recapture region is 9.1 mm, as extrapolated from the measurement of the beam width in the detection chamber presented in Section 4.5. With an optical power of 13.5 mW per beam the trapping transition is well saturated. The laser power is provided by a broad-area laser system (compare Section 3.1), which delivers up to 130 mW of spatially filtered light. Retroreflected beams would require only half of the laser power. However, this solution is not desirable in case of a large atom number in the cloud, as absorption of the light by the cloud leads to an imbalance of the spontaneous light force. The six laser beams are configured such that two counter-propagating pairs travel horizontally in x- and z-direction perpendicular to the surfaces of the vacuum glass cell.

To minimize the overlap with the atomic beam and avoid undesirable photon scattering of the atoms in the beam, the third pair of laser beams is configured with a small angle from the vertical axis (see Figure 3.2). The overlap with the atomic beam is further reduced by focusing this third pair and reflecting the beams off a small mirror, which is installed close to the atomic beam, towards a vacuum viewport. This configuration of the six MOT beams has the advantage, that the MOT beams do not have to be sent under 45° through the quartz cell. This avoids unwanted reflections at the inner surfaces of the quartz cell. (An anti-reflection coating of the inner surfaces of the quartz cell is technically not possible.) Moreover, in this configuration the magnetic field coils can be brought as close as possible to the quartz cell, and so the strongest possible magnetic confinement can be achieved.

5.2 Loading of the MOT

The MOT is loaded by the atomic beam source in 2D+ configuration (compare Chapter 4), which shows a narrow maximum of the atomic flux as a function of the background vapor pressure (compare Figure 4.3). In order to guarantee a reproducible atom number loaded into the MOT the vapor pressure in the source has to be kept stable. This is conveniently done by working with saturated vapor. At a room temperature of 24 °C the vapor pressure is about 3 × 10⁻⁷ mbar. At this pressure we achieve 30% of the maximal flux leaving some room for further improvement. It is further noted here that after these measurements were carried, out new types of laser diodes became available (Sanyo DL-7410-001) providing 66% more laser power yielding 53% more atomic flux.

The atom number loaded into the MOT is measured as a function of the loading time by means of absorption imaging, as described in Section 3.5. The images were taken after sub-Doppler cooling, which is described in the next section, and after a period of free ballistic expansion. From the images the central profile along the vertical and horizontal directions were extracted. By a best fit of the profiles to a Gaussian shape (see Section 2.3.2) the dimensions and the maximum absorption of the cloud were determined. With the assumption that the size of the cloud along the direction of observation of the imaging laser beam equals the vertical size the number of atoms (compare Equations (2.32) and (2.33)) was deduced (In these two directions the gradient of the quadrupole magnetic field is equal.).

The measured loading curve is shown in Figure 5.2 (squares). The loading is compared with an exponential growth expression, \( N(t) = N_{\text{sat}}(1 - e^{-t/\tau_{\text{load}}}) \), for the atom number,
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FIGURE 5.2: Loading curve of the MOT: After 10 s typically $10^{10}$ atoms are loaded (squares). The transfer efficiency from the loading beam is about 70%. It can be slightly enhanced (circles) by optically pumping the atoms in a state, which is dark for the trapping light (‘depumping’).

where $N_{\text{sat}}$ is the number of atoms in case of saturation and $\tau_{\text{load}}$ is the time constant of the loading process. This describes in good approximation the loading process even in the case of high atom number, where the atom loss from the trap due to intra-trap collisions is dominating the loss due to collisions with particles from the residual gases in the vacuum chamber [Anderson et al., 1994]. From a best fit to the loading curve $N_{\text{sat}} = 1.3 \times 10^{10}$ and $\tau_{\text{load}} = 6.3 \text{s}$ are obtained. The effective loading flux at short times is $2.1 \times 10^9 \text{atoms/s}$, whereas the measured atomic beam flux is measured to be $3 \times 10^9 \text{atoms/s}$. The transfer efficiency is thus about 70%.

The loss of atoms from the loading beam can be explained by two mechanisms. First, as the loading beam is overlapping with the vertical MOT beams, atoms can be driven transversely out of the loading beam by photon recoil from scattered photons. Second, the fluorescence light emitted by the large MOT in the direction of the atomic beam leads to a net light force repelling the atomic beam from the recapture region of the MOT.

One possibility to further improve the effective loading flux is to optically excite the atoms of the atomic beam by an additional laser beam, before the atoms enter the vertical MOT beams. This so called ‘depumping’ beam drives the transition $|5S_{\frac{1}{2}}, F = 0\rangle \rightarrow |5P_{\frac{1}{2}}, F = 1\rangle$. 

\begin{align*}
\text{exponential loading:} & \quad N(t) = N_0 (1 - \exp(-t/\tau_{\text{load}})) \\
& \quad \bullet \text{ with depumper:} \\
& \quad N_0 = 1.5 \times 10^{10}, \tau_{\text{load}} = 4.5 \text{s} \\
& \quad \bullet \text{ without depumper:} \\
& \quad N_0 = 1.3 \times 10^{10}, \tau_{\text{load}} = 6.3 \text{s}
\end{align*}
5.3. LOADING OF THE MOT FROM VACUUM BACKGROUND

2) $|5P_{3/2}, F = 2\rangle$. From the exited state the atoms can decay to the state $|5S_{1/2}, F = 1\rangle$. From this state they are not excited by the trapping light anymore, until they are pumped back by repumping light, when they enter the recapture region. Therefore, the repumping light has to be overlapped with only the horizontal MOT beams and not with the vertical ones. The effect of using the depumping beam is demonstrated in Figure 5.2 (circles). The initial loading flux, the number of atoms in saturation and the loading time constant are slightly enhanced. However, also light resonant to the repumping transition is scattered from the MOT cloud towards the atomic beam. Therefore, the application of the depumping beam could be further improved by enlarging the overlap of the depumping beam with the atomic beam as it approaches the recapture region.

Another possibility to improve the loading flux is by using unbalanced beam intensities in the vertical pair of MOT beams, in order to partially compensate the MOT fluorescence.

For simplicity of the experiment the MOT is loaded without the use of the depumping light. In daily operation it takes 10s to load the MOT with $10^{10}$ atoms. Due to imperfections in the alignment of the laser beams, the atomic cloud is not spherical as one would expect in the density-limited regime. The dimensions (radius at a 1/e-fraction of the peak density) of the cloud measured immediately after sub-Doppler cooling are $r_{0,y} = 3.1 \text{ mm}$ and $r_{0,z} = 3.5 \text{ mm}$.

A very similar result can be obtained by using a coil configuration that differs from the anti-Helmholtz configuration used in a standard three-dimensional MOT. As the central density in the MOT is limited by radiation trapping, the volume of the cloud has to be increased in order to trap a higher atom number. This can be realized by applying a strong magnetic field gradient produced by the Ioffe coils of the magnetic trap and a weak gradient produced by the pinch coils. This gives rise to a large trapped cloud elongated along the axis of the Ioffe-coils. It was found out, that it is possible to trap atom numbers comparable to the ones described above. This configuration is not used in the experiments, as at lower densities the transfer to the magnetic trap (Section 6.1) was found to be less efficient.

5.3 Loading of the MOT from vacuum background

In contrast to other experiments working with loading of the MOT in the UHV cell by a vapor cell based atomic source, in this experiment comparatively high vapor pressure used in the vapor cell. Therefore, it is necessary to experimentally investigate, whether the differential pumping, as described in Section 3.2, guarantees a sufficiently good vacuum in the UHV cell. For this purpose, the MOT was loaded without the use of the atomic beam. In absence of the loading beam residual loading of the MOT from background rubidium gas in the UHV cell can be observed [Anderson et al., 1994]. In this experiment an initial capture rate of $R = 2.6 \times 10^5 \text{ s}^{-1}$ and an atom number of $1.6 \times 10^6$ after saturation were found. From the capture rate $R$ the room temperature rubidium partial pressure $P_{\text{Rb}}$ in the UHV cell can be estimated by [Gibble et al., 1992]

$$P_{\text{Rb}} = \frac{R k_B T}{\pi^2 r_c^2 v_c^4} \left(\frac{2\pi k_B T}{m}\right)^{3/2}, \quad (5.1)$$
with the capture range $r_c = 11\text{ mm}$ and the capture velocity $v_c = (r_c h\Gamma/(2\lambda m))^{1/2} = 35\text{ m s}^{-1}$ for the given MOT parameters. The rubidium partial pressure was estimated to be on the order of $P_{Rb} \approx 4 \times 10^{-12}\text{ mbar}$, which is negligible for atom trapping.

Furthermore, it was experimentally verified that the effusive beam which leaves the vapor cell through the differential pumping hole and points to the trapping region, does not noticeably contribute to the loading rate of the MOT. This follows, as the same loading rate was obtained while applying the plug beam, as described in Section 4.4, which removes atoms with velocities smaller than the capture velocity of the MOT from the effusive beam.

### 5.4 Temperature of the cold cloud after optical cooling

After loading, the trapped cloud is cooled by the method of polarization gradient cooling in $\sigma^+ - \sigma^-$ configuration [Dalibard and Cohen-Tannoudji, 1998]. The temperature of the cloud is deduced from a time-of-flight spectrum after free ballistic expansion of the cloud.
5.4. TEMPERATURE OF THE COLD CLOUD AFTER OPTICAL COOLING

The density distribution of the expanded cloud is given by the convolution of the spatial distribution before the expansion, which is approximately Gaussian, with the Maxwell-Boltzmann velocity distribution of the atoms in the cloud. For collisionless expansion over a time $\tau_{\text{exp}}$ the 1/e-radius of the cloud is

$$r_{0,i}(\tau_{\text{exp}}) = \sqrt{r_{0,i}^2(0) + \tau_{\text{exp}}^2 2k_B T/m}.$$  \hspace{1cm} (5.2)

In Figure 5.3 time-of-flight measurements for different experimental conditions are compared. In all measurements a cooling time of 15 ms has been used. From a best fit of Equation (5.2) to the data the temperature of the cloud was determined. The temperature was found to depend on the atom number. At high atom number, $1.2 \times 10^{10}$, polarization-gradient cooling typically results in a temperature of 40 $\mu$K (circles). This is significantly above the low temperatures of less than 10 $\mu$K which can be achieved with atom numbers below $10^7$. The increase in the observed temperature is attributed to due a disturbance of the polarization gradient by fluorescence light, which is reabsorbed in the cloud [Cooper et al., 1994].

The temperature after polarization gradient cooling is within certain limits proportional to the dynamical Stark-shift parameter $I/\delta$, e.g. the ratio of laser intensity $I$ and detuning $\delta$. This behaviour is demonstrated in Figure 5.3 by varying the detuning for a fixed small atom number (triangles and squares). To minimize the temperature at high atom number the maximal available detuning of $-65$ MHz was used. This detuning is limited by the band edge of the acousto-optic modulator used for control of the laser detuning. By reducing the laser intensity a small decrease of the temperature was observed, but also a significant drop in the number of atoms. Under typical conditions only 10% of the atoms are lost. This was realized by applying a peak intensity of 9.5 mW/cm$^2$ for each of the MOT beams.