Characterization of cold atomic cloud in a magneto-optical trap

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The results of characterization of cold cloud of cesium (Cs) atoms trapped in a magneto-optical trap (MOT) have been presented. The MOT is a part of the Physics package of the Cs Fountain Clock being developed at National Physical Laboratory (NPL), India. The number of atoms, size and temperature of the cloud have been measured and calculated. It is also been investigated how the number of trapped atoms changes with the trapping laser's beam intensity, detuning and magnetic-field gradient of the trap.

Keywords: Laser cooling and trapping, Frequency control, Magnetic field

1 Introduction

Cold atoms produced using laser cooling and trapping techniques have been widely used for high-resolution spectroscopy[1,2], precision measurements[3-6], highly precise atomic clocks[7,8] etc. A magneto-optical trap (MOT) is, generally, used to create a cold, dense cloud of atoms[9,10]. Some of the crucial experiments performed with a MOT are cold collisions[11], quantum degenerate gases experiments[12] and atomic standards of time and frequency. We have been developing a primary standard of time and frequency namely a Cs fountain clock at National Physical Laboratory (NPL) India and the MOT is a part of the Physics package of the clock. In a fountain clock, atoms are first cooled and trapped in a MOT and then launched up to about a meter high and fall under gravity. The cold atomic cloud interacts with microwaves on the way up and down and undergoes state interrogation in the detection zone. This way the frequency of an external oscillator is locked to the transition frequency of the atomic hyperfine states to form an extremely accurate clock. MOT is the first and most crucial part of the fountain clock.

In our fountain clock, the MOT has been successfully demonstrated with a trapped Cs atomic cloud recently. Once the cloud is formed, measurements are done to characterize the cloud in terms of size of atomic cloud, number of atoms in the cloud, temperature of the cloud. Particularly for the fountain clock, parameters like temperature and number of atoms in the MOT are critical. The density/number of atoms are optimized in a way to have maximum *S/N* ratio with minimum frequency

shifts. The temperature has to be low enough (<5 µK) (small velocity/kinetic energy) in order to keep all the trapped atoms together during the flight time. In order to optimize the performance of the fountain clock, measurements of these parameters become essential. This paper is a comprehensive report on details of measurement, calculations and results of characterization of cold atomic cloud trapped in a MOT.

2 Experimental Details

The optical system as shown in Fig. 1 delivers three mutually orthogonal pairs of counter-propagating laser beams, which are well balanced with respect to their intensities (5 mW/cm^2 each) and have diameters of about 15 mm each for the horizontal beams and 10 mm each for the vertical beams. There are two vertical beams-upward and downward (*z*-axis) and four horizontal beams, counter-propagating along the *x* and the *y*-axis of a cartesian coordinate system, respectively. Besides the six cooling beams, the optical system delivers two beams for detection after the fountain operation cycle. The optical set-up provides the means for changing the laser intensity and frequency v_c in a precisely controlled way in order to properly cool, launch and detect the atoms. Generation of cooling, re-pump, launch and detection beams, and finally coupling them into eight single mode polarization maintaining (SM-PM) optical fibers is done on an environmentally controlled vibration free optical table of dimensions 1 m×1.9 m. An extended cavity diode laser (ECDL) in Littrow configuration is frequency locked to a Cs D$_2$ line
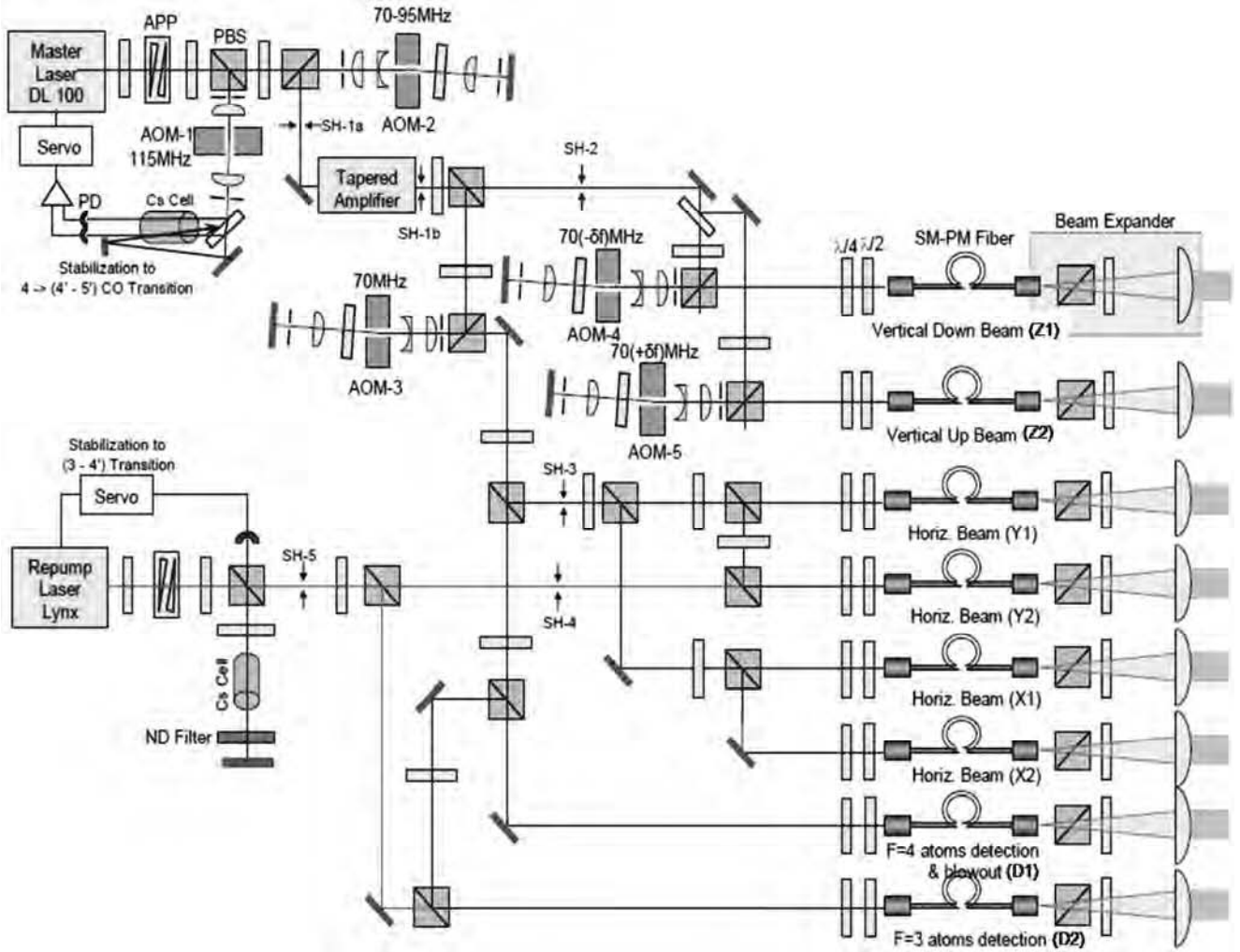
Fig. 1 — Schematic of the optical system to deliver six cooling beams of the MOT

[crossover peak of ^{133}Cs $6^2S_{1/2}$ (F=4) → $6^2P_{3/2}$ (F′= 4 and 5) at 852 nm], generated by high resolution saturated absorption spectroscopy.

The frequency and intensity of all the beams are controlled by acousto-optic modulators (AOM) in a double pass configuration[13]. The double pass AOM2 output is used to seed the tapered amplifier TA-100 system which produces frequency locked optical power of about 400 mW at the desired frequency. Combination of half wave plate and polarizing beam splitter (PBS) is used to split the TA output and direct it to each of the three cat's eye double pass arrangements of AOM3, AOM4 and AOM5 for frequency and intensity control. The output of AOM3 is further split into six separate beams for cooling and detection. These are four horizontal cooling beams X1, X2, Y1 and Y2 and two detection beams D1 and D2, respectively. The AOM4 and AOM5 outputs produce the two vertical beams Z1 and Z2.

While the cooling laser beams address the cyclic transition $6^2S_{1/2}$ F=4 → $6^2P_{3/2}$ F′ =5, non-resonant spontaneous emission populates $6^2S_{1/2}$ F=3 level eventually. To avoid such a population trapping in $6^2S_{1/2}$ F=3 level, a second (re-pumping) laser is tuned and locked to the transition ^{133}Cs $6^2S_{1/2}$ (F=3, M_f = 0) → $6^2P_{3/2}$ (F′= 4, M_f = 0) also by saturated absorption spectroscopy. The locked re-pump beam is split and mixed with one of the cooling beams, Y2 and the detection beam, D_2.

The six cooling/re-pump beams and two detection beams are delivered from the optical table to the MOT chamber using 10 m long SM-PM fibers. At the output end of the fibers, the beams are collimated with home-built beam expanders that produce the desired beam size and polarization. Fig. 2 shows the schematic of the MOT.

The Cs atoms are cooled in a MOT in an octagonal stainless steel chamber with five optical viewports on
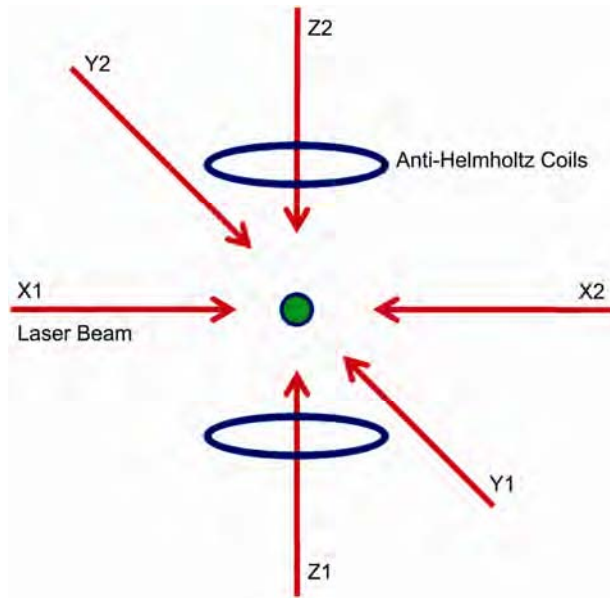
Fig. 2 — Schematics of magneto-optical trap with six cooling beams and anti-Helmholtz coils

the sides and one each at the top and bottom. Two coils with coil axis along the Z-axis, each of 75 mm radius and 100 turns, in anti-Helmholtz configuration are used to create a magnetic field gradient both along radial and axial directions. However, the gradient is twice as much along the axis than in the radial direction. In addition, three pairs of rectangular Helmholtz coils (in X-Y-Z directions) around the MOT region compensate the residual magnetic field at the centre of the MOT. The source of Cs is a temperature controlled cold finger attached to the MOT chamber on the side. The temperature of source is normally maintained at 10°C in order to generate adequate Cs vapour pressure in the chamber.

The MOT region and the flight tube region are pumped with ion pumps to keep the pressure to about 10^{-10} Torr. Attaining this level of ultra high vacuum is important for the fountain operation.

To characterize the cloud of cold atoms, a fluorescence collector ensemble and a CCD camera is mounted on one of viewports. Each ensemble consists of a pair of achromatic plano-convex imaging lenses (50 mm diameter and 75 mm focal length) and placed back-to-back to focus light onto a large area silicon photodiode (10 mm square).

3 Results

The detailed characterization of the Cs atomic cloud trapped in the MOT has been done recently. The number of atoms in the trap was determined from the fluorescence signal[14]. For calculating number of

atoms, fluorescence signal from the cold cloud was collected on a large area silicon photodiode using imaging optics consisting of lenses and irises.

The rate at which an individual atom scatters photons is given by:

$$\gamma_{sc} = \frac{\pi\Gamma(I/I_s)}{1+(I/I_s)+4(\Delta/\Gamma)^2} \qquad \ldots(1)$$

where I is the sum of the intensities of the six trapping beams, Γ the natural line width of the transition, Δ the detuning of laser frequency from the resonance and I_s is the saturation intensity. Changing the intensity of laser beams or frequency detuning changes the photon scatter rate as is evident from Eq. (1). The fluorescence received in the photo diode is the ratio of solid angle subtended by the area of imaging lens and total solid angle (4π).

The voltage signal generated by the photodiode is converted to an optical power by converting the signal to a current using the sensitivity and the amplification factor for the detection system. The total optical power at the photodiode is given by the relation:

$$P = \left(\frac{\Omega}{4\pi}\right)N\gamma_{sc}\left(\frac{hc}{\lambda}\right) \qquad \ldots(2)$$

where Ω is the solid angle subtended by the photodetector, N is the number of atoms, γ_{sc} is the scatter rate of photons and λ represents the wavelength of the emitted photons.

As the size of this photodiode, its spectral response (sensitivity and amplification factor) and distance to the trapped atoms are known one could calculate the overall power of the emitted fluorescence light, which enables one to measure the number of atoms in the trap using Eqs (1 and 2).

$$N = \left(\frac{\lambda}{hc}\right)\left(\frac{4\pi}{\Omega}\right)\left(\frac{1}{\gamma_{sc}}\right)\left(\frac{\alpha}{s}\right)U_{osc} \qquad \ldots(3)$$

U_{osc} is the amplitude of the voltage signal from the photodiode measured on the oscilloscope, α the amplification factor and S is the sensitivity of the photodetector. The solid angle subtended by the photodiode on the cloud is calculated as the ratio of area of the imaging lens to its distance from the cloud. Number of trapped atoms depends upon several MOT parameters such as magnetic field gradient, frequency
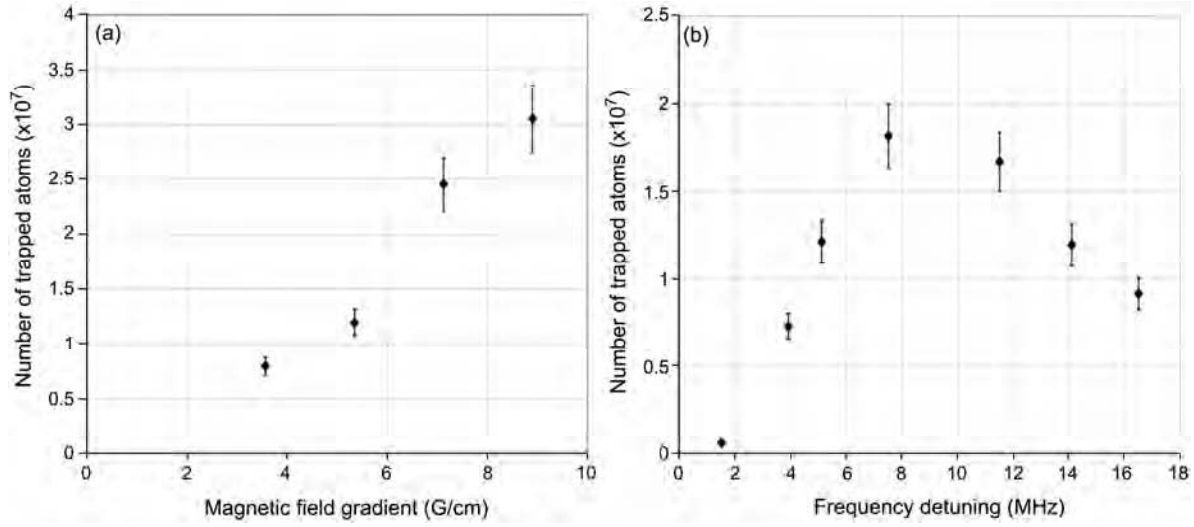
Fig. 3 — Number of trapped atoms as function of (a) magnetic field gradient, with 14.1 MHz detuning and (b) laser frequency detuning, with a magnetic field gradient of 5.34 G/cm.

detuning, intensity and diameter of the laser beams etc. With appropriate operating parameters, we could cool and trap cloud of cesium atoms with 10^7 atoms at the center of the MOT. It was verified that an increase in laser intensity leads to an increase in total number of trapped atoms.

For 40% increase in laser beam intensity, the total number of atoms increased 8-folds. In addition, dependence of total number of atoms on the magnetic field gradient and frequency detuning was checked to optimize the operating parameters. We have found that for each beam size and beam intensity, there is an optimum magnetic field gradient and optimum frequency detuning. The maximum number of atoms that can be trapped is however limited by the background pressure. The loading time constant of the MOT depends on the capture rate and the loss rate. Some of the atoms trapped are lost due to collisions with the background atoms and with the untrapped Cs atoms. By improving the vacuum, background collisions reduce and hence, the number of atoms increase but the upper limit comes due to collisions with untrapped Cs atoms. Fig. 3(a) shows how the number of atoms depends on magnetic field gradient at a fixed detuning and Fig. 3(b) shows how the number of atoms depends on detuning at a fixed magnetic field gradient. The results are in agreement with previously reported works[15-17].

The size of the cold atom cloud is determined from the CCD image. Fig. 4 shows the image of a trapped cloud of Cs atoms captured with a CCD camera mounted on one of the viewport of the octagonal chamber. The pixel output value of the CCD camera
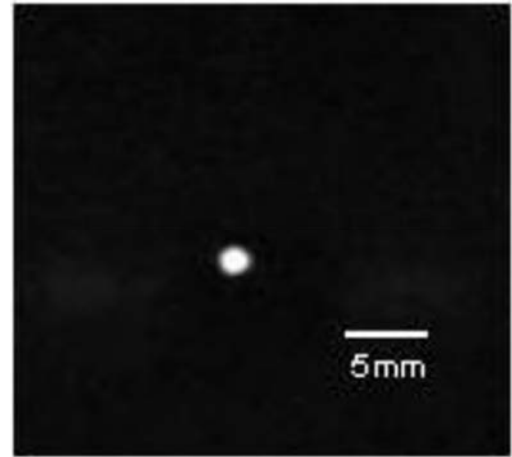

Fig. 4 — Image of the cold Cs atom cloud captured with a CCD camera

is proportional to the light intensity. The trapped atom cloud has a Gaussian density distribution. A two-dimensional picture of the MOT is taken by CCD camera. Using a Matlab program, Gaussian function is fitted to the intensity values in both X and Y direction. The CCD camera has a light sensitive array of 768×576 pixels. The pixel array has a size of 6.4 mm×4.8 mm. To determine the size, the CCD camera with lens system is calibrated by keeping a metric scale in the similar configuration. From this, one can calculate how many pixels correspond to 1 mm size in vertical and horizontal directions. Assuming spherical symmetry, the typical Gaussian half width diameter of the cloud is estimated. In our case, the cloud size (diameter) was estimated to be 1.5 mm for a magnetic field gradient of 2.1 G/cm and detuning of 14.1 MHz.

Of many attributes of the cold atomic clouds formed in a MOT, temperature is perhaps the most important one and there exist a number of techniques developed for its measurement. These include release and recapture[18] (R&R) and time of flight[19-22] (TOF) techniques, and also other more elaborate methods based on forced oscillation of the cloud[23], fluorescence spectrum analysis[24], recoil induced resonances[25] and four wave mixing[26]. We measured temperature of the cloud using release and recapture method. This method is one of the simplest techniques first used by Chu[18] and his collaborators in their study of Doppler cooling of atoms in an optical molasses. A similar technique is used here to measure the temperature of cold atoms trapped in a MOT. The MOT beams are turned off for time Δt. The fluorescence signal from the cloud is recorded using a photodetector as explained in earlier section. In the absence of MOT beams, atoms expand ballistically and go out of detection region, which is imaged by a lens on the photo detector. The fraction of remaining atoms in detection region is detected in the fluorescence signal by turning on the MOT beams. We assume that the atomic cloud's density is uniform over a sphere with radius σ_0. If the atoms move with the most probable velocity $v_p(T) = \sqrt{(2K_B T)/m}$ from the Maxwell-Boltzmann distribution, the radius of the sphere would increase with this velocity. So $\sigma_1 = \sigma_0 + v_p \cdot \Delta t$. From this, one can get an expression for the temperature T and the ratio N_1/N_0:

$$T = \frac{m}{2K_B}\left[\frac{\sigma_0}{\Delta t}\cdot\left\{\left(\frac{N_0}{N_1}\right)^{1/3}-1\right\}\right]^2 \Leftrightarrow \frac{N_1}{N_0}$$

$$= \left(1+\frac{\Delta t}{\sigma_0}\cdot\sqrt{\frac{2K_B T}{m}}\right)^{-3} \qquad \ldots(4)$$

where σ_1 is the size of the cloud after switching off the MOT beams during time Δt. k_B is Boltzmann's constant and m the mass of the atom, N_0 is number of atoms trapped in the MOT (in saturation) before turning off the MOT beams and N_1 is number of atoms in the MOT after time Δt when MOT beams are turned on again. As only half the numbers of atoms move out of the sphere with volume V_0 carrying N_0 number of atoms, a factor of ½ is added in the formula and as $N \propto U$ (voltage), the modified formula is:

$$T = \frac{m}{2K_B}\left[\frac{\sigma_0}{\Delta t}\cdot\left\{\left(\frac{2U_0}{U_1}\right)^{1/3}-1\right\}\right]^2 \qquad \ldots(5)$$

Figure 5 shows the release and recapture signal observed on an oscilloscope. After the MOT reaches saturation, all six confining beams are switched off with the help of mechanical shutters for 26 msec. During this time, atoms leave the trap center with their instantaneous velocities. When the beams are turned back again, a fraction of atoms is captured at
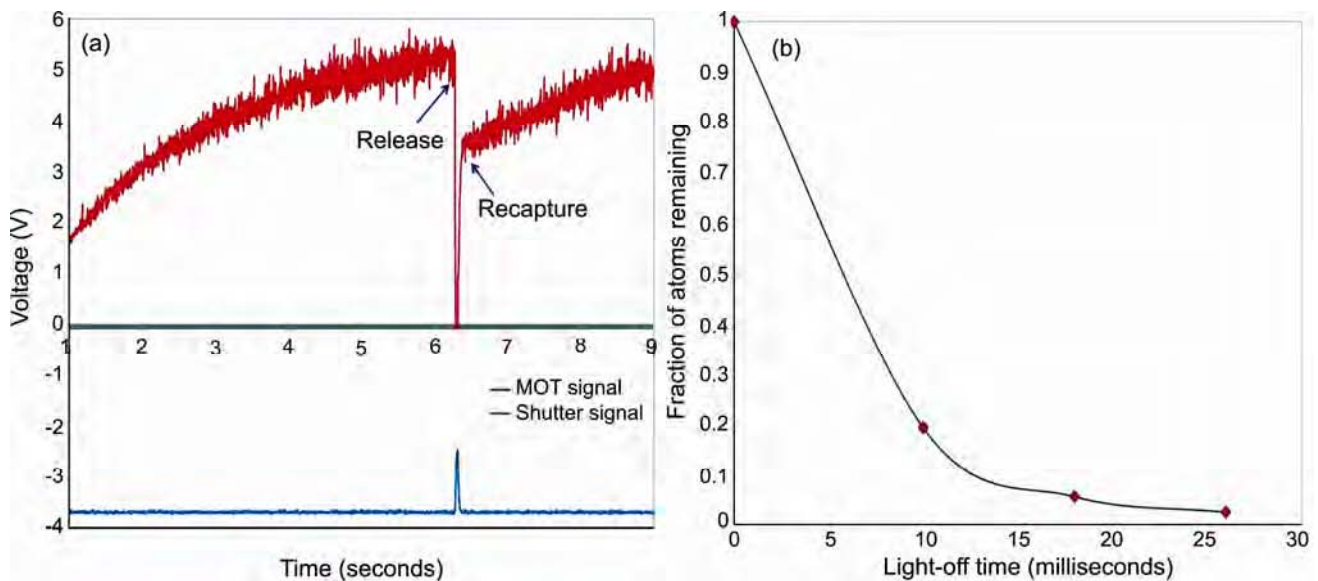

Fig. 5 — (a)-Fluorescence signal from the MOT and shutter signal as a function of time, (b) Fraction of atoms trapped in the MOT as a function of light-off time

the trap center as shown in Fig. 5(a). From this data, the temperature of the cloud is calculated using Eq. (5) for different light-off times as shown in Fig. 5(b) and the average temperature of the cloud in MOT was 125 µK which is close to the Doppler limit for Cesium. However, some amount of sub-Doppler cooling is also taking place as we use red-detuned light for Doppler cooling. For further cooling of the atoms, polarization gradient cooling is used which, in general, brings the cloud temperature to less than 5 µK. In this technique, frequency of laser beams is detuned to about 25 MHz from resonance and amplitude is reduced as well. The final temperature after polarization gradient cooling was measured using the time-of-flight data by launching the atomic cloud to different launch heights and was estimated to 6 µK for our system.

This measurement of temperature using both R&R and TOF method gives approximate estimation as the model used for calculation assumes that the cloud of atoms expands uniformly with the same velocity. However, using these methods one can get a quick estimate of the temperature and hence the velocity of atoms in the trapped cloud.

4 Conclusions

A detailed description of the measurement process and characterization of cold atomic cloud in a MOT has been presented in this paper. The number of atoms trapped in MOT depends on parameters like beam intensity, magnetic field gradient, frequency detuning etc. With this characterization, it is possible to desirably vary the number of trapped atoms. Measurements of temperature after Doppler cooling is done using release and recapture method and the average temperature of the cloud is found to be 125 µK. Time-of-flight data was used to find the final temperature of the cloud after sub-Doppler cooling and was found to be 6 µK. The details of measurements and results presented in this paper will be useful reference for starting researchers in the laser cooling field.

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