

Chapter 2

The Experimental Setup

The experiments described in this work were performed in a new experimental setup designed and built during the PhD. I first give a brief description of the new apparatus which is necessary for the understanding of the experiments. Following, I elaborate on the various subsystems of the new setup. In particular, I describe the sequence which leads to Bose-Einstein condensation.

2.1 Brief Description of the New Apparatus

In the experiment, cold ^{87}Rb atoms are trapped in a far-off-resonance laser (see Fig. 2.1). The two relevant internal states are $|1\rangle = |F = 1; m_f = -1\rangle$ and $|2\rangle = |F = 2; m_f = 1\rangle$ in the $5^2S_{1/2}$ manifold, which are, to first order, Zeeman insensitive to magnetic fluctuations in the applied magnetic field of 3.2G [1]. Initially $\sim 10^9$ atoms are trapped and cooled in a magneto-optical trap, and further cooled by Sisyphus and Raman sideband techniques. The technique of rapid adiabatic passage with constant RF radiation and a ramped magnetic field is then used to transfer the atoms from state $|5^2S_{1/2}, F = 1; m_f = 1\rangle$ ending with 80% of the atoms at $|1\rangle$, and the rest in state $|5^2S_{1/2}, F = 1; m_f = 0\rangle$. The atoms are loaded into an optical dipole trap created by two horizontal crossing beams at an angle of 28° , creating an oval trap with an aspect ratio of 1:3.9. The $50\text{ }\mu\text{m}$ waist laser beams originate from a single frequency Ytterbium fiber laser at 1064nm. Their polarization is parallel to the magnetic field, and frequency differ by 120MHz to eliminate standing waves. The external control is composed of RF radiation at 2.15MHz and microwave radiation at $\sim 6.8\text{GHz}$, both locked to an atomic standard. The state populations is measured by recording the fluorescence of a detection beam resonant with a transition to an excited $5^2P_{3/2}$ state [2]. An effect which should be taken into account is the levels shift induced by the MW field [3]. We have carefully measured this shift, which in the maximum MW power reaches to $\sim 50\text{Hz}$, and it is taken into account when setting the frequency of the external fields. We carry out evaporative cooling for 2.5s to a

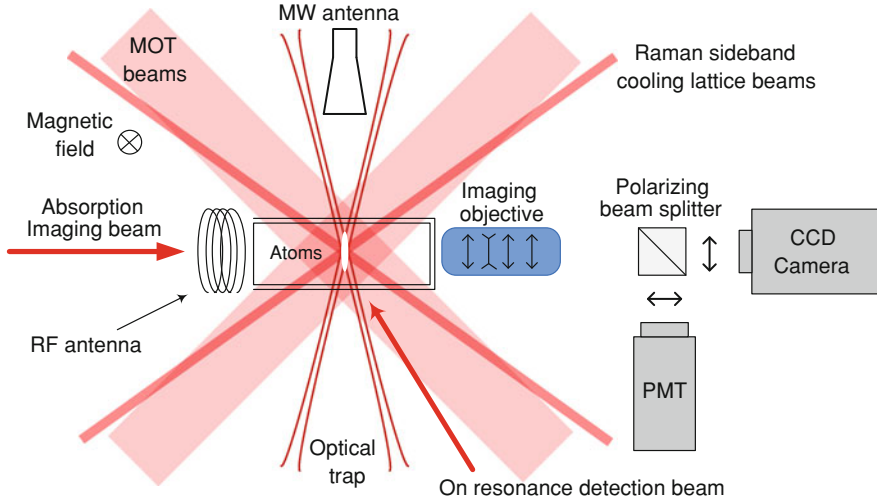


Fig. 2.1 We laser cool ^{87}Rb atoms and trap them in a crossed red-detuned laser beams configuration. We employ state sensitive detection using a detection beam and a photomultiplier tube (PMT), and measure the density and temperature using absorption imaging on a CCD camera

laser power of 0.16 W and back to the final laser value which determines the thermodynamic conditions in the experiment. The typical spontaneous scattering rate is less than 1 s^{-1} and the trap lifetime is longer than 5 s. The temperature is measured by an absorption imaging after a time of flight.

2.2 General Considerations

The design of the new setup is based on several considerations. The two main goals are that the new setup will work with high data acquisition rate, and that it will enable good optical access to incorporate the optical lattice beams, detection and trapping lasers. In conventional BEC setups based on two chambers and magnetic trapping the evaporation sequence takes around a minute, and the typical data acquisition rate is therefore a data point every $\sim 100\text{ s}$. The long evaporation times are a consequence of the low collision rates and low densities in the magnetic trap. In order to increase this rate we have decided to use an optical dipole trap instead. The natural densities and collision rates in an optical trap are much higher, and this allows for much faster evaporation, typically on the scale of a few seconds [4, 5]. The short evaporation times ease the vacuum requirements, and enables us to work in a single chamber. Since we do not use magnetic trapping, it is not necessary to work with very short distances which are usually required to obtain large gradients of the magnetic field. Thus, the size of the vacuum chamber can be larger, which provides a better optical

access. Another advantage of the larger size is that one can use large diameter MOT beams, which increase the number of atoms collected into the MOT for a given ^{87}Rb background vapor pressure. We have designed the MOT coils in such a way that we gain optical access to the atoms at 45° , which then can be used to construct a 3D cubic optical lattice for all sides of the chamber.

To further improve the initial conditions for the evaporative cooling, we have implemented a third optical cooling scheme, Raman sideband cooling [6, 7], in addition to the conventional MOT and polarization gradient cooling schemes (PGC). The details of the implementation and the scheme will be given later, but in short, it works for 10 ms, during which the phase space density of atoms is increased by two orders of magnitude and the temperature is lowered to $\sim 1.5 \mu\text{K}$.

The MOT beams have a diameter of 30 mm and are retro-reflected by a cat-eye setup. The total power of the MOT beams is $\sim 650 \text{ mW}$ (adding the power of the retro-reflected beams), and it is derived from an external cavity diode laser amplified by a tapered amplifier. The repump power is $\sim 20 \text{ mW}$. All lasers are prepared on a separate table and delivered to the setup by optical fibers. Around the chamber there are three pairs of compensating coils through which a current is tuned to cancel residual magnetic fields at the location of the atoms. Very good cancelation is attained though the use of MW spectroscopy of the Zeeman levels. The residual magnetic noise in the lab was measured to be 5 kHz. Rubidium emerges from dispensers operated in a steady state current of 2.4 A, chosen as a tradeoff between longer vacuum lifetime and smaller number of atoms in the MOT. For a given ^{87}Rb background pressure, we use ultra-violet LEDs which desorb atoms from the chamber walls and increase the number of atoms in the MOT and the loading rate [8, 9].

A typical experimental sequence is composed of the following stages:

- Three seconds of Magneto-optical trap loading. Typically 10^9 atoms are collected.
- 30 ms of compressed MOT phase. Magnetic field is not changed, but the repump intensity is lowered and the cooling light frequency is shifted to the red.
- Two consecutive PGC phases, separated by 5 ms, each is 2 ms long.
- Raman sideband cooling phase, 12 ms long.
- During all this time the dipole trap is on, and at typically $t = 3.023 \text{ s}$ all cooling lasers are shut off.

2.3 Magnetic Coils

The design of the new set of coils had to reach the necessary anti Helmholtz fields required for the MOT operation (typical gradients are 10 G/cm), be able to produce in a Helmholtz configuration a magnetic field of 1007 G required for a Feshbach resonance in ^{87}Rb , and finally preserve the optical access at 45° relative to the axis connecting the centers of the two coils for future use (i.e. in constructing optical lattices). The new design is based on two coils with 49 windings each of copper tubes with an outer diameter of $1/8''$. To comply with the third requirement we used

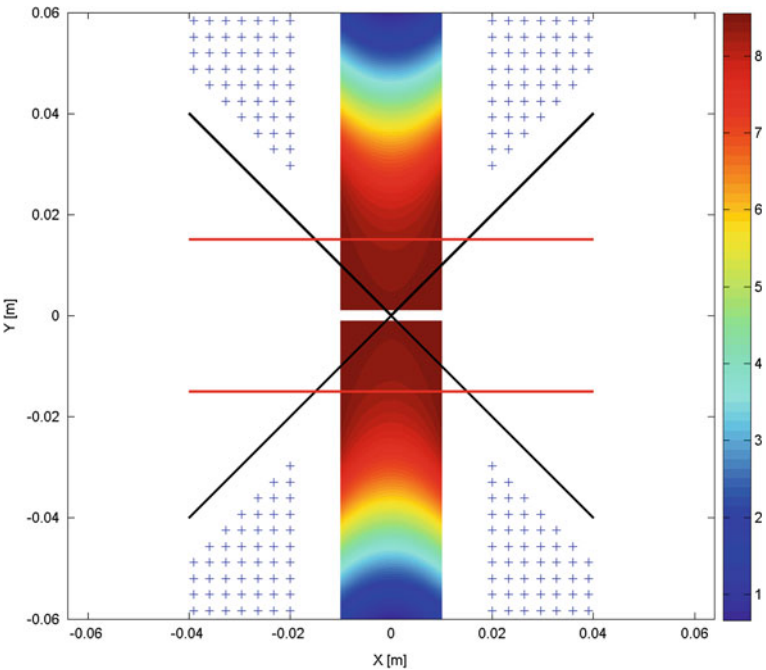


Fig. 2.2 Magnetic field magnitude [G] in a Helmholtz configuration of the coils with 1 A current. The *blue* markers are the cross sections of the coils windings. The *black lines* in the figure are the optical axes at 45° to the coils axis. The *red lines* depict the diameter of the MOT beams

Table 2.1 Physical characteristics of the new coils

	Calculated	Measured
Current to produce magnetic field of 1007 G	120 A	126 A
Resistivity of a single coil	0.09 Ω	0.076 Ω
Optimal current for MOT	10 A	8 A
Exiting water temperature at $I = 100$ A	60°	80–60°

a conical hollow center for the coils. The design and the Helmholtz fields created by a current of 1 A are shown in Fig. 2.2. From this calculation we see that a current of 120 A will be needed in order to achieve the 1007 G Feshbach resonance. The use of tubes enabled us to use cooling water, which is available in the lab, to cool the coils efficiently at such high currents. In Table 2.1 we compare the designed and achieved values of several physical characteristics of the new coils.

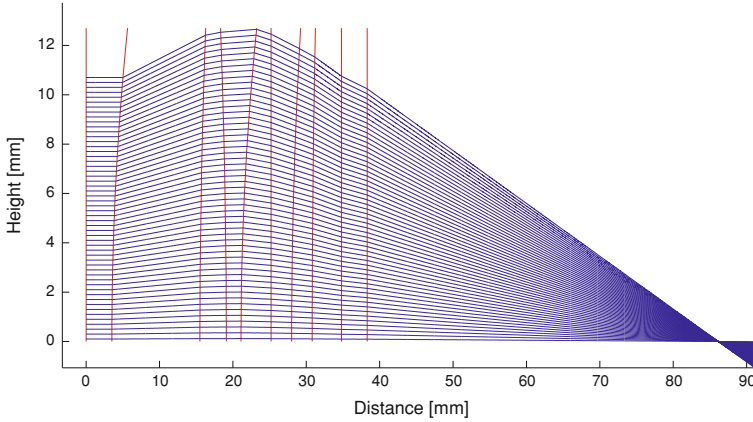


Fig. 2.3 Raytracing of the designed objective. The *red lines* are the surfaces of the lenses. The final set of *red lines* is the chamber wall

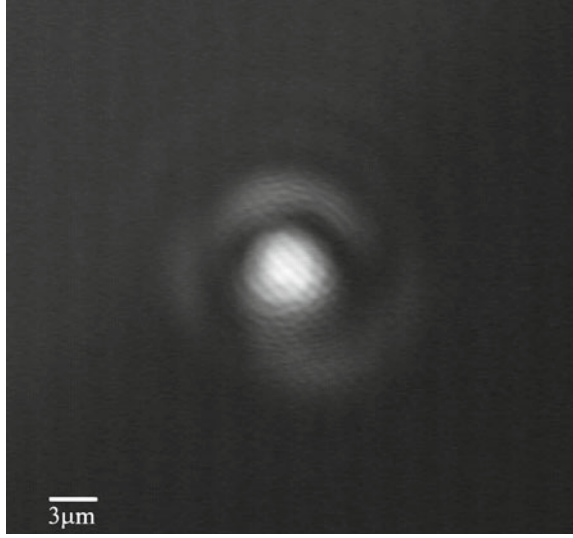
2.4 Imaging Setup

The imaging setup is a conventional on resonance absorption imaging setup [10] with two unique features: First, the imaging setup objective lens was designed and built according to our calculations, and it gives a resolution of $\sim 3.3 \mu\text{m}$ with a relatively large working distance of 50 mm. Second, a new technique was developed in order to take a reference picture in less than $100 \mu\text{s}$ after the absorption picture with the atoms. With such a short waiting time, there is a substantial reduction of the noise in the analyzed picture. The technique relies on an intense pumping of the atoms into a far detuned state before taking the reference picture. The pumping process is very short, and therefore enable us to take pictures $40 \mu\text{s}$ long and separated by only $50 \mu\text{s}$. This effectively freezes the movement of the fringes which usually appear in the absorption beam and produces a background which is almost shot noise limited.

2.4.1 The Imaging System Objective

The heart of the imaging system is the objective lens. Due to the sizes of the chamber, we wanted a diffraction limited lens, with a working distance of at least $\sim 50 \text{ mm}$, a diameter of an inch and preferably a lens which is made of standard optical elements (and thus cheaper). We have written a raytracing script in Matlab (the code is given in Appendix B), and used as a starting point the design given in Ref. [11]. We restricted ourselves to use only standard lenses from Thorlabs, and used their published physical properties in the raytracer. Our final design is given in Fig. 2.3. The lenses used in this design are LC1582 LB1676 LA1608 LE1202, and the distances and properties are given in the Appendix. The designed objective has a NA of 0.2 and spherical

Fig. 2.4 Airy pattern measured for the home built objective



geometric aberrations much less than the diffraction limit, which is $\sim 2.5 \mu\text{m}$ at a wavelength of 780 nm . The designed effective focal length of the objective is 50.8 mm .

We have built the objective using mounting tubes and rings we had bought from Thorlabs. We have tested the resolution of the objective with the following setup; 780 nm collimated light emerged from a single mode fiber (waist $\sim 1.1 \text{ mm}$). Afterwards it was enlarged by a telescope of $7.5\text{--}50 \text{ cm}$ lenses (magnification of $\times 6.66$), and injected into the objective. We made sure that the objective is indeed parallel and centered to the beam. After that we have placed a 3.7 mm long window to simulate the vacuum chamber wall. Afterwards, we used a commercial $\times 60$ objective held on a xyz translation stage and imaged the spot onto a calibrated camera. The measured picture is given in Fig. 2.4. The measured resolution (half the Airy disk) is $\sim 3.3 \mu\text{m}$.

2.4.2 Absorption Imaging with Very Short Delay Times Between Pictures

Absorption Imaging is usually the main diagnostic in BEC experiments. Two images are taken, in the first one the light interacts strongly with the atoms (i.e. absorption) whereas in the second not. The background is then subtracted from the two images, and the absorption signal can be calculated. Each picture of the absorption beam contains many fringes arising from interference from parallel planes in the way of the absorption beam (i.e. windows, vacuum chamber, lenses, and so forth). These fringes tend to change their position at acoustic timescales, which results in a structured

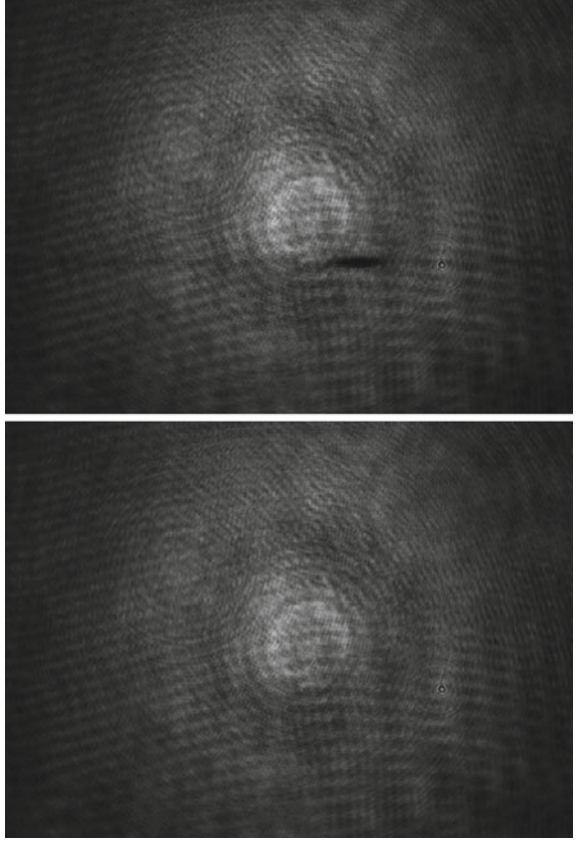
noise left in the picture which is not related to information from the atoms. In order to eliminate this noise it is necessary to reduce the time delay between the pictures. Nevertheless, going down to short delay poses an inherent problem: the atoms do not move fast enough to be absent from the second picture. There are numerous possible solutions for this problem, and we are going to describe here one of them which we have implemented successfully in the setup.

The atoms can initially be either in the $F = 1$ or $F = 2$ state. The absorption beam is resonant with the $F = 2 \rightarrow F' = 3$ transition, and thus it is necessary to add to the first pulse also a repump beam resonant with the transition $F = 1 \rightarrow F' = 2$. After the first absorption pulse is over (usually its duration is $50 \mu\text{s}$ or less), we switch on a depumping beam resonant with the transition $F = 2 \rightarrow F' = 2$. This beam is on for only a short time (typically less than $50 \mu\text{s}$), and it efficiently drives the atoms into the $F = 1$ state. Then, only $100 \mu\text{s}$ after the first pulse, a second pulse is switched on, but this time it only includes the absorption beam and not the repump. Since ideally there are no atoms in $F = 2$ there will be no atomic absorption in this pulse, and it will serve only as the background picture. Since the repump in the first pulse is not collinear with the absorption beam, only the absorption beams enters the camera directly. The intensities of the two pictures is on the average the same. The differences that still exists arise due to the fact that the camera technically can't close the shutter in the second image quickly and therefore collects more background noise.

To demonstrate the technique we cool and trap ^{87}Rb in a dipole trap. The trapping laser is shut off exactly before the absorption pulse time in order to avoid substantial *Stark* shifts. The imaging consists of two $50 \mu\text{s}$ pulses as described before, separated by a time delay of $50 \mu\text{s}$ in which a depumper beam is switched on. The imaging optics is constructed by the objective described earlier and a second $f = 150 \text{ mm}$ lens that image the picture into a *PCO Pixelfly* *qe* double shutter camera with resolution of 1024×1392 pixels. With this optical setup, each pixel correspond to $2.24 \mu\text{m}$ in the plane of the atoms.

The raw images are shown in Fig. 2.5. There are many fringes and inhomogeneities in the two pictures, but the atomic absorption signal is still apparent. The intensity in the two pictures is different by only 2%. For weak absorption beams ($I \ll I_{\text{sat}}$), the pictures are analyzed by first subtracting the relevant dark pictures (taken before the experiment without lasers), dividing the two pictures with the appropriate intensity correction (so they have the same average intensity), and finally a logarithm is taken. The result is the optical density of the atoms, an example of which is shown in Fig. 2.6. A zoom of the atoms in the trap is shown in Fig. 2.7. The standard deviation of the background noise is ~ 0.048 (in the optical density), which corresponds to ~ 8 atoms per pixel. The shot noise of the laser beam can be calculated in the following way. In a pulse duration of Δt we calculate the number of photons n that incident on a single pixel. The shot noise in the optical density is then given by $\log(n + \sqrt{n})/(n - \sqrt{n}) \approx \log 1 + 2/\sqrt{n}$. For a $50 \mu\text{s}$ pulse of $100 \mu\text{W}$ laser, and taking into account the quantum efficiency of the camera (25%), this results in a noise of ~ 0.035 in the optical density. All this assumes a uniform distribution of the

Fig. 2.5 Raw images taken in the absorption scheme described



laser on all pixels. We see that the noise in the absorption picture is 40% higher than the shot noise limit.

When the optical density is substantially higher than unity, there is an advantage to work with absorption beam with higher intensity [12]. In this case, a more careful analysis of the absorption picture is required. Let us denote by I_{in} the incident absorption light, then the number of photons scattered by an atom in one second is given by $\Gamma_{sc} = \gamma/2 \cdot (1 + I_{sat}/I)^{-1}$, where I_{sat} is the saturation intensity, γ is the natural linewidth of the transition, and we assume an on resonance light. Notice that if the optical density is high, and if I is comparable to I_{sat} , there will be an exponential decrease in the transmitted intensity, which in turn modifies the scattering rate. This effect is the deviation from the usual analysis described before. We can write a differential equation describing the propagation of the absorption beam intensity through the atoms:

$$\frac{\partial I}{\partial z} = -\rho \frac{\hbar\omega\gamma}{2} \frac{I}{I + I_{sat}},$$

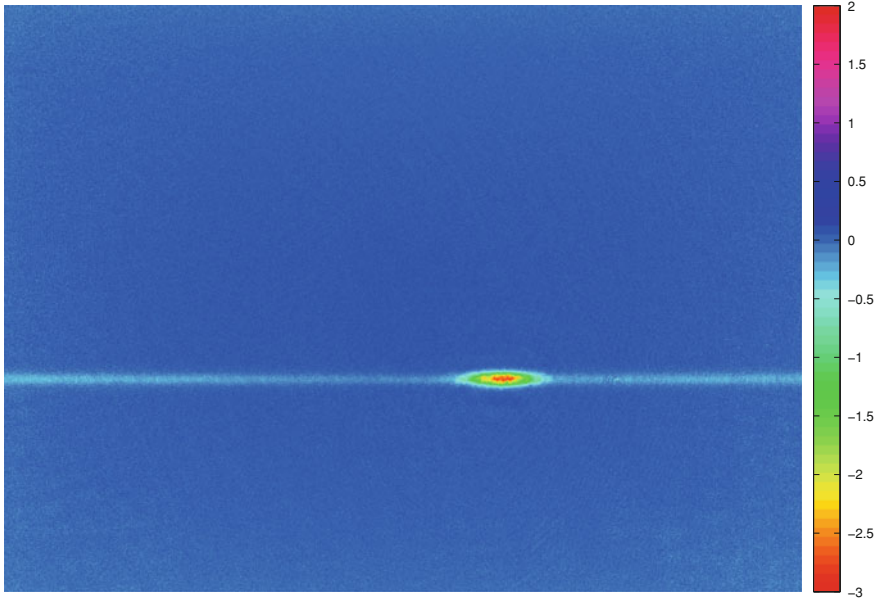


Fig. 2.6 Absorption image of atoms in a $80\ \mu\text{m}$ dipole trap. The colors represent the optical density. The crossing high optical density oval shaped cloud is the crossing region of the two crossed trapping beams. One can see that many atoms are also captured in the “wings” of these two beams

where ω is the transition frequency, ρ is the density of the atoms and z is the propagation direction. We shall multiply the equation by $(1 + I_{sat}/I)$ and integrate along z to arrive at the result:

$$\frac{I_{out} - I_{in}}{I_{sat}} + \ln(I_{out}/I_{in}) = -\rho_s \frac{\hbar\omega\gamma}{2I_{sat}},$$

where we define the surface density by $\rho_s(x, y) = \int \rho(x, y, z)dz$, and use the notations I_{in} and I_{out} for the incoming and outgoing beams, respectively. The calibration of the camera enables us to translate the recorded picture into intensity, and because the intensity difference between the two pictures is very small (normally no more than 2%) we can assume that the absorption pictures gives I_{out} and the reference picture gives I_{in} (in both picture we subtract a “dark” picture without the beams to eliminate any systematic background noise). Once we have I_{out} and I_{in} we can plug it into the equation and obtain $\rho_s(x, y)$. Since the system has a cylindrical symmetry, from $\rho_s(x, y)$ we can infer $\rho(x, y, z)$. This is especially easy if we assume a certain shape of the cloud, i.e. a Gaussian.

From the measurement of the density distribution in different times we can measure all other parameters; temperature can be measured by the time of flight technique, oscillation frequency can be measured by observing the shape of the atomic cloud after some disturbance is made in the trap (more details on this later) and finally the

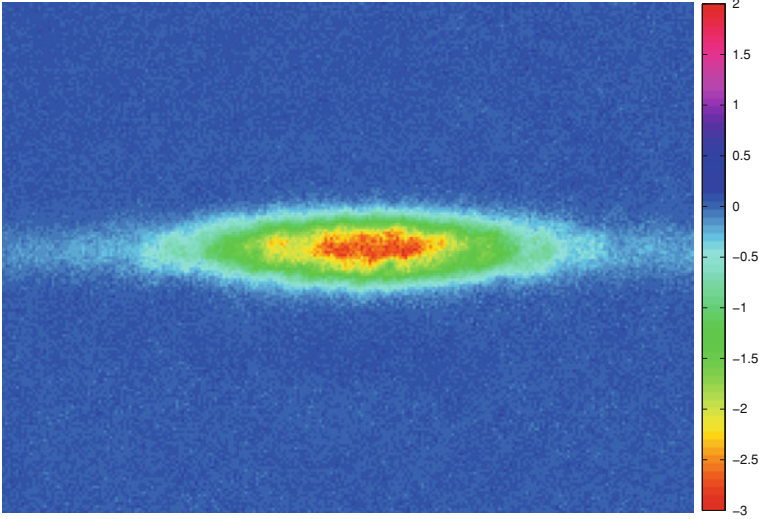


Fig. 2.7 Absorption image of atoms in a $80\,\mu\text{m}$ dipole trap, zoomed. The colors represent the optical density

total number of atoms can be found by integration over the density distribution. From measurements of T , ω_{osc} , N and ρ we can also calculate the phase space density and collision rate.

2.5 State Manipulation and Detection

In this thesis the two relevant internal states are $|1\rangle = |F = 1; m_f = -1\rangle$ and $|2\rangle = |F = 2; m_f = 1\rangle$ in the $5^2S_{1/2}$ manifold (see Fig. 2.9). The advantage of working with these two levels is that, to first order, they are Zeeman insensitive in an applied magnetic field of 3.2G [1]. Since $\Delta m = \pm 2$ between these two states, the external control $\Omega(t)$ is done by a two-photon transition, employing RF radiation at 2.15 MHz and microwave radiation at 6.832527928 GHz (see Fig. 2.9). An effect which should be taken into account is the microwave dressing effect, namely the shift of the energy levels due to the applied MW field [3]. We have carefully measured this shift as a function of the MW power and found it can typically reach a maximum of about $\sim 50\text{Hz}$. This shift has to be taken into account when setting the frequency of the external fields.

We measure the Rabi frequency, Ω , of the external field in the following way; We detect the population at state $|2\rangle$ while scanning the duration of the applied external field pulse. An example of such a measurement is given in Fig. 2.8. We fit the oscillating data points with the function $y = a \cos[\Omega t] + b$ and extract the Rabi frequency. In the given example the fit yields $\Omega/2\pi = 628.5 \pm 0.8\text{Hz}$, where the error margins are given with a confidence level of 95%. The accuracy of this measurement

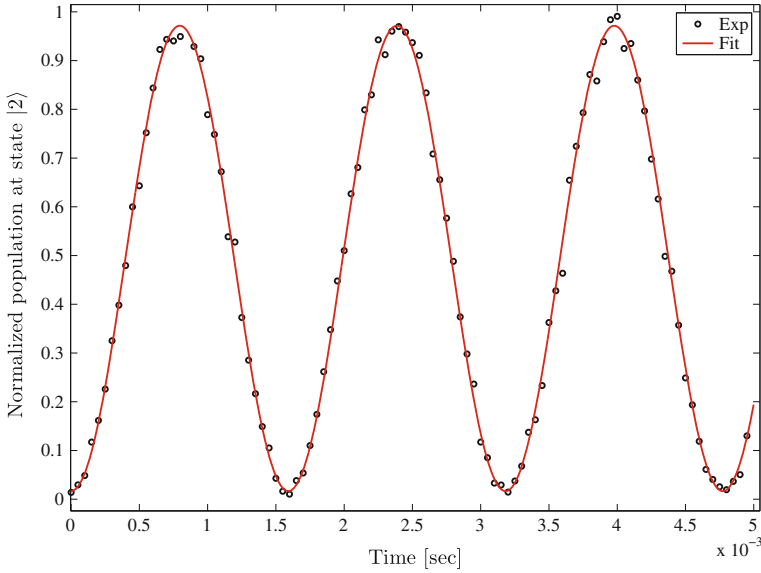
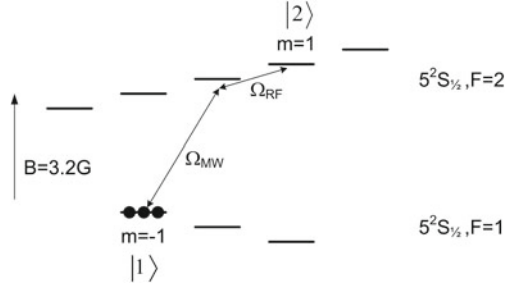


Fig. 2.8 Calibration measurement of the Rabi frequency of the control field. The x-axis is the duration of the pulse, and the y-axis is the normalized population at state $|2\rangle$. We fit the data to the function $y = a \cos[\Omega t] + b$ to find the Rabi frequency Ω

Fig. 2.9 Diagram of the hyperfine ground states of ^{87}Rb , with the two relevant magnetically insensitive states. A two-photon transition is employed, with a large enough detuning from the intermediate level



is 0.13%. Also note that the time resolution we have in setting the external pulse duration is 25 ns. Spatial variation of the external control field over the ensemble are very small since the wavelength of the microwave radiation is ~ 4.4 cm compared to the typical size of the atomic cloud which is ~ 100 μm . The single π -pulse fidelity was measured to be $F = 0.995$ in an experiment in which we induce more than 100 sequential pulses and measure the oscillations decay.

The state detection scheme is similar the one described in Ref. [2]. We use a detection laser beam which is resonant with the transition $|5^2S_{1/2}, F=2\rangle \rightarrow |5^2P_{3/2}, F'=3\rangle$. We first give a 1 ms long detection pulse which probes the population in the state $|2\rangle$. We measure the fluorescence signal from the atoms using

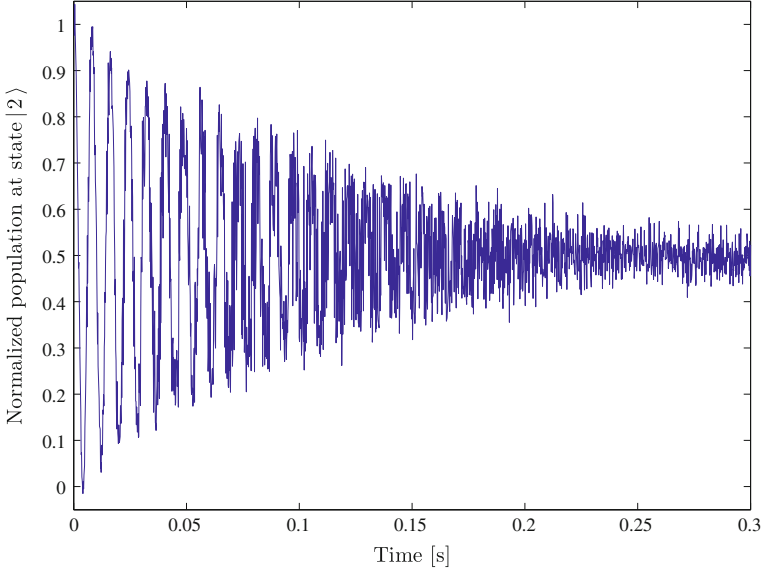


Fig. 2.10 A typical result of a Ramsey experiment with $\Gamma = 130 \text{ s}^{-1}$. The duration of a $\pi/2$ pulse is $250 \mu\text{s}$

a photomultiplier tube. This detection pulse also gives the atoms at $|2\rangle$ momentum kicks which drive them out of resonance due to the doppler shift. We then give a short pulse of a repump laser which is resonant with the transition $|5^2S_{1/2}, F=1\rangle \rightarrow |5^2P_{3/2}, F'=2\rangle$. The purpose of this pulse is to transfer the atoms at state $|1\rangle$ to $|5^2S_{1/2}, F=2\rangle$. Finally, we give another 1 ms long detection pulse which detects the atoms that were in $|1\rangle$. We normalize the signal of atoms at state $|2\rangle$ to the total signal, and we obtain the probability to find an atom at $|2\rangle$. Note that this three pulse sequence is carried in the same experimental run.

As will be explained in the next chapter, we use a time-domain Ramsey experiment to measure the coherence; a short $\pi/2$ pulse produced by the external control field prepares the atoms in a superposition $|\psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle)$ followed by a waiting time t , then a second $\pi/2$ pulse and finally a measurement of the population at $|2\rangle$. A typical result can be seen in Fig. 2.10. Such a measurement consists of 2000 points taken with different waiting times between the two $\pi/2$ pulses. The fast oscillations are a manifestation of the detuning between the transition frequency and the control field. To facilitate the extraction of the decoherence envelope function, we set this detuning to be much larger than the decay rate which ensures a separation of timescales. The envelope function is extracted by taking the standard deviation of n points, where n is the average number of points in a single fast oscillation period.

2.6 The Trap Setup

The heart of the new setup is the optical dipole trap. The use of a far detuned dipole trap has many advantages; The depth of the trap depends only weakly on the Zeeman sublevel of the atoms. The initial conditions of the atoms are much more favorable than those in a magnetic trap, probably due to a local increase in the phase space because of the dimple effect [13], and also suppression of re-scattering. Another advantage is the high initial collision rate, which in turn enables shorter evaporation times. Nevertheless, the main disadvantage is the lack of a similar effect to the so called ‘RF knife’ in a magnetic trap [10], namely the removal of the hottest atoms in a controlled way without changing the oscillation frequency of the trap. In a gaussian beam trap, the radial oscillation frequency can be approximated by $\omega_{osc}^2 = 4U_0/m\sigma^2$ where U_0 is the trap depth, m is the mass and σ is the beam waist (e^{-2} radius). The common and easiest way to force evaporation is to decrease the power of the laser [4]. Since this procedure also lowers the trap depth U_0 it decreases the oscillation frequency. Thus, the efficiency of the evaporation deteriorate as evaporation progress and it is not possible to carry runaway evaporation (evaporation process in which the collision rate increases). One way which was proposed to circumvent this problem is to dynamically change the waist of the beam during the evaporation [5].

In order to change the waist of the laser we have designed and built an optically compensated zoom system. Also, to keep the aspect ratio of the trap constant we have decided to work with a two beam trap in a crossed configuration. The aspect ratio is directly controlled by the crossing angle between the two beams. The trapping laser setup is depicted in Fig. 2.11. The trap laser is an Ytterbium fiber laser manufactured by IPG, model YLR-50-1064-LP-SF. This is a 50 W single frequency fiber laser (linewidth < 50 kHz) with a wavelength of 1064.347 nm and a waist of 1.5 mm. We tested the new laser with a high speed detector (8 GHz BW) and verified that there are no more than a single mode, at least at the measured bandwidth. The setup produces a 28° crossed beam trap with a waist range of 50–250 μm and an aspect ratio of 1 : 4. The total power reaching the atoms is $\sim 30\text{--}32$ W. The laser emerges with a linear polarization through an optical isolator. It is then passed through a telescope which is focused to a waist of 800 μm on an AOM (Model 35060-30-3-1.06-I-HGM-W with driver model 39060-30DMA05-A, manufactured by NEOS Tech). After the telescope there is a polarization beam splitter (PBS1) and a mirror (M1) which create the two beams that are going to enter the AOM. The ratio between the two beams can be controlled using a $\lambda/2$ placed just after the laser head. The two beams are aligned such that they heat different spots on the AOM. The right (left) beam is resonant with the moving acoustic scattering lattice in the AOM and diffracts into the order +1 (−1). The remaining zero orders of both beams are removed by a beam dump. The two diffracted beams are then mode matched and recombined on a beam splitter (PBS2). Since the AOM is sensitive to the incident polarization we rotate the polarization of the left beam before and after the AOM. The AOM operates at 60 MHz, therefore the frequency difference between the two diffracted beams is 120 MHz which effectively prevents effects of standing waves. Mirrors M3 and M4 are used to align the beam

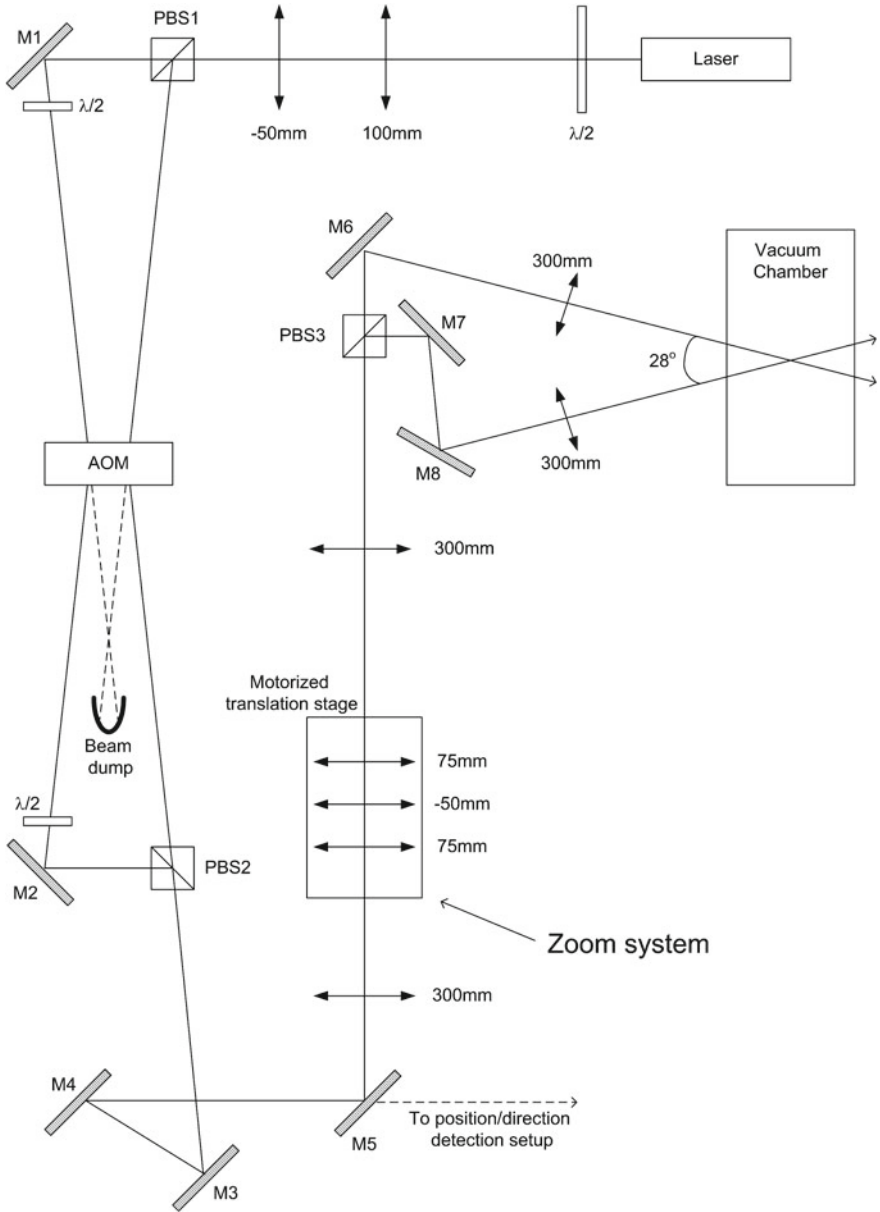


Fig. 2.11 A sketch of the experimental setup of the trapping laser

to a specific mode which is measured by two quadrant detectors placed after the leakage of mirror **M5**. In case of problems before Mirror **M5**, this enables us to correct the problems and then realign very accurately the beam such that it does not

require further realignment after M5. The lenses after M5 create the zoom system (it will be described afterwards in more detail). The two beams are finally separated by polarizing beam splitter (PBS3) and sent into the chamber. The final polarization state of the two beams can be further manipulated by waveplates just after mirrors M6 and M8. The holders of mirrors M6 and M8 include piezoelectric elements that enable real time fine tuning of the crossed position. After the trap beams leave the chamber we image them on a position sensitive quadrant detector, and lock their position using the piezoelectric mirror mounts. The position locking corrects small displacements of the focus position during the dynamic compression of the zoom. Also, we continuously monitor the beams power (we do this also at the leakage after M5), and lock the power to the desired value. This value changes during the evaporation, and so the power locking system keeps the beams power locked to this value dynamically.

In an ideal zoom system the beam waist changes without affecting its position. However, to a certain extent a movement of the waist is acceptable if it is kept under some limitations. At the crossing point of the two trapping beams the potential depth is twice the depth of each single beam. If the waist is more than one Rayleigh range away from the crossing point, another local minima of the potential appear at the waist of each beam. Therefore, it seems reasonable to tolerate a movement of the waist position up to one Rayleigh range of the beam.

It is well known that an ideal zoom system requires an independent movement of at least two optical elements (mechanically compensated zoom systems). There is a different approach which require only a single moving platform (so there is only a single independent moving variable), but allow the concurrent movement of several optical elements. This approach gives an approximation of a zoom system, and is called optically compensated zoom system [14]. In the lowest order of implementation we allow the concurrent movement of two lenses, where in between there is a static third lens (the moving lenses does not change their relative distance).

We have designed optically compensated zoom system which achieve a waist range of 50–250 μm . Design parameters were optimized using Gaussian ABCD matrices simulations. Our design is based on two positive moving lenses with focal length of 75 mm positioned 10 cm apart from each other, and in between one fixed negative lens with a focal length of -50 mm . The result of the simulation of our design is given in Fig. 2.12. We have built this system and verified that indeed we get the designed waist range.

2.7 Raman Sideband Cooling

Raman sideband cooling is an optical cooling scheme first proposed and demonstrated by Steven Chu's group in 1998 [6, 7]. In this scheme, one uses a magnetic field to shift the relative energy of two vibrational ladders of two Zeeman sub levels such that the states $|m; n\rangle$ and $|m + 1; n - 1\rangle$ are degenerate (m is the Zeeman index and n is the vibrational state index). Once the levels are degenerate, Raman

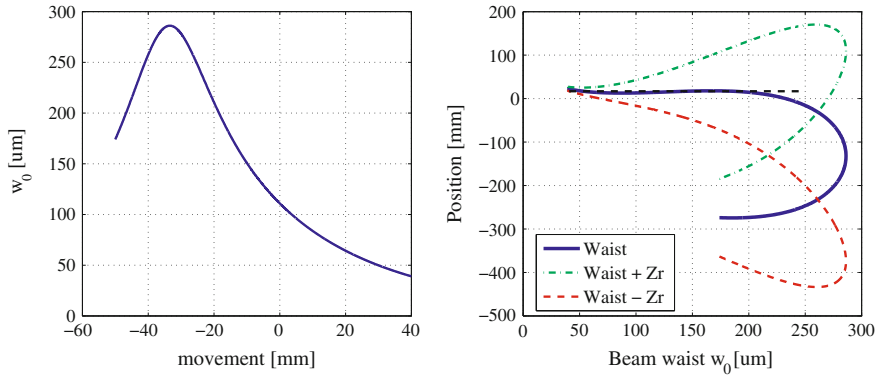


Fig. 2.12 Simulation of a three component optically compensated zoom system. Simulation are done using ABCD matrices. *Left* graph is the waist size as a function of translation stage position. We can verify that we have a factor of over six magnification of waist size for 85 mm of motor travel. *Right* graph is the waist position as a function of the waist size. The position of the $\pm$ Reighley range from the waist position is also depicted. The *black dashed line* indicate that we can choose a fixed position in space in which our criterion of waist position movement is fulfilled

transitions move the atoms from $|m = -1; n + 1\rangle$ to $|m = 1; n - 1\rangle$. In this transition the atoms loose two vibrational quanta. The final stage of the scheme is optical pumping back into the $m = -1$ state. One has to make sure that the confinement is strong enough such that the atoms are in the Lamb-Dicke regime, and thus the probability for a change in the vibrational level during the optical pumping process is small. To accomplish this and also to create a well separated vibrational ladder, we built a four beam optical lattice. The lattice beams also induce the degenerate Raman transitions.

The implementation of the scheme in ^{87}Rb is depicted in Fig. 2.13. Magnetic field of ~ 200 mB is applied in the z axis. The Raman lattice is composed of four beams in exactly the same geometry and polarizations as in Ref. [6]. The total power of the raman lattice beams is 350 mW and the frequency is detuned by +13 GHz with respect to the $D2 F = 1 \rightarrow F' = 2$ transition. The optical pumping is done with a strong $\sigma +$ ($\sim 20 \mu\text{W}$) and a weak π beam ($\sim 2 \mu\text{W}$), both detuned +10 MHz with respect to the $D2 F = 1 \rightarrow F' = 0$ transition. Also needed is a repumper which pumps back atoms transferred to $F = 2$ state. All beam waists are ~ 1.1 mm.

The cooling sequence starts just after the second PGC phase. We ramp up adiabatically the lattice, and switch on the magnetic fields, optical pumping and repumper lasers for 10 ms. Finally, the lattice is ramped down, while the magnetic field is still on. A temperature measurement done in a time of flight technique is shown in Fig. 2.14. Temperatures of $\sim 1.5 \mu\text{K}$ are typical. We end up with few 10^8 atoms, in a typical waist of $500 \mu\text{m}$, which gives a typical phase space density of 5×10^{-4} . We have also performed MW spectrometry experiments after the sequence, a typical result of which is given in Fig. 2.15. The optical pumping produces a typical distribution of 80% of atoms in $m = 1$, 15% in $m = 0$ and 5% in $m = -1$.

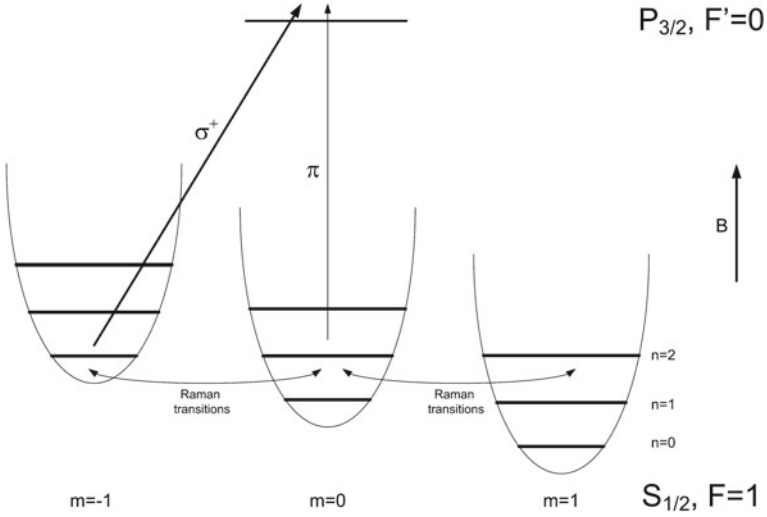


Fig. 2.13 Raman sideband cooling in ^{87}Rb atoms

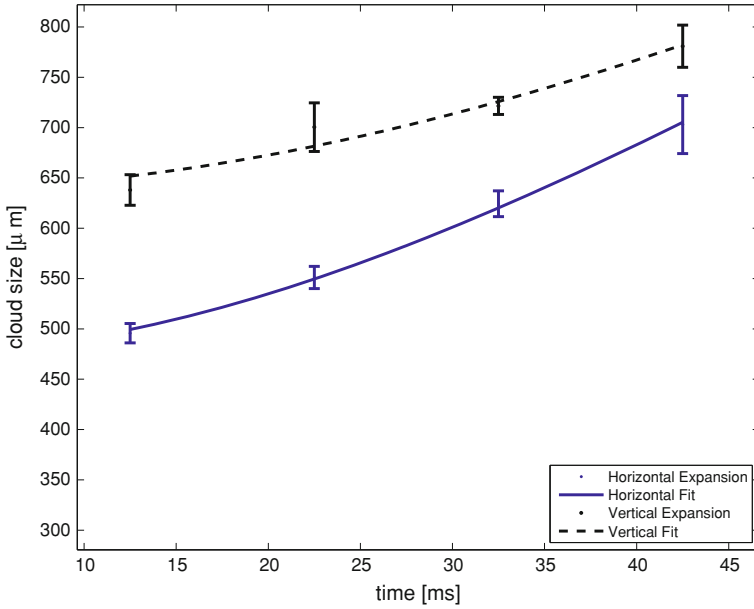


Fig. 2.14 Time of flight measurements of ^{87}Rb atomic cloud after Raman sideband cooling. Fits correspond to temperature of $1.58 \pm 0.06 \mu\text{K}$ in the horizontal direction and $1.20 \pm 0.25 \mu\text{K}$ in the vertical direction. Cloud size, σ , is found by fitting to a density distribution function: $n(r) = n_0 e^{-\frac{r^2}{2\sigma^2}}$. Time is the expansion time of the cloud measured from the sudden shut down of the lattice. Error bars are standard deviations of three measurements done for each point

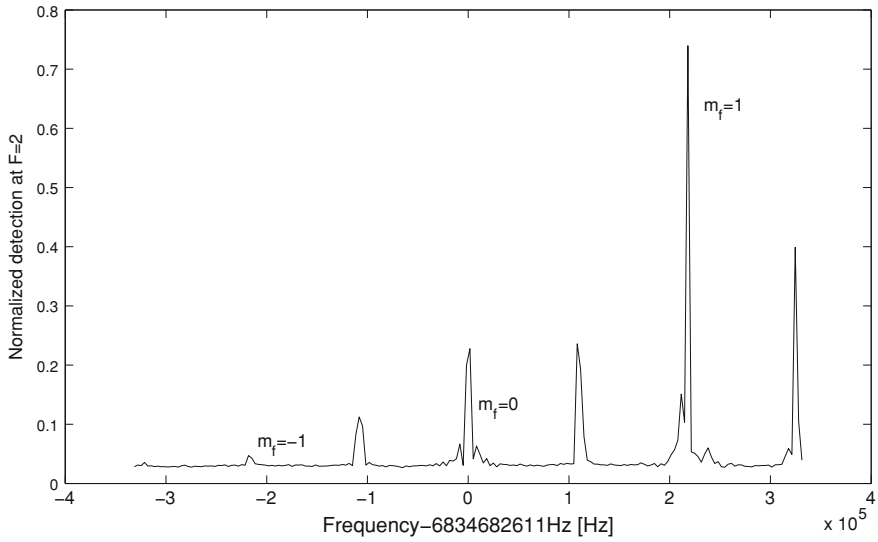


Fig. 2.15 Zeeman level distribution measured by RF magnetic transitions spectrometry. x axis is the RF photons frequency and y axis is the normalized detection signal which corresponds to the Zeeman level population. Besides the peaks of the equal m transitions there are also transition with $\Delta m \neq 0$ due to RF photons with $\sigma+$ and $\sigma-$ polarizations. In this measurement there is a magnetic field of ~ 160 mG

2.8 Levitation

Raman sideband cooling enables to reach temperatures as low as $1.5 \mu\text{K}$. The needed trap depth to load such cold atoms is very low, and thus for a given laser power larger trap waists can be used. Nevertheless, when going to larger trap waists, the gravitational energy difference across the trap can be larger than the trap depth. As an example, for a $200 \mu\text{m}$ distance the gravitational energy for ^{87}Rb is $21 \mu\text{K}$. A useful tool in cold atomic experiments is the use of some force to contradict gravitation and to effectively create levitation in the location of the atoms.

In our setup we have implemented levitation using magnetic forces. The main idea is to use the magnetic dipole moment of the atoms, and to create a magnetic field gradient such that the force equals mg . The magnetic dipole interaction energy is given by $H_B = m_f g_f |B|$, where we assume magnetic dipole moment adiabatic following of the magnetic field direction. For our case $m_f = 1$ (this is the resulting state after the Raman sideband cooling), and $g_f = 0.7 \text{ MHz/G}$. We use the main coils of the MOT to create the field gradient needed for the levitation. We have carried out a 3D calculation of the magnetic fields, and determined that the needed current in the coils in an anti-Helmholtz configuration is 13 A. In the experiment we have found that the value should be 12 A. The use of two coils in an anti-Helmholtz configuration facilitates the current requirement from the current driver, but the drawback is stronger

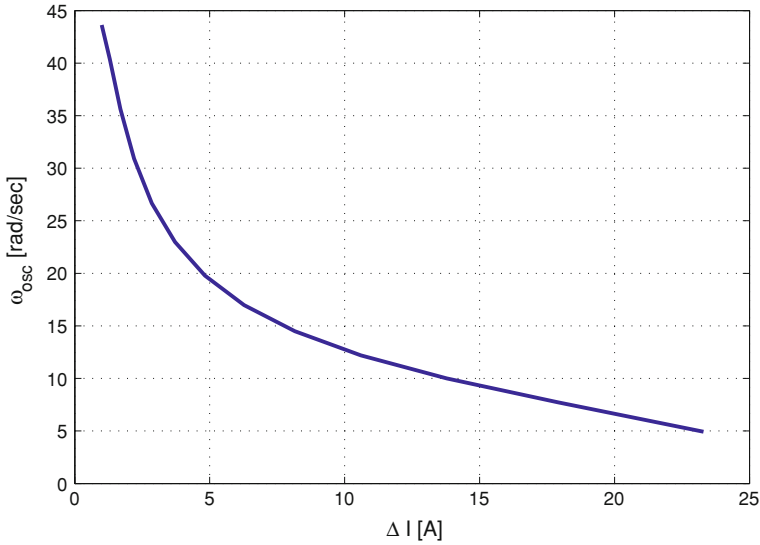


Fig. 2.16 Calculation of the transverse anti trapping oscillation frequency induced by magnetic field gradients in the transverse plain as a function of ΔI which is the difference between the current in the *upper* and *lower* coils. The sum of the two currents is kept constant at 24 A to produce the axial magnetic field gradients necessary for levitation

transverse magnetic field gradient which induces anti trapping in the transverse plain. On the other hand one can use a current of 24 A in a single coil to get better results. The calculated transverse anti trapping oscillation frequency is depicted in Fig. 2.16. We have found that the small anti trapping effect in the transverse plain can be useful to get rid of the atoms that are weakly trapped in the wings of the two trapping beams. We have found that these atoms cause excessive heating when they collide with atoms inside the crossing region. Since the transverse trapping frequencies are usually very low, these anti trapping effect helps to spill these atoms without changing effectively the potential in the crossing region.

To summarize, we have used an unbiased current in an anti Helmholtz configuration of the MOT coils to levitate the atoms. We have found and verified the exact parameters of the levitation by optimizing the number of atoms is a very shallow trap (which does not trap without levitation), and also by time of flight measurement in which we verified that there is no free fall.

2.9 Lifetime Measurements

The vacuum measured by the vacuum ion pump is $\sim 2 \times 10^{-11}$ Torr. The ambient vapor pressure at the position of the atoms is determined by the current in the Rb dispensers. This value is a tradeoff between high current which would result in more

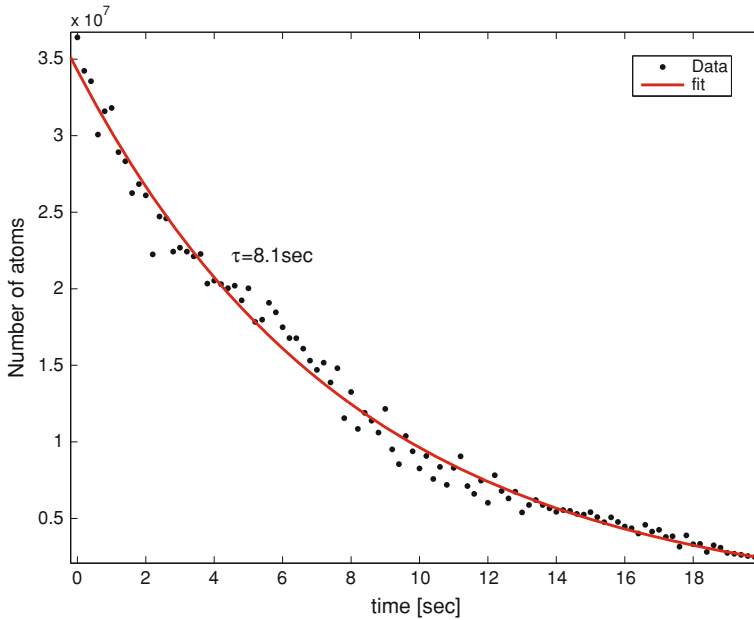


Fig. 2.17 Lifetime measurement in a magnetic trap. We fit to exponential function $N = N_0 e^{-t/\tau}$. In this measurement the atoms are prepared in $F = 1$ state

atoms gathered in the MOT and low current which will result in longer lifetimes and thus more efficient evaporation. We can measure the lifetime in different ways. One of the most sensitive ways is to measure the lifetime of atoms loaded into a magnetic trap. This is a very sensitive probe to m changing transition, because such a transition immediately transfer the atom to an untrapped state, in contrast to other heating mechanisms which require many photons to cause a loss of a single atom. Such m changing transitions occurs mainly due to stray light. We have found that with very small leakage, lifetime measured using this method are an order of magnitude shorter than as measured in other methods. The results of a typical measurement is given in Fig. 2.17, where the measured exponential decay time is 8.1 s (in this measurement the current in the getters is 2.7 A). Notice that the exponential fit describes the data well, which implies that in this measurement there is no density dependent loss. This is expected since the densities we obtain in magnetic trap are quite low. Measurements with optical dipole trap with different beam waists give similar results. Recently we have reduced the current in the getters to 2.4 A, and the lifetime increased to more than 10 s.

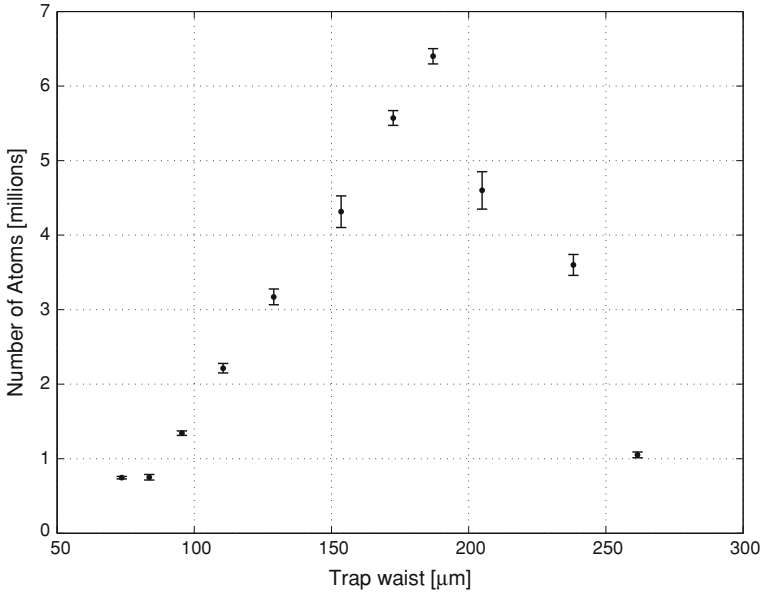


Fig. 2.18 Number of loaded atoms in the trap as a function of the trap waist. The error bars are the standard deviation of the average of seven measurements. The measurement is done 100 ms after the end of the cooling and loading phases. No levitation in this measurement

2.10 Trap Loading

The trapping laser is present throughout the optical cooling phases since we did not notice any improvement when it was shut off during this time. The number of collected atoms as a function of the trapping laser waist when the laser is at full power is given in Fig. 2.18. The graph shows that there is an optimum around $\sim 200 \mu\text{m}$ waist size. At larger waists gravitation starts to lower substantially the trap depth, and in lower trap depths the capturing volume is smaller. Actually, when trying to take these two considerations into account it seems that there is another mechanism in smaller trap waists which helps to keep the number of atoms higher than expected. We believe this mechanism to be the so called dimple effect, as was demonstrated in Ref. [13, 15]. In short, the dimple effect is a local increase of the phase space density in comparison to the phase space density of a reservoir, in a region of space where the potential is lower than the potential at the reservoir, and in thermal equilibrium. When using smaller waist traps we gain in the phase space since the potential in the trap is lower than in the Raman sideband cooled cloud. When adding levitation we gain in the number of atoms (typically not more than 20%), and the drop in the number of atoms shifts to larger waists.

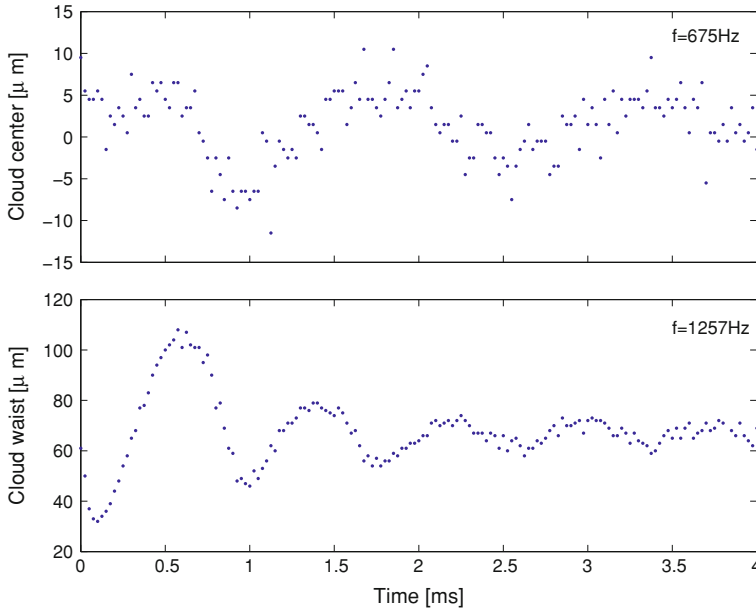


Fig. 2.19 Oscillation frequency measurement by a rapid trap switching. We switch off the trap for 1 ms and measure the cloud center (*upper* graph) and waist (*lower* graph) after 1 ms time of flight. Trap parameters are: power 15 W, $\sigma = 75 \mu\text{m}$

2.11 Oscillation Frequency Measurements

One of the most important characterizations of the trap is the measurement of its oscillation frequency. We have employed two measurement techniques which we present here: rapid switching of the trap and parametric excitation. In both techniques, besides the oscillation frequencies there are numerous interesting physical phenomena we were able to observe such as trap non harmonicity, parametric cooling and more.

2.11.1 Oscillation Frequency Measurement by a Rapid Trap Switching

In this technique we switch off the trap for a short duration and then switch it on again and measure the atomic cloud geometric parameters as a function of time. The measurement is carried by absorption imaging pictures of the cloud which we fit to a gaussian and find its center and waist. The switching duration should be smaller than the oscillation period. An example of such a measurement is shown in Fig. 2.19.

The upper graph shows the oscillation of the center of mass of the cloud, and as expected its damping which is only connected to the non harmonicity of the trap is quite small. The center of mass oscillation in the trap can be written as $x = x_0 \sin(\omega_{osc}t)$, where t is the time, ω_{osc} is the oscillation frequency and x_0 is the initial displacement. After a time of flight duration of t_{tof} the measured center of mass position is given by $x_{tof} = x + vt_{tof} = x_0 \sin(\omega_{osc}t) + t_{tof}\omega_{osc}x_0 \cos(\omega_{osc}t)$ which can always be written as $x_{tof} = x_0\sqrt{1 + (t_{tof}\omega_{osc})^2} \sin(\omega_{osc}t + \phi)$, with some phase ϕ . We see that we may gain a “magnification” factor of $\sqrt{1 + (t_{tof}\omega_{osc})^2}$ by the use of the time of flight technique. since for a given ω_{osc} the maximum measurable time of flight duration is limited, the typical value is $t_{tof}\omega_{osc} = 10$. Still, since the displacement relative to the atomic waist is small, and since the typical atomic waist is few tenths of microns, the typical x_0 is on the order of a few microns. This results in a measurable displacement of $\sim 10 \mu\text{m}$, which is small and thus this kind of measurement tends to be noisy.

The lower graph at Fig. 2.19, on the other hand, shows the measurement of the waist of the atomic cloud. This is the so called “breathing mode” and it is damped due to collisions. It is quite easy to induce a large relative waist change, and this translates to a measurable change of many tenths of microns. This kind of measurement tends to be easier and with better signal to noise. Nevertheless, there are two points to remember. First, as a result of the damping it is usually difficult to measure more than 10 oscillations, which limits the accuracy of the measured frequency. Second, due to non harmonicity of the trap the instantaneous frequency measured by the breathing mode shifts up as time goes on. This is because the amplitude of the motion decreases and due to non linear effect of the oscillator the frequency increases. On the average it means that this measurement technique has a small bias towards lower frequencies. Saying all that, it is still our preferred way of measuring the oscillation frequency due to the good signal to noise and accuracy.

From the damping rate of the breathing mode we could infer the collision rate directly. This is appealing since direct measurements of this value are not easy to perform [16]. The main issue which needs to be taken into account here is the effect of anharmonicity of the trap. The slow decay of the center of mass mode, however, shows that at our typical collision rates this effect is rather small. More details on this technique are given in Chap. 5.

2.11.2 Parametric Excitation of Atoms in a Dipole Trap

Another technique to measure the oscillation frequency is by modulating the trapping laser intensity and measuring the response of the atoms. In the experiment, we give a modulation at a certain frequency and measure the number of remaining atoms and their temperature. In a perfect harmonic oscillator we expect to see a resonance behavior at each of the oscillation frequencies of the trap. A typical measurement is given in Fig. 2.20. The temperature of the atoms show two clear peaks at the radial and

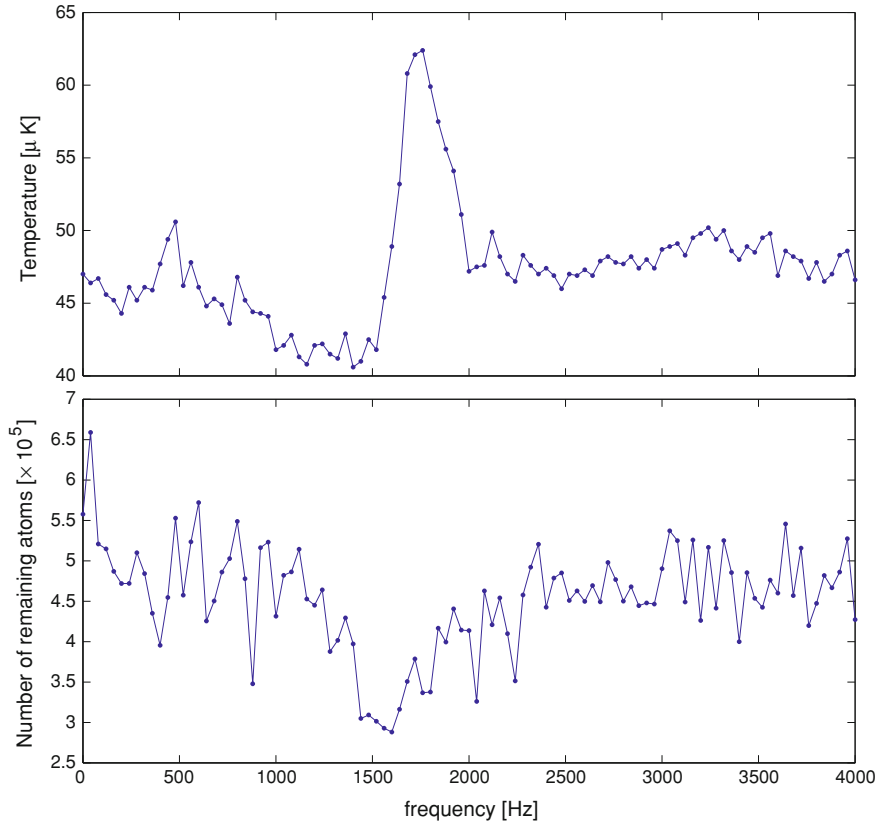


Fig. 2.20 Parametric modulation of the trap depth. *Upper* graph is the remaining atoms' temperature and *lower* graph is the number of remaining atoms. We give 100 ms of modulation which ends just before the measurement. Trap parameters: power 15 W, modulation peak to peak 3 W, waist is $\sim 60 \mu\text{m}$

axial oscillation frequencies. An interesting feature is a decrease of the temperature at frequencies of 1000–1500 Hz (the temperature without any modulation is $\sim 47 \mu\text{K}$). This decrease is due to the anharmonicity of the trap. The hotter atoms fill the higher energy levels of the trap, which due to the anharmonicity also have smaller oscillation frequencies. When we induce parametric excitation with smaller frequencies than the resonance frequency we on the average excite hotter atoms out of the trap and thus the remaining atoms are colder. In the lower graph in Fig. 2.20 one can see that indeed the largest number of atoms which are lost exactly in this frequency range. This effect which we call parametric cooling was already reported in Ref. [17–19].

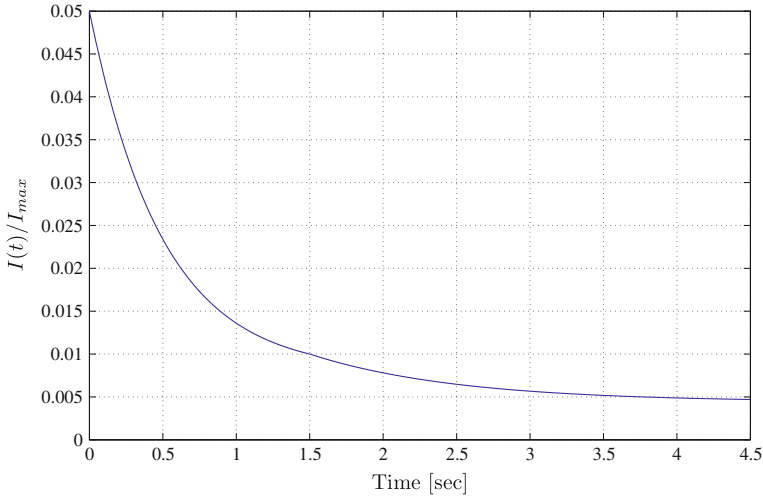


Fig. 2.21 Trapping laser power relative to its maximum value, $I_{\max} = 30 \text{ W}$, in the evaporation sequence

2.12 Evaporation to BEC

Our sequence to achieve quantum degeneracy is composed of several stages. First, we use optical cooling, as explained before, which brings the phase space of our ensemble to be better than 10^{-4} . The atoms are then loaded into the dipole trap. In order to collect a large number of atoms, we set the waist of the trapping beams to $\sim 200\text{--}250 \text{ }\mu\text{m}$ and its power to maximum ($\sim 30 \text{ W}$). We then let the atoms freely evaporate for 0.5 s . Next, we compress the trap to a waist of $\sim 50 \text{ }\mu\text{m}$ during 1.5 s . This compression reduces the volume by a factor of ~ 100 , and consequently the density and elastic collision rates increase dramatically. Unfortunately, also the inelastic scattering rate is increased, and we have found experimentally that the most efficient evaporation is achieved when the laser power is reduced gradually during the compression down to 5% of its maximum value. At this point there are typically 10^6 atoms at a phase space density of 10^{-2} , a temperature of $6.5 \text{ }\mu\text{K}$, a maximum density of $\rho = 3 \times 10^{13} \text{ cm}^{-3}$ and a maximum elastic collision rate of $\Gamma_{\text{col}} = 1000 \text{ s}^{-1}$. This constitutes an evaporation process with an efficiency of ~ 2.6 .

Next, evaporation is continued only by reducing the power of the trapping laser. The best results to date were obtained with the following power reduction scheme: for the first 1.5 s , the power follows the function $I(t) = Ae^{-t/\tau_1} + B$ with $\tau_1 = 0.5 \text{ s}$, and A and B such that $I(0) = 0.05I_{\max}$ and $I(1.5) = 0.01I_{\max}$. For the next 3 s , the power is given by $I(t) = Ce^{-t/\tau_2} + D$ with $\tau_2 = 1 \text{ s}$ and C and D chosen such that $I(1.5) = 0.01I_{\max}$ and $I(4.5) = 0.0047I_{\max}$. The total evaporation sequence is plotted in Fig. 2.21.

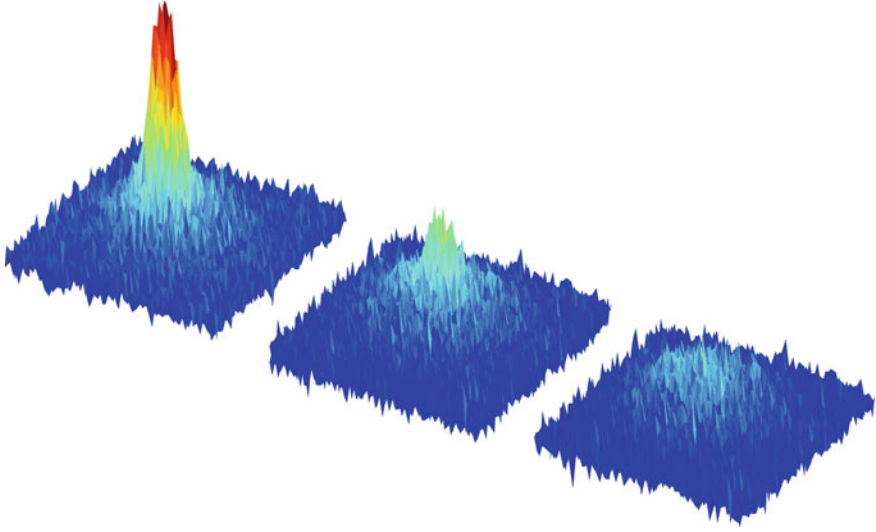


Fig. 2.22 Different stages in the condensation process, taken after a time of flight of 18 ms. The height is proportional to the optical depth in each image. In all these experiments we used the same sequence, and the different ending conditions stem from fluctuations in the initial number of atoms before the evaporation

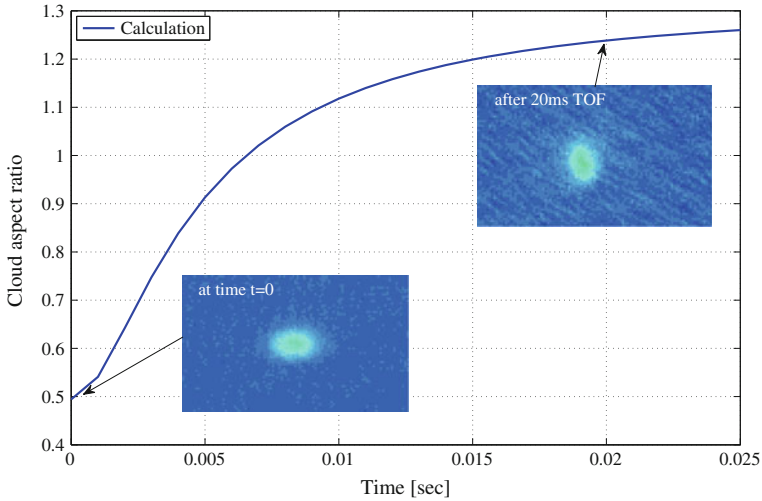


Fig. 2.23 The condensate aspect ratio calculated in the Thomas–Fermi limit using the measured oscillation frequencies. The insets show the measurements

The resulting BEC contains ~ 5000 – 1000 atoms. We have measured it after a time of flight of 15–20 ms. At this point, and mostly due to the fluctuation in the initial conditions before the evaporation, the conditions after the evaporations are quite fluctuating. In future work we plan to perform the last stage of the evaporation by increasing the gradients of an applied magnetic field. Thus a higher trapping frequency can be maintained and therefore also a better efficiency. In Fig. 2.22 we depict different stages of the condensation process. In addition, we have measured the oscillation frequencies in the trap just at the condensation point and obtained $\omega_r = 2\pi \times 84$ Hz and $\omega_z = 2\pi \times 41$ Hz. Using these values, we calculate the aspect ratio of the condensate as a function of the time of flight (in Thomas–Fermi regime) and plot it in Fig. 2.23 [10]. It is important to note that since the aspect ratio is close to unity, in the calculation of the chemical potential from experimental data the kinetic energy in both axes has to be taken into account. Doing so we find that the typical chemical potential is $\mu = 2\pi \times 300$ Hz. We extract the temperature from the thermal wings around the condensate (but still not too close) and get a typical value of $T = 50$ nK.

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