Bose-Einstein condensation with high atom number in a deep magnetic trap
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Chapter 6

Magnetic Trapping

After collecting the atoms in the MOT and polarization-gradient cooling the following experimental step towards BEC is magnetic trapping of the atoms. In order to magnetically trap the gas it has to be spin polarized. Therefore, the atoms are optically pumped into the state $|5S_{\frac{1}{2}}, F = 2, m_F = 2\rangle$. The trapping is realized by switching on a shallow magnetic potential preserving the size of the cloud ('size matching'). This transfer is followed by adiabatic compression of the cloud, which is done by slowly increasing the currents through the magnetic field coils. Aside from the procedural steps of loading the trap, in this chapter also the performance of the trap is described. Measurement of the lifetime of the sample in the compressed magnetic trap gives information on whether efficient evaporative cooling is possible and BEC can be achieved. Measurement of the harmonic trap frequencies is essential for subsequent quantitative analysis of the trapped Bose-gas in the degenerate regime.

6.1 Magnetic trap loading

After polarization-gradient cooling the gas is not spin polarized. Only a fraction of the atoms would be trapped when switching on the magnetic trap at this stage. In order to spin polarize the atoms, they are optically pumped into the state $|5S_{\frac{1}{2}}, F = 2, m_F = 2\rangle$ with respect to the symmetry axis of the trap (z-direction). During optical pumping the quantization axis is defined by applying a magnetic guiding field of 220 mG along the z-direction. For this purpose the Earth-field compensation coils are used. For the optical pumping two overlapping laser beams are applied also along the symmetry axis of the trap. One beam is tuned resonant with the optical pumping transition (compare Section 2.1.1), the other with the repumping transition. Both laser beams have $\sigma^+$-circular polarization with respect to the axis of quantization. The atoms are exited to the $|5P_{\frac{3}{2}}, F = 2\rangle$ state by $\Delta m_F = +1$ transitions. From this state they decay spontaneously into both hyperfine ground states, from where they are reexcited by the lasers. After a few cycles, the atoms are pumped into the $|5S_{\frac{1}{2}}, F = 2, m_F = 2\rangle$ state. They stay in this state, as they do not interact with the light fields anymore. In this way it is possible to
optically pump all parts of the gas cloud, although it is originally optically dense for the resonant light fields.

The efficiency of the optical pumping process is limited by reabsorption of unpolarized fluorescence light. This light pumps the atoms out of the dark state to undesired Zeeman states. For a long optical pumping time the efficiency will not be further increased, but the cloud will be heated due to continuous scattering of light.

In order to estimate the time needed for optical pumping the absorption cross-section averaged over the optical pumping and repumping transitions is calculated to be

$$\sigma_{\text{abs}} = \frac{3\lambda^2}{8\pi} \approx 7 \times 10^{-10} \text{ cm}^2.$$  

Assuming a density of the cloud of about \( n = 10^{10} \text{ cm}^{-3} \), the penetration depth is on the order of \( (n\sigma_{\text{abs}})^{-1} = 140 \mu\text{m} \). Thus, the time needed for optical pumping of the cloud of 1 cm size is about 70 times longer, than the optical pumping time for a single atom. If one roughly assumes, that on the average a single atom has to scatter 20 photons before ending up in the \( |F = 2, m_F = 2\rangle \) state, the optical pumping time for a single atom is in case of saturation \( 1 \mu\text{s} \). This results in an optical pumping time for the entire cloud of approximately \( 140 \mu\text{s} \). In the experiment the optimum optical pumping time was found to be \( 200 \mu\text{s} \). In order to produce this short light pulse the optical pumping beam is switched by means of an AOM. The repumping laser is switched by a mechanical shutter. It is switched off a few milliseconds later than the trapping laser. This prevents the atoms from ending up in the \( |5S_\frac{3}{2}, F = 1\rangle \) state. Atoms, which remain in the \( |5S_\frac{3}{2}, F = 2, m_F = 1\rangle \) 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 40\%, as \( 4 \times 10^{9} \) atoms are trapped in the magnetic trap, starting with \( 10^{10} \) atoms in the MOT.

After optical pumping the magnetic trap is switched on for recapture of the atoms. The current through the pinch coils rises within 1.5 ms to its set value, followed by a 20\% overshoot. The total settling time is 10 ms. The current in the Ioffe coils is switched on within 2.5 ms with a 25\% overshoot and a settling time of 15 ms. As the current in the pinch coils rises faster than the current through the Ioffe coils, the axis of quantization is preserved during the initial rise of the currents. When the full current is reached the minimum value of the magnetic field inside the trap is \( 37 \text{ G} \). As the quadrupole field catches up with the axial field the magnetic moments of the atoms follow adiabatically the direction of the local magnetic field (compare Section 2.2).

To avoid heating of the gas cloud its size must be conserved in the transfer process. For \( B_0 = 37 \text{ G} \) the trap is approximately harmonic over the size of the gas cloud. Therefore, the density distribution has a Gaussian shape (compare Section 2.3.2). For a given temperature the harmonic trap frequency \( \omega_i \) in the \( i \)-direction has to be matched to the \( 1/e \)-radius \( r_0_i \) of the cloud, according to Equation (2.17). For different values of \( \omega_i \) the cloud would not be in thermal equilibrium and would start to expand or shrink after the transfer. This would lead to an increased temperature after thermalization.

In the experiment, the trap frequencies were adjusted, to minimize the temperature increase during the transfer process. The temperature of the transferred cloud was measured after a thermalization time of 4s using the time-of-flight method as described in in Section 5.4. As the density distribution in the Ioffe-quadrupole trap is not Gaussian,
6.2. ADIABATIC COMPRESSION

the time-of-flight method was applied only in the limit of long expansion times, where the density distribution of the trapped gas is of no importance.

Starting with a 3 mm gas cloud at a temperature of 40 µK the optimum trapping parameters were found to be $B_0 = 37$ G, $\alpha = 37$ G/cm, and $\beta = 36$ G/cm$^2$. This corresponds to a roughly isotropic trap of $\omega = 2\pi \cdot 7.5$ Hz. From an estimate based on Equation (2.33) one calculates $\omega = 2\pi \cdot 4.6$ Hz. A strict agreement is not to be expected, as for $\alpha < \beta r_z$ the radial confinement is significantly reduced as can be seen from Equation (2.8). In order to prevent atom loss the quadrupole gradient and with it the radial frequency as calculated by Equation (2.12) is slightly increased. Another reason for using a slightly stronger confinement is the increased temperature of the trapped cloud after the transfer, which is typically 66 µK. The rise in temperature during the transfer is attributed to momentum diffusion due to photon scattering during optical pumping or imperfections of the compensation of the gravitational shift described in the following paragraph.

Due to gravity the minimum of the magnetic trapping potential is not at the same position as the minimum of the magnetic field. For the harmonic potential the shift is

$$\Delta y_{\text{grav}} = \frac{g_{\text{earth}}}{\omega_p^2} \approx 4 \text{ mm}, \quad (6.1)$$

where $g_{\text{earth}}$ is the gravitational acceleration of the Earth. However, the center of the cloud produced by the MOT is independent of gravity, as magneto-optical trapping is not based on a conservative potential. A motion of the center of mass of the cloud during and after the transfer to the magnetic trap has to be prevented, as it would result in an increased temperature after thermalization. Therefore, the center of the magnetic potential has to coincide with the center of the cloud. This is achieved by shifting the symmetry axis of the Ioffe-quadrupole field in the vertical direction, which can be realized by reducing the current in the upper one of the four Ioffe-coils $I_{\text{ioffe1}}$ relative to the current through the other Ioffe coils $I_{\text{ioffe2-4}}$ (compare Figure 3.5). For small variations of the currents the shift of the quadrupole axis is proportional to the relative difference of the currents $y_0 (I_{\text{ioffe2-4}} - I_{\text{ioffe1}})/I_{\text{ioffe2-4}}$ with the constant $y_0 = 7.7$ mm. For compensation of the gravitational shift a current of 25 A is used in the Ioffe bypass (branch D).

6.2 Adiabatic compression

Crucial for efficient evaporative cooling is a high elastic collisional rate allowing a short thermalization time of the gas. Therefore, it is essential to adiabatically compress the magnetically trapped gas, until the condition for runaway evaporative cooling is met (compare Section 2.54). To realize the adiabatic compression the currents in the Ioffe- and pinch- and compensation coils are gradually increased to 400 A during a period of 6.615 s. Adjusting the offset magnetic field to $B_0 = 0.85$ G by means of the bypass resistor results in trap frequencies of $\omega_z = 2\pi \cdot 21.6$ Hz and $\omega_p = 2\pi \cdot 486.6$ Hz as follows from Equations (2.11) and (2.12) and the trap parameters given in Table 3.2. These values are in good agreement with the measured trap frequencies presented in Section 6.4. After the adiabatic compression the temperature of the cloud is approximately 760 µK. During the adiabatic compression no significant atom loss was observed. At this temperature and
with the measured atom number of $4 \times 10^9$, the peak density of the cloud is calculated to be $7 \times 10^{11}$ cm$^{-3}$. The elastic collisional rate as defined in Equation (2.58) was increased from approximately $\tau_{el}^{-1} \equiv n(0) \sigma v_T = 3 \text{s}^{-1}$ before the compression, to $\tau_{el}^{-1} = 275 \text{s}^{-1}$ after compression, with the thermal velocity $v_T = \sqrt{\frac{3 k_B T}{m}}$. Note that the thermalization rates are slightly smaller, as for the calculation of the elastic collision rate only the peak density is considered. The degeneracy parameter of the gas is $n(0)\Lambda_T^3 = 2 \times 10^{-7}$, many orders of magnitude away from quantum degeneracy (compare Equation 2.19).

During adiabatic compression the currents in the magnetic field coils were changed in four successive steps. The order of these steps depends on the technical possibilities provided by the electronic control of the trap currents, which is shown in Figure 3.5. In the following the steps are briefly described. Table 6.1 summarizes the the values of the magnetic trap parameters and the cloud temperature after each of the steps.

0. **Start:** The magnetic trap is switched on with a shallow confinement in order to recapture the optically pumped cloud (path A closed, path B open, compare Figure 3.5). The gravitational shift is compensated by reduction of the current in the upper Ioffe-coil (path D & E used).

1. **Step:** The cloud is radially compressed, by increasing the current through the compensation coils (opening path A) and decreasing $B_0$. At the same time the compensation of the gravitational shift of the position of the cloud in the magnetic potential is gradually switched off (closing path D). For this purpose, the current bypassed from the upper Ioffe coil is reduced to zero.

2. **Step:** For compression in the direction along the symmetry axis of the trap the current through the pinch coils is increased to 400 A (power supply A). Although at the same time the current through the compensation coils increases (path A), the central magnetic field $B_0$ does not remain constant, but increases. In order to keep the radial trap frequency constant during this step the current in the Ioffe coils is also increased (power supplies B & C). After this step the trapping potential is almost spherical.

3. **Step:** To increase the linear gradient of the quadrupole field the current in the Ioffe coils is increased to 400 A (power supplies B & C).

4. **Step:** In the last step full radial compression is achieved by lowering $B_0$. Almost the full current through the pinch coils runs also through the compensation coils (by closing path B). The exact value of $B_0$ is adjustable by the current running through the resistor bypassing the compensation coils. If no current runs through the bypass resistor, the central magnetic field is $B_0 = -2.8$ G and negative with respect to the positive z-axis. Typically 4.3 A has to run through the bypass to adjust $B_0$ to a value of about 0.85 G.

In Table 6.1 the duration for the different steps is listed. The change of the trap parameters during the individual steps is realized by using continuous, arbitrary waveforms of the computer control. Duration $\Delta t$ and update interval $\Delta \tau_{wf}$ of the waveforms are listed in Table 6.1. The duration and form of the waveforms were designed to fulfill the
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TABLE 6.1: Adiabatic compression takes place in four successive steps. The table summarizes the changes of the trapping parameters during the compression. The measured temperature increase after each compression step is compared to the value which is calculated by assuming adiabatic compression. The excess temperature increase after the first step is probably due to the deviation of the trapping potential from a power-law potential, which is used in the calculation.

adiabaticity condition as discussed in Section 2.3.3. It was experimentally verified for each step, that with a slower compression rate no lower temperatures are achieved.

The measured temperatures after each step are compared with the temperatures calculated using Equation 2.39, which includes the temperature measured after the previous step and the change of the trap parameters during the step. The significant increase in temperature after the first step is probably due to imperfect matching of the trap shape to the size of the gas cloud after optical pumping. Moreover, the optical pumping process gives rise to a slight center-of-mass motion due to photon recoil, and results in a temperature increase. The excess temperature observed after the third step remains unexplained.

6.3 Life time of the magnetic trap

Next to a high elastic collisional rate, another important requirement for efficient evaporative cooling is a long life time of the magnetically trapped gas sample (see Section 2.54). After adiabatic compression, where the density of the cloud is about $7 \times 10^{11}$ cm$^{-3}$, trap loss due to inelastic three body-recombination can be neglected [Söding et al., 1999]. Loss due to two-body spin relaxation has been theoretically predicted to be negligible even at high densities [Julienne et al., 1997], and has not been experimentally observed, yet. At the density of the compressed cloud the dominant loss of atoms from the magnetic trap is due to collisions with particles from the room temperature vacuum background.
CHAPTER 6: MAGNETIC TRAPPING

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 $N(t) = N(0)e^{-t/\tau_{bg}}$, where $\tau_{bg}$ is the trap life time. The life time was measured by repeatedly performing loading and adiabatic compression of the trap as described above, and measuring the atom number after a variable trapping time. The atom number was measured by absorption imaging after release of the cloud from the trap as described in Section 5.2. The decay curve of the cloud is shown in Figure 6.1. Fitting the data to an exponential decay results in a magnetic trap life time of $\tau_{bg} = 64$ s.

It was found that the magnetic trap life time depends on the value of the magnetic field $B_0$ in the trap center. This field is measured by repetitively applying an rf-evaporative cooling ramp (as will be described in Section 7.1), and lowering the final frequency, until all atoms are removed from the trap. The central magnetic field can then be calculated from the final frequency with the help of Equation (2.61). Increasing $B_0$ to a value of 2 G by changing the current in the compensation coils leads to an increase of the observed life time to 85 s. Further increase of $B_0$ does not increase the life time significantly. In the opposite case, at $B_0 = -1.4$ G, the life time is reduced to 45 s. The decrease in the life time is attributed to non-adiabatic spin transitions in the low magnetic field near the trap center (see Section 2.2).

**FIGURE 6.1:** Decay of the number of atoms due to background collisions. A fit to an exponential decay results in a life time of 64 s.
6.4 Measurement of the harmonic trap frequencies

In the following the measurement of the harmonic frequencies of the magnetic trap is described. The axial and radial oscillations of the cloud are driven by modulating the magnetic potential. The oscillation is observed by imaging the cloud after a variable holding time.

The harmonic approximation of the magnetic trapping potential in the radial direction is only valid for small distances from the trap center. After adiabatic compression the harmonic radius of the trapping potential in radial direction, as defined by Equation (2.10), is \( \rho_h = 32 \mu m \). This corresponds to a 1/e-radius of the Gaussian density profile of the trapped cloud at a temperature of \( T = \rho_h^2 \omega_p^2 m/(2k_B) = 48 \mu K \). As after adiabatic compression the temperature of the cloud is 760 \( \mu K \), the cloud mainly covers the linear part of the trapping potential. For measurement of the trap frequencies in axial and radial direction the cloud was evaporatively cooled (see Chapter 7.1) to temperatures of 1 \( \mu K \) and 1.6 \( \mu K \), respectively.

After evaporative cooling the trap oscillation was driven by sinusoidally displacing the center of the trapping potential by means of the tuning coils. A drive of five periods at a frequency of 20.64 Hz in the axial direction or ten periods at a frequency of 453 Hz in the radial direction was applied. After a variable holding time \( t \) the cloud was released from the trap and an absorption image was taken after 10 ms of ballistic expansion. From the absorption images the centroid of the cloud was determined. Figure 6.2 shows the axial and radial oscillations of the cloud centroid.

In order to determine the trap frequencies the measured positions \( x_{z,\rho}(t) \) along the radial and axial directions of the cloud were fitted to an exponentially damped sinusoidal function

\[
x_{z,\rho}(t) = A \sin(\omega_{z,\rho} t + \phi) \cdot e^{-\frac{t}{\tau}} + \text{const.}
\]

where \( A \) is the amplitude of the oscillation, \( \phi \) is a phase factor, and \( \tau \) a damping time. An additional constant defines the center of the trap. The resulting values from the fit for the axial and radial trap frequencies are \( \omega_z = 2\pi \cdot 20.64 \) and \( \omega_\rho = 2\pi \cdot 477.4 \) Hz respec-

![FIGURE 6.2: Harmonic trap oscillation of the cloud centroid. The fits correspond to an axial frequency of \( \omega_z = 2\pi \cdot 20.64 \) and a radial frequency of \( \omega_\rho = 2\pi \cdot 477.4 \).](image-url)
tively. This is within 5% (axial) and 1.9% (radial) agreement with the trap frequencies calculated by Equations (2.11) and (2.12) and the magnetic field strengths of the trap as listed in Table 3.2. In order to measure the 0.85 G offset field in the trap center, the method as described in Section 7.2 was applied, which employs evaporative cooling to the bottom of the trap.

The trap oscillations exhibit damping with $\tau = 0.9$ s for the axial and $\tau = 58$ ms for the radial oscillation. This is attributed to dephasing as a result of the anharmonicity in the trapping potential.