Characterisation of focused-beam trap: FORT loading optimisation

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Abstract. We investigate the properties of the focused-beam magneto-optical trap (FBT) of Rb⁸⁵ atoms, which provides more optical accessibility in contrast to typical magneto-optical trap (MOT). We have characterised the relations between temperature, number and density of trapped atoms versus trap parameters. In this paper, we discuss some distinctive features of the FBT comparing to those of standard MOTs, and determine a suitable condition in which loading atoms into a far-off-resonance optical dipole trap (FORT) is possible. Although the trap can capture fewer atoms comparing to the standard MOTs, due to its asymmetric geometry, it may offer an alternative trap configuration for preparing single atom.

1. Introduction
The Magneto-Optical Trap (MOT) have become the most widely employed technique to prepare cold dense atomic cloud from room-temperature vapour since its realisation in 1987 [1]. However, evolution of cold atoms physics leads to diverse applications which require traps with properties departing from standard MOTs. For examples, highly precise optical clock [2] requires cooling in an optical dipole trap at the magic wavelength to overcome severe limitations caused by magnetic field, or a tight trap with more unoccupied optical axes is highly demanded for cavity QED experiments [3].

The Focused-beam magneto-optical trap (FBT) is a modification of the two-beam magneto-optical trap (TBT) [4, 5]. To provide more optical accessibility, the FBT design is relatively simpler comparing to standard MOTs. The trap consists of a pair of two confocal cooling beams aligned along an axis (z-axis) and two normal pairs of counter-propagating repump beams in the normal plane; all the rest were configured similarly to the MOT. In this paper, the FBT was characterised in order to find a suitable condition for loading atomic cloud into the far-off-resonance optical dipole trap (FORT).

2. Background and experimental details
By using slightly red-detuned laser, the counter-propagating atoms scattered and loses momentum from spontaneous emitting photons in random directions. Such consecutive momentum exchanges correspond to spatially dependent restoring force centering at the zero magnetic field. The concept of compensation between the Doppler shift and linearly varying
Zeeman shift applies to our FBT. The polarisation gradient cooling (PGC) mechanism [6] is involved as the temperature of atoms drop under the Doppler cooling limit.

Without additional loading-assisted beams, the underlying mechanisms of our FBT are the same as that described in the original TBT [4, 5]. The distribution of trapped atoms is well-demonstrated Gaussian profile in all axes. Due to the difference in forces acting on the axial and radial directions, the density of atomic cloud in steady state is described by a function 

\[ \rho(r, \phi, z) = \rho_m \exp \left[ -\left( \frac{r^2}{2\sigma_r^2} + \frac{z^2}{2\sigma_a^2} \right) \right], \]

where \( \rho_m \) is the maximum density, and \( \sigma_r \) and \( \sigma_a \) are the radii measured at \( e^{-1/2} \) along the radial and axial directions respectively. Since the trap is axial symmetric and the surface of equal density is an ellipsoid, the geometry of the cloud is a prolate spheroid with volume defined by 

\[ V_{\text{MOT}} = \frac{\pi}{6} R_r a R_a^2, \]

where \( R_r, a \) is the volume and trapped velocity of the FORT, and \( f(v, T) \) is the Maxwell-Boltzmann distribution.

The following experiment is designed to characterise the relation between number, density and temperature of trapped atoms versus cooling laser intensity, which are needed in order to calculate \( N_F \). We fixed detuned frequency and magnetic field gradient within the interval that would maximise the number of trapped atoms (as shown in figure 2). The values of controlled parameters in each experiment are listed in the table 1. The optical layout of the experiment is shown in figure 1 (\( I_c \) and \( I_r \) stand for cooling and repump laser intensity respectively), where the cooling circle and repump processes were performed in D2 line transitions. Both beams were frequency-locked at \( F = 3 \rightarrow F' = 4 \) and \( F = 2 \rightarrow F' = 3 \) respectively using Doppler free saturation spectroscopy before amplified with individual tapered chip. The acousto-optic modulators were used as frequency shifter and fast switch. The beams were sent through optical fibers and separately entered the experimental area. Here the two counter-propagating cooling beams with different circular polarizations were expanded and refocused in con-focal configuration along the z-axis using aspheric lenses. When both Fourier planes coincided with

**Figure 1.** Schematic drawing for the FBT.
Figure 2. Number (star) and density (dot) vs detuned laser frequency (a) and magnetic field gradient (b).

the inner surfaces of the rectangle borosilicate cell that contained rubidium vapor. Instead of Feeding both cooling and repump beams along the axial direction, two repump beams were sent through and got reflected at four mirrors in order to make $\sigma^+$, $\sigma^-$ counter-prorogating cross beams on the radial plane. The process ended with a series of pictures of the cold cloud taken using Andor iXon EMCCD camera.

Table 1. Controlled parameters in each experiment

|                  | $I_r$ (mW/cm$^3$) | Detune (MHz) | B Gradient (G/cm) |
|------------------|-------------------|--------------|-------------------|
| Number vs $I_c$  | 16.33             | -12.01       | 16.48             |
| density vs $I_c$ | 16.33             | -12.01       | 16.48             |
| Temperature vs $I_c$ | 16.33         | -14.01       | 15.20             |

3. Result and discussion

The plots of number and density of atoms against cooling laser intensity is shown in the figure 3(a). For the FBT, the cooling laser only affects the density of the cloud within a small range i.e. from 0 to 8 mW/cm$^2$. The number of trapped atoms (as well as density) reaches its peak around $I_c \sim 3$ mW/cm$^3$ with $N \sim 10^5$ which is a very small number comparing to standard MOTs that can collect atoms up to $10^{10}$ [7]. In this limited regime, the relation between density and number of atom is monotonically increasing function (almost linear) [8]. Atom loading should be perform at the peak of density to maximise the number of atoms transferred into the FORT.

The plots between temperature and laser intensities are shown in the figure 3(b). The temperature in the axial direction ($T_a$) agrees with the theoretical prediction [9] i.e. linearly increase with laser intensities. The cooling process involves PGC mechanism since the temperature drops down below the Doppler limit. However, the temperature in the radial direction is higher than the Doppler limit, due to the weaker radiation pressure. Furthermore, the temperature in the radial direction ($T_r$) is not well-described by a linear relation. This
is possibly the result of atoms leaking out from the trap, therefore, atoms in this direction is not in the steady state. For some particular values of $I_c$, the geometry of the cloud deviates from a perfect prolate spheroid; $R_r$ is not well-defined which affects the measured temperature. Such a problem may be improved by changing the focal length of the cooling beam, which will be the subject of future study. Nevertheless, we will assume a linear fit for $T_r$ in order put a rough estimation of $N_F$. Hence the temperature in axial and radial direction at the peak are $T_a = 22.38I_c \sim 67\mu K$ and $T_r = 66.18I_c \sim 198\mu K$. If the FORT is designed such that the trap depth is the same order as the cloud temperature, then from Eq. (2.1) (note that the beam waist of our FORT is $w_0 = 1.2\mu m$) we have $N_F \sim \sqrt{8/\pi} \times 1.9 \times 10^{15} \times 1.4 \times 10^{-13} \times 0.43 = 720$.

4. Conclusion
We have characterised some properties of atomic cloud in the FBT including number, density and temperature as functions of cooling laser intensity, detuning frequency and magnetic field gradient. For the FBT the control of number and density of atomic cloud through cooling laser is available in a small range, and the number of trapped atoms is very small comparing to standard MOTs. However, we have shown that the number of atoms transferred into the FORT is sufficiently high for single atom trap.

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