PRAMANA
— journal of
physics

Vol. 82, No. 2
February 2014
pp. 419–423

Optimization of transfer of laser-cooled atom cloud to a quadrupole magnetic trap

S P RAM*, S K TIWARI, S R MISHRA and H S RAWAT

Laser Physics Applications Section, Raja Ramanna Centre for Advanced Technology, Indore 452 013, India

*Corresponding author. E-mail: spram@rrcat.gov.in

DOI: 10.1007/s12043-014-0700-2; ***e*****Publication:** 8 February 2014

Abstract. We present here our experimental results on transfer of laser-cooled atom cloud to a quadrupole magnetic trap. We show that by choosing appropriately the ratio of potential energy in magnetic trap to kinetic energy of cloud in molasses, we can obtain the maximum phase-space density in the magnetic trap. These results guide us to choose the value of current to be switched in the quadrupole coils used for magnetic trapping for a given temperature of the cloud after molasses. This study is also useful to set the initial phase-space density of the cloud before evaporative cooling.

Keywords. Laser cooling; optical molasses; double-MOT; magnetic trapping; phase-space density.

PACS Nos 52.55.Jd; 37.10.De; 67.85.–d

To achieve Bose–Einstein condensation (BEC) in alkali atomic gases [1], laser cooling of these gases is the first stage of cooling, which is followed by the second stage of cooling by evaporation method. One approach to perform evaporative cooling is to trap laser-cooled atom cloud in a magnetic trap and then apply the radio frequency radiation to force the evaporation process by ejecting out the higher-energy atoms from the trap. In this method, the transfer of laser-cooled atom cloud to magnetic trap is an important step, which involves consideration of several parameters such as magnetic field gradient of the trap and the temperature of the laser-cooled cloud. In this work, we have aimed to study the optimization of phase-space density of the cloud in a magnetic trap when laser-cooled ^{87}Rb atom cloud of known temperature is transferred into the magnetic trap.

After cooling of atoms in magneto-optical trap (MOT) and molasses, atoms are optically pumped to a trappable state [1] before the magnetic trap field is switched on for trapping of atoms. When atoms are trapped in the magnetic trap, several parameters play important role. For example, the number of atoms transferred into the magnetic trap depends on the optical pumping efficiency and the magnetic trap switching time. Owing to finite switching time of the current in the magnetic trap coils, the laser-cooled atoms may fall under gravity or go out of trap volume due to cloud expansion, which affects the final number in the trap (i.e. transfer efficiency from MOT to magnetic trap). A large expansion or fall under gravity also increases the temperature of the cloud when it interacts with the magnetic trap field, and this change in temperature is dependent on the magnetic field gradient of the trap. To achieve BEC by evaporative cooling of atoms in the magnetic trap, both number and temperature in the magnetic trap are important initial parameters, which are expressed by a single parameter known as phase-space density (D), given as $D = n\lambda_{\rm dB}^3$, where n is the number density and $\lambda_{\rm dB}$ is the thermal de Broglie wavelength. Usually phase-space density (D) of an atom cloud is reduced after it is transferred from MOT (or molasses) to a magnetic trap. However, with appropriate switching of the magnetic trap field (called mode-matched trap), the severe loss of D can be avoided [1]. In this paper, we present our results to show that for a certain choice of mode-matching parameter α (=PE/KE, where PE is the potential energy in the magnetic trap and KE is the kinetic energy of the cloud in the molasses), the maximum phase-space density in the magnetic trap can be obtained. Since further adiabatic compression of the trap conserves the phase-space density (D), the optimized D obtained at the time of switching the trap can be preserved as initial phase-space density for evaporative cooling process.

We performed experiments on a double-MOT set-up designed for BEC of ^{87}Rb atoms (figure 1) and its details are described in ref. [2]. In the set-up, the vapour cell MOT (VC–MOT) is formed in a chamber at $\sim 2\times 10^{-8}$ Torr pressure, whereas ultra-high-vacuum MOT (UHV–MOT) is formed in a glass cell chamber at $\sim 6\times 10^{-11}$ Torr pressure, which is suitable for magnetic trapping. To transfer atoms from VC–MOT to UHV–MOT, a red detuned ($\delta/2\pi = -1.0$ GHz from $(5S_{1/2}F = 2) \rightarrow (5P_{3/2}F' = 3)$ transition of ^{87}Rb atom) push laser beam was focussed on VC–MOT. Typically, we trap $\sim 1\times 10^{8}$ atoms in VC–MOT and $\sim 3\times 10^{8}$ atoms in UHV–MOT. The UHV–MOT atoms are kept in a compressed-MOT (for a duration of $\sim$20 ms) by increasing the detuning of the cooling laser beams to red side in order to increase number density. Then, atoms from compressed UHV–MOT are kept in molasses for a variable duration (3–9 ms) to obtain desirable temperature of the cloud. The atoms are cooled in UHV–MOT and optical molasses and then optically pumped to $(5S_{1/2}|F = 2, m_{\rm F} = 2\rangle)$ state for magnetic trapping, and thereafter transferred to a quadrupole magnetic trap. The pulse sequence shown in figure 1 describes the duration of various stages of cooling and trapping, from the formation of VC–MOT to magnetic trapping and detection.

To perform optical pumping of atoms to $(5S_{1/2}|F = 2, m_{\rm F} = 2\rangle)$ state, a small part of the cooling laser and re-pumping laser ($\sim$2 mW power in each) were mixed and passed through an AOM in double pass. The output of this AOM ($\sim$50 μW, peak intensity of the beam is $\sim$1.6 mW/cm^2), called optical pumping beam, was aligned to a UHV–MOT beam. This circularly polarized optical pumping beam (700 μs duration) in the presence of a small bias field ($\sim$2 G, $\sim$1.5 ms duration) transferred laser-cooled atoms to $(5S_{1/2}|F = 2, m_{\rm F} = 2\rangle)$ state. The optical pumping beam and bias field parameters were set to maximize the number in quadrupole trap at 100 ms after the magnetic trap loading. The current in the quadrupole coils for magnetic trapping was switched on at different values in $\sim$7.5 ms duration using an IGBT-based circuitry. The sequence of different pulses (shown in figure 1) was generated using a controller module operated by PC and LabVIEW programming. The details of this controller module are described elsewhere [3].

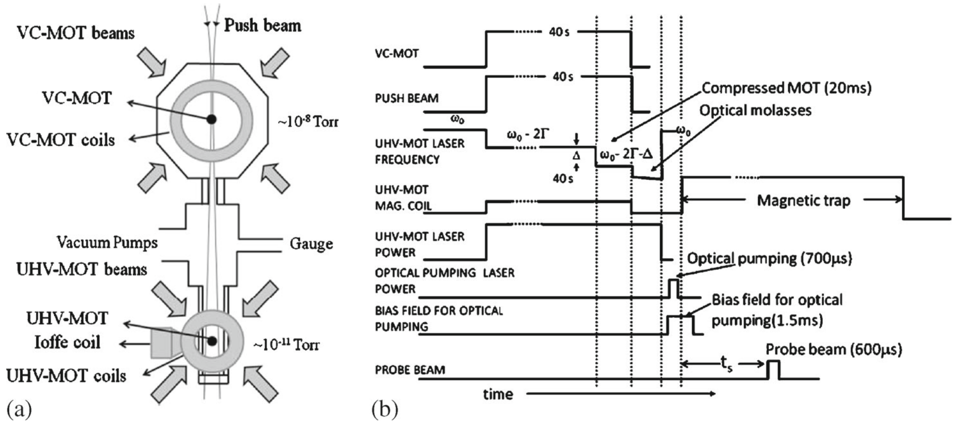

Figure 1. Schematic of the experimental set-up (**a**) and the sequence of pulses (**b**) used for magnetic trapping of ^{87}Rb atoms.

We have measured the number of atoms in the magnetic trap by the well-known fluorescence imaging method. Figure 2 shows the decay in measured number in the trapped cloud with time after switching ON the current in magnetic trap coils (current $\sim$13 A). From this figure, it is evident that the number in quadrupole trap remains nearly constant after $\sim$20 ms, which indicates the final number loaded in the magnetic trap. From the figure, it is also established that an image of a cloud taken after 100 ms in a quadrupole trap is appropriate to obtain information about the number density and phase-space density in the quadrupole trap.

The phase-space density (D) in the magnetic trap was estimated from the number density n and λ_{dB}. To find λ_{dB} $(= (h^2/2\pi m k_{\mathrm{B}} T_{\mathrm{MT}})^{1/2})$, we have estimated the temperature of the atom in the quadrupole trap (T_{MT}) from the size of cloud in the trap [4]. We define the ratio α =PE/KE, where PE $= g_{\mathrm{F}} m_{\mathrm{F}} \mu_{\mathrm{B}} B' r$, KE $= (k_{\mathrm{B}} T_{\mathrm{OM}})/2$, g_{F} is the Lande g-factor, μ_{B} is the Bohr magneton, m_{F} is the projection of the total angular momentum of the atom on the magnetic field axis, B' is the magnetic field gradient of the quadrupole trap, r is

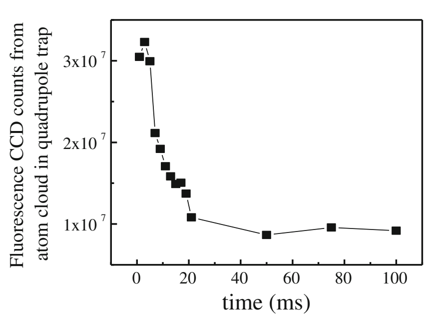

Figure 2. Variation in the number of atoms trapped with time in quadrupole magnetic trap for $\sim$13 A of current in the coils.

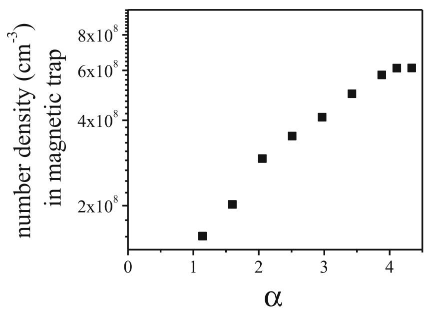

Figure 3. Measured variation in number density of the atoms trapped in quadrupole trap with α.

the size (FWHM) of the cloud in the quadrupole magnetic trap, k_B is the Boltzmann constant and T_{OM} is the temperature of the atom cloud in optical molasses (measured by free expansion method). To optimize the atom transfer from molasses to the magnetic trap, we have varied the ratio α and studied the variation in n and D in the magnetic trap.

To vary the value of α, we varied the value of current at which quadrupole trap was switched ON for a known temperature of cloud after molasses. The measured number density (n) and phase-space density (D) for different values of α are shown in figures 3 and 4, respectively. We observed that with increase in α, n first increases and then saturates, whereas D first increases and then decreases with a maximum value at $\alpha \sim 2.5$ (which corresponds to a current of ~15 A in quadrupole coil). The reduction in D after it increases to the maximum value is due to increase in the temperature in the magnetic trap. Further, for lower values of current in the trap, the loss of atoms due to fall under gravity is higher, which results in a smaller value of D, whereas for higher values of current switched on in the coils, the trap becomes too steep and results in higher heating of the atom cloud during the transfer. This again results in a lower value of D due to increased temperature of atom cloud. Therefore, we obtained a maximum for D with respect to variation in α.

We note that the initial value of D is an important parameter for evaporative cooling experiments and its optimization is of considerable interest. However, the evaporative

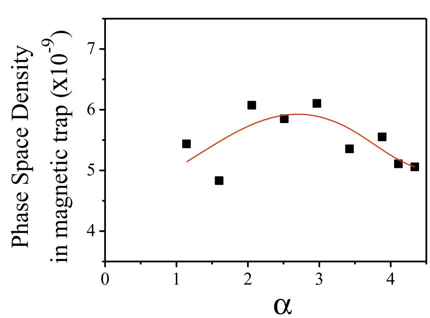

Figure 4. Variation in phase-space density of atoms trapped with α. Continuous curve is for guidance of the eyes.

cooling rate governed by elastic collision rate (Γ_{el}) is less affected by this increase in D, which is given as $\Gamma_{el} \propto n^{4/3} D^{-1/3}$. Therefore, higher D in the magnetic trap is desirable to begin evaporative cooling to achieve BEC, as one has to improve the value of D to ~ 1 for BEC.

To conclude, we present our results to show that by appropriately choosing the ratio of potential energy in the magnetic trap to the kinetic energy of cloud in molasses, the maximum phase-space density in the cloud in the magnetic trap can be obtained. These results guide us to choose the value of current to be switched on in the quadrupole coils used for magnetic trapping for a given temperature of the cloud after molasses. This study is useful to set the initial phase-space density of the cloud before evaporative cooling.

Acknowledgements

The authors thank L Jain, V P Bhanage, P P Deshpande, M A Ansari, H R Bundel and C P Navathe (all are from Laser Electronics Support Division, RRCAT) for the development of the controller system for the set-up and H S Vora, Laser Electronics Support Division, RRCAT, for providing the image-processing software.

References

[1] M Inguscio *et al* (eds), Bose–Einstein condensation in atomic gases, *Proc. of the International School of Phys. "Enrico Fermi,"* Course CXL (Varenna, 1998)
[2] S P Ram, S K Tiwari, S R Mishra and H S Rawat, *Rev. Sci. Instrum.* **84**, 073102 (2013)
[3] P P Deshpande, V P Bhanage, L Jain, M A Ansari, S Tiwari, H R Bundel and C P Navathe, *Proc. National Laser Symposium* (NLS-08) (LASTEC, New Delhi, 2009) P13-002
[4] H J Lewandowski, D M Harber, D L Whitaker and E A Cornell, *J. Low Temperature Phys.* **132**, 309 (2003)