Optimizing and measuring properties of a magneto-optical trap in a dilute rubidium-87 gas

A thesis submitted in partial fulfillment of the requirements of a degree of Bachelor of Arts in Physics and Astronomy at Pomona College

Joel Shuman with advisor Dwight Whitaker, Ph.D. Associate Professor, Pomona College

April 22, 2011
Figure 1: A 30 second exposure of the atom cloud and MOT chamber.
Contents

Acknowledgments ........................................... 3

Abstract .................................................. 4

1 Introduction ............................................. 4

1.1 Bose-Einstein Condensation ......................... 4

1.1.1 Creating a BEC .................................. 7

1.2 The Cooling Process .................................. 9

1.2.1 The MOT ......................................... 9

1.2.2 Dipole Trapping .................................. 11

1.2.3 Evaporative Cooling ............................. 11

2 Theory ................................................. 12

2.1 Bose-Einstein Condensation ......................... 12

3 The MOT ................................................. 15

3.1 Interactions between Atoms and the Laser ............. 15

3.2 The BoosTA Laser Amplifier ......................... 17

3.3 Doppler Cooling .................................... 18
# List of Figures

1  Picture of a MOT ............................................. 2

1.1 Overlapping BECs ........................................ 5

1.2 Phase Space Density ....................................... 8

1.3 The setup of a MOT ....................................... 10

2.1 Counting Statistics ....................................... 13

3.1 Scattering Rate vs Laser Detuning and Intensity .......... 17

3.2 The BoosTA Laser ......................................... 18

3.3 Scattering Rate vs Laser Frequency ........................ 20

3.4 Doppler Cooling ........................................... 21

3.5 The Zeeman Effect ......................................... 21

3.6 Axial Magnetic Field of antiHelmholtz Coils .............. 22

3.7 1-D Representation of Zeeman Trapping .................. 23

3.8 Photon Polarization and Energy Levels in the Zeeman Shift . 24

4.1 Current to Voltage Converter Circuit Diagram ............ 26

4.2 Loading a MOT ........................................... 27

4.3 Fluorescence Measurement Setup .......................... 28
Acknowledgments

A few people have been extremely important in the writing of this thesis and deserve mention before it even gets started. Eric Dodds and Zack Lasner both helped me tremendously throughout the process in addition to giving me an in depth introduction to the lab. Glenn Flohr on numerous occasions helped me to build various small parts for the chamber. Tony Grigsby has taught me a lot about electronics over the past year, certainly without him we could not have made any progress. Finally Dwight, your passion for teaching continues to enthrall me anew each day.
Abstract

A Bose-Einstein Condensate (BEC) is a cloud of atoms at low enough temperature and high enough density to collapse a large portion of atoms into the ground state energy and display the weirdness of quantum mechanics on a relatively large scale. The first step in creating a BEC is collecting and cooling the atoms from room temperature and low pressure to just a few hundred microKelvin in a vacuum chamber. Our magneto-optical trap (MOT) cools and confines rubidium-87 atoms by creating a magnetic field with antiHelmholtz coils for Zeeman trapping and using laser light from a 780 nm diode laser and the BoosTA laser amplifier for Doppler cooling. I use fluorescence measurements to determine the number of atoms loaded into the MOT for different laser intensities and frequency detunings, and I discuss the number of atoms collected into the MOT when using the BoosTA laser amplifier compared to unamplified laser light.

1 Introduction

1.1 Bose-Einstein Condensation

Einstein proposed the existence of lasers and the existence of Bose-Einstein condensation (BEC) at around the same time, in 1917 and 1924 respectively, but neither these two purely theoretical predictions were realized until a successful laser was not demonstrated until 1960. While lasers are now commonplace, there is one just about everywhere you look, BECs have just begun to be created. It was not until 1978 [9], when laser cooling was
first proposed, that BEC even seemed possible. But in 1995, for the first
time, Anderson et al. created a BEC using evaporative cooling to cool a
cloud of atoms down to condensate temperatures [1]. A magneto-optical
trap and laser cooling were both integral in his experiment.

Lasers have a few properties that make them especially useful. All of
the photons in a laser share the same quantum state and phase; thus they
all have roughly the same frequency and can be used to make precise mea-
surements in many different applications, from scanning the surface of a CD
to scanning the surface of the moon. BECs work in a similar fashion. In
a BEC, a substantial number of atoms have fallen into the ground state
energy level and share the same quantum state and phase. This creates a
macroscopic quantum object, a cloud of atoms that displays the weirdness
of quantum mechanics on a macroscopic scale.

Perhaps the most striking demonstration of the quantum nature of BECs
is to allow two of them to overlap. In the classic Young double slit experi-

![Figure 1.1: Overlapping BECs showing the quantum nature of BEC. [2]](image)

Figure 1.1: Overlapping BECs showing the quantum nature of BEC. [2]
ference fringes where the wavefunctions of the two beams constructively or destructively interfere. This experiment can be repeated with Bose-Einstein condensates. Two BECs are prepared in separate traps and then pushed together using a combination of magnetic fields and laser light. Once they overlap, they are allowed to interfere with each other to form the familiar fringes. In a BEC, all the atoms in the ground state share the same wavefunction, and so in allowing these two condensates to overlap, their two wavefunctions interfere with each other and the classic experiment is repeated using macroscopic systems. [8]

BECs are important in a wide variety of fields. Superfluid helium-4 is a type of Bose-Einstein condensate, as the atoms are cooled below the critical condensation temperature, a superfluid is created where a macroscopic percentage of the atoms have fallen into the ground state, causing them to move with no viscosity. Cooper pairs, the pairs of electrons that allow superconductivity in solids to occur at extremely low temperatures, are also a type of BEC. This may be counter-intuitive since electrons are spin-1/2 particles, and do not obey Bose-Einstein statistics. But the pair together is a total spin-1 system. Indeed any experiment to be done on a single atom, such as measuring the Casimir-Polder force, the force between an atom and a dielectric plate, can be made easier by using a condensate instead of a single atom [7]. For any of these experiments, the larger the BEC, the easier the experiment is to perform. Using the BoosTA amplifier to load more atoms into the MOT directly correlates to more atoms eventually loaded into the BEC. To this end, we test the laser amplifier to provide more photons and more trapping force. With more photons, more atoms
are eventually loaded into the trap and a denser trap is created, compared
to the a MOT with less laser light. As shown in section 2, the denser the
trap, the warmer the critical temperature for condensation is, so a denser
MOT makes BEC at higher temperature.

1.1.1 Creating a BEC

An intuitive way of thinking about what a BEC is and how it forms is to
think about a concept known as phase space density defined in [4] as

\[ \rho_{PS} = n \lambda_{dB}^3 \]  

where \( n \) is the number density of the particles \( \left( \frac{N}{V} \right) \) and \( \lambda_{dB} \) is the thermal
deBroglie wavelength, \( \lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}} \), where \( m \) and \( T \) are the particle’s
mass and temperature respectively [10]. This equation defines two distances:
the average inter-atomic spacing \( \left( n^{-1/3} \right) \), and thus the volume available per
atom, is represented by the number density, and the average quantum radius
of each atom is described by \( \lambda_{dB} \), and thus the volume occupied by each
atom is \( \lambda_{dB}^3 \). \( \rho_{PS} \) is a unitless quantity; it represents the ratio of these two
volumes. Notice that \( \lambda_{dB} \propto T^{-1/2} \), so that as \( T \) decreases, \( \lambda_{dB} \) increases.
By cooling the atoms below a certain limit, and confining them to a very
tight space, the phase space density can increase from order \( 10^{-22} \) [6] for a
gas of atoms in a vacuum to order 1, a BEC. When \( \rho_{PS} \geq 2.612 \), BEC is
achieved [11]. Figure 1.1.1 shows intuitively how high phase space densities
should lead to macroscopic quantum effects. In the case on the left, an
Figure 1.2: A representation of phase-space density at different temperatures in the cooling process.

In the early stage in the cooling process, the atoms are hot, thus their thermal deBroglie wavelengths are small. This is represented in the small quantum volume occupied by the atoms. Note that the quantum volume is not a literal volume, but the uncertainty in position of the particle within that sphere. So while the atomic nucleus and electron cloud take up much less than a typical $\lambda_{dB}^3$, the atom cannot be localized to a smaller space. The distance between the atoms is also important. $n$, the number density, is the number of atoms divided by the volume of the cloud, so when $n^{-1/3}$ is small, the spacing between the atoms is large. On the right is a cloud at low temperature and high number density. The quantum volumes overlap because the interatomic spacing is less than $\lambda_{dB}$. To reach these temperatures in our gas of rubidium-87 atoms, temperatures on the order of hundreds of nanoKelvin need to be reached [4].
1.2 The Cooling Process

In order to achieve the phase space density required for BEC, several different stages of confinement and cooling are necessary. The first and largest change in $\rho_{PS}$ is in the magneto-optical trap (MOT). Here a velocity dependent damping force and a spatially dependent confining force give the largest changes in phase space density. A MOT can be loaded with atoms room temperature and density, so it provides the initial cooling phase. The next step, a dipole trap, needs to be loaded from an already cool and dense trap. A CO$_2$ laser at wavelength 10.6 microns, far red-detuned from the resonant frequency of rubidium, confines the atoms to an even colder and tighter atom cloud. Finally, the most energetic atoms are boiled off in a process called evaporative cooling until the temperature is low enough for a condensate to form.

1.2.1 The MOT

The MOT consists of anti-Helmholtz coils to provide a spatially dependent force, and laser beams propagating and retro-reflecting back along three orthogonal axes. The anti-Helmholtz coils provide a magnetic field that pushes the atoms towards the center of the chamber in a process known as Zeeman trapping. The further an atom is from the center, the stronger the force it will feel from the Zeeman trapping effect. They serve to confine the atoms to a known location in the chamber so that the CO$_2$ beam can overlap with the MOT.
The second important consideration is getting the atoms cool enough to fall into the dipole trap. Laser light, slightly red-detuned from an energy transition in the rubidium spectrum is sent in along three orthogonal axes and retro-reflected back for a total of six total trapping beam lines. In a process known as doppler cooling, the red-detuned light is doppler shifted in the rest frame of the moving atom to a frequency at which the atom is more likely to interact with the beam. This shift only makes the atom more likely to interact with the laser if the atom is moving opposite the direction of propagation of the laser. The beams are set up such that no matter what direction the atom is traveling, it will feel a force opposing its velocity. Since rubidium forms a (mostly) monatomic gas, and, especially at these low temperatures, all other modes of energy storage are frozen out, temperature is just a function of kinetic energy. We further cool the atoms
by lowering the velocities of the atoms and therefore the kinetic energy as well; this ultimately leads to lower temperatures. The MOT can achieve microKelvin temperatures and phase space densities of order $10^{-12}$, a factor of $10^{10}$ higher than room temperature gas. A compressed MOT (CMOT), discussed by Webster in [11], further cools and confines the atoms before overlapping them with the CO$_2$ beam.

1.2.2 Dipole Trapping

Once the CMOT has formed, a 100 Watt CO$_2$ laser is overlapped with the atom cloud. Its wavelength of 10.6 microns is far red-detuned from the resonant frequency of rubidium atoms. So, when atoms interact with the electric field of the laser, it lowers their potential energy compared to atoms interacting at light at resonance, like the light from the trapping beam in the MOT. In the region of maximum intensity, there is a potential energy minimum that the atoms tend to fall into if they are cool enough. Webster provides a more thorough description in [11].

1.2.3 Evaporative Cooling

Once the atoms are in the dipole trap, the laser intensity is lowered, thus lowering the walls of the potential energy barrier. The most energetic atoms escape and the remaining atoms rethermalize to a lower temperature. By repeating this process with small intensity drops at each time interval, the temperature can be lowered another three orders of magnitude and BEC
2 Theory

2.1 Bose-Einstein Condensation

A BEC forms when an appreciable number of atoms have fallen into the ground state energy level. The statistics that we use to count these energy levels, and predict which energy state an atom will be in for a given temperature, depends upon the type of particle being counted. The theory of Bose-Einstein condensation rests on the fact that spin-1 particles do not obey the Pauli exclusion principle and thus can occupy the same quantum state. Fermions, which are spin-1/2 particles, must obey the Pauli exclusion principle and cannot share the same quantum state and therefore cannot become a BEC, they obey Fermi-Dirac statistics. So called ‘boltzmannons’ obey a a classical distribution that holds only at high temperature, for these particles spin does not matter since they have so much energy that the quantum limit does not hold. This classical limit, Maxwell-Boltzmann statistics, does not account for quantum mechanics and assumes that there are many more states than particles. Bose-Einstein statistics apply only to integer spin particles such as photons, helium-4 nuclei, and rubidium-87 nuclei at very low temperatures.

Figure 2.1 shows the different counting statistics, with the Bose-Einstein distribution blowing up as $\frac{\epsilon}{kT}$ goes to 0, where $\epsilon$ is the energy...
of each state. Bose-Einstein statistics show the usual exponential decay associated with higher energy states but includes a -1 in the denominator from quantum effects:

\[
n_{BE}^\epsilon = \frac{1}{e^{\frac{\epsilon - \mu}{kT}} - 1},
\]  

(2.1)

where \( n_{BE} \) is the occupation of energy state \( \epsilon \). \( \mu \), the chemical potential is used as a scaling factor here; it changes with the temperature. It serves to normalize \( n_{BE} \) to the correct occupation. However \( \mu \) cannot be less than zero, otherwise, for some energy states there would be negative occupation. \( \mu \) decreases as temperature decreases until it becomes zero at the critical temperature for BEC to occur and we need to use other tricks to correctly count the number of atoms [10].

To count the total number of atoms, we also need to find the density of states \( g(\epsilon) \); this counts the number of available states at each energy level \( \epsilon \). The density of states for particles in a quantum mechanical box is given
by [10] to be
\[ g(\epsilon) = \frac{2}{\sqrt{\pi}} \left( \frac{2\pi m}{\hbar^2} \right)^{3/2} \epsilon^{3/2} V \sqrt{\epsilon}, \] (2.2)
where \( h \) is Planck’s constant, \( m \) refers to the mass of a rubidium-87 atom and \( V \) is the volume of the cloud. This density of states does not count the ground state energy, where \( \epsilon = 0 \) due to the \( \sqrt{\epsilon} \) dependence. For most purposes the approximation is fine, but as temperatures get very low, many atoms start to fall into the ground state and the approximation that there are no atoms in the ground state no longer holds. \( \mu \) also can no longer help us here since we are interested in the behavior of the atoms below the critical temperature.

To find the total number of atoms, multiply the occupation of each energy state by the number of available states at that energy and sum over all possible energies:
\[ N = \sum_i g(\epsilon_i) n_{BE} = \frac{2}{\sqrt{\pi}} \left( \frac{2\pi m kT}{\hbar^2} \right)^{3/2} V \int_0^{\infty} \frac{\sqrt{x}}{e^x - 1} dx, \] (2.3)
where I have converted the sum to a dimensionless integral, and chosen \( \mu = 0 \) since I am examining the case where \( T \) is less than the critical temperature and BEC has occured. This misses the ground state energy, so \( N \), the number of atoms, is really \( N_{\text{excited}} \), the number of atoms above the ground state energy. This integral belongs to a family of integrals that can be evaluated as the product of a Riemann Zeta function and a gamma function, namely \( \int_0^{\infty} \frac{\sqrt{x}}{e^x - 1} dx = \Gamma(3/2)\zeta(3/2) = 2.315 \). The number of exited atoms depends on temperature and at high enough temperature, the number of excited atoms equals the number of atoms, since no atoms are in the ground state.
The temperature at which an appreciable percentage fall into the ground state is called the critical temperature, it is given by

\[ T_c = 1.897 \left( \frac{\hbar^2}{2\pi mk} \right) \left( \frac{N}{V} \right)^{2/3} \]  

and is on the order of hundreds of nanoKelvins for rubidium-87. Notice that \( T_c \) is dependent on density. The higher the density, the higher the critical temperature. So, a more dense MOT will lead to a higher density BEC, one with a higher critical temperature for condensation.

3 The MOT

In the quest for ever cooler and denser clouds, the MOT is the first step in confining and cooling atoms. Previous experiments in this lab have used a 50 mW external cavity diode laser to provide the trapping force, but with additional laser power comes even higher densities and lower temperatures. The BoosTA laser amplifier provides more than 600 mW of power and using it creates a denser, colder MOT when compared with the previous laser power.

3.1 Interactions between Atoms and the Laser

An atom can absorb energy from a photon only if that photon excites a transition between the energy state an atom is currently in and a higher energy state. The energy gap between these two states \( \Delta E \) must match
the energy from the photon, $h\nu$, for the atom to absorb the photon. If the photon is absorbed, then the atom gets a momentum boost of $\frac{h\nu}{c}$ and then reradiates a photon of the same energy in a random direction. The number of scattering events a second, called the scattering rate, is given by [5] to be:

$$R = \frac{(I/I_s)\pi\Gamma}{1 + (I/I_s) + 4(\Delta/\Gamma)^2} \quad (3.1)$$

where $I$ is the intensity of the trapping beam, $I_s$ is the saturation intensity of the transition, $\Gamma$ is linewidth of the transition, and $\Delta$ is the detuning [5]. The detuning is a measure of the difference between the frequency $\nu$ associated with an energy level transition, and the frequency of the laser. The scattering rate, $R$, is a function of laser intensity and trapping beam detuning, it is plotted below for a few different values of laser intensity.

For the top graph, $R$ vs the detuning of the trapping beam, larger detunings mean fewer scattering events. This feels intuitively correct because as the wavelength of a laser goes further from resonance (as $h\nu$ gets further from $\Delta E$), atoms should interact with the laser less. The higher curves are higher laser intensities while the lower curves are low laser intensities. Since intensity is a measure of the number of photons interacting with the atoms at a given time, higher intensities should lead to increased scattering.

The lower graph tells a different story, it shows that larger laser intensities mean more scattering events as above, and it confirms the conclusions about detuning, but it also shows that the increase in $R$ due to laser intensity comes at low intensities and then asymptotes at higher intensities. This means that if intensities are large enough, about 200 mW/cm$^2$ for $\Delta=20$
Figure 3.1: Scattering rate from equation 3.1, plotted against trapping beam detuning and intensity.

MHz, there will not be a noticeable difference in the scattering rate between two different laser intensities, even if they are widely spaced.

3.2 The BoosTA Laser Amplifier

Higher laser powers translate to more atoms captured in the MOT, so the BoosTA laser amplifier amplifies a 50 mW diode laser to more than 600 mW.
The BoosTA works much the same way as a diode laser: the power supply creates a population inversion and as laser light is pumped through, it creates stimulated emission and the diode lases. What is unique in the BoosTA is that it is seeded with a lower power laser, passes that beam through much more lasing material, and outputs a laser at the same frequency but with a much higher power.

![BoosTA Laser Diode](image)

Figure 3.2: The amplified laser light from the BoosTA laser.

### 3.3 Doppler Cooling

In order to achieve the cold temperatures wanted in a MOT, the rubidium atoms are slowed down to reduce their kinetic energy. At these low temperatures, kinetic energy directly translates to temperature so if the atoms are moving slowly, they are also cold. In order to do this, we take advantage of the momentum imparted by a photon on an atom.

Every time a photon is absorbed by a rubidium atom, the atom receives a momentum boost in the direction of propagation of the laser. When it reradiates the photon, it again receives a momentum boost, but because it
reradiates in a random direction, it receives no net momentum boost from reradiation. In this way, an atom traveling opposite the direction of propagation of the laser (towards the laser) will be slowed down. But, this in itself will not slow down every atom, for instance an atom traveling in the same direction as the laser will be sped up.

To prevent this effect, doppler cooling takes advantage of the Doppler effect, a shift in the apparent frequency of a source at rest as seen in the reference frame of a moving object. When an atom is traveling towards the laser it will see a doppler shift in the frequency of $+\Delta\nu_{dopp}$ in its rest frame, and when it is traveling away from the laser it will see a frequency of $-\Delta\nu_{dopp}$. The doppler shift can be used to make an atom traveling towards the laser interact with a photon at a frequency closer to resonance, an atom at rest interact with a photon at the laser’s actual frequency, and an atom traveling away from the laser experiences an even larger difference between the resonance frequency and the laser frequency. Because the scattering rate (and thus the force on an atom) is peaked at resonance, this means that an atom traveling towards the laser feels a larger force than one traveling away from it, or even one at rest.

Figure 3.3 shows that an atom traveling towards the laser, and observing a frequency closer to the resonance frequency, experiences a larger force than any other. Changing the detuning is one way of controlling the magnitude of this force, and it drastically effects the number of atoms in the atom cloud.

Doppler cooling creates a velocity dependent force. It slows down atoms selectively based on the magnitude and direction of their velocity. In three
Figure 3.3: The force on an atom is dependent on the frequency that it observes the laser to have. The detuning is the distance from the frequency of the laser to the resonance frequency.

dimensions, as shown in figure 1.2.1, 6 beams are necessary; two along each coordinate axis, one from the positive direction and one from the negative. In this way, no matter what direction the atom is traveling, it will be slowed.

3.4 Zeeman Trapping

A spatially dependent confining force is necessary to localize the atom cloud to the center of the trap. It also serves to increase the number density and phase space density. Doppler cooling lowers the temperature of the atom cloud, but does not differentiate between an atom far from the middle of the trap and one at the center. A magnetic field takes advantage of the Zeeman effect to provide this localizing force.

Atoms can have different amounts of angular momentum for a given
energy state, that is, the projection of the angular momentum on some axis, $m$, can have a value of $+1,0,-1$ at the same energy level. When a magnetic field is turned on, it interacts with the angular momentum of the atom and splits the energy state into sublevels, depending on the projection of the angular momentum in the direction of the B field. This energy change is given by:

$$\Delta U = -\vec{\mu} \cdot \vec{B}$$  \hspace{1cm} (3.2)
where $\Delta U$ is the change in energy level $B$ is the field and $\mu$ is the magnetic dipole moment of the atom. So, the energy change is proportional to the strength of the field and dependent on the direction of the B field. Larger B fields cause the shift to be more pronounced.

The anti-Helmholtz coils outside the MOT chamber create a magnetic field that changes sign at the origin, so there are regions of positive field, negative field, and zero field. These three regions mean that the Zeeman effect will split the energy levels differently for each region. Near the center of the trap there will be no shift because there is no B field, in the region with positive field the $m=-1$ will have greater energy (because of the minus sign in equation 3.2), and in the region with negative field, $m=+1$ will have greater energy. By sending in photons with the correct angular momentum projection to drive the transition, we can spatially confine the atoms by

Figure 3.6: The magnetic field created by anti aligned Helmholtz coils. Note that it changes sign at the origin.
providing a spatially dependent force.

Imagine a 1D system as shown in figure 3.7. When an atom is on the right side, there is positive B field, and the lower energy state is $m=+1$. This energy state corresponds to the transition driven by the frequency of the red-detuned trapping laser. This atom already has 1 unit of angular momentum so it cannot interact with a photon that also has $m=+1$. Only a photon with $m=-1$ will interact and drive the transition. When $m=+1$ is the lower state, that is, when the B field is positive, the atom will interact more strongly with the red-detuned laser and get a momentum boost back towards the center. As shown in figure 3.6, the further from the center of the chamber, the larger the field, so the further an atom is from the center, the larger the force it will feel back towards the center. As before, the magnitude of the force is related to the number of photons hitting the atom; the Zeeman shift brings the transition energy closer to the energy

![Figure 3.7: On the right, the B field is positive and so the atom interacts with $\sigma^{-}$ light and is pushed left. The opposite is true on the left side.](image)


associated with red-detuned light, so atoms scatter more photons further from the center of the trap. In order to ensure that the atom interacts with a $m=-1$ photon, the light is circularly polarized so that it carries one unit of angular momentum opposite the direction of the B field. This light drives the transition from the $m=+1$. This is called $\sigma^-$ light. On the left side, $\sigma^+$ light drives a transition from $m=-1$.

Since the B field on the left side is negative, $m=-1$ is the energy state that corresponds to the frequency of the red detuned laser. By having the correct polarization coming in along each of the coordinate axes, and having the beam returning along that axis have the opposite polarization, a spatially dependent, confining force is created. The further an atom is

Figure 3.8: B field increases towards the right on the diagram, and as the magnitude of B increases the energy shift for $m=-1,+1$, becomes more pronounced compared to $m=0$. Only the correct circular polarization of light can drive the transition.
from the center, the more it is pushed back there, because the energy shift becomes larger, and the atoms interact more with the red detuned laser. Atoms will be localized to the center of the trap. The details of the 3-D setup are shown in figure 1.2.1.

4 Absorption Measurements

Using only a photodiode, amplifier, and an oscilloscope to read the voltage, the amount of light reradiated from the MOT after absorption can be used to determine the number of atoms in the MOT.

4.1 Using a Photodiode to Measure MOT Number

The photodiode that is attached to the MOT chamber detects photons from light emitted from the atom cloud and photons from light scattered by the walls of the chamber. When an atom absorbs a photon, it re-emits another of the same wavelength in a random direction. Any photon propagating through the atom cloud has a probability of being absorbed and then re-emitted in a random direction. So with more atoms trapped in the MOT, a photodiode looking at the chamber will detect light scattered from the MOT. The photodiode outputs a current proportional to the power incident on its surface.

The photodiode connects to a current to voltage converter with a variable amplifier and low-pass filter and a gain $G$ of $3 \times 10^6$ V/A. A simplified diagram
of the circuit is shown in figure 4.1. The actual circuit also has several capacitors to provide a tunable cutoff frequency for the low pass filter. The circuit also inverts the signal, so in figure 4.2, the higher voltages actually correspond to lower powers incident on the photodiode.

In order to detect the effect of the MOT on the light levels, the magnetic field is turned off for about two seconds, and then turned back on. When the coils are turned off, the atom cloud disappears and a baseline voltage is taken. Then the coils are turned back on, a MOT forms, and the voltage with light from the cloud is also taken. The difference between these two voltages, $V_{MOT}$, can be used to determine the number of atoms in the cloud.

Notice that figure 4.2, shows four distinct phases, a baseline voltage, a jump, another flat area and finally an exponential decay. The first baseline is the MOT before the magnetic coils are shut down. The next flat area at a larger voltage but smaller incident power is from photons reflected from
the lasers in the MOT chamber without interacting with the atomic cloud. When the coils are turned back on, a MOT loads from the background rubidium. The final low voltage shows a return to the fluorescence present with a robust atom cloud.

4.2 Calculating the Number of Atoms

The number of atoms, $N$, in a cloud can be calculated from the power incident on the photodiode, $P_{PD}$.

$$P_{PD} = \frac{V_{MOT}}{\eta G},$$  \hspace{1cm} (4.1)
where $\eta$ is the current per incident power, known as the responsivity of the diode, and $G$ is the gain of the amplifier between the photodiode and the oscilloscope. $V_{MOT}$ is the amplified voltage measured by the photodiode and the factors of $\eta$ and $G$ serve as a sort of unit conversion from voltage to Watts. The photodiode only collects a percentage of the total photons emitted by the atom cloud. Since the atom cloud emits photons in every direction, a correction factor of $\frac{4\pi r^2}{A_{PD}}$ is needed.

$$P_{MOT} = \frac{V_{MOT} \cdot 4\pi r^2}{\eta G \cdot A_{PD}},$$  \hspace{1cm} (4.2)
$P_{MOT}$ is now the power radiated from the atom cloud, $A_{PD}$ is the surface area of the photodiode and $r$ is the distance of the photodiode to the cloud; the ratio of the surface area of the sphere centered at the MOT that intersects the photodiode at radius $r$ to the area of the photodiode, $A_{PD}$, corrects for the photons that are not incident on the photodiode, shown in figure 4.3. The actual number of atoms is found by dividing by the rate at which atoms scatter photons $R$ and the energy per photon to convert the units from energy to photons,

$$N = \frac{P_{MOT}}{R} \frac{\lambda}{hc} = \frac{V_{MOT} 4\pi r^2 \lambda}{\eta GR A_{PD}hc}.$$  \hfill (4.3)

This equation unites the frequency with which rubidium will scatter photons with the number of photons and their energies. Figure 4.4 is a table of the necessary constants. In $R$ there are two additional quantities

<table>
<thead>
<tr>
<th>Table of Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
</tr>
<tr>
<td>$r$</td>
</tr>
<tr>
<td>$A_{PD}$</td>
</tr>
<tr>
<td>$\eta$</td>
</tr>
<tr>
<td>$I_s$</td>
</tr>
<tr>
<td>$\Gamma$</td>
</tr>
</tbody>
</table>

Figure 4.4: Constants necessary in equation 4.3.

that need to be measured, $I$ the intensity of the laser, and $\Delta$, the detuning. $I$ is measured with a power meter located at the peak intensity. Only a small 3mm by 3mm square of light sensitive area had light incident on it in order to find the peak intensity at the center of the beam. By dividing the power on the meter by the area of the portion with light incident on it, power can
be converted to peak intensity. Since the MOT is located near the center of the chamber, the peak intensity is a more accurate representation of the intensity at the atom cloud, although some atoms do experience a smaller intensity further from the center.

$\Delta$, the detuning, is measured on the oscilloscope. Using the saturated absorption spectroscopy and DAVLL system discussed in [11], the distance in from the resonance frequency to the actual frequency of the laser can be measured.

5 Optimizing the MOT

Using a photodiode as discussed in section 4, I was able to calculate the number of atoms trapped in the MOT for various laser detunings at 4 different laser intensities. The DAVLL laser locking system discussed in [4] precisely controls the detuning of the wavelength of the trapping beam. Taking data with detunings between about 10 and 50 MHz, I was able to calculate the number of atoms trapped for each detuning. By slightly misaligning the seeding laser to the BoosTA, the power it emits can be diminished. This tests the assumption that more laser light is necessarily better. Unfortunately the accuracy of the experiment was limited by noise on the DAVLL and saturated absorption signals, this led to some data points with especially large detuning uncertainties. When this paired with a poor repump lock, some data points were unusually small. I have eliminated the most obviously anomalous points to clear up the data.
5.1 Results

As expected, with increased laser power there are a larger number of atoms loaded into the MOT, and for higher intensities, larger detunings lead to larger MOTs. Quadratic fits match the data fairly well showing a clear trend of higher laser power creating larger MOTs, especially when error bars are taken into account (I have omitted them in figure 5.1 for clarity), but the real value of the fit is to provide a way to find uncertainty in opti-

Figure 5.1: The number of atoms loaded in a MOT versus the detuning with second order polynomial fits for 4 laser powers.
minimum detuning and peak MOT number. The quadratic fit is merely a way of showing a trend in the information, rather than being based off of any theoretical prediction. Notice that the optimum detuning for the larger two intensities is nearly the same. This effect is probably due to the diminishing returns to increased laser power in $R$. In addition, the intensity of the BoosTA is so far above saturation that there is less benefit from increased laser power than around the saturation intensity.

Because of noise on the DAVLL signal, some of the data points are anomalously high while others are too low. Take the data points around 25 MHz for $I = 252 \text{ mW/cm}^2$. There are 4 points all around $1.2 \times 10^9$ while a fifth is all the way up at $1.75 \times 10^9$. The spread in this data could be from uncertainty in detuning or differences in repump frequency. The size of a MOT is a function of laser alignment, repump intensity and wavelength, and trapping intensity and wavelength. This graph only considers two of these variables, but all of them are important. It is possible that something in the alignment could have changed to make smaller MOTs, thus skewing the data.

Figure 5.2 clearly shows a more intense laser beam traps more atoms. Again, the two larger intensities have nearly the same peak number of atoms, especially considering the uncertainty. Figure 5.3 also shows the more intense the laser beam, the larger the optimum detuning. This is because the more photons a second that are passing through the atom cloud, the more opportunities an atom will have to be slowed by an incoming photon. Since larger detunings make collisions less likely, according to equation 3.1, they are only possible at higher intensities when there are enough photons to
make up for the reduced absorption.

Figures 5.4, 5.5, 5.6 and 5.7 show the error bars clearly for each power and the uncertainty in the fit parameters. The error is 2.6 MHz for each detuning, because R contains the detuning squared, this error turns out to be about 20%. The curve fits shown in these equations provide a means to calculate the uncertainty in the peak number and peak detuning.

### 5.2 Calculating the Uncertainty

When fitting the data in Kaleidagraph, each fit parameter is given an uncertainty, shown in for example 5.4. Using Mathematica, I found the peak...
Figure 5.3: The optimum detuning of the trapping beam versus the intensity of the laser beam.

number using the largest limits on the values of the fit parameters by adding the uncertainty and the smallest limit on the values by subtracting the uncertainties to get a range of possible peak numbers and detunings. Then, the best guess is the average of the two limits while the uncertainty is given by the distance from the average to the largest limit in the possible detunings or MOT numbers. This probably overestimates uncertainty, since it is unlikely that both fit parameters would be at the same extreme at the same time, but it does provide sound upper and lower limits.

One surprising result is the fact that the ideal detunings and peak number of trapped atoms for the higher two intensities are identical given the uncertainty ranges. This means that the BoosTA, really does make a big
Figure 5.4: The number of atoms loaded in a MOT versus the detuning of the trapping beam for $I = 68$ mW/cm$^2$.

Figure 5.5: The number of atoms loaded in a MOT versus the detuning of the trapping beam for $I = 118$ mW/cm$^2$. 
Figure 5.6: The number of atoms loaded in a MOT versus the detuning of the trapping beam for $I = 178 \text{ mW/cm}^2$.

Figure 5.7: The number of atoms loaded in a MOT versus the detuning of the trapping beam for $I = 252 \text{ mW/cm}^2$. 
difference over the unamplified diode laser. Using the BoosTA, we can create a colder, denser cloud than before and dipole trapping from that cloud will be easier. While the similarity between the peak number for the larger two intensities could be explained by that asymptotic behavior of $R$, this could also be explained by uncertainty. For 252 mW/cm$^2$, the peak number of trapped atoms is $1.2 \pm 0.4 \times 10^9$, and an optimum detuning of $21 \pm 4$ MHz, while for 178 mW/cm$^2$, the peak number of trapped atoms is $1.2 \pm 0.3 \times 10^9$, and an optimum detuning of $20 \pm 4$ MHz. These data points are the same when taken to significant figures, and indeed for the other two data points are also similar given the uncertainty. The optimum settings are shown in the table below.

The uncertainty in the data make it difficult to draw exact conclusions about the benefits of increased laser intensity. But, it is clear that higher intensities do provide a benefit over smaller intensities, and that the unamplified laser cannot reach high enough intensities to reach the upper limit on the number of atoms trapped in the MOT.

<table>
<thead>
<tr>
<th>$I$ (mW/cm$^2$)</th>
<th>Optimum Detuning (MHz)</th>
<th>Peak Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>252</td>
<td>21 ± 4</td>
<td>$1.2 \pm 0.4 \times 10^9$</td>
</tr>
<tr>
<td>178</td>
<td>20 ± 4</td>
<td>$1.2 \pm 0.3 \times 10^9$</td>
</tr>
<tr>
<td>118</td>
<td>15 ± 3</td>
<td>$0.9 \pm 0.3 \times 10^9$</td>
</tr>
<tr>
<td>68</td>
<td>14 ± 5</td>
<td>$0.7 \pm 0.3 \times 10^9$</td>
</tr>
</tbody>
</table>

Figure 5.8: The largest number of atoms trapped in the MOT for each intensity, and the optimum laser detuning.
6 Conclusions

The BoosTA is a powerful instrument and it emits a lot of laser light. It can set fire to dark pieces of paper in just a few seconds. Without this additional power, the atom cloud trapped in the MOT does not reach the billion atom mark. Because the ultimate goal of this lab is BEC, and a larger MOT leads to a larger BEC, the data show that the BoosTA creates a larger BEC than would be possible with just 50 mW of laser power. The data also show that after a certain level, there are diminishing returns to the increases in power and that it will not be difficult to align the BoosTA well enough to provide virtually the best possible MOT for a given set-up.

In the future, there are a few things that could be done to truly optimize the MOT. If the stability of the of the DAVLL signal on the trapping beam can be improved then much more accurate data on the detuning could be taken. In addition, using the imaging system to calculate the number of atoms loaded into the MOT could provide a valuable way to double check for systematic errors in the data.

The MOT itself is as robust as has been attained in the Whitaker Labs. With MOTs consistently loading a billion atoms, the large atom cloud should be an easy target for dipole trapping in the future.

References


