Studies on cold atoms trapped in a 
Quasi-Electrostatic optical dipole trap

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Abstract. We discuss the results of measurements of the temperature and density distribution
of cold Rubidium atoms trapped and cooled in an optical dipole trap formed by focussed CO$_2$
 laser beams at a wavelength of 10.6 $\mu$m from a cold, collimated and intense atomic beam of flux
$2 \times 10^{10}$ atoms/s produced using an elongated 2D$^+$ MOT. A large number of rubidium atoms
($\geq 10^{10}$) were trapped in the MOT and the number density of atoms were further increased
by making a temporal dark MOT to prevent density-limiting processes like photon rescattering
by atoms at the trap centre. Subsequently, between $10^7$ to $10^8$ cold atoms at a temperature
below 30 K were transferred into a Quasi-Electrostatic trap (QUEST) formed by focussed CO$_2$
 laser beams at the MOT centre. Both single beam and crossed dual beam dipole traps were
studied with a total output power of 50 W from the CO$_2$ laser with focal spot sizes less than 100
microns. Various measurements were done on the cold atoms trapped in the dipole trap. The
total atom number in the dipole trap and the spatial atom number density distribution in the
trap was measured by absorption imaging technique. The temperature was determined from
time-of-flight (TOF) data as well as from the absorption images after ballistic expansion of the
atom cloud released from the dipole trap. The results from measurements are used to maximize
the initial phase-space density prior to forced evaporative cooling to produce a Bose-Einstein
Condensate.

1. Introduction
The advent of Laser cooling techniques has proved to be one of the most significant milestones
in the progress of atomic physics. Cold atoms have enabled many precision experiments which
were difficult, or considered impossible, with room temperature atoms. Magneto-optical trap
(MOT) is a well known and widely used system to cool atoms to sub-millikelvin temperatures.
With sub-doppler cooling in a MOT, atoms can be cooled to a few times the single photon
recoil limit. For further cooling of atoms close to or below the single photon recoil limit, dark
traps are required which are devoid of near-resonant light. Two kinds of dark traps are used
for cooling of atoms to sub-recoil temperatures by using the evaporative cooling technique:
magnetic traps and optical dipole traps. Magnetic traps are more widely used for evaporative
cooling of atoms to produce Bose-Einstein condensation but has a limitation that only one spin
state can be trapped. In optical dipole traps [1, 2, 3, 4] atoms in all spin states or in general in
a superposition of different spin states can be trapped, which enables the study of interesting
spin dynamics in all-optical Bose-Einstein condensates. In this paper, we present the results
of studies on atoms trapped in both single beam and crossed beam Quasi-Electrostatic optical
dipole trap produced by focussing CO$_2$ laser beams of wavelength 10.6 microns.
Alkali Atoms have a permanent magnetic dipole moment which enables trapping of atoms in magnetic traps resulting from the interaction of magnetic dipole moment of atoms with the inhomogeneous magnetic field of the trap. On the other hand, atoms in their ground state are devoid of any permanent electric dipole moment. Hence, for optical trapping of atoms, it is required to induce an electric dipole moment in the atoms by subjecting them to either dc fields or optical frequency fields. DC field trapping of atoms is favorable only for atoms with closely spaced levels of low energy like those in Rydberg atoms. For trapping of atoms in their ground state, it is preferable to use optical frequency fields.

Optical dipole trapping is based on the interaction of the induced atomic dipole moment and the far-detuned optical field. Detuning far from the atomic resonance is required to keep the optical excitations quite low and to provide a conservative trapping potential. In the simple classical picture, an atom placed in a laser light field can be considered as a simple oscillator subjected to a classical radiation field. The electric field $E$ of the laser light induces an atomic dipole moment $p$ which oscillates at the frequency $\omega$ of the driving oscillating electric field. The relation between the driving electric field $E$ and the induced atomic dipole moment $p$ is given by

$$p = \alpha(\omega) E$$

where $\alpha(\omega)$ is the complex frequency dependent atomic polarizability.

When a single Gaussian laser beam, which is far red-detuned to the atomic transition, is focussed at the atomic cloud, the AC stark shift $\Delta E$ produced due to the trapping light field lowers the ground state energy of the atoms proportional to the local intensity $I$ of the light field according to the equation (considering two-level atomic system)

$$\Delta E = \pm \frac{3\pi c^2}{2\omega_o^3} \Delta I$$

where $I = 2\varepsilon_o c |\hat{E}|^2$, $\Gamma$ is the spontaneous decay rate of the excited state of the atom, $\omega_o$ and $\omega$ are respectively the optical transition frequency of the atom and the laser frequency and $\Delta = \omega - \omega_o$ is the detuning of the laser frequency from the atomic transition.

The spatial dependence of the light intensity $I(r)$ corresponds to the spatial dependence of the atomic potential energy $U_{dip}(r)$. In the case of a far-off resonant trap (FORT) [5] where the laser detuning $\Delta \ll \omega_o$,

$$U_{dip}(r) = -\frac{3\pi c^2}{2\omega_o^3} \Delta I(r)$$

and the corresponding photon scattering rate by the atom is given by

$$\Gamma_{sc} = -\frac{3\pi c^2}{2\hbar \omega_o^3} \left(\frac{\Gamma}{\Delta}\right)^2 I(r)$$

From equations (2) and (3), a simple relation can be obtained between the atomic scattering rate and the atomic dipole potential energy,

$$\Gamma_{sc} = \frac{\Gamma}{\hbar \Delta} U_{dip}(r)$$

From equations (2) and (3), the atomic dipole potential $U_{dip} \propto \frac{1}{\Delta}$ whereas the atomic scattering rate $I_{sc} \propto \frac{1}{\Delta^2}$. Hence, to optimize the dipole potential depth in order to maximize the transfer of atoms into the dipole trap, it is desirable to have high intensity of the laser used for producing the dipole trap. To minimize the scattering rate for making the dipole trap as close as possible
to an ideal conservative trap, it is beneficial to keep the detuning as large as possible. In an extreme case where \( \omega \ll \omega_o \), the dipole potential is given by

\[
U_{dip}(r) = \frac{3\pi c^2 \Gamma}{\omega_o^4} I(r) = -\frac{\alpha_{st}}{2\varepsilon_0 c} I(r)
\]

and the scattering rate is given by

\[
\Gamma_{sc} = -\frac{2\Gamma}{\hbar \omega_o} \left( \frac{\omega}{\omega_o} \right)^3 U_{dip}(r)
\]

where \( \alpha_{st} = \frac{6\pi \varepsilon_0 \omega_o}{\omega^3} \) is the static polarizability, and \( \alpha_{st} \approx \alpha (\omega = 0) \). Since, in this case, the frequency of the trapping laser is much smaller than the optical transition frequency of the atom, the atom sees the polarizing laser electric field as almost a static one and hence such a trap is considered as a Quasi-Electrostatic trap (QUEST) \([1, 6]\) for the atoms. An ideal example of a quasi-electrostatic trap is a high power CO\(_2\) laser with wavelength 10.6 microns for trapping atoms such as Rubidium, Cesium etc. whose optical transition wavelength is less than 1 micron. Since the well depth of the dipole trap is inversely proportional to the detuning of the trapping laser, the intensity of the trapping laser is required to be as high as possible to compensate for its extremely large detuning, in order to maintain a reasonable trap depth for maximum atom number loading in the QUEST.

In our experiment, we produced a quasi-electrostatic trap for rubidium atoms using a 50 Watt CO\(_2\) laser focussed at the magneto-optical trap centre using both single and crossed beam configuration. One of the biggest advantage of using quasi-electrostatic trap is that the optical excitation rate of the atoms is negligible, less than \(10^{-3}/s\), due to the extremely large detuning of the trapping laser and hence it is ideally suited for evaporative cooling towards producing a Bose-Einstein condensate. We have made various measurements on the atoms trapped in the Quasi-electrostatic trap and optimized the trap parameters in order to maximize the phase-space density of atoms in the trap.

2. Experimental set-up

![Figure 1](image)

Figure 1. The schematic diagram of the experimental arrangement to produce the cold atomic beam from a 2D\(^+\)MOT which loads atoms into a 3D-MOT.
For loading a large number of atoms in an optical dipole trap and evaporative cooling to produce a Bose-Einstein condensate, it is always beneficial to start with a large initial number of atoms and more importantly, a high atom number density in the magneto-optical trap. In a background loaded magneto-optical trap, the need for loading a large number of atoms within the MOT life-time conflicts with the requirement of having a good background vacuum to ensure long life-time of the trap. To circumvent this limitation we have loaded our magneto-optical trap from a cold atomic beam with high flux [7] produced from a 2D\textsuperscript{+}MOT [8] which enables ultra-fast loading of the 3D-MOT in 500 msec to an atom number exceeding $1 \times 10^{10}$, at a density of $1.5 \times 10^{11}$ atoms/cm\textsuperscript{3}.

2.1. 2D\textsuperscript{+} MOT and 3D-MOT

The experimental set-up comprises of a two-chamber vacuum system connected through a narrow differential pumping duct. The schematic of the experimental set-up is shown in Fig 1. The first chamber where the 2D\textsuperscript{+}MOT and the cold atomic beam are produced has a cuboidal shape. The pressure in this chamber is maintained at a pressure range of $3 \times 10^{-8} - 2 \times 10^{-7}$ mbar. The other vacuum chamber, an octagonal chamber with 4 CF 35, 8 CF 16 and 2 CF 100 ports, maintained at a UHV pressure of around $5 \times 10^{-11}$ mbar using an ion pump and a Ti sublimation pump, is where the 3D-MOT is produced from atoms loaded from the 2D\textsuperscript{+}MOT. The details of the experimental set-up is described in a previous paper [7].

The cooling laser for the 2D\textsuperscript{+}MOT of $^{87}$Rb atoms is derived from a 780 nm external cavity diode laser (ECDL). The frequency of the cooling laser was 2\textsuperscript{nd} red-detuned from the $^5S_{1/2}, F = 2 \rightarrow ^5P_{3/2}, F = 3$ transition of $^{87}$Rb. The repumping beam was derived from a 795 nm ECDL and its frequency was kept at resonance to the transition $^5S_{1/2}, F = 1 \rightarrow ^5P_{1/2}, F = 2$ of $^{87}$Rb. The cooling beams were appropriately circularly polarized. The cooling and repump laser beams were expanded to a circular beam of waist 9 mm. The transverse cooling beams and repump laser beam were then elongated along the atomic beam axis to a horizontal waist of 96 mm using a cylindrical lens pair. In order to eliminate the need for large $\lambda/4$ plates, the transverse cooling beams were retro-reflected using long right angle prisms. The power in each of the transverse cooling beams was 20 mW.

Four rectangular coils were used for the magneto-optic trapping in the transverse direction which produced a line of zero magnetic field as well as zero magnetic gradient along the central axis of the cuboid chamber. The transverse gradient is about 15 G/cm. An additional pair of linearly polarized laser beams having circular cross-section with beam waist of 9 mm were used for longitudinal cooling without any trapping along the atomic beam axis. One of the longitudinal cooling beams is reflected from a 45° mirror with a (differential pumping) narrow duct at the centre and therefore has a shadow along its axis. The imbalance in radiation pressure due to the two longitudinal cooling beams is used to push the cold atoms from the 2D\textsuperscript{+}MOT through the differential pumping hole into the adjacent UHV chamber to form a 3D-MOT.

The source of rubidium atoms is a 5g rubidium ampule contained in a tube that is connected to the cuboid chamber through an inline valve. The rubidium vapor pressure was kept around $2 \times 10^{-7}$ mbar in the 2D\textsuperscript{+}MOT chamber for optimized loading of the 3D-MOT from the cold atomic beam.

2.2. Dipole trap parameters

We have used a commercial RF excited single mode CO\textsubscript{2} Laser (GEM Select 50\textsuperscript{TM}, Coherent Inc.) with ultra-high power stability and the spatial mode of our CO\textsubscript{2} Laser is TEM\textsubscript{00} Gaussian. The spatial intensity profile of a focussed Gaussian laser beam propagating in the z-direction is given by
\[ I(x, y, z) = \frac{2P}{\pi w^2(z)} \exp \left[ -2 \left( \frac{x^2 + y^2}{w^2_0} \right) \right] \]  

where \( P \) is the trapping laser power in Watts, \( w(z) \) is the \( 1/e^2 \) radius given by

\[ w(z) = w_0 \sqrt{1 + \left( \frac{z}{z_R} \right)^2} \]

where \( w_0 \) is the beam waist radius, \( z_R = \frac{\pi w_0^2}{\lambda} \) is the Rayleigh length and \( \lambda \) is the trapping laser wavelength.

The trapping potential is given by

\[ U(x, y, z) = U_0 \exp \left[ -2 \left( \frac{x^2 + y^2}{w^2_0} \right) \right] \]

and the trap depth \( U_0 \) is given by

\[ U_0 = \frac{1}{4\pi \varepsilon_0} \frac{4\alpha_{sl}}{cw_0^2} P \]

The value of the static polarizability \( \alpha_{sl} \) for \(^{87}\text{Rb} \) ground states is \( \alpha_{sl} = 5.3 \times 10^{-39} \text{ m}^2 \text{ C}^{-2} \). The calculated trap depth for the crossed beam configuration in our experiment with 18 watts in each of the beams with about 50 micron waist radius of the focus is about 660 micro-Kelvin. This is more than 16 times the initial temperature of the atoms loaded into the dipole trap. The margin is large enough to accommodate well the possible imperfections in the dipole trap focus.

2.3. Single beam configuration

For producing the single beam trap, the 50 Watt output of the CO\(_2\) laser was first expanded in free space taking advantage of the fact that the CO\(_2\) laser beam has a natural divergence of 7.5 mrad. The beam waist diameter of the CO\(_2\) laser beam is about 2 mm at the output of the laser and it was allowed to travel in free space for more than 2 metres so as to expand to 15 mm. This was done in order to avoid placing a beam expander in the beam path since the laser beam profile critically depends on the beam expander alignment. Before the expansion of the CO\(_2\) laser beam, it was passed through an Accousto-optic modulator (AOM) (IntraAction Corp.), placed at a distance of about 30 cm from the laser output port, and one of the first order diffracted output from the AOM was taken for the dipole trapping. This enables precise computer control of the laser beam intensity by variation of the input RF power to the AOM which is very useful for evaporative cooling in the dipole trap. After the expansion, the laser beam was focussed at the magneto-optical trap centre using a ZnSe lens of diameter 38 mm and focal length 100 mm to a waist of approximately 70 microns. The lens was mounted on a stage with adjustability in all three orthogonal axes since the dipole trap loading is critically dependent on the alignment of the focussing lens, and it is important to have the focal spot right at the centre of the magneto-optic trap for maximum transfer of atoms in the dipole trap. About \( 5 \times 10^7 \) atoms could be trapped in the single beam dipole trap. The details of the measurement technique will be provided in the subsequent sections.

2.4. Crossed beam configuration

In the crossed beam configuration of the quasi-electrostatic trap, the 50 Watt output of the CO\(_2\) laser was passed through a 50-50 beam splitter. Each of the beams after the 50-50 beam-splitter were then passed through 40 MHz CO\(_2\) Accousto-optic modulators (IntraAction Corp.). For
one of the laser beams the negative first diffraction order was taken while for the other beam the positive first order diffracted beam was taken. This was done in order to have a frequency difference of the order of 80 MHz between the two laser beams in the crossed configuration so that there is no formation of unwanted interference patterns between the beams. The Accousto-optic modulators serve two purposes: (1) They enable full control of the variation of the powers in the two beams which is a crucial requirement for evaporative cooling in the crossed dipole trap configuration. (2) They ensure elimination of unwanted standing-wave effects between the two laser beams in the crossed configuration. The zeroth orders of each of the accousto-optic modulators were appropriately dumped using CO\textsubscript{2} beam dumps. The alignment of the CO\textsubscript{2} accousto-optic modulators was optimized to obtain 75 percent efficiency. The expansion of the beams after the accousto-optic modulators were done in a manner similar to the single beam configuration. Both the beams were allowed to expand in free space for about 3.5 metres and hence the initial CO\textsubscript{2} laser beam of waist diameter 2 mm was expanded to about 20 mm. Each of the two beams were then focussed at the magneto-optical trap centre in a right angle configuration in the horizontal plane using ZnSe meniscus lenses of diameter 38 mm and focal length of 100 mm to a waist radius below 50 microns each. Each of the ZnSe lenses were put on a stage with X-Y-Z adjustability so as to optimize the individual beam focussing at the trap centre as well as the accurate crossing of the two beams at the magneto-optic trap centre which is the most critical part in producing a crossed dipole trap with maximum atom number loading.

3. Dipole trap loading
The initial phase-space density of atoms in the MOT is a crucial parameter for transferring maximum number of atoms from the MOT to the dipole trap. The trap depth of the trapping potential formed in this crossed beam configuration with 18 Watt power in each of the beams was estimated to be about 290 micro-Kelvin. The initial cold atomic sample in the magneto-optical trap should be cooled well below this trap depth for maximum transfer of atoms to the dipole trap, and this poses no problems in our set up. The radial dimension of the trap in each of the single beam trap is less than about 140 microns. This means that the central density of the atoms trapped in the magneto-optical trap has to be enhanced significantly to ensure that a large number of atoms are transferred into the dipole trap.

![Figure 2.](image)

Figure 2. Ultra-fast loading of atoms in a 3D-MOT with atoms from the cold atomic beam from a 2D\textsuperscript{+}MOT with a flux of $2 \times 10^{10}$ atoms/sec.

Hence, for optimized loading of atoms into the dipole trap, there is a requirement of reduction of temperature of the trapped atoms along with the enhancement of the atom number density. This is achieved by using a combination of molasses cooling and the temporal dark MOT
technique [9]. The atom number density obtained in our 3D magneto-optical trap loaded from the high flux atomic beam is about $1.5 \times 10^{11}$ atoms/cm$^3$. This is almost at the limit of atom number density possible in the magneto-optical trap because of the photon re-scattering process which is particularly significant in high density magneto-optical traps with large number of atoms as in our experiment. In this process, the fluorescence light emitted by some trapped atoms is absorbed by the other trapped atoms which gives them a momentum kick opposite to the recoil momentum of the emitting atoms and thereby causes a repulsive force between the trapped atoms. Hence, to further increase the atom number density at the centre of the MOT, the photon-re-scattering process must be prevented at the trap centre. For this purpose, the atoms must be transferred to the F=1 hyperfine ground state or the dark state where the atoms are no longer resonant with the near-resonant cooling laser and hence are not affected by the photon re-scattering process. This allows for a further increase in the density in the magneto-optical trap. Moreover, it is known that the atoms trapped in the optical dipole trap in lower (F=1) ground state has larger life-time as compared to atoms in upper (F=2) ground state since atoms in the upper (F=2) hyperfine state is greatly affected by the hyperfine-changing collisional losses [10]. Hence it is absolutely essential to transfer the atoms to the lower F=1 state to maximize the efficiency of the dipole trap loading and to increase the life time of the trapped atoms.

Figure 3. Demonstration of the increase in density of atoms after Temporal Dark MOT phase by taking the difference of the absorption images of atoms in a MOT and atoms after a temporal dark MOT phase.

Initially, the 3D-MOT is loaded to about $1.2 \times 10^{10}$ atoms in about 500 msec from a high flux atomic beam from the 2D$^+$MOT as shown in Fig. 2. During the temporal dark MOT phase, first the repump intensity was lowered to 1 percent of its initial value using an AOM. After 20 msec, the detuning of the cooling laser was increased to 44 MHz to enable molasses cooling of the atoms. After a duration of 40 ms, the repump beam was completely extinguished and after 2 msec the cooling laser beams and magnetic field were also switched off. The process of lowering the repump intensity and finally switching it off 2 msec before the cooling beams are switched off causes the atoms in F=2 hyperfine ground state to transfer to the F=1 hyperfine ground state. The efficiency of transfer of atoms to the F=1 hyperfine ground state was measured to be 95 percent. In the absence of photon rescattering during the temporal dark MOT phase, the atomic cloud is compressed and the atom number density increased by a factor of 40 at the centre of the magneto-optical trap after the temporal dark MOT phase. Also a spatial dark spot MOT [9] works at the centre of the magneto-optic trap since the large AC stark shift at the focus of the CO$_2$ Laser makes the repump laser beam out of resonance with the rubidium atomic transition and hence contributes to enhancement of the atom number density at the
Figure 4. Absorption image of Dark MOT a) without magnetic compression b) with magnetic compression.

magneto-optic trap centre due to inhibition of the density-limiting photon re-scattering process. The dipole trap was kept on at full power throughout the MOT loading and temporal dark MOT phase. A further enhancement of atom number density in the trap by a factor of 4 was observed after a magnetic compression immediately after the temporal dark MOT phase by ramping up the MOT magnetic field from 15 Gauss/cm to 60 Gauss/cm within a time span of 40 msecs. However this compression technique for density enhancement was not used in the measurements described in this paper. The criteria for optimization of the various parameters for the temporal dark MOT phase was to obtain the maximum transfer of atoms to the dipole trap.

Figure 5. Comparison of the Time-of-Flight (TOF) signals of (a) atoms released directly from a MOT with (b) atoms released after implementing molasses cooling and temporal Dark MOT technique.

4. Detection and Measurements
The atoms trapped in the dipole trap were detected using both absorption imaging and time-of-flight (TOF) technique.

4.1. Absorption imaging
A weak probe beam of circular cross-section with beam waist of 10 mm and intensity of 15 \( \mu W/cm^2 \) was pulsed for a duration of 1 ms after releasing the dipole trap and allowing the atom cloud to expand freely for a variable time. The probe beam was tuned to resonance to the \( ^5S_{1/2}, F = 2 \to ^5P_{3/2}, F = 3 \) transition of \(^{87}Rb\). The absorption probe beam was passed
Figure 6. Time-of-flight signal from the atoms released after holding for 200 msec in the single beam dipole trap. The first saturated signal at the left of the graph is from the atoms not captured in the dipole trap after temporal dark MOT and falling off after the near resonant cooling lasers and magnetic field are switched off. The signal at the right is from the atoms released from the dipole trap.

Figure 7. Time-of-flight images of atoms trapped in a single beam dipole trap. The absorption images are taken after expansion times of 0, 2 and 5 ms from left to right. The initial temperature of the atom cloud is $25 \mu K$. The field of view is $2.5 \text{ mm} \times 2.5 \text{ mm}$.

through an AOM in double-pass configuration so as to accurately control the pulsing of the absorption probe beam during the detection process. The absorption imaging probe beam was retro-reflected for radiation pressure balance so as to prevent any disturbance of the atoms due to the resonant probe beam (this, however, is not a serious issue for heavy alkali atoms like Rb and Cs). The retro-reflected beam was then imaged on to a CCD Camera using a meniscus lens of focal length $35 \text{ cm}$ and the absorption images were recorded for determination of the trapped atom parameters. The imaging lens was kept at a distance of $70 \text{ cm}$ (twice the focal length of the lens) from the centre of the trap and the frame transfer EMCCD camera (Andor iXon DV887) was placed $70 \text{ cm}$ from the lens so that the image of the cold atoms are taken with unity magnification. The MOT repump beam was kept on during the detection process. The spatial density distribution of the atoms, optical density of atoms in the trap and the temperature of the atoms trapped in the magneto-optical trap both before and after the temporal dark MOT phase and magnetic compression as well as atoms trapped in the quasi-electro-static trap were
measured using the absorption imaging technique.

The intensity of the absorption probe beam was kept much below the saturation intensity in order to keep the probe beam absorption proportional to the atom number density in the cloud. The intensity profile of the probe beam after passing through the atom cloud and propagating in the z-direction is given by

\[ I(x, y) = I_0(x, y) \exp(-n_c \sigma_{ab}) \]  

(12)

where \( n_c = \int n(x, y, z) \, dz \) is the column density and the optical density \( D \) of the cloud at location \((x, y)\) is given by

\[ D = \sigma_{ab} n_c(x, y) = -\ln T(x, y) \]  

(13)

where \( T(x, y) \) is the relative transmission of the probe beam which is determined by comparing the probe beam intensity profile with and without the presence of atoms in the probe path. Defining the probe absorption image signals with and without the presence of atoms as signal image \( S_{sig}(x, y) \) and reference image \( S_{ref}(x, y) \) respectively and a background image \( S_{bg}(x, y) \) without the probe beam, the optical density is determined as

\[ D(x, y) = -\ln \frac{S_{sig}(x, y) - S_{bg}(x, y)}{S_{ref}(x, y) - S_{bg}(x, y)} \]  

(14)

The subtraction of the background image eliminates the effect of stray scattered light and electronic noise from the image.

The momentum distribution of the atom cloud in the trap is mapped to the spatial distribution of the atom cloud after releasing the atom cloud from the trap and allowing the atom cloud to expand ballistically. The temperature of the thermal cloud trapped in the optical dipole trap was determined by measuring the cloud size at different times after releasing the atoms from the dipole trap. The temperature of the atom cloud can be estimated as

\[ T = \frac{m}{k_B} \left( \frac{\sigma_2^2 - \sigma_1^2}{t_2^2 - t_1^2} \right) \]  

(15)

where \( \sigma_1 \) and \( \sigma_2 \) are the sizes of the atom cloud at times \( t_1 \) and \( t_2 \) respectively. The time of flight absorption images, at various expansion times, of atoms released from a single beam dipole trap are shown in Fig. 7.

4.2. Time-of-Flight

In the time-of-flight technique for atom detection, a thin sheet of probe beam of width 0.8 mm was kept 7 mm below the centre of the Magneto-optic trap. The probe beam was tuned to the resonance frequency for the \(^5S_{1/2}, F = 2 \rightarrow ^5P_{3/2}, F = 3\) transition of \(^{87}\text{Rb}\). The initial beam derived from the External cavity diode Laser (ECDL) with horizontal and vertical beam waists of 3 mm and 1 mm respectively was expanded in the horizontal direction using a pair of cylindrical lens to get a thin sheet of probe beam. The probe beam was then passed through a narrow slit just before entering the MOT chamber to obtain a width of 0.8 mm and to get rid of unwanted scattered light. The probe beam must be kept as thin as possible since the width of the probe beam also contributes to the width of the time-of-flight signal used for temperature determination of the trapped atoms. The probe beam was retro-reflected to prevent radiation pressure imbalance and the retro-reflected beam was detected using a photodiode. The intensity of the time-of-flight probe beam was kept at 25 \( \mu \text{W/cm}^2 \) just below the saturation intensity of the detector. The signal from the detector was passed through an amplifier (PDA-100S, Toptica) and then put into a Lock-in-amplifier for lock-in-detection. The reference signal to the Lock-in-amplifier was provided from the Diode laser controller for the ECDL from which the probe beam
Figure 8. Absorption images of atoms trapped in two single beam dipole trap before crossing.

Figure 9. Absorption image of atoms trapped in the crossed dipole trap.

is derived. The reference signal had a frequency of 4.5 KHz which is same as the modulation frequency of the laser used for locking the laser. Due to the high sensitivity of the time-of-flight technique, it was used as a reliable detection technique for temperature measurement along with absorption imaging method. A typical time-of-flight signal of atoms trapped in a single beam dipole trap is shown in Fig. 6.

To determine the temperature of atoms, the TOF signal was fitted with the following formula for short TOF measurement [11] given by

\[
S(t) = \frac{a}{\sqrt{\sigma_a^2 + \sigma_v^2 t^2}} \exp \left[ - \left( \frac{g(t_0^2 - t^2)}{2\sqrt{2\sigma_a^2 + \sigma_v^2 t^2}} \right)^2 \right]
\]  \hspace{1cm} (16)

where \(\sigma_a = \sqrt{\sigma_0^2 + \sigma_p^2}\), \(\sigma_0\) is the initial size of the atom cloud, \(\sigma_p\) is the width of the thin sheet.
of probe beam kept below the atom cloud and \( t_0 \) is the free fall time. The fitting parameter is given by \( \sigma_i^2 = k_B T / m \) where \( T \) is the temperature of the trapped atoms, \( m \) is the atomic mass and \( k_B \) is the Boltzmann constant. The scaling factor ‘a’ in the signal amplitude term depends on atom number and intensity of the detection probe.

5. Observations and Results

After the implementation of the temporal dark MOT phase, a significant increase in the density was observed. The atom number density of \( 1.5 \times 10^{11} \) atoms/cm\(^3\) in the magneto-optical trap was increased to \( 5 \times 10^{12} \) atoms/cm\(^3\) after the temporal dark MOT phase. Fig. 3 depicts the density enhancement by showing the difference in the absorption images before and after the temporal dark MOT phase. Further increase in the atom number density in the MOT by a factor of 4 after magnetic compression is shown in Fig. 4.

![Figure 10](image1.png)

**Figure 10.** Plot of the number of atoms versus the trapping time in a single beam dipole trap.

![Figure 11](image2.png)

**Figure 11.** Plot of the temperature of the atoms versus the trapping time in a single beam dipole trap. The points are the experimental data and the continuous line is provided as a guide to the eye.

The reduction in temperature and the density enhancement after the molasses cooling and temporal dark MOT phase is depicted by the time-of-flight(TOF) signals in Fig 5 where the
TOF signals after molasses cooling and dark MOT are significantly narrower and enhanced as compared to the TOF signal from the MOT. The temperature in the MOT was about 200μK which reduced to 40 μK after molasses cooling and temporal dark MOT.

After the loading of the dipole trap, the number of atoms trapped in the dipole trap was determined from both the time-of-flight signals and absorption images by comparison with the corresponding TOF signal and absorption image of the MOT since the atom number in the MOT was precisely determined using fluorescence detection. A typical time of flight signal of atoms trapped in the dipole trap after a holding time of 200 msecs is shown in Fig. 6. The number of atoms trapped in a single beam dipole trap was $5 \times 10^7$ atoms whereas $10^8$ atoms could be trapped in the crossed dipole trap as determined from the time-of-flight signal. An average atom number density of $10^{13}$ atoms/cm$^3$ was measured from the absorption images of atoms trapped in a single beam dipole trap where the atoms were confined to a waist of 300 μm in the axial direction and a waist of 100 micron in the radial direction. The density was increased to $1 \times 10^{14}$ atoms/cm$^3$ in the crossed dipole trap configuration as estimated from the measurement of optical density in the absorption images of atoms trapped in the crossed dipole trap. Fig. 8 shows the absorption image of atoms trapped in two single beam dipole trap before crossing and Fig 9. shows the absorption image of atoms in the crossed dipole trap.

After loading of the atoms in the dipole trap it was observed that there is a rapid evaporation of trapped atoms from the dipole trap in the initial few hundred milliseconds as shown in Fig 10. This can be attributed to spontaneous evaporation of the hotter atoms from the trap which reduces the trapped atom number by a factor of 7 in 1 second. The rapid spontaneous evaporation then gives way to a much slower decay which lasts for several seconds and it takes place mainly due to the collisions of the trapped atoms with the background thermal atoms. There is also a significant reduction of temperature due to the spontaneous evaporation process as shown in Fig. 11. The temperature reduces from 30μK to 15μK after spontaneous evaporation for 1 sec and then the temperature reduction rate slows down significantly. This indicates the need for forced evaporative cooling in the optical dipole trap for further reduction of temperature to proceed towards producing a Bose-Einstein condensate.

6. Conclusion
In this paper we have reported efficient loading of about $5 \times 10^7$ atoms in a single beam dipole trap and about $1 \times 10^8$ atoms in a crossed Quasi-Electrostatic trap, formed using a CO$_2$ laser operating at $\lambda = 10.6 \mu$m. The starting point for the dipole trap loading was a high density MOT with $1.5 \times 10^{11}$ atoms/cm$^3$ and with high atom number exceeding $10^{10}$ atoms, loaded from a cold atomic beam at a flux of $2 \times 10^{10}$ atoms/sec. Molasses cooling and temporal dark MOT technique were implemented which resulted in a temperature reduction to 40 μK from 200 μK and a density enhancement to $5 \times 10^{12}$ atoms/cm$^3$. The initial temperature of the atoms which could be trapped in both single beam and crossed beam dipole trap has a temperature of about 30 μK which is a factor of 3 to 4 less than the initial temperature observed in other similar experiments [12]. The atom number density reaches close to $10^{14}$ atoms/cm$^3$, ensuring an initial phase space density in the crossed dipole trap larger than $10^{-3}$. We have also measured the further reduction of the temperature in the dipole trap to about 14 μK within a second by spontaneous evaporation.

In a subsequent paper, we shall discuss about forced evaporative cooling of the atoms trapped in the optical dipole trap to reach quantum degeneracy.

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