

Atom Sources for Cold Atoms Experiments

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Abstract

Light-induced atomic desorption (LIAD) was first investigated, Rb atoms were loaded into a magneto-optical trap (MOT) by shining an ultraviolet light on a quartz glass coated with Rb. Secondly, double MOT setup with a push beam used to transport atoms from one MOT to the other without any magnetic confinement mechanism was successfully demonstrated. Rb atoms were first captured in a vapor-cell MOT then a push beam was flashed for about 5ms to transfer the atoms into another MOT inside the second chamber which a better vacuum was maintained. About 3.2×10^8 atoms were successfully loaded into the second MOT. We achieved a transfer efficiency of about 60% and the loading time required to fully load a MOT was about 3 times faster than using a thermal Rb source. For these studies, free-running lasers which do not suffer from any mechanical or acoustical noise were used as cooling beams for our Rb MOT. We also shown that the orientation of conventional atoms dispenser inside vacuum chamber was not important in order to make a decent MOT.

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Chapter 1

Introduction

Ultracold atom research have made a number of important contributions to improve our understanding of fundamental physics, quantum state manipulation, frequency standard, Bose-Einstein condensate and many other related fields. Several atom cooling techniques developed in the last decade such as dipole force trap, magnetic trap and optical lattices encouraged further advances in these fields. All of these experimental techniques rely on the laser cooling and trapping technique which was made possible in the 70's [1–3]. A key development was the establishment of magneto-optical trap (MOT), a relatively simple and inexpensive technique which is able to easily trap about 10^9 atoms at micro-Kelvin regime [4]. Currently, the MOT is a widely used technique for cooling different species of atoms. Most of the experiments dealing with ultracold atoms nowadays rely on MOT as a first step to capture, cool and manipulate atoms.

In general, most cold atoms experiments would benefit from a MOT with faster loading rate of atom, slower loss rate and greater number of trapped atoms. A widely used method to load atom trap is by passing current through an atom dispenser, which is not ideal in terms of having a good loading and trapping efficiency. First of all, the chamber would be a vapor pressure which

would jeopardize the lifetime of the MOT. Secondly, passing current to the dispenser in order to release atoms always accompanied by a ohmic heating effect which made the pressure inside vacuum chamber need a longer time to recover after the dispenser was switched off.

There were several experiment techniques proposed and deployed to improve the loading and trapping efficiency of MOT. Several groups relied on a setup of two MOTs, the first MOT captured atoms in a vapor pressure chamber and the pre-cooled atoms were transferred using a push beam to a second MOT inside another chamber where a better vacuum was maintained [5–8]. Better vacuum essentially decreased the loss of atoms from trap as the collisions between trapped and untrapped atoms were significantly reduced. The next generation of such configuration employed a magnetic transport mechanism to move pre-cooled atoms from one chamber to another region with better vacuum [9, 10]. MOT loaded using a pulsed thermal atom dispenser was also studied. According to reference [11], Rubidium atoms were captured into MOT within a few seconds and the lifetime after switching off the source became longer when compare with a MOT loaded using a non-pulsed thermal atom dispenser. Many of the most recent experiments use a technique called light-induced atomic desorption (LIAD). Atoms were first absorbed at the inner walls of vacuum chamber, and they were desorbed and loaded into atom trap when an incoherent light was shined on the wall [12–15]. This method effectively eliminated the heating effect of atom dispenser.

In this project, light-induced atomic desorption and double MOT configuration were studied. The aim of the project was to study how well these two techniques in terms of making a MOT with higher efficiency, i.e. fast loading time of MOT, greater number of atoms trapped and a longer MOT lifetime.

A vacuum system capable to study both the techniques was designed and constructed. The advantage of our vacuum system was its compactness for the case of double MOT technique. Two chambers were connected via a 76mm long transfer tube, which was about 5 times shorter

than those double MOT configuration previously demonstrated by other groups [5, 7].

Two free-running diode laser systems with wavelength 780nm were assembled. Unlike grating stabilized laser which is widely used in many atomic physics laser system, these free-running laser worked without any external frequency tuning element such as grating. These two lasers were used as the cooling lasers for the MOT in this project. Furthermore, we showed that the orientation of an atom dispenser is not important in terms of making a decent MOT and we are allowed to orient the dispenser in a way which benefit us the most ¹.

As for our main studies, we successfully loaded atoms into MOT using LIAD but the MOT size we obtained was not very satisfactory, only about 6×10^6 atoms were loaded into MOT by using a 395nm UV desorption light. The reason for this small amount of atoms captured by MOT was due to the 2cm $\times$ 2cm quartz glass we used as the desorption area, which in the end we concluded it was not big enough to release sufficient number of atoms to load the MOT when desorption light was turned on. We also observed a negative effect of the 395nm desorption light on Rb MOT. Rb atoms were found to escape from trap when the desorption light was shined directly onto an existing MOT. When the light missed the MOT, no negative effect was observed. Based on our study on atomic energy level of Rb-87, we suspected that the trapped atoms were ionized by the 395nm light and thus ejected out from MOT which was only able to trap neutral atoms.

For the double MOT experiment, we successfully used a push beam to ballistically transfer atoms from a MOT inside a vapor pressure chamber to a MOT inside a chamber with good vacuum. Under optimal experiment parameters, a MOT with 3.2×10^8 atoms was made. The transmission efficiency was about 60% and the time required to fully load a MOT was about 3 times faster than a MOT loaded using thermal Rb dispenser.

¹In a dipole force trap setup in our laboratory, a negative effect on the trapping lifetime due to a atom dispenser which orientated such that its filament facing directly the trap was observed. The freedom to choose whichever orientation of the dispenser would essentially eliminate or decrease this negative effect and increase the trapping lifetime.

The details about the project will be presented in the following: first the background on laser cooling and trapping, light-induced atomic desorption and double MOT will be introduced in chapter 2. Experiment setup including the vacuum system and optics will be presented in chapter 3. Then the results of LIAD and double MOT will be presented and discussed in chapter 4. Conclusions and discussions on future works of this project will be presented at the end of this thesis.

Chapter 2

Background

2.1 Laser Cooling and Trapping

The velocity of a sample of atoms is directly related to its temperature given by

$$\frac{1}{2}mv^2 = \frac{3}{2}k_B T, \quad (2.1)$$

for example given a Rubidium atom which has a mass of 1.44×10^{-25} kg, its velocity at room temperature is about

$$v = \sqrt{\frac{3k_B T}{m}}, \quad (2.2)$$

$$\approx 293\text{ms}^{-1}. \quad (2.3)$$

Laser cooling is a technique which employ the monochromatic laser to decelerate atoms and thus cool atoms to very low temperature. It was first proposed simultaneously by Wineland and Dehmelt and by Hansch and Schawlow in 1975 [1, 2], and first successfully demonstrated by Letokhov, Minogin and Pavlik in laboratory in 1976 [3]. Since then, many variety of laser

cooling and trapping techniques have been developed and demonstrated in order to cool atoms to lower temperature. These include optical molasses, magneto-optical trap, sub-Doppler cooling, magnetic trapping, evaporative cooling and dipole force trap. Here, we focus on those theory and techniques relevant to this project, namely the scattering force and the operation of the MOT.

2.1.1 Scattering

Maxwell's equations showed that light is one kind of electromagnetic radiation and thus has momentum as well as energy. It follows that a momentum of an object would change after radiation is absorbed by it. The force by a beam of light acting on an object equals to the rate of change of its momentum, this is the same as the rate of energy delivered by the light over the speed of light. Therefore, this radiation force can be written as

$$F_{rad} = \frac{IA}{c}, \quad (2.4)$$

where I is the intensity of the light and A is the area of the force which the light acts on.

For the case of atom interact with photon at resonance, this scattering force can be written as the product of the scattering rate and the photon momentum, given by

$$F_{scatt} = (\hbar k) \times (R_{scatt}), \quad (2.5)$$

$$= (\hbar k) \times \left(\frac{\Gamma}{2} \frac{\Omega^2/2}{\delta^2 + \Omega^2 + \Gamma^2/4} \right), \quad (2.6)$$

where $\delta = \omega - \omega_0 + k\nu$ is the frequency detuning from atomic resonance with taking the Doppler shift $k\nu$ into account. The Rabi frequency, Ω is related to the saturation intensity

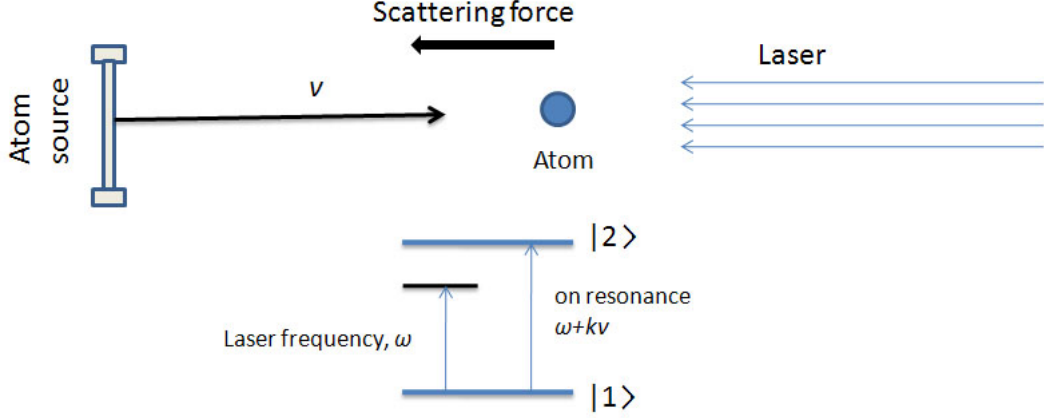


Figure 2.1: When an atom absorbs a photon and jumps to the excited state, the momentum of the photon will be transferred to the atom, thus the atom experiences a scattering force in the direction of the incoming laser. In practice, the laser frequency is tuned slightly below the resonance frequency of the atom to take Doppler effect due to the relative motion between the atom and photon into account.

given by $\frac{I}{I_0} = \frac{2\Omega^2}{\Gamma}$, thus equation 2.6 can be rewritten as

$$F_{scatt} = \hbar k \frac{\Gamma}{2} \frac{I/I_0}{1 + I/I_0 + 4\delta^2/\Gamma^2}. \quad (2.7)$$

2.1.2 Optical Molasses

The previous section showed the interaction between photon and atom, and how the momentum transferred from the photon to the atom, now we look at a three-dimensional setup of laser cooling, the optical molasses.

Optical molasses is a technique which decelerate atoms regardless of the propagating directions of the atoms. It uses six laser beams with equal intensity aligned in the cartesian coordinate, i.e. the $\pm x$, $\pm y$ and $\pm z$ -directions and crossing each other at the same center position. The laser frequency is slightly detuned below the resonance frequency. Due to Doppler effect, an atom travels in the opposite direction to the incoming photon will be blue-shifted and an atom travels in the same direction as the incoming photon will be red-shifted. As such, an

atom that travels opposite to the direction of the laser beam will have an effective frequency closer to the resonance frequency. In contrast an atom travels in the same direction as the laser beam will have an effective frequency shifted further away from the resonance frequency. Due to the fact that the interaction strength between photon and atom is strongly frequency dependent, an atom travels opposite to the laser beam will have stronger interaction than an atom travels in the same direction as the laser beam. The result of this configuration is an effective deceleration of atoms which the atoms always experience a force against their propagating directions within the laser overlapping region at the center.

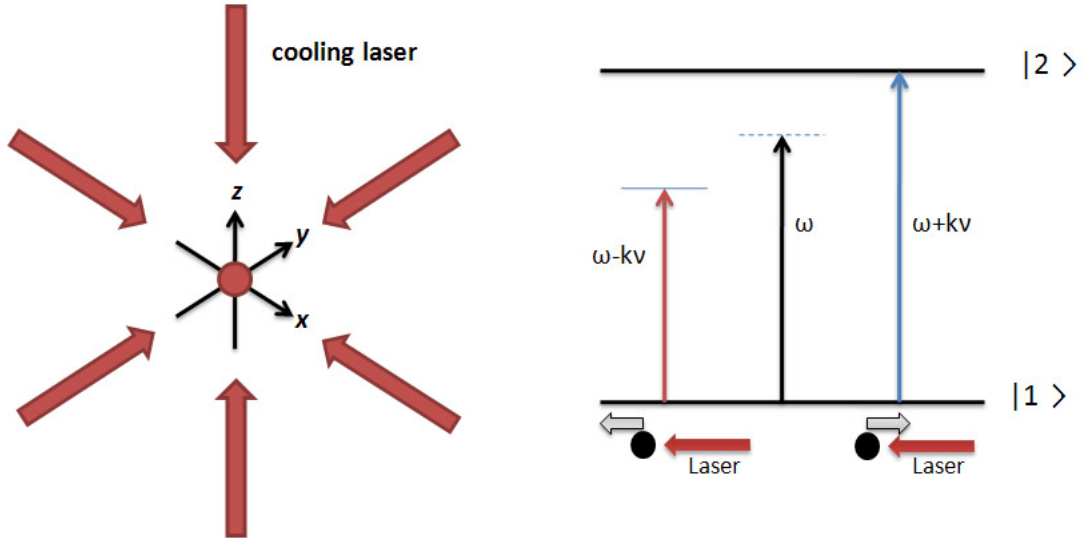


Figure 2.2: Six beams of orthogonal laser beams along the Cartesian axes. The laser frequency is tuned slightly below the resonance, as a result the atoms always experience a force opposite to its propagating direction.

Expressed mathematically, from equation 2.7, the net scattering force acting on an atom in one-dimension is

$$F_{molasses} = F_{scatt}^+ - F_{scatt}^-, \quad (2.8)$$

$$= F_{scatt}(\omega - \omega_0 - kv) - F_{scatt}(\omega - \omega_0 + kv), \quad (2.9)$$

where superscript + and - in equation 2.8 denotes scattering forces experienced by atom with

laser beam travels against its direction and laser beam travels in the same direction as the atoms respectively.

From equations 2.5 and 2.7, equation 2.8 can be rewritten as

$$F_{molasses} = \hbar k (R_{scatt}^+ - R_{scatt}^-), \quad (2.10)$$

with the scattering rate R_{scatt} for different laser propagating directions with respect to atom given by

$$R^\pm = \frac{\Gamma}{2} \frac{I/I_0}{1 + I/I_0 + 4(\omega - \omega_0 \mp kv)^2/\Gamma^2}, \quad (2.11)$$

by neglecting terms of order $(kv/\Gamma)^2$ and higher, the force experienced by atoms can be approximated as the following,

$$F_{molasses} = \frac{8\hbar k^2 \Delta}{\Gamma} \frac{s}{(1 + s + (2\Delta/\Gamma)^2)^2} v, \quad (2.12)$$

where $s = I/I_0$ and $\Delta = \omega - \omega_0$. Writing the force equation 2.12 in differential form, we get

$$m \frac{dv}{dt} = -av, \quad \text{with} \quad a = \frac{8\hbar k^2 \Delta}{\Gamma} \frac{s}{(1 + s + (2\Delta/\Gamma)^2)^2}. \quad (2.13)$$

Solving this differential equation, we obtain the time dependent velocity

$$v(t) = v_0 e^{-t/\tau_{damp}}, \quad \text{with} \quad \tau_{damp} = \frac{m}{a}. \quad (2.14)$$

The damping time τ_{damp} gives the time-scale for the cooling of atoms when they interact with laser. Equation 2.14 indicates that the atoms decelerate drastically if τ_{damp} is small. Under optimum conditions of a optical molasses setup, the damping time is on a microsecond scale.

Note that optical molasses is not a trap as there is no restoring force on atoms toward an equilibrium point when they are displaced from the center, it merely slows down the atom entering the light field region. However, it is a basic element for laser cooling technique and in particular for, the magneto-optical trap. The details of MOT will be described in the next section.

2.1.3 Magneto-Optical Trap

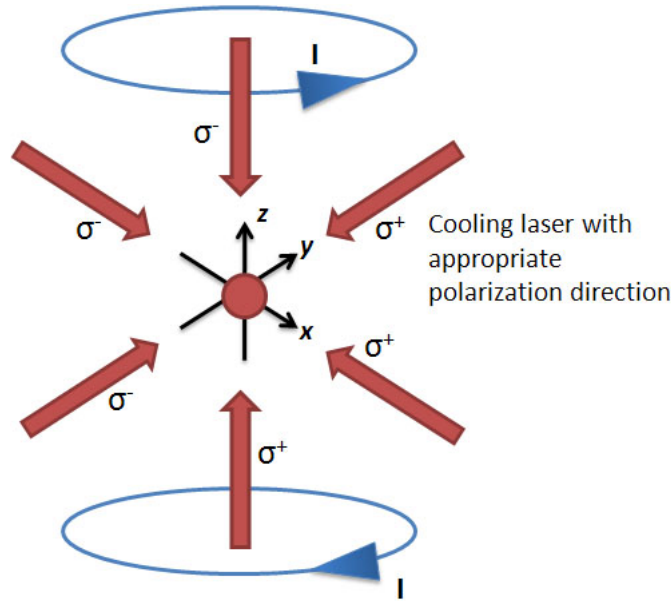


Figure 2.3: MOT is essentially a optical molasses setup with an additional pair of anti-Helmholtz coils with appropriate choice of laser polarization direction.

A magneto-optical trap essentially uses the optical molasses technique with addition a pair of anti-Helmholtz coils. The magnetic field used in this trap is not strong enough to trap the atoms by itself ¹. It merely produces a quadrupole magnetic field which has zero field strength at the center and at a distance closed to this center point, the atoms' energy is perturbed by a uniform magnetic field gradient. The result is that the atom's energy levels are Zeeman shifted, with the m_j degeneracy lifted. Together with an appropriate choice of the polarization direction

¹A typical setup of a magnetic trap has a magnetic gradient of about 30 times the magnetic gradient of a MOT.

of the laser beam, atoms can be trapped within a small region. In this case, the laser beams are incident such that any pair of counter-propagating beams are polarized in opposite direction, one in the right circular direction and the other in the left circular direction. The frequency of the laser beams are detuned such that it is slightly lower than the resonance frequency of the atom.

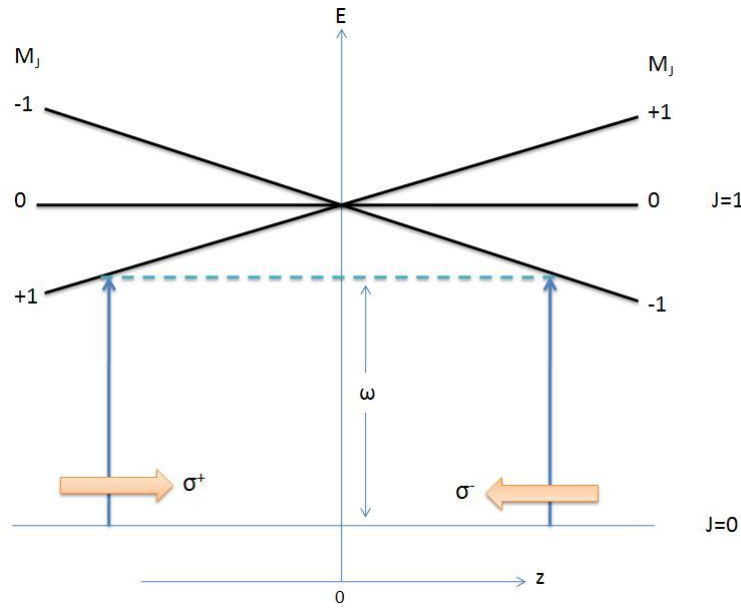


Figure 2.4: Atom at positive z -axis would have $m_j = -1$ level shifted down and able to absorb a left circular polarized photon which eventually push the atom toward the center. Similar effect goes to atom at negative z -axis but now the $m_j = +1$ level shifted down and right circular polarized photon would be absorb by the atom. In three-dimension, this effectively trapped atoms by pushing them toward the center whenever they are displaced from the center.

The principle of a MOT is illustrated in figure 2.4. Consider a two level atom with ground state $J = 0$ and excited state $J = 1$, at the $J = 1$ level, the magnetic field gradient causes the sub-level $m_j=1$ level shifted upward in the positive z -direction, and downward in the negative z -direction. Oppositely, the $m_j=-1$ level shifted downward in the positive z -direction and downward in the negative z -direction. As a result, this configuration with combination of magnetic field and laser light field creates an imbalance in the radiation force on the atom. Remembering that the laser light is detuned slightly lower than the resonance frequency, atoms lie on the

positive z-axis would thus absorb the left circular polarized photons and jump to the $m_j=-1$ sub-level of the $J = 1$ excited state. Similarly, atoms lying on the negative z-axis would absorb the right circular polarized photons incident on it and jump to the $m_j=1$ state, at the same time the atoms would be pushed toward the center of the trap. In the three dimensional space, this configuration effectively creates a trap which is able to constantly push atoms toward the center whenever the atoms are off center.

We can also describe the magneto-optical trap in terms of mathematics. Modifying equation 2.9, which describes the force experienced by an atom in an optical molasses setup, we can write the net force on an atom in a MOT by adding the effect on atoms due to the magnetic quadrupole field,

$$F_{MOT} = F_{scatt}^{\sigma+}(\omega - kv - (\omega_0 + \beta z)) - F_{scatt}^{\sigma-}(\omega + kv - (\omega_0 - \beta z)), \quad (2.15)$$

$$\cong -2\frac{\partial F}{\partial \omega}kv - 2\frac{\partial F}{\partial \omega}\beta z, \quad (2.16)$$

where $\omega_0 + \beta z$ is the new resonant absorption frequency for the $\Delta m_j=1$ transition at positive z and $\omega_0 - \beta z$ corresponds to the $\Delta m_j=-1$ transition at negative z . It is then very obvious to see from equation 2.16 that the atom experiences a restoring force which keeps pushing the atoms towards the center of the trap due to the imbalance in radiation force caused by the Zeeman effect.

2.2 Dynamics of a MOT

The conventional method to load a MOT is by passing current through an atom dispenser and filling the vacuum chamber with atom vapor. The six light beams overlapping at the center of the chamber would thus slow down the atoms. Together with the magnetic quadrupole

field provided by the anti-Helmholtz coils, atoms would eventually be trapped at the center. However, atoms would also escape from the MOT due to collisions, there are mainly two types of collision involved in the dynamic of a MOT, namely the collision between trapped atoms and background atoms, and collision between trapped atoms inside the MOT. Mathematically, the dynamic of a MOT can be written as

$$\frac{dN}{dt} = R - N \left(\frac{1}{\tau_{Rb}} + \frac{1}{\tau_b} \right) - \beta \int n^2 dV, \quad (2.17)$$

where N is the number of trapped atoms, R is the loading rate of atoms into the MOT, the $1/\tau_{Rb}$ term represents the trap loss rate due to collision between trapped Rb atom and untrapped Rb in the background and $1/\tau_b$ is the loss rate due to trapped Rb and other atoms in the background. The loss rate $1/\tau_{Rb}$ is proportional to the Rb partial pressure in the chamber and loss rate $1/\tau_b$ is proportional to the background pressure other than Rb in the chamber. The last term in the equation represents the loss due to atom-atom collision inside MOT, it is dependent on the trapped atom density n with a proportional constant β [12, 13]. Oftenly, it is assumed that the MOT is not saturated during the loading phase and thus the density dependent collision loss is neglected, we can write the rate equation as

$$\frac{dN}{dt} = R - \frac{N}{\tau_{MOT}}, \quad (2.18)$$

where

$$\frac{1}{\tau_{MOT}} = \frac{1}{\tau_{Rb}} + \frac{1}{\tau_b}. \quad (2.19)$$

Equation 2.18 can be solved easily to obtain number of atoms as a function of time, given by

$$N(t) = N_{max} \left[1 - \exp \left(-\frac{t}{\tau_{MOT}} \right) \right], \quad (2.20)$$

the τ_{MOT} appears in equation 2.20 can be defined as a time constant of the MOT loading time. Normally we can approximate this τ_{MOT} to be τ_{Rb} as we fill the chamber with Rb when loading a MOT, the Rb partial pressure would be much larger than the background partial pressure of non-Rb atoms, i.e. $1/\tau_{Rb} \gg 1/\tau_b$. N_{max} is the maximum number of atom can be loaded into the MOT. When the number of atoms trapped reaches this number, the loading rate equals to the loss rate, thus we have $dN/dt = 0$ in equation 2.18, yielding

$$N_{max} = R\tau_{MOT}. \quad (2.21)$$

Now we consider a MOT with loading rate $R = 0$. Equation 2.18 can be rewritten as

$$\frac{dN}{dt} = -\frac{N}{\tau_{MOT}}, \quad (2.22)$$

which can be solved easily:

$$N = N_0 \exp \left(-\frac{t}{\tau_{MOT}} \right). \quad (2.23)$$

This equation describes how the number of trapped atoms decays when there is no loading of atom into the MOT. N_0 is the initial number of trapped atoms, for most of the cases this quantity is equal to N_{max} as atoms are continuously loaded into the MOT until reaching the maximum number of trapped atoms before the Rb source is turned off.

A faster loading rate and a slower loss rate are desired in most cold atoms experiments. As

suggested by equation 2.17, this means that we need to make the loading rate, R as large as possible and make the other terms in the equation as small as possible. Using thermal atom source method which by passing current through the dispenser and load Rb atoms into a vapor-cell MOT, the number of trapped atoms could be increased by increasing the Rb partial pressure in the chamber, the downside of doing so is the lifetime of the MOT would be compromised according to equation 2.23, as the Rb partial pressure limiting the trapping lifetime.

A variety of techniques have been developed to achieve higher trapping efficiency in terms of a faster loading rate, slower loss rate and more trapped atoms. Among these techniques, LIAD and double MOT configuration were demonstrated as promising candidates to solve the problem that loading rate and loss rate limiting each other. In this project, LIAD and a double MOT configuration with a push beam as transport mechanism were studied, the details of these two techniques will be illustrated in the following sections.

2.3 Light-Induced Atomic Desorption

Light-induced atomic desorption was first demonstrated by A. Gozzini *et al.* in 1993 [16]. Since then LIAD technique has been investigated for a number of atoms of different species, such as Rb, Cs, Na, Ni, Zn, and K. For Rb atoms it has been shown to be able to load Rb MOT [12, 14] and with a high loading rate [15]. Most of these research used a setup whereby atoms were coated on quartz glasses, pyrex, sapphire and stainless steel surfaces as desorption surfaces.

Although LIAD has been shown to be a promising technique for fast loading a MOT and with a longer lifetime, the mechanism for how atoms desorb from surfaces when shined with incoherent light was still unknown. C. Klempt *et al.* studied the intensity and wavelength dependences of the desorption light for Rb and K atoms absorbed on un-coated quartz cell [13].

It was shown that the efficiency in terms of desorbing atoms and loading them into a MOT was the highest when a 395nm UV desorption light was used, and an intensity at about 10mW/cm² of this wavelength was able to give a loading of 8×10^8 atoms per second for a Rb MOT.

One advantage of LIAD technique is its non-thermal process when releasing atoms into the trapping region. Unlike an atom dispenser whereby the ohmic heating effect always accompany the atom release process, atoms were simply released from the surface when desorption light shined on them. Without the heating process, the pressure inside vacuum chamber would recover faster and effectively increase the trapping efficiency of MOT. Secondly, using LIAD as atoms source could be shut off immediately when we turned off the desorption light. This is not the case for a thermal atom source, which atoms would still be released due to a residual heating effect although current was already shut off.

2.4 Double MOT Configuration

Using double MOT to achieve a higher trapping efficiency was first demonstrated by Kurt Gibble *et al.* in 1995 [6] and extensively studied by C. J. Myatt *et al.* in 1996 [5].

The basic idea of such double MOT setup deploys two chambers with a pressure gradient well maintained between them so that the pressure inside each chamber is independent of the other. A MOT would be first made inside the first chamber with atoms captured from vapor pressure background, a typical setup of such vapor cell would have a pressure of about 10^{-9} torr. After sufficient amount of atoms accumulated into the first MOT, a transport mechanism would then be deployed to transfer the atoms to another MOT inside the second chamber with better vacuum. There were also a variety of transport mechanisms demonstrated, some used a push beam to transfer atoms with magnetic confinement along the path of flight [5–8], some used a purely magnetic transport mechanism [9, 10].

Double MOT setup with push beam as transport mechanism was studied in this project. There were several advantages of this technique. Firstly, the push beam was aligned such that it crossed the center laser overlapping region, thus the atoms pushed into the second chamber would be immediately captured by the MOT when they enter the center region. As compare to thermal source method where atoms were first filled the chamber and then subsequently slowed down by the light field and accumulated into the MOT, push beam method effectively increased the loading rate of atoms. Furthermore, the second chamber would be maintained at better vacuum, typically at about 10^{-11} torr, the trapping lifetime and the number of atoms able to be trapped would increase due to a smaller loss rate due to the lower pressure inside this chamber.

Chapter 3

Experiment Setup

3.1 Vacuum System

3.1.1 Design and Construction

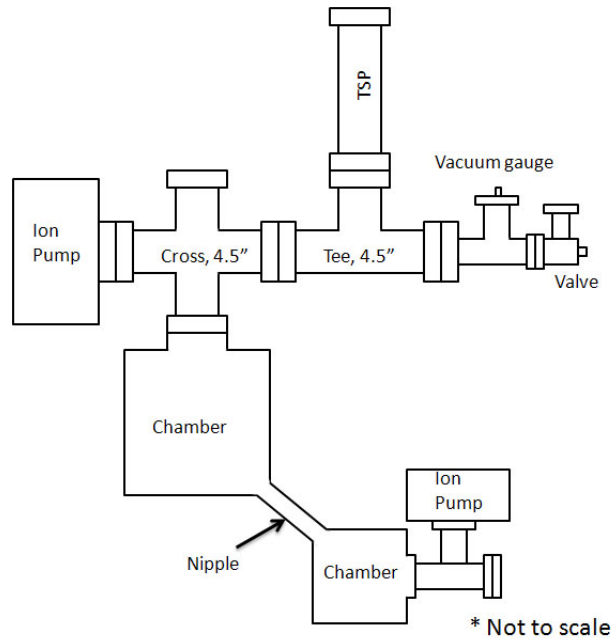


Figure 3.1: A 2D schematic figure of the vacuum system.

We designed our vacuum system in order to study the double MOT technique, this design also allowed us to add in one simple feature for us to study the LIAD technique.

The schematic of the vacuum system is shown in figure 3.1. The setup consisted of two stainless steel cubic chambers, two ion pumps, one titanium sublimation pump unit, and a vacuum gauge for pressure measurement, a valve was connected at the end of the system to allow initial pumping of the vacuum system.

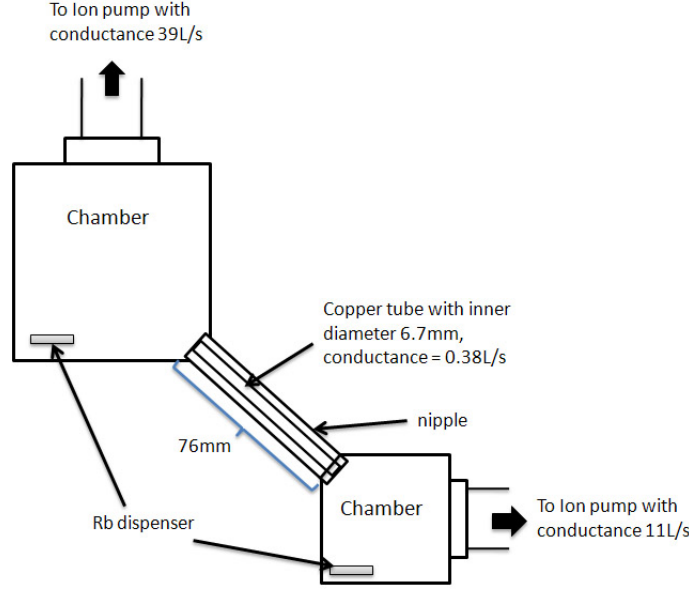


Figure 3.2: Detail setup of the vacuum chambers. The copper tube placed inside the nipple maintained a pressure gradient between the two chambers so that pressure inside each chamber was independent of the other. This copper tube also served as the transfer tube whereby atoms would be pushed from the smaller chamber into the larger chamber via this tube.

The two stainless steel chambers were different in their size. The bigger chamber had a diameter of 180mm and the other one had a diameter of 114mm. Two ion pumps were used in the vacuum system. A 50L/s pumping speed ion pump was used to serve the bigger chamber and a 20L/s ion pump was used to serve the smaller chamber. The two chambers were connected by a $1\frac{1}{3}$ inches nipple, a copper transmission tube with inner diameter 6.7mm was attached inside the nipple, the purpose of this narrow tube was to provide a higher pressure gradient between the two chambers, which was important for the double MOT experiment. The conductance of the bigger chamber and its ion pump was 39L/s, the conductance of the smaller chamber and its ion pump was 11L/s and the conductance of the copper transmission tube was 0.38L/s.

(The calculation of conductance of vacuum components is presented in details in appendix A.) By comparing the value of these conductances, we could say that the pressure inside each chamber was independent of each other, even though the two chambers were connected. This was essential for the double MOT experiment, as a better vacuum was required inside the large chamber.

3.1.2 Pumping Vacuum

In order to make a good MOT, ultra high vacuum (UHV) condition at about 10^{-11} torr or less was desired. Several procedures were conducted to achieve the UHV in our vacuum system.

The initial vacuum pumping was performed by connecting a mechanical pump to the valve of the vacuum system, by doing so pressure at about 10^{-7} torr was achieved. Due to the fact that outgassing by the process which atoms or molecules desorb from the inner vacuum wall and chamber wall would destroy the vacuum, we need to minimize this gas load in order to have a good UHV condition. The entire vacuum system was baked during the initial vacuum pumping process at about 170°C . This process was to force atoms or molecules desorb from the inner wall of vacuum system as much as possible so that the outgassing process would not compromise the vacuum. The bakeout process was done by putting the vacuum system inside an oven for a duration of about 4 days. The temperature was monitored using four thermocouples attached to different parts of the system. Before the bakeout, Rubidium filaments inside the system and the titanium filaments of the TSP unit were fired at 3.0A and 30.0A respectively. This was to heat the filaments and facilitate initial outgassing from these filaments as a cleaning process.

At the end of the bakeout process, the pressure inside the system measured using the vacuum gauge as shown in figure 3.1 was about 3.2×10^{-7} torr. The oven was then dismantled and the ion pumps were switched on. The mechanical pump was detached from the vacuum system

when the pressure inside the system reached about 2.0×10^{-10} torr. At this stage, the titanium sublimation pump was turned on to pump away hydrogen molecules inside the vacuum system which the ion pump was less efficient at.

The entire vacuum system was then moved to an optical table for latter experiment setup. Ultimately after the whole pumping procedure, an UHV with pressure about 4.0×10^{-11} torr was achieved and maintained throughout the rest of the time when experiments were conducted.

3.2 Optics and MOT setup

Two 780nm free-running laser were used in the project. They were the main lasers which do the cooling process for the Rb atoms. Both the 780nm lasers were produced using commercial laser diodes, custom made current controllers and temperature controllers were used to provide stabilized laser beams. The laser diode was placed inside a metal housing each to ensure the stability of the temperature of the diode and eventually the laser beam would not be affected by the fluctuation of temperature at surrounding environment. Each laser was used to serve each MOT chamber respectively. Beam from each laser was split into three and coupled into three fibre optics respectively. The fibre optics then were directed into the MOT chamber with each fibre providing laser beams in one direction using a retroreflect method. This was made possible by placing a mirror at the opposite end of the chamber which reflect the beam back into the incoming direction. Due to the fact that both the vacuum windows and the mirror were 780nm coated, the intensities of the incoming and reflected laser beams remain approximately the same, which was essential in laser cooling process. The balanced of intensities of laser beams result a better condition to cool atoms as they experience forces of same magnitude in any direction.

For the cooling process, atom in the $F = 2$ state first absorbed a photon matched the

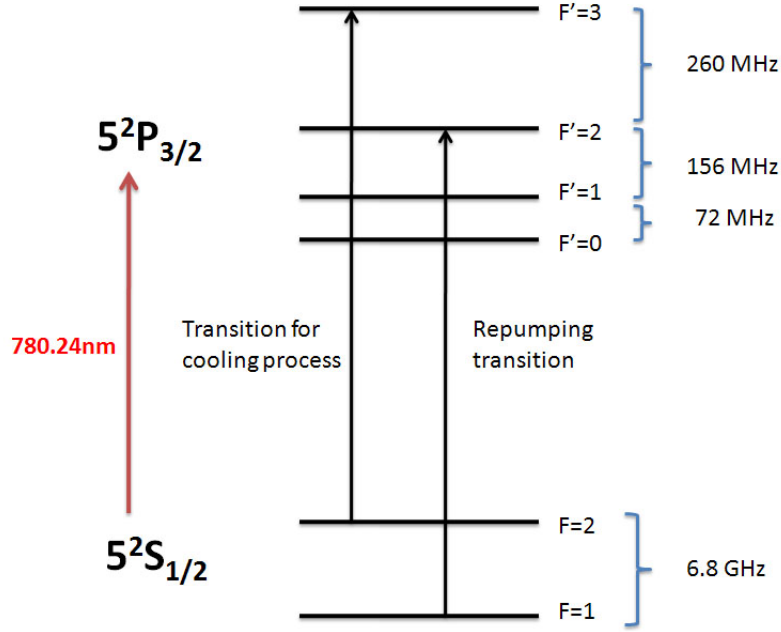


Figure 3.3: Atomic hyperfine transition $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ of Rb-87. The $F = 2 \rightarrow F' = 3$ was the transition used for cooling process. The $F = 1 \rightarrow F' = 2$ transition was a repumping transition to make sure the population of $F = 2$ was always non-zero to sustain the cooling process.

resonance frequency and excited to the $F' = 3$ state. According to the dipole transition selection rule, the atoms in the excited state could then only undergo spontaneous emission to $F = 2$ state, this allowed continuous and sustained the cooling process so that the atoms would be trapped. However, due to the detuning of the light and the Doppler effect between atoms and light, the transition $F = 2 \rightarrow F' = 2$ and $F = 2 \rightarrow F' = 1$ would also happen. As a result, atoms in the excited states would decay to $F = 1$ state and atoms in this state would not interact with the cooling laser, which was locked to $F = 2 \rightarrow F' = 3$. As such, a repumping laser that constantly excite the atoms from the $F = 1$ to $F' = 2$ state was essential. This repumping laser make sure that the $F = 2$ population was non-zero at any time and sustained the cooling process. In the setup, this repumping laser beam was taken from one of the existing laser sources in the laboratory. The beam was coupled into one of the three fibres which used to direct the cooling beams to the MOT chamber.

Saturated absorption spectroscopy was used to give a Doppler-free signal so that the laser could be locked at the correct cooling transition frequency. In terms of making a MOT, the laser frequency should be detuned slightly below the resonance frequency. This was done by locking the laser on the left-hand slope of the transition peak. In order to have more control on the detuning of the laser frequency, a magnetic coil in a solenoid fashion was constructed and the Rubidium cell used for frequency reference was placed in the middle of the solenoid. Passing current through the solenoid would cause the spectral line to split, by doing so we could adjust the detuning of the laser frequency by changing the current supplied to the solenoid to make an optimum MOT.

The polarization directions of the cooling beams were important in terms of making a MOT. Laser beams in each direction incident into the MOT chamber were set to σ^- or σ^+ polarizing direction depending on the location and current flow direction of the anti-Helmholtz coils, the setup is illustrated in figure 2.4. The polarization direction of each beam was adjusted accordingly by putting a quarter waveplate in appropriate locations. On the contrary, because the magnetic state of the repumping transition was not involved in the trapping process, the polarization of the repumping laser was not important. It would excite the atom from $F = 1 \rightarrow F' = 2$ state for any polarization direction of the incoming photon.

For the anti-Helmholtz coils which produce the magnetic quadrupole field. Two pairs of magnetic coils were constructed to serve each chamber respectively. For the larger chamber, each coil was made up from 64 turns of copper wire. The diameter of each coil was about 8cm and they were attached to the chamber with a distance between the coils about 17.5cm. As for the anti-Helmholtz coils for the smaller chamber, they were made up from 40 turns of copper wire and the diameter was about 8cm, they were separated about 13.5cm. In order to compensate the background magnetic field generated by other equipments in the laboratory and the earth magnetic field, three pairs of bias coils for each chamber were constructed. Each pair

of bias coils were set up in a Helmholtz coils fashion to produce uniform magnetic field at the center region along the three orthogonal axes. The currents supplied to each pair of bias coils were adjusted to counter the background magnetic field and produced a zero magnetic field at the center of the chambers.

Both the MOTs were optimized in terms of maximizing the number of trapped atoms by changing the magnetic field gradient produced by the anti-Helmholtz coils, together with the detuning of the laser frequency. After optimization, the magnetic gradient at the center of the large chamber was about 4.7Gcm^{-1} and 6.6Gcm^{-1} for the small chamber. In addition, the six beams of laser lights were well aligned and the background magnetic field was well compensated using the bias coils so that the MOTs would be located at the center of each chamber, which was crucial for the double MOT experiment. The laser frequency for both the lasers were chosen to be 13Mhz below the $F = 2 \rightarrow F' = 3$ resonance frequency.

3.2.1 Optics and setup for LIAD

For the study on light-induced atomic desorption, the atoms were to be released from a quartz glass located inside the large chamber and load the MOT inside this chamber. The setup of MOT was described above but now only one chamber and one cooling laser was used.

UV light peak at 395nm was chosen to be the desorption light. This choice was based on the study on the wavelength dependence of the desorption light conducted by C. Klempt *et al.* [13]. For all the different wavelengths of lights they studied, UV light with a wavelength of 395nm was the best candidate to be used as the desorption light to release atoms previously coated on the quartz glass, in terms of having faster loading rate and greater number of atoms trapped in MOT. Our UV light was generated by an array of LED. It was focused onto the quartz glass and the intensity measured at the surface of the glass was about 3.5mW.

There were two Rb dispensers placed inside the vacuum system, one for each chamber. Each of them was connected to an electrical feed-through which the other end was connected to power supply. The dispenser inside the large chamber was placed about 1cm above the quartz glass and orientated such that the filament facing directly the glass. By doing so the Rb atoms would be sprayed and coated onto the glass when a current was allowed to pass through the dispenser. This configuration also meant that the filament was not pointed at the center of the vacuum chamber where the MOT would be located. For the coating process, a current of 4.6A was supplied to the dispenser and the pressure inside the vacuum system rose to about 10^{-9} torr. After a duration of 2 hours, the current was switched off and the vacuum system was left for three days to let the pressure returned to equilibrium before any experiment was to be conducted.

3.2.2 Optics and setup for Double MOT Configuration

Both the chambers and lasers were required for the double MOT experiment. Other than this, a laser light with frequency tuned to exactly the resonance frequency of $F = 2$ to $F' = 3$ transition was used as the push beam to transfer atoms from the small chamber to the other. This push beam was taken from an existing laser source in the laboratory and coupled into a fibre optics then directed into the vacuum system via a 1.33" viewport.

In the setup and alignment of the push beam, we required that the push beam hit the first MOT in the small chamber, passing through the transfer tube, and crossing the center overlapping region of light field in the large chamber but miss the second MOT. This was because the push beam which tuned to the resonance frequency of the cooling transition, would have the same pushing effect to the second MOT as it did to the first MOT.

The procedure to load atoms into the MOT in the larger chamber began with making a

MOT inside the smaller chamber for some times. Then the first MOT was switched off by shutting off the cooling lights using a shutter built in-house ¹. Immediately after the light fields were off, the push beam was turned on to accelerate the atoms into the larger chamber via the transfer tube. Atoms travelled down the tube and enter the second chamber would then be captured into the MOT in this chamber. After this the light field for the first MOT was turned on again to accumulate atoms into the first MOT for subsequent push. High precision in milli-second regime for each step in the loading sequence was required and this was done by computer control using *Labview*.

3.3 Measurement Setup

For both of the techniques studied in this project, we were interested in the number of atoms trapped inside the MOT in the large chamber. The numbers of atoms were calculated by measuring the intensity of light released by the MOT using a sensitive power meter. As an atom stimulated absorbed a 780nm photon and jumped from $F = 2$ to $F' = 3$ state, it would spontaneously emit a photon with the same wavelength and return to ground state. The photon emitted in this way was random in their direction, and it was very difficult to attach measuring tools all around the MOT to cover every single possible emission direction of photon. But as the atoms trapped inside the MOT kept interact with the laser field and oscillate between the ground state and the excited state, the probability for the atom to emit photon in any direction was equal. Thus a power meter looking at the MOT on a fixed position was sufficient, in this case the intensity measured was only a fraction of the total intensity being emitted by the MOT.

The total intensity need to be calculated using the concept of numerical aperture which will be

¹This shutter made use of the voice-coil motor and the swing-arm actuators in a commercial available harddisk. A shutting time of $500\mu s$ was achieved on a 1.2mm waist laser beam.

discussed later.

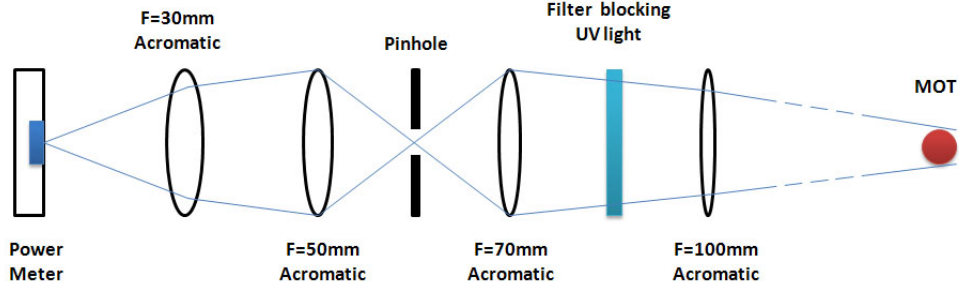


Figure 3.4: The imaging system used to measure the intensity of the light emitted from the MOT. The number of atoms can be calculated according the equation 3.6.

The measuring imaging system used to calculate the number of atoms in the MOT was schematically shown in figure 3.4. Four acromatic doublet lenses were used to image the MOT and focus it onto a sensitive power meter. A pinhole was placed in the middle of the imaging system, the size of the pinhole could be adjusted so that the power meter only see the MOT and any reflection from the inner wall of the stainless steel chamber would be minimized. Other than this, due to the fact that we were operating the UV light at a substantial high intensity in the study of LIAD technique, the UV light would be detected by the power meter and give inaccurate readings on the MOT intensity. This problem was solved by putting an UV filter which block the UV light and allowed only the 780nm light to pass through. The transmittivity of this filter for 780nm was measured to be 75% and there was no observable UV light transmission via this filter.

If the opening of the imaging system have a diameter d , and this imaging system is placed at a distance D from the center of the MOT (measured from the front of the imaging system to the center), it would just receive a fraction of light with the ratio given by the area of the first lens over the total surface area of a sphere with radius D , i.e.

$$\frac{\pi(d/2)^2}{4\pi D^2}, \quad (3.1)$$

this can be simplified to a term called numerical aperture,

$$\left(\frac{d}{4D}\right)^2. \quad (3.2)$$

For our case, the diameter of the first lens (F=100mm acromatic doublet) was 1.6cm and the front of the lens was located about 8.1cm from the MOT. From these information, the ratio between the intensity obtained by the power meter and the total intensity emitted by the MOT could be calculated.

Another important factor to be taken into account when calculating the intensity was the transmittivities of the lenses used in the imaging system. For each of the acromatic doublet lens, the transmittivity was 0.98 for 780nm light. Together with the transmittivity of the filter used to block UV light going into the detector, the total transmittivity, or the optical efficiency for the entire imaging system was 0.69.

So far we only discussed how the intensity of the light emitted from the MOT was measured. We need to relate the intensity to the number of atoms. This is given by the following;

$$n_{photon} = N_{atom} \times r_{scatt}, \quad (3.3)$$

where n_{photon} is the number of photon released by the MOT, N_{atom} is the number of atom and r_{scatt} is the scattering of photons by atoms. The numbers of photons can be calculated by the intensity measured using the power meter, and the relationship between energy and the wavelength of the photon, given by

$$Intens. = \frac{n_{photon}hc}{\lambda}, \quad (3.4)$$

the intensities measured by the power meter was already area normalized by the equipment

we used, and the measurement given by the power meter was in the unit of mW, appropriate conversion was required to correctly calculate the number of photons. The scattering of photons by atoms is given by

$$r_{scatt} = \frac{I/I_0}{1 + I/I_0 + 4\Delta^2/\Gamma^2}, \quad (3.5)$$

with the symbols having same meaning as those mentioned in the second chapter, i.e. I is the total intensity of the cooling beams incident to the MOT, I_0 is the saturation intensity for Rubidium, which is $3.68\text{mW}/\text{cm}^2$, $\Delta = \omega - \omega_0$ is the detuning of the cooling beam and Γ is the natural linewidth of Rubidium's $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transition.

Combining equations 3.2, 3.3, 3.4 and 3.5, the number of atoms can be calculated using the following,

$$N_{atom} = \frac{Intens.}{(\frac{hc}{\lambda})(\text{optical efficiency})(\text{numerical aperture})(r_{scatt})}. \quad (3.6)$$

Chapter 4

Results and Discussions

First of all, we showed that the orientation of Rb dispenser in vacuum chamber was not important in order to make a decent MOT when being turned on. Normally an atom dispenser would be placed in vacuum chamber in a way that its filament facing the location where the atom trap would be, the reason behind this was to spray atoms directly towards the atom trap so a faster loading rate could be achieved. However, a negative impact on the lifetime of a dipole force trap was observed when atoms were sprayed out from a dispenser with its filament facing directly the trap. This observation suggested that atoms trapped inside a trap would be knocked out by atoms sprayed from dispenser and towards the trap. In our setup, the Rb dispenser was placed in the large chamber in a way that the filament was facing directly the quartz glass used for LIAD technique so that we were able to coat Rb on the glass whenever we want, this also meant that the filament was facing opposite the center of the chamber. We successfully loaded atoms into MOT using such configuration when a current was allowed to pass through the dispenser. Figure 4.1 shows the number of atoms in MOT grew as a function of time when we turned on a 4.0A current to this Rb dispenser.

The size of MOT in terms of the number of atoms trapped was dependent on the current

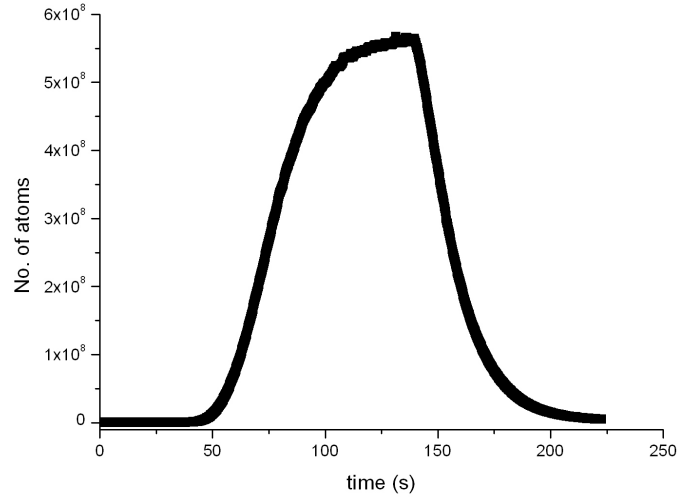


Figure 4.1: A typical loading of atoms into MOT as a function of time using thermal Rb source. A current of 4.0A was turned on at 0 second, note that there was a lag time between current being turned on and atoms numbers started to have substantial increment. It took about 100 seconds to reach maximum. After that the current supplied to the dispenser was switched off and atoms started to escape from the MOT.

put through to the atom dispenser. The greater the current, the greater the number of atoms would be released from the dispenser, and thus resulted a MOT with greater number of trapped atoms. Figure 4.2 shows a relationship between the number of atoms able to be trapped in our setup of MOT and the current supplied to the dispenser.

4.1 Light-Induced Atomic Desorption

MOT in the larger chamber was successfully loaded by shining a 395nm UV light onto the quartz glass previously coated with Rb atoms. There were several observations on the study of LIAD, which will be discussed in details in the following sections.

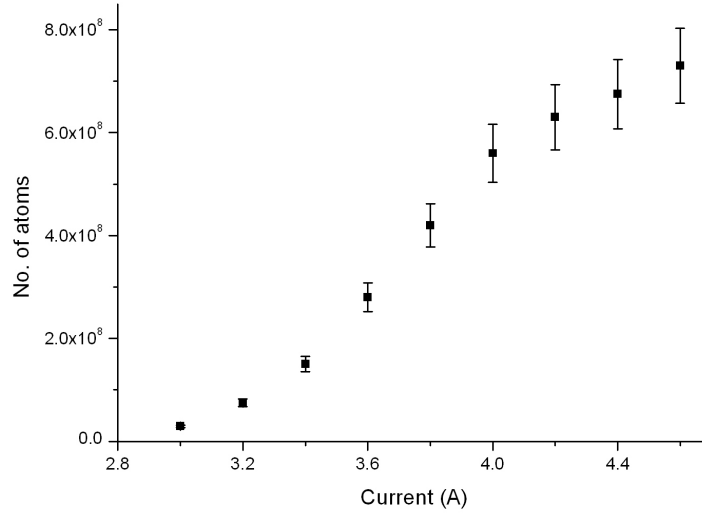


Figure 4.2: The number of atoms in MOT made by thermal Rb dispenser againsts the current supplied to the dispenser. As current increased, more atoms would be released thus more atoms would be loaded into MOT.

4.1.1 MOT size

By shining the desorption light onto the quartz glass, the pressure in the chamber increased rapidly and atoms were loaded into the MOT in a relatively short time, but the number of atoms successfully loaded into the MOT were much less than those MOTs loaded by using the thermal atom dispenser method. With all experiment parameters optimized, the greatest number of atoms loaded into MOT using LIAD was about 6×10^6 , which was about two order of magnitude difference compare to those MOTs loaded by passing current through atom dispenser.

This was also contradictory with results reported by other research groups who used LIAD to load a MOT. For most of them, about 10^8 atoms were able to be effectively loaded into a MOT. Though there were several variations of LIAD technique whereby atoms were coated on surfaces made by different materials and different choice of desorption light's wavelength, in general LIAD experiments performed by other research groups deployed a larger desorption area

as compare to us [13–15]. In this project, Rb atoms were coated on a glass of dimension about $2\text{cm}\times 2\text{cm}$, a surface area much smaller than the one used by C. Klempt *et al.* in reference [13]. For them, a quartz cell with dimension $5\text{cm}\times 5\text{cm}\times 14\text{cm}$ was used and Rb atoms were coated onto all the inner wall of the vacuum chamber. For comparison, the effective surface area for desorption was about hundred times larger than ours in our LIAD setup. C. Klempt *et al.* were able to load about 10^9 Rb atoms into their MOT by shining a 395nm ultraviolet light onto the entire quartz cell.

This difference in the experiment setup gave a simple explanation on why the number of atoms able to be trapped inside our MOT was much less than expectation: as the desorption area became larger, there would be more atoms released from the surface when the desorption light shined on it, thus there would be more atoms loaded into the MOT and resulted a bigger MOT.

4.1.2 Negative Effect of UV

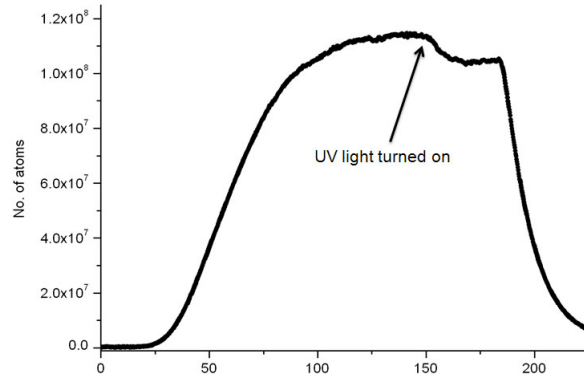


Figure 4.3: UV light hitting an existing MOT. Rb atoms loss from the MOT when UV light is turned on.

One interesting observation during the study on LIAD technique was a negative effect when using the UV light at 395nm wavelength. Explicitly, the number of trapped atoms was found

to decrease when the UV light was shined directly onto an existing MOT. This phenomenon was shown in figure 4.3.

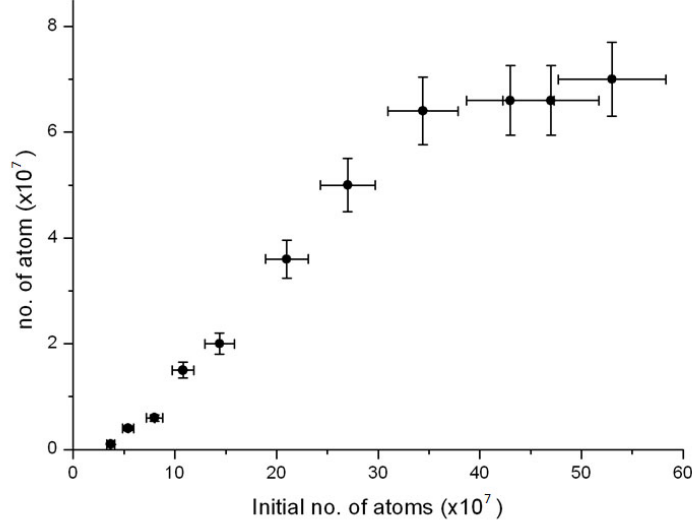


Figure 4.4: This figure shows the relationship between the number of atoms loss from MOT when UV light was turned on and the number of atoms initially trapped inside the MOT. A linear relationship between them was observed.

We furthered our study on this negative impact of the UV light on MOT. The dependence of UV's negative effect on the MOT size were investigated, this was done by shining UV light with a same intensity on MOTs with different initial numbers of trapped Rb atoms and recording the number of atoms loss from the trap. The results were presented in figure 4.4.

A linear relationship between the two quantities was observed, which mean that MOTs were losing a fixed percentage of atoms when the UV light was turned on. This lose mechanism was similar with the lose mechanism due to background pressure. One possibility was that the UV light was desorbing atoms other than Rb out from the glass and thus decrease the number of trapped atoms in the MOT. However, when the UV light was positioned and focused onto the quartz glass such that it missed the existing MOT, the number of atoms trapped inside the MOT increased, as shown in figure 4.5. This observation immediately discarded the hypothesis that

the negative effect was due to any atom-atom collision effect, as this figure provided evidence that atoms desorbed from the quartz glass were loaded into the existing MOT when UV light was shined on them but missed the MOT.

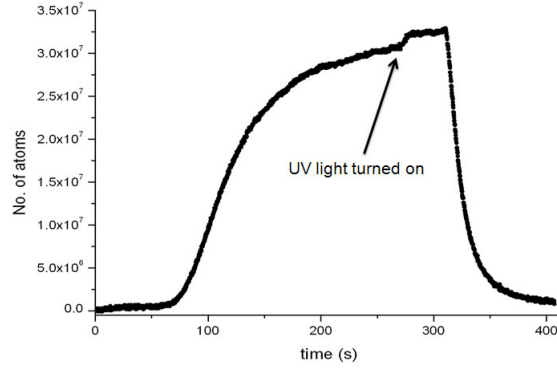


Figure 4.5: UV light being focused on quartz glass without hitting the MOT. Instead of atoms loss from the trap, the number of Rb atoms trapped in MOT increased. This observation suggested that the negative effect of UV light must be due to the interaction between the UV light and the trapped atoms.

Based on all the above observations, we concluded that the negative effect of atoms loss from the MOT must be due to interaction between the UV light and the trapped atoms and we suspected that it was due to the ionization of neutral first excited state Rb to singly charged Rb state. A simple energy level diagram of Rubidium was shown in figure 4.6. The energy required to ionize a Rb atom from the $5^2S_{1/2}$ to the continuum is about 4.18eV, which is equivalent to 1.01×10^{15} Hz or 297nm. The 395nm UV light used as the desorption light did not have enough energy to ionize a ground state Rb atom, but the energy of UV light at this wavelength was energetic enough to excite Rb from the $5^2P_{3/2}$ state to the singly charged state.

The cooling process for Rubidium was achieved by the transition from $F = 2$ in the $5^2S_{1/2}$ state to $F' = 3$ in the $5^2P_{3/2}$ state. In another words, the Rubidium atoms were jumping between these two states in the atom trap. When these trapped atoms populating the $5^2P_{3/2}$

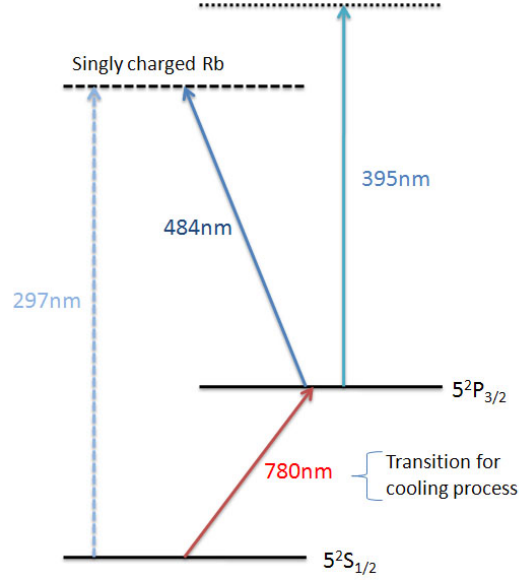


Figure 4.6: Although the 395nm wavelength UV light was not energetic enough to excite ground state Rb atom to the singly charged state. Photon at this wavelength was able to excite Rb atoms from the $5^2P_{3/2}$ first excited state to the continuum. Since the laser cooling process made the Rb atoms jumping between the $5^2S_{1/2}$ and $5^2P_{3/2}$ states, UV light would be able to remove those atoms confined in the MOT due to the fact that MOT could only trap neutral atoms.

excited state and the UV light was turned on and shined onto them, these atoms would be ionized and excited to the continuum. This also explained why the UV light did not ionize the Rb atoms coated on the quartz glass and would only have effect on those atoms trapped in MOT. A 450nm light powered by an array of LED was also used to shine towards an existing MOT, Rb atoms were found to escape from the trap and the number of atoms inside the MOT decreased as 450nm photon was energetic enough to ionize Rb atom from $5^2P_{3/2}$ excited state to the continuum.

In contrast, many research groups have used LIAD technique successfully, with no negative effect of UV lights on MOT reported. This might be because their setup for loading MOT using LIAD had a much faster loading rate that would offset the negative effect of UV light on their MOT. The loading rate of our MOT was restricted by the 2cm×2cm quartz glass, as a result the loss rate dominated in the process when UV light was turned on.

As a summary, the results we obtained from the studies on LIAD technique in this project

was not as good as expected in terms of making a good MOT, this was due to the fact that the desorption area in the setup was not large enough to deposit greater amount of atoms when the desorption light was turned on. Secondly, a negative impact of UV light on MOT was observed. Though, these observations provide valuable information that need to be taken into consideration when designing a cold atoms experiment using LIAD to load atom trap. A better LIAD setup should use a glass cell with the ultraviolet light hitting most of the inner wall of the cell but miss the MOT. By doing so, a faster loading rate can be achieved and there would have no atom being kicked out by the UV light.

4.2 Double MOT

We successfully loaded atoms into a MOT in the large chamber by pushing atoms from the vapor-cell MOT in the small chamber. This was done by a collimated push beam tuned to the resonance frequency of Rb $F = 2$ to $F' = 3$ transition. The details of the sequences to push the atoms were illustrated in section 3.2.2. Under optimized parameters, e.g. the delay time between each push as 0.9s and the push duration as 5ms, the transfer efficiency for each transfer was about 60%. By using this method, a MOT with about 3.2×10^8 atoms was successfully loaded in the large chamber. This push beam duration actually deviated a lot from our theoretical calculation for an appropriate push duration needed to transfer the atoms. (The detail of the calculation of the push beam duration is presented in appendix B.) This was a question yet to be answered but we suspected that this was due to deflection of atoms caused by the inhomogeneous magnetic field generated by the MOT coils. One solution to solve this problem was to switch off the magnetic quadrupole fields together with the light field during each transfer. However, this was not done due to unknown equipment issues whereby cooling laser lose lock when magnetic field was switched off. This also suggested that our double MOT

configuration was yet to be exploited to its maximum. Future work on switching off magnetic field together with changing related experiment parameters should further optimize the transfer efficiency.

The loading of atoms into the second MOT is illustrated in figure 4.7. Note that the zigzag pattern in this figure, during each push the atoms in the first MOT was transferred into the second MOT, some of the atoms escaped from the MOT during the delay time when we allowed the first MOT gathered enough atoms for the subsequent transfer.

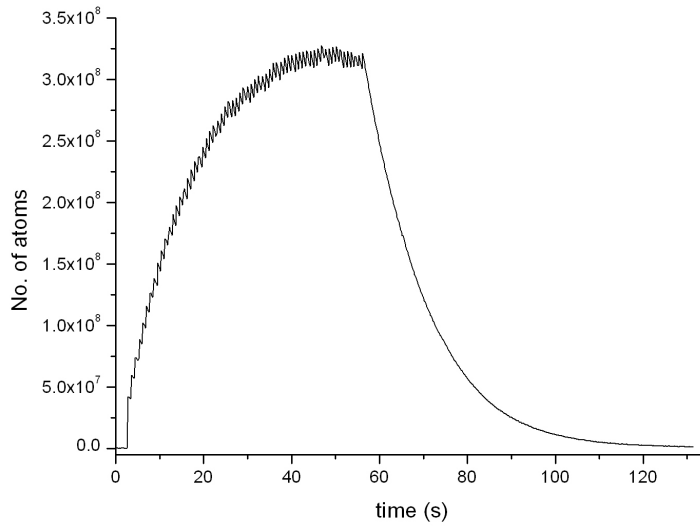


Figure 4.7: Number of atoms loaded into the MOT as a function of time. This experiment was performed with 5ms push length and 0.9s delay. 3.2×10^8 Rb atoms were successfully accumulated in the second MOT.

The double MOT result and a thermal Rb source result were compared and shown in figure 4.8, both of them have similar number of atoms at equilibrium. One of the advantages of the double MOT configuration was its fast loading rate of atoms into MOT. In this case, the loading time for double MOT was about 3 times faster than the thermal source method. This fast loading is advantageous in many cold atoms experiments where short time scale to conduct experiment are required.

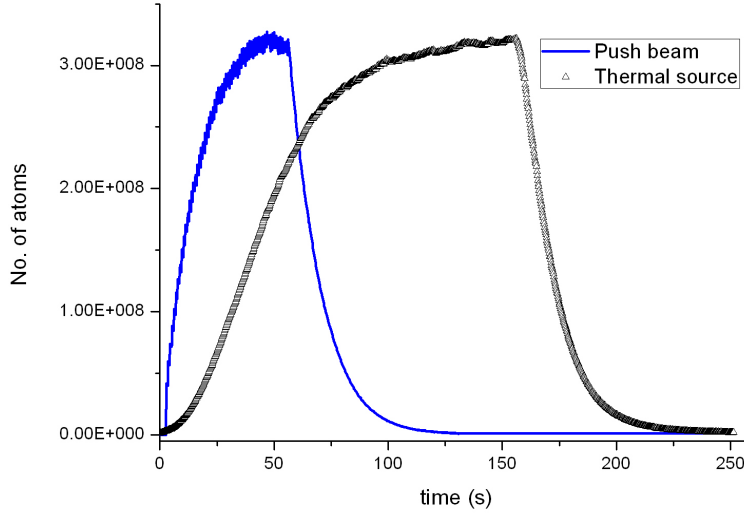


Figure 4.8: MOT loaded using push beam technique was 3 times faster than the MOT loaded using thermal source method.

Another issue was the lifetime of the trap. The lifetime of a MOT is defined as the time where number of atoms drops from the maximum to about 36.8 percent of the maximum. The lifetime of both the MOTs shown in figure 4.8 were fitted using *Mathematica* numerically with the following model:

$$N = N_0 \exp\left(-\frac{t}{\tau_{MOT}}\right). \quad (4.1)$$

This equation is same as equation 2.23, which describe the dynamic of a MOT with a zero loading rate of atoms into MOT. The lifetime of the MOT made by double MOT setup, τ_{dmot} was about 13.6s and the lifetime of the MOT made by thermal Rb source, τ_{ts} was about 14.7s. In another words, we did not gain much benefit from this double MOT technique in terms of having a longer trapping lifetime. This was an unexpected result as MOT loaded using double MOT setup should have a longer lifetime.

This result might be explained briefly by the fact that the model we used was not really the ideal model for the MOT loaded using thermal source. When we turned on the current passing through the Rb dispenser, Rb atoms were sprayed out and filled the entire chamber. Atoms that passed through the center laser overlapping region would be then captured into the MOT. Furthermore, it was observed in another experiment setup that a Rb atoms would still be released from a dispenser even though the current supplied to it was shut off and this residual heating effect lasts for more than 10 minutes. Due to these two phenomena described above, we were uncertain on how many atoms would be eventually loaded into MOT after current was shut off. In contrast, the push beam laser was aligned in such a way that it hit the vapor-cell MOT in the first chamber, passing through the transfer tube, and incident into the center laser overlapping region inside the second chamber. Thus, the atoms pushed into the second chamber would enter the center region directly and immediately captured by the MOT, the number of atoms in the background was much less than the case of thermal dispenser method. After the transfer sequence turned off, atoms would only escaped from the MOT with no atom loaded into the MOT. In another words, the loading rate of atoms for the thermal source case was not equal to zero as suggested in equation 4.1. Furthermore, the potential of this double MOT technique was yet to be exploited to its maximum, a longer lifetime is expected if we can further optimize the loading efficiency.

Chapter 5

Conclusions

We explored two different techniques to load a MOT, namely the Light-Induced Atomic Desorption (LIAD) and the double MOT configuration with push beam as transfer mechanism.

Restricted by our desorption area, a MOT with about 6×10^6 atoms were made and this did not meet our expectation. Other than this, atoms were found to escape from MOT when the UV desorption light was shined directly on an existing MOT. Though the actual mechanism of the loss was not confirmed, we suspected that the Rb atoms were ionized by the UV and thus kicked out from the MOT. This post a possible future work which the loss mechanism can be studied in more depth. In spite of what is the actual reason behind the negative effect, we concluded that a good LIAD setup should use a large chamber with desorption light shined onto most of the inner wall of the chamber but miss the center of the MOT so that no atom would be knocked out from trap due to the negative effect of desorption light.

For the double MOT experiment, a transfer efficiency of about 60% without any magnetic confinement mechanism was achieved. 3.2×10^8 atoms were successfully loaded into the second MOT with loading time of about 50 second. Another achievement on our double MOT technique was the compactness of our experiment setup. The pressure gradient between the two chamber

was maintained by a 6.7mm inner diameter and 76mm length copper tube, compare to other groups which use a much longer transfer tube. Furthermore, due to this relatively shorter transfer tube, we did not use any magnetic confinement mechanism along the tube, which make our setup much simpler and more compact. C. J. Myatt *et al.* used a 400mm transfer tube to maintain pressure gradient, they also deployed a magnet powered by a current of 300A to generate hexapole field for confining atoms along the transfer tube [5]. Lan-Sheng Yang *et al.* used a 500mm transfer tube and a similar magnetic confinement mechanism along the transfer tube [7]. The compactness of our double MOT setup allows us to be able to attach the small chamber to other vacuum systems for other cold atoms experiment in the laboratory. However, this double MOT technique has yet to be exploited to its full potential, better transfer efficiency and resulting loading efficiency of the second MOT is expected to be achieved by adjusting the alignment of the push beam and related experiment parameters.

Other than those mentioned above, a free-running diode laser at 780nm was shown to be able to be used as the cooling laser for Rb MOT. This is advantageous as this free-runing laser was pardoned from any mechanical or acoustical noise present in the lab. We also showed that a commercially available Rb dispenser was allowed to be positioned in a way that its filament not facing the center of vacuum chamber which a MOT would be located. A MOT with better loading efficiency would benefit as the atoms sprayed out from dispenser would not hit directly and knock the trapped atoms out from MOT.

Appendix A

Conductance of Vacuum Components

In the double-MOT configuration setup, a pressure gradient between the two chambers connected by a 1.33'' nipple need to be established. As such, how fast gas molecules were pumped out from the chambers by the two ion pumps and how fast gas molecules allowed to travel between two chambers via the 1.33'' nipple were crucial to us. We will discuss these matters in the notion of conductances. As a simple description, conductance of a vacuum component measures how fast gas molecules enter the vacuum component in one end and exit at the other end.

The conductance of a vacuum tube is given by

$$C = \frac{1}{4}avA, \tag{A.1}$$

where A is the cross section area of the tube, $a = a(L)$ is the transmission probability that gas particles enter the tube and leave at the other end, and it is a geometry dependence quantity

with L is the reduced length of the tube. v is the average thermal velocity of gas, at 22°C v has a value of 464.5ms^{-1} . The transmission probability $a(L)$ is given by

$$a(L) = K_1(L) - K_2(L), \quad (\text{A.2})$$

with

$$K_1(L) = 1 + \frac{L^2}{4} - \frac{1}{4}L\sqrt{L^2 + 4}, \quad (\text{A.3})$$

$$K_2(L) = \frac{\left(L^2 + (8 - L^2)\sqrt{L^2 + 4} - 16\right)^2}{72L\sqrt{L^2 + 4} - 288\ln\left(L^2 + \sqrt{L^2 + 4}\right) + 288\ln 2}, \quad (\text{A.4})$$

$L = l/r$ is the reduced length of the tube where l and r are the tube length and radius respectively. From above equations, we can calculate the conductances of various vacuum components easily. A detail description on how to calculate the conductance of a vacuum component can be found in NUS 2008 Honour thesis by Chua Boon Leng.

A.1 Conductance of 4.5" Tee

A 4.5" Tee was connected between a 50L/s vacuum pump and the bigger chamber, it has a length of 17.17cm and 3.01cm radius. Together with the value of $v=464.5\text{ms}^{-1}$, the conductance is calculated to be 78.24L/s. However, in order to take into account the fact the the vacuum pump and the chamber were connected in a right-angle fashion using the Tee, we divided the calculated conductance by half to approximate the effective conductance, which end up to be 39.12L/s.

A.2 Conductance of the 2.75" Tee

The smaller chamber was connected to a 20L/s vacuum pump similar to the bigger chamber, but for this case the Tee was a standard 2.75" vacuum part. The length and the radius of this Tee are 12.5cm and 1.74cm respectively. The effective conductance with the right-angle connection taken into account was calculated to be 11.38L/s.

A.3 Conductance of the copper transfer tube

It was crucial to know what is the conductance of the copper transfer tube so that we could have an idea how good a pressure gradient could be maintained by this component. The length and the inner radius of this tube are 7.6cm and 0.34cm respectively. The conductance was thus calculated to be 0.38L/s.

Appendix B

Push beam calculation

When an atom absorbs a photon at resonance, the atom would travel in the same direction as of the incoming photon due to conservation of momentum. This effect is always accompanied by the spontaneous emission process which causes the atom to recoil in random directions. These random kicks result a random walks of the atom's velocity, which is similar to the Brownian motion of particles in air. If an atom scattered N photons in a given time, there would have a random walk of N steps, and the mean radial displacement would be proportional to $\sqrt{N}$.

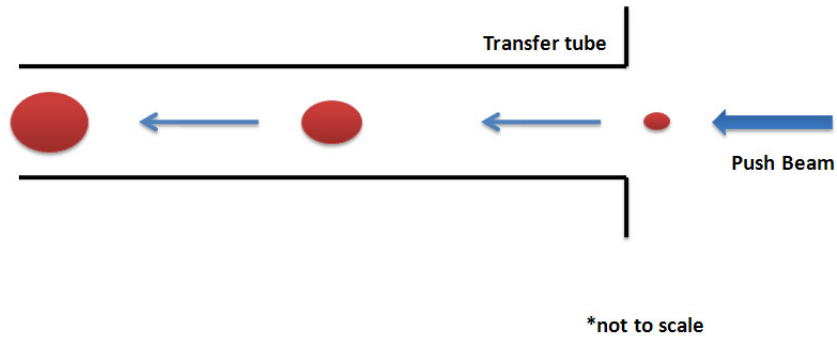


Figure B.1: The atom cloud expand during the transfer due to random walk process resulted from the scattering of photon. We need to ensure that the cloud does not expand beyond the diameter of the tube to maintain transfer efficiency.

In our case, the atom cloud would expand due to the random walk of atoms when they

travel down the transfer tube. Thus we need to know what is the number of photons each atom allowed to scatter so that the atoms would not hit the inner wall of transmission tube due to the random walk in the process of pushing. We denote r as the radius of the transfer tube, which is 3.4cm, and $d = 130\text{mm}$ is the distance between the center of the first MOT and the end of the tube. Assuming that the displacement along each cartesian axis are equal, the number of photons allowed to scattered is thus given by

$$\sqrt{\frac{N}{3}} \frac{1}{N} = \frac{r}{d}, \quad (\text{B.1})$$

where the square root of $1/3$ comes from the fact that only one dimension of the displacement due to random walk is important to us. Put in the value of r and d , the number of scattered photon is

$$N = \frac{3d^2}{r^2}, \quad (\text{B.2})$$

$$\approx 4500. \quad (\text{B.3})$$

Thus we are only allowed to have a minimum of 4500 photons scattered from each atom when the push beam is in action. After each Rubidium atom absorbed a photon, its velocity gained by 6mms^{-1} , which is defined as the recoil velocity, v_r . After absorb 4500 photons, its velocity gained by $4500v_r$, which is equal to 27ms^{-1} . This is a reasonable velocity for the atoms enter the second chamber to be captured by MOT in this chamber.

Given the scattering rate of photons from Rb atom, $\Gamma/2$ and the calculated number of photons allowed to be scattered per atom, we can calculate the interaction time, τ_{int} between

the push beam photon and the atoms, which is

$$N = \frac{\Gamma}{2}\tau_{int}. \quad (\text{B.4})$$

Note that this equation does not include the intensity and detuning factor for sake of simplicity.

Given $\Gamma = 2\pi \times 6 \times 10^6$, the interaction time required is calculated to be about $100\mu\text{s}$.

Due to the fact that the atoms are flying across the transfer tube for a certain time without any guiding or confinement mechanism, it is probably important to know what is the effect of gravitational force on the atoms. The total distance between the center of two MOTs is about 200mm, which take a atom travel at 27ms^{-1} about 7.5ms to finish their journey. During this period of time, the total displacement due to the gravitational force can be calculated using equation

$$S = \frac{1}{2}gt^2, \quad (\text{B.5})$$

$$\approx 280\mu\text{m}. \quad (\text{B.6})$$

Thus we can safely say that the gravity-induced displacement has negligible effect on atoms during the time of flight.

Appendix C

Experiment Setup

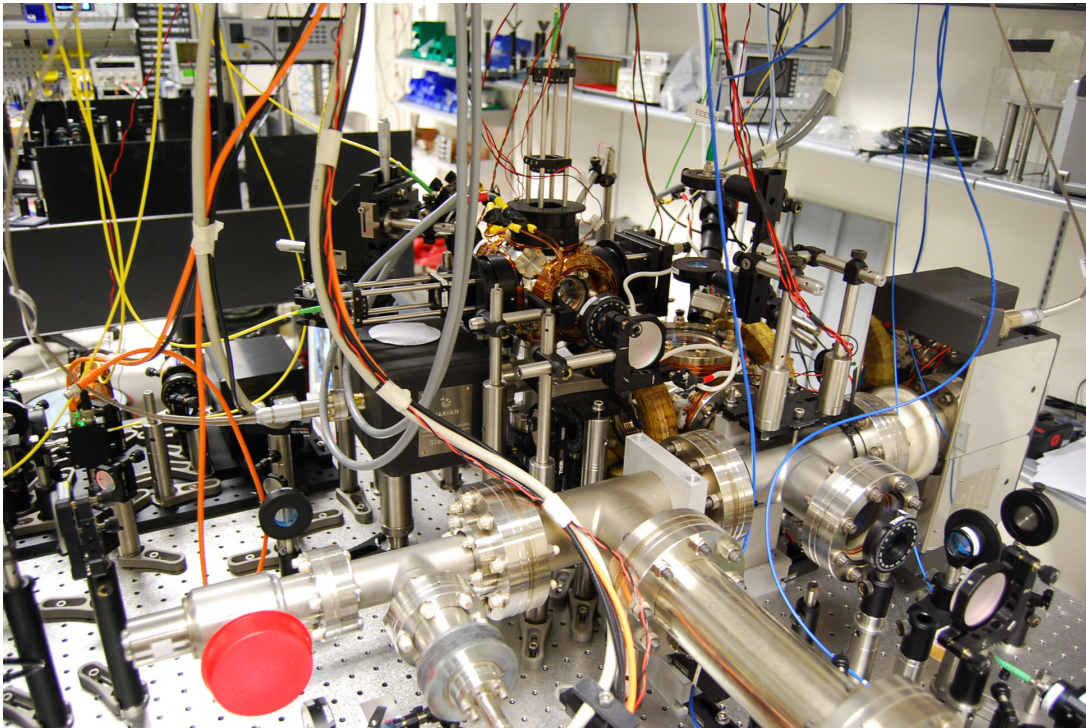


Figure C.1: Vacuum system including two stainless steel chambers, two ion pumps, one TSP unit, a vacuum gauge and a valve was designed and setup for this project.

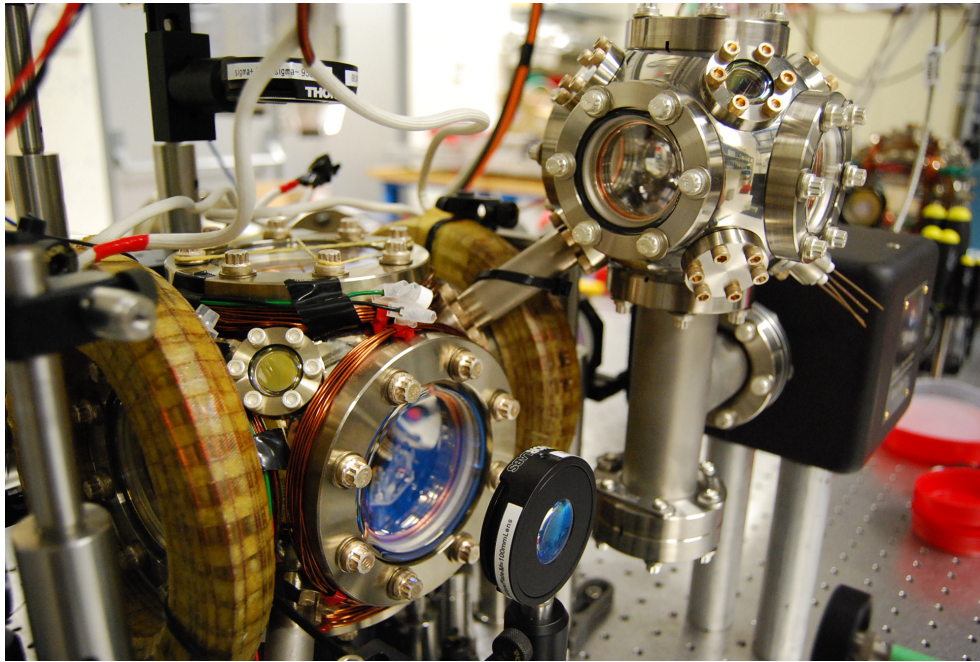


Figure C.2: This figure shows both the chambers before magnetic coils and optics were setup for the small chamber. The chambers were connected by a 1.33" nipple.

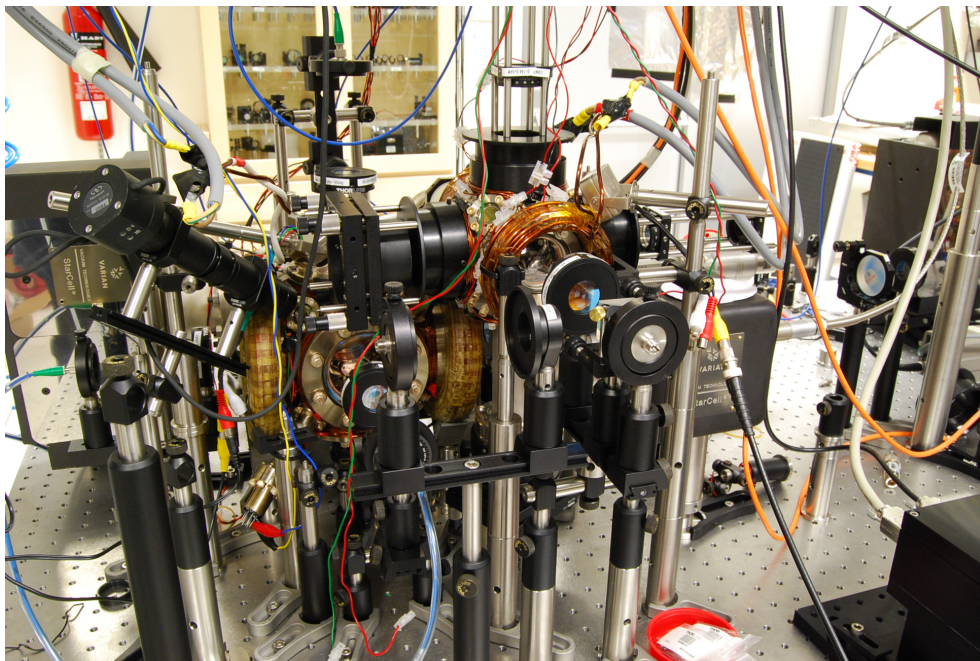


Figure C.3: This figure shows the entire setup for both the chambers, including the optics, magnetic coils for MOTs and measurement tool.

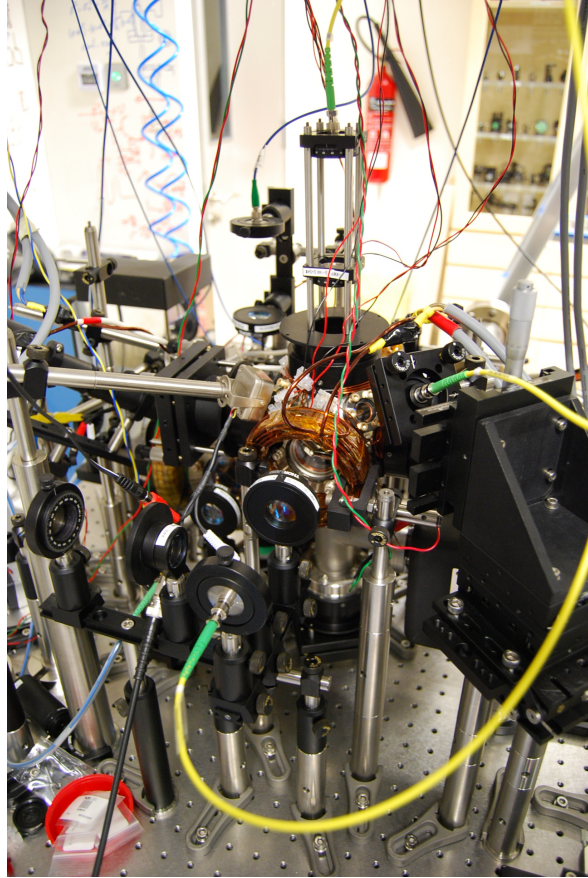


Figure C.4: Another angle view of the MOTs setup. Laser beam including the push beam were directed into chambers using fibre optics.

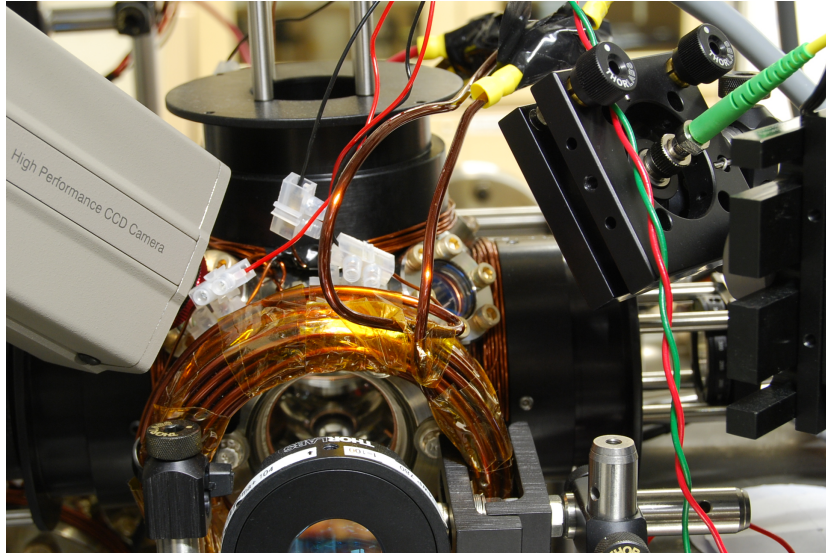


Figure C.5: The push beam (top right) was incident into the small chamber via a 1.33" viewport. A CCD camera on the left of this picture was used to measure number of atoms in the vapor-cell MOT inside this chamber.

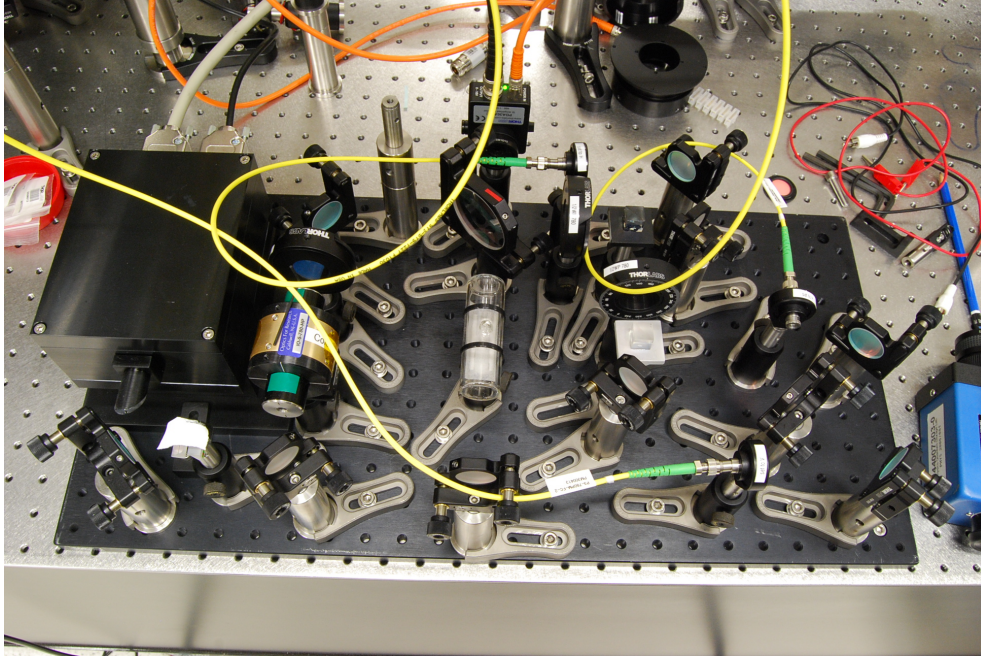


Figure C.6: This figure shows the optics setup of one of our cooling laser for Rb MOT. Laser beam exit the housing (black box at left) and in the end split into three beams which coupled in to fibre optics (yellow cables). A cell containing Rb atoms located at the center was used as a reference by deploying saturated absorption spectroscopy.

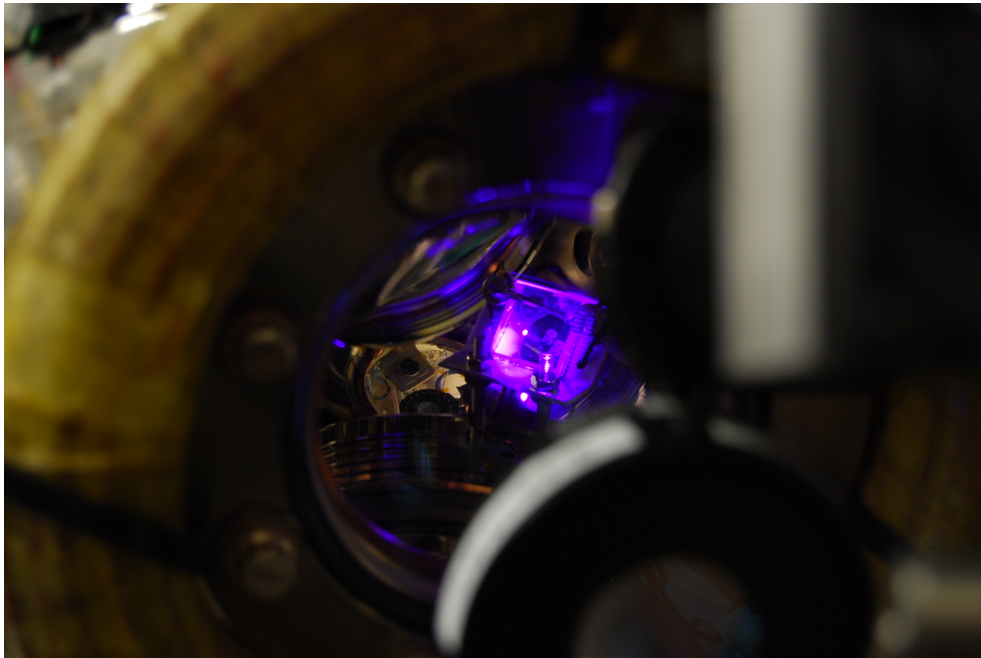


Figure C.7: UV light was incident on the quartz glass coated with Rb. The silver bar located slightly above the glass was a Rb dispenser which allowed us to make a MOT and coat Rb onto the glass when a current passed through it.

Reference

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