In fig. 5.8 finally, the magnetic trap has been switched off and the atoms rest inside the dipole trap, slightly skewed by gravity.

5.2 Loading into the hybrid trap

5.2.1 Adiabatic temperature change

Observing the changes in atom density has already hinted at the fact that temperature changes will be expected while changing from one potential to another. These changes will happen adiabatically in the experiment, and since we deal with temperatures $\sim 5\,\mu\mathrm{K}$ in this step, classical thermodynamics allows us to consider this process analytically. The following approach is based on the work in [Mel17] and will be used to first calculate the temperature change in a system of N noninteracting particles between two potentials $V_1(\mathbf{r})$ and $V_2(\mathbf{r})$.

Calculating the entropy from a product of non-interacting single-particle partition functions and equating them, we find

$$0 \stackrel{!}{=} \frac{1}{T_1}\frac{J(T_1)}{I(T_1)} - \frac{1}{T_2}\frac{J(T_2)}{I(T_2)} - k_B \log\left(\frac{T_2^{3/2} I(T_2)}{T_1^{3/2} I(T_1)}\right). \tag{5.10}$$

A full derivation of this is done in the appendix section A.1.4. We have to solve this integral equation in order to obtain the temperature T_2 of the cloud in the new potential V_2. An example of this is shown in fig. 5.9, where eq. 5.10 in dependence of T_2 is plotted in the rightmost panel. We numerically find its root, which is the desired T_2.

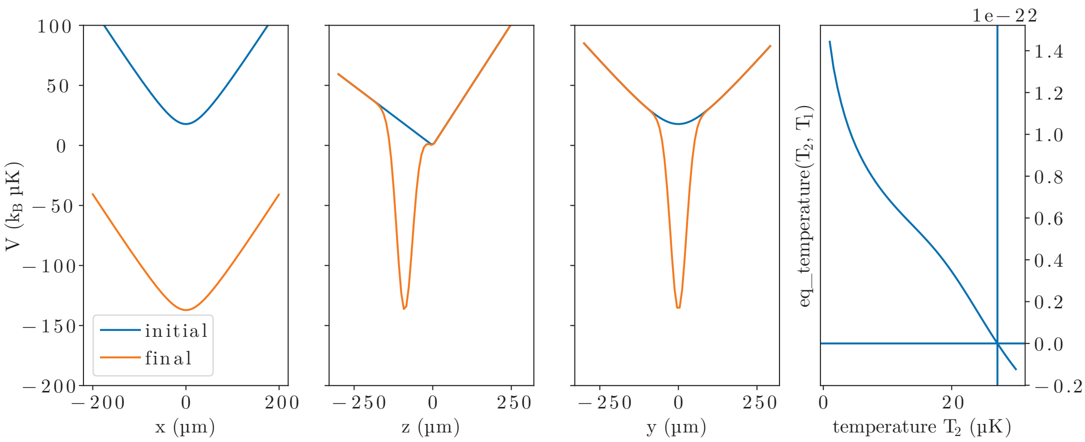


Figure 5.9: Adiabatic change between the magnetic trap and hybrid trap potential (between figures 5.4 and 5.5). The figure shows the potential $V(\mathbf{r})$ in three cuts around the trap minimum. The cloud heats up from $10.0\,\mu\mathrm{K}$ to $27.1\,\mu\mathrm{K}$ during this step, owing to the increased confinement in the hybrid trap. The panel on the very right plots eq. 5.10 and its root.

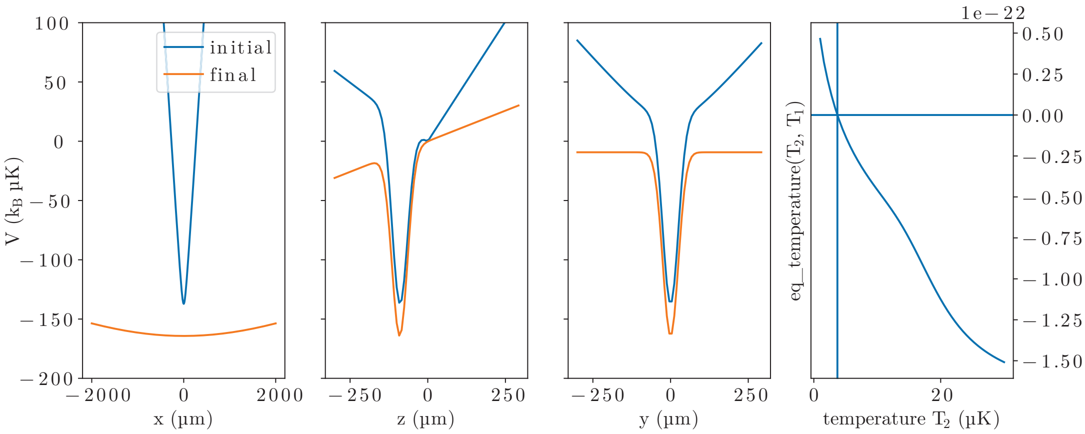


Figure 5.10: Adiabatic change between the hybrid and pure dipole potential (figures 5.5 and 5.8). The cloud cools from $10.0\,\mu$K to $3.7\,\mu$K during this, owing to its axial expansion (leftmost panel).

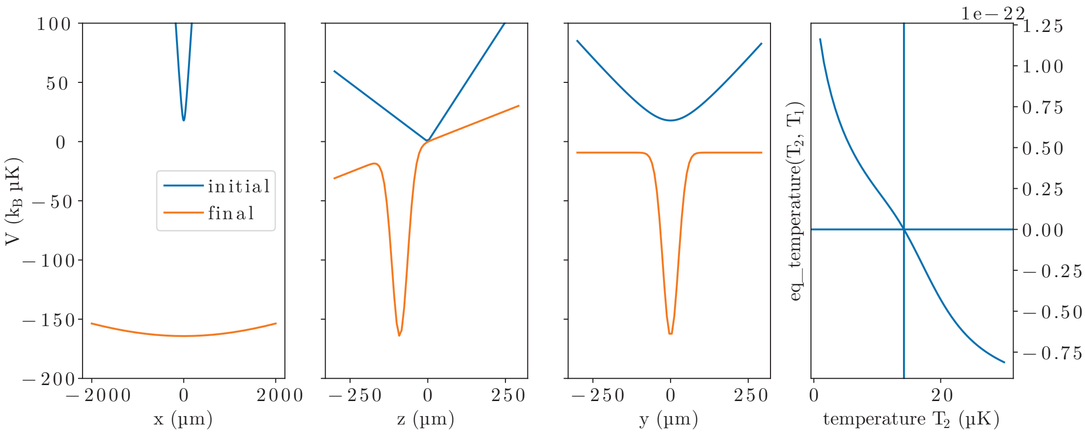


Figure 5.11: Whole transfer cycle: Adiabatic change between the magnetic and pure dipole trap potential (between figures 5.4 and 5.8). The cloud heats from $10.0\,\mu$K to $14.2\,\mu$K during this step due to the combined effects of the two previous figures.

This powerful tool gives us the ability to systematically assess and optimise the effects of different experimental parameters on the heating or cooling of the atom cloud. The most crucial ones for the shape of the potential are the current through the quadrupole coils and the laser power, which are shown in fig. 5.12. We can see that for increasing dipole power, the heating of the cloud changes rather drastically. This is due to the increased confinement within the optical trap, which imparts energy on the atoms. The magnetic field on the other hand appears to have little effect on the temperature change, as it only slightly skews the dipole beam potential.

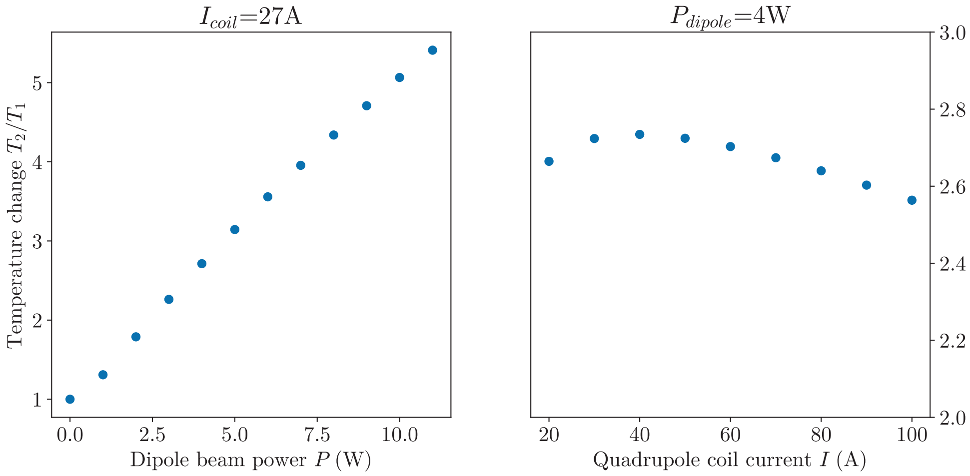


Figure 5.12: Temperature change over the first part of the cycle, for a dipole beam of waists $w_{y,z} = 50\,\mu$m.

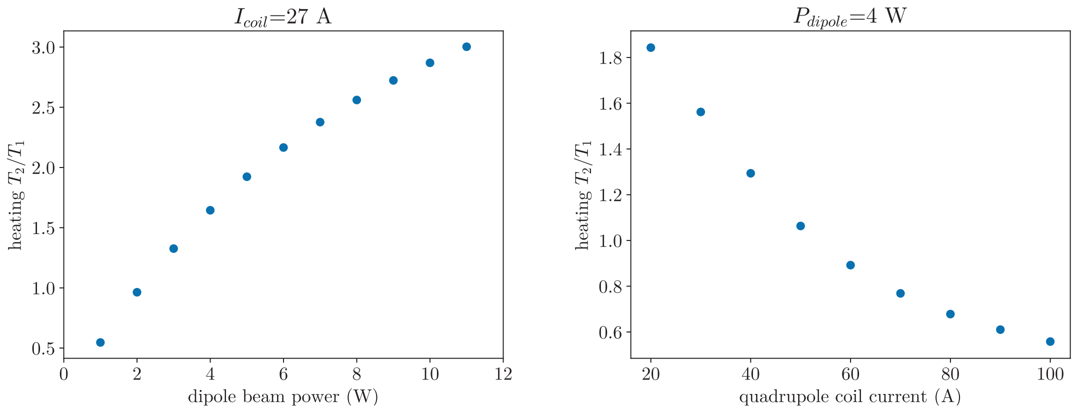


Figure 5.13: Temperature change over the whole cycle, for a dipole beam of waists $w_{y,z} = 50\,\mu$m. Note that the dipole beam is the only confining potential after this, such that $P_{\text{dipole}} \to 0$ approaches an untrapped system.

5.2.2 Fraction of transferred atoms

Another interesting data point is the fraction η of atoms which still remains in the trap after the swift change between two trapping potentials $V_1(\mathbf{r})$ and $V_2(\mathbf{r})$. As is shown in fig. 5.14, we assume a Maxwell–Boltzmann distribution of kinetic energies,

$$f(E_{\text{kin}}) = 2\sqrt{\frac{E_{\text{kin}}}{\pi}} \left(\frac{1}{k_B T}\right)^{3/2} \exp\left(-\frac{E_{\text{kin}}}{k_B T}\right). \tag{5.11}$$

This holds also in the case of an external potential, as the potential does not influence the momentum distribution. We are looking for the fraction of atoms in the initial potential V_1 which has less kinetic energy than the depth of the final potential V_2. For any given point $\mathbf{r}$ in space we find the fraction of atoms with $E_{\text{kin}} < V_2(\mathbf{r})$ to be

$$\eta(\mathbf{r}) \equiv \int_0^{-V_2(\mathbf{r})} f(E)\, dE. \tag{5.12}$$

As V_2 will be negative, we need to add a sign here. We then have to multiply by the normalised atom density $n(\mathbf{r})$ from eq. 5.6 and integrate over all space to find the overall transferred fraction

$$\eta = \int d^3r\, n(\mathbf{r})\eta(\mathbf{r}). \tag{5.13}$$

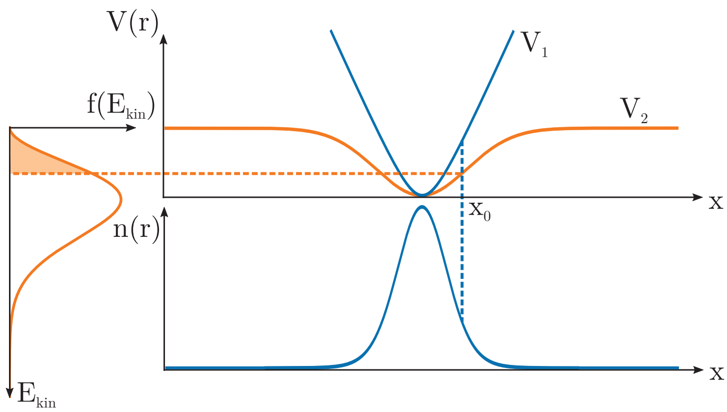
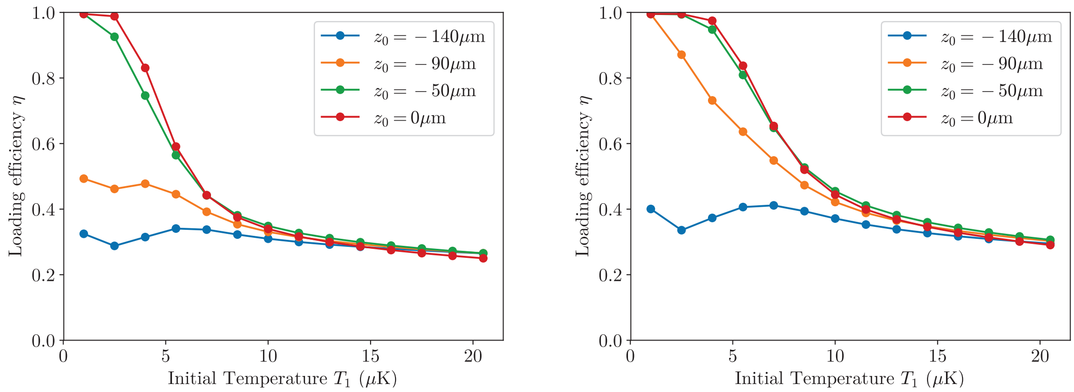


Figure 5.14: Schematic depiction of the algorithm to obtain the fraction η of atoms which is still trapped after a transition from V_1 to V_2. The fraction of the shaded area is $\eta(\mathbf{r})$ which gets multiplied by the value of the normalised density $n(\mathbf{r})$, and we integrate all these values over space.

This was done numerically, the results of which can be found in fig. 5.15 for several initial cloud temperatures T_1. We can observe that the transfer efficiency strongly decreases with increasing temperature. This effect is not too detrimental though, as this favours colder atoms to be transferred and thereby achieves a net cooling effect. Note that before the transfer efficiency was calculated, the cooling of the cloud due to its axial expansion (see fig. 5.10) was taken into account. Figure 5.15 tells us that if we choose the frequency sweep in the radiofrequency evaporation phase according to a specific final temperature, we can in principle achieve an arbitrary transfer efficiency when loading into the dipole trap.

Due to gravity, the atom cloud tends to be centred vertically below the magnetic field zero, which increases the loading efficiency for small temperatures, as can be seen by comparison with fig. A.2. These results inform our choice of displacement z_0 and trap beam waists $w_{y,z}$: where fig. 5.15 suggests that $z_0 = -50\,\mu$m would be a better choice, this of course results in increased Majorana losses (cf. fig. 5.5). A wider trap with $w_{y,z} = 70\,\mu$m of course favours loading for all temperatures, but requires a beam of twice the power in order to achieve the same trap depth. Whether this is feasible will mainly be decided by whether the focus-tunable lenses discussed in section 2.5 induce significant aberrations at these powers, and also whether the increased Rayleigh range z_R that comes with it still enables efficient transport. This will be the topic of the next section.



(a) $P_{\text{dipole}} = 4$ W, $I_{\text{coil}} = 27$ A, $w_{y,z} = 50\,\mu$m **(b)** $P_{\text{dipole}} = 8$ W, $I_{\text{coil}} = 27$ A, $w_{y,z} = 70\,\mu$m

Figure 5.15: Transfer efficiency for the whole loading cycle (from magnetic trap into pure dipole trap) in dependence of the initial cloud temperature T_1, for several beam offsets z_0. This takes into account the cloud heating which this process involves. We can observe the dependence on the trap width: For a slightly wider trap (b), the loading efficiency stays large even for higher T_1, but to get the same trap depth we require a more powerful beam. Another interesting observation is that a bigger z_0 favours the small temperature loading rate due to gravity. The connecting lines are guides to the eye.

5.3 Counterdiabatic driving

After the loading of the hybrid trap is completed and the magnetic quadrupole field is switched off, we want to translate the cloud of atoms from the 3D MOT chamber to the science chamber (see fig. 4.1). The distance between those is approximately $d = 400$ mm, although this value has not been finalised yet. In order to achieve this, the focus tunable lenses from section 2.5 will be utilised to axially shift the focus of the dipole beam. As was discussed there, this does not affect its transversal waist, thereby also conserving the Rayleigh range z_{R}, i.e. the axial trap frequency. In the following, we want to find the effect of the translation on the trapping potential and point out how to remedy its effect, assuming the trap is approximated in second order by a harmonic potential of frequency ω. We further assume the transport of a cloud of thermal (uncondensed) atoms at $T \sim 10\,\mu$K. Note that this is only $\sim 8\%$ of the trap depth and hence allows for a classical treatment of this problem.

For the sake of arriving at an adiabaticity condition for the translation, let us consider the case of a trap that is accelerated with a during the first half (for $t < t_f/2$) and $-a$ during the second half of the protocol (for $t > t_f/2$). In such a protocol, the average velocity has half of its maximal value at $t = t_f/2$, i.e. $d/t_f = \bar{v} = v_{\max}/2$. We now require that within an oscillation period $T_{\text{osc}} = 2\pi/\omega$, the trap move over much less than

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