CONSTRUCTING A MAGNETO-OPTICAL TRAP

FOR COLD ATOM TRAPPING

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I. Introduction

The study of the interaction between light and matter at the atomic level became considerably more intriguing in 1975 [1], when several groups of physicists first proposed that light can be used to trap and cool atoms. At room temperature, most atoms travel at thousands of meters per second ($\sim10^3$ m/s) [2]. The high velocity and random thermal motion of an atom at room temperature makes it extremely difficult to study and observe. For this reason the concept of trapped atoms, which travel at significantly lower velocities (~10 cm/s) [3], is especially attractive to atomic physicists and scientists studying cold quantum systems, such as Bose-Einstein condensates.

Trapping and cooling atoms using light, a technique referred to as laser cooling, can reduce the temperature of an atom sample to the μK range [3], allowing scientists to observe the sample more effectively and gain a better understanding of the interaction between atoms and light and the interaction between atoms and other atoms. Among other applications, cold atom samples can be deposited into optical lattices for use in quantum computing, can be used to produce better atomic clocks, high-precision acceleration and rotation measurements, and measurements of CP violation [1, 4].

One device that is used to trap and cool atoms to the μK range is called a magneto-optical trap (MOT). A MOT traps atoms in one location between three pairs of opposing perpendicular laser beams through absorption and spontaneous emission of photons, which essentially "pushes" the atoms to one point from each direction in space. A magnetic quadrupole field splits the energy levels of the atoms in the trap. This increases

the likelihood that the atoms will selectively absorb photons from either left circularly polarized or right circularly polarized light, a technique that keeps the atoms trapped at one point in space. A MOT also contains a vacuum chamber that houses the atom sample, which will be pumped down to ~10^{-9} Torr and filled with a sample of ~2×10^9 Rb^{87} atoms in our experiment.

Ten years after the concept of laser cooling was first proposed, physicist Steven Chu and his colleagues at Bell Laboratories in New Jersey cooled a sample of ~10^6 Na atoms between laser beams converging from different directions in space [5]. Around the same time, at the National Bureau of Standards (NBS), William D. Phillips was trapping atoms using a purely magnetic trap, called a Zeeman Slower, while in France, Claude Cohen-Tannoudji was theoretically determining the Doppler Limit for cooled atoms, the lowest temperature at which trapped atoms can be cooled by laser light [5]. For their work in the field of trapping and cooling of atoms to the μK range, Steven Chu, Claude Cohen-Tannoudji, and William Phillips were awarded the Nobel Prize in Physics in 1997 [5].

Every MOT utilizes a method called Doppler cooling, the same scheme by which Steven Chu was able to first cool atoms around 1995. The optical system we employ in our MOT consists of two diode lasers, which are used for reducing the velocities of the atoms by way of Doppler cooling, pumping them to specific energy levels, and providing a feedback system in which the wavelengths of the lasers remain extremely stable over months at a time. Our magnetic quadrupole field is generated by running current through two spools of wires oriented in the anti-Helmholtz configuration, which are mounted just

above and below the vacuum chamber. Upon completion of our MOT, Rb^{87} atoms will be trapped and cooled to the µK range, where they can be transferred to a light trap in the diffraction pattern behind a pinhole for future studies in quantum computing.

II. Theory

    a. Doppler Cooling

The essence of how a MOT works lies in a mechanism called Doppler Cooling. By tuning the laser light to a frequency just below the atomic resonance frequency at which the atoms absorb photons from the laser beams, momentum transfer to the atoms by way of absorption and emission of photons will always decrease the velocities of the atoms, which reduces the temperature of the atom sample. Because the atoms are most likely to absorb photons with energies equal to the difference in their atomic energy levels, it is important to keep the laser light tuned to very precise frequencies.

In a simplified model of Doppler cooling, let two energy levels of our atom be called E1 and E2, and the frequency of the incoming laser light be ω_L. Photons with energies equal to the difference in energy between E1 and E2 are most likely to transfer their momentum to the atoms by way of absorption and spontaneous emission. By tuning the frequency of the laser beam ω_L to produce photons of energies that are slightly lower than the energy difference between E1 and E2, we can insure that an atom at rest between the laser beams will on average absorb equal amounts of photons from both lasers. This causes the atom

to experience equal forces from each direction (Figure 1). Hence, an atom at rest experiences the same frequency ω_L from both Laser 1 and Laser 2 and does not feel a net force from the laser beams.

E2 ——————————————————

—— —— —— —— ——
ωL

Laser 1   Atom at rest   Laser 2

➡   ●   ⬅
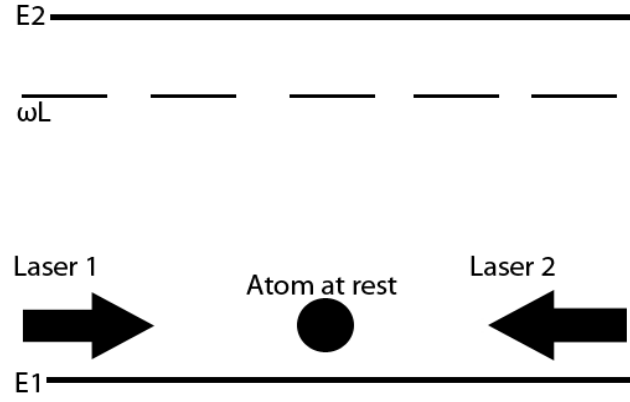
E1 ——————————————————

Figure 1: Atom at rest.

In contrast, an atom that is not at rest between the intersecting laser beams will experience different frequencies from Laser 1 and Laser 2 due to the Doppler shift. An atom moving to the left inside the trap sees an increase in the frequency of Laser 1, ω_1, because it is moving against the direction of the propagation of light from Laser 1 (Figure 2). At the same time, the atom experiences a decrease in the frequency of light from Laser 2, ω_2, because it is moving in the direction of light propagation from Laser 2. This insures that the atom absorbs many more photons from Laser 1 than it does from Laser 2. Absorbing more photons from Laser 1 effectively reduces its leftward velocity, and absorbing fewer photons from Laser 2 ensures that the atom cannot be accelerated to the left.
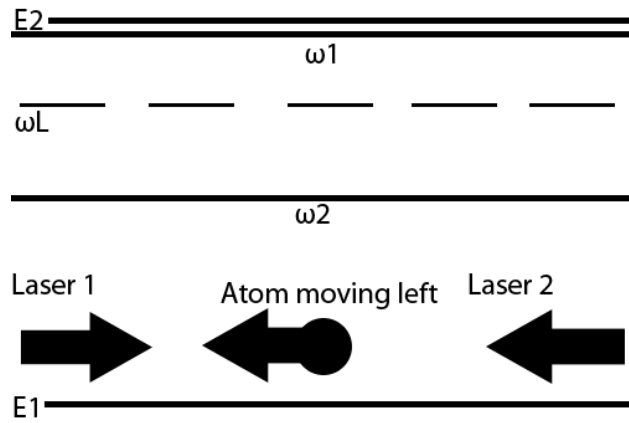
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Figure 2: Atom moving left.

By the same reasoning, an atom moving to the right experiences an increase in the frequency of Laser 2, ω_2, because it is moving against the direction of the propagation of light from Laser 2 (Figure 3). At the same time, it experiences a decrease in the frequency of light from Laser 1, ω_1, because it is moving with the direction of light propagation from Laser 1. The atom does not absorb nearly as many photons from Laser 1 as it does from Laser 2, which reduces the atom's velocity and ensures that it cannot be accelerated to the right.
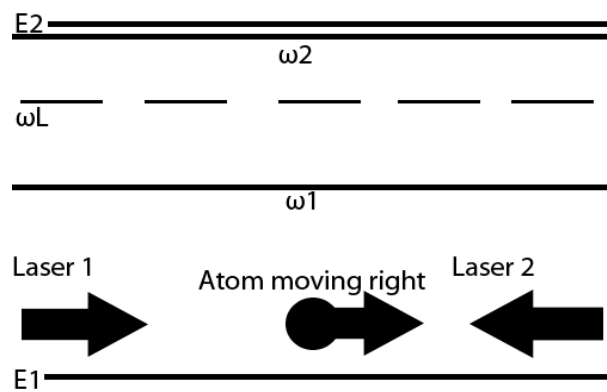

Figure 3: Atom moving right.

In general, an atom moving to the left against the direction of light propagation from Laser 1 slows down because it absorbs many photons from Laser 1 and very few photons from Laser 2. An atom moving to the right, against the direction of light from Laser 2, is slowed down by Laser 2 and absorbs very few photons from Laser 1. By this process, the laser light always reduces the velocities of the atoms, but never increases them. A stationary atom inside the trap absorbs equal numbers of photons from both Laser 1 and Laser 2, and is not accelerated in either direction. When three pairs of laser beams propagate from each direction in space and converge on a single point, the atoms radiated by the beams are slowed down from each direction in space. The atom sample begins to cool as the velocities of the atoms in the sample decrease. The likeness of the laser beams to a thick liquid that hinders the motions of the atoms is referred to as "optical molasses." It is this optical molasses that attenuates the motion of the atoms in every direction in space and cools the sample.

b. The Lasers

Of course every Rb^{87} atom has many different energy states, but the technique of laser cooling can be more easily understood when the discussion is limited to just two energy states. As an example, we use the previously mentioned states E1 and E2. Occasionally, an atom will undergo spontaneous emission of a photon that leaves the atom in an energy state lower than E1. This means that even a photon with an energy that matches that of the difference between E1 and E2 has a small probability of being absorbed by the atom, which increases the chances that the atom can drift out of the trap without being slowed

by the lasers. A "pump" laser beam incident on the atoms that shines at a slightly higher frequency than the "trap" laser beam helps to ensure that the atoms remain inside the trap. An atom that absorbs photons from the pump laser beam is driven to an energy level just below E2, where it can spontaneously emit a photon and fall back to E1. While the trap laser beam reduces the velocities of all the atoms, the pump laser beam helps return them to the energy state E1 where they can again absorb photons from the trap laser. Atoms will drift out of the trap only if the rate at which they fall to a different energy state than E1 is greater than the rate at which they are pumped back to E1 by the pump laser.

The laser beams are circularly polarized, which means that the tip of the electric field vector in each beam traces out a circle in space as the beam propagates. Each pair of opposing laser beams contains one left circularly polarized beam (σ_-) and one right circularly polarized beam (σ_+). The three pairs of oppositely polarized beams incident upon the atoms from each direction in space make it possible for an applied magnetic field to trap the cooled atoms in one location, as described in the next section.

c. The Magnetic Field

Although the method of laser cooling can successfully lower the velocities of atoms in a sample, an applied magnetic field is required to force the atoms to coalesce at one point, thereby "trapping" them. The z-component of the magnetic field along the vertical z-axis of the MOT is denoted B(z) (Figure 4). Trapping atoms requires the application of an external magnetic quadrupole field oriented so that the point of the minimum field

strength $B(z) = 0$ lies at the intersection of the laser beams, where $z = 0$. The same is true along both the x and y axes.
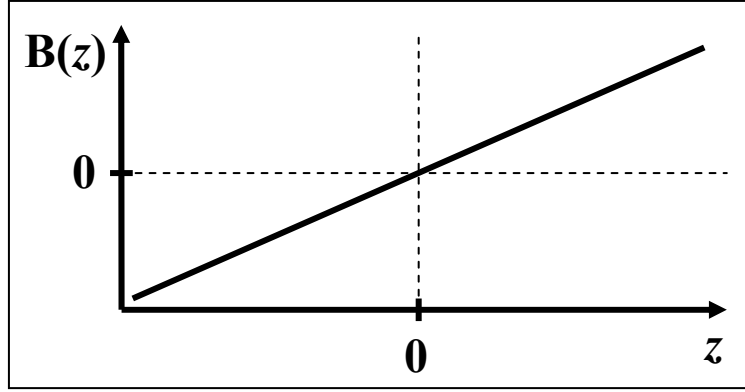

Figure 4 [5]: Magnetic field strength as a function of position.

Let us say that σ_+ light propagates from laser beam 1 and σ_- light propagates from laser beam 2. As an atom drifts away from the position $z = 0$, the magnitude of the magnetic field increases, and the atom experiences increased Zeeman splitting of its energy levels. As a simplified example, let us consider an atom with two energy states: one with $j = 0$ ($m_j = 0$) and one with $j = 1$ ($m_j = 0, \pm 1$), even though the energy levels of Rb^{87} are more complicated than this. The magnetic field causes the energies of the $m_j = 1$ and $m_j = -1$ atomic substates to split (Figure 5). If the atom is located to the left of $z = 0$, its $m_j = 1$ substate gives the atom a better chance of absorbing more σ_+ photons and absorbing less σ_- photons. Absorbing more σ_+ photons than σ_- photons causes the atom to be pushed back towards $z = 0$, because the σ_+ photons propagate to the right.
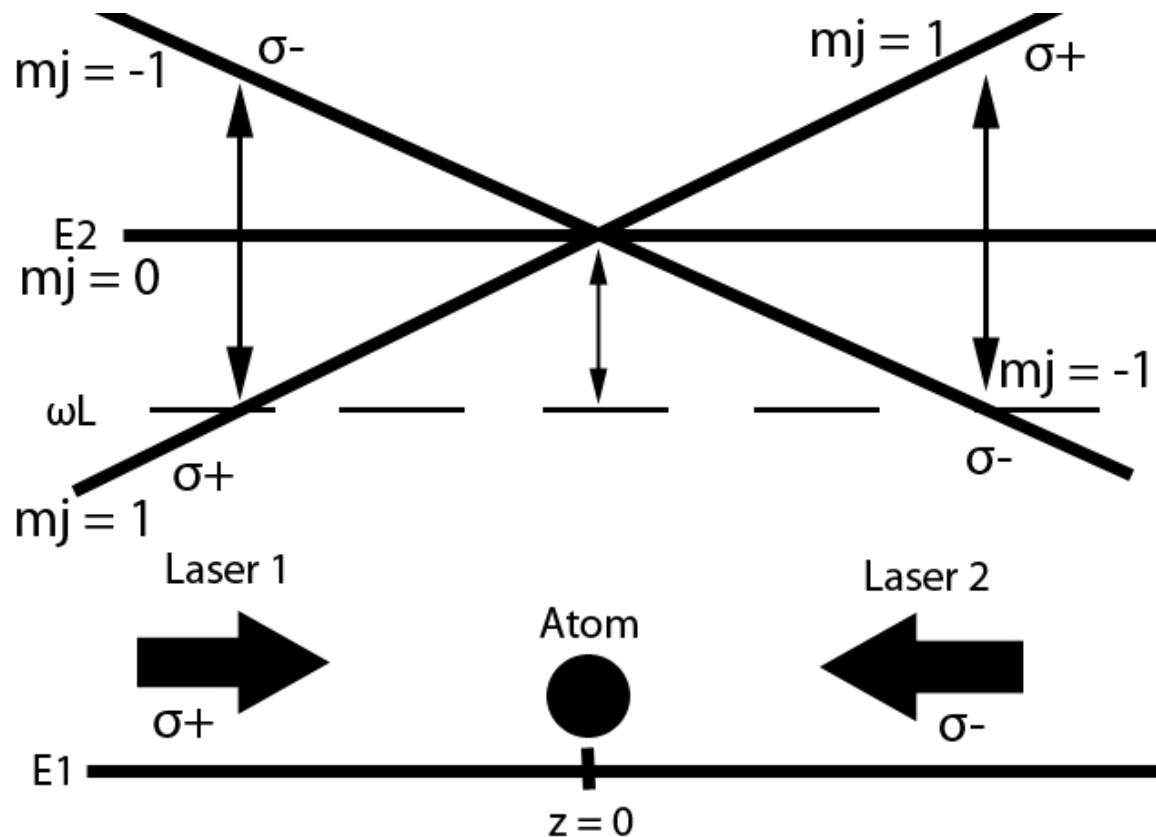
Figure 5: Zeeman splitting of trapped atom.

In contrast, an atom that is located to the right of z = 0 has its m_j = -1 substate shifted in a way that increases the likelihood that the atom will absorb more photons from the σ_- beam and less photons from the σ_+ beam. Absorbing more photons from the σ_- beam and less from the σ_+ beam effectively pushes the atom back towards z = 0 where it absorbs equal amounts of both σ_+ and σ_- photons.

Since current in a wire produces a magnetic field, two spools of wire in an anti-Helmholtz coil configuration with current running through them (Figure 6) are used to produce the appropriate quadrupole field. The field strength increases linearly in all three

directions in space along the three pairs of laser beams. When the current in one loop

runs in the direction opposite to that of the other, a zero-point minimum arises in the

magnetic field between the spools. This magnetic field permeates the vacuum chamber

that houses the atoms and increases the likelihood that the atoms will specifically interact

with either σ_- photons or σ_+ photons, depending on the atom's position inside the trap.

The applied magnetic field creates a situation in which the atoms are more likely to

absorb different photons depending on the atoms' positions, while Doppler Cooling

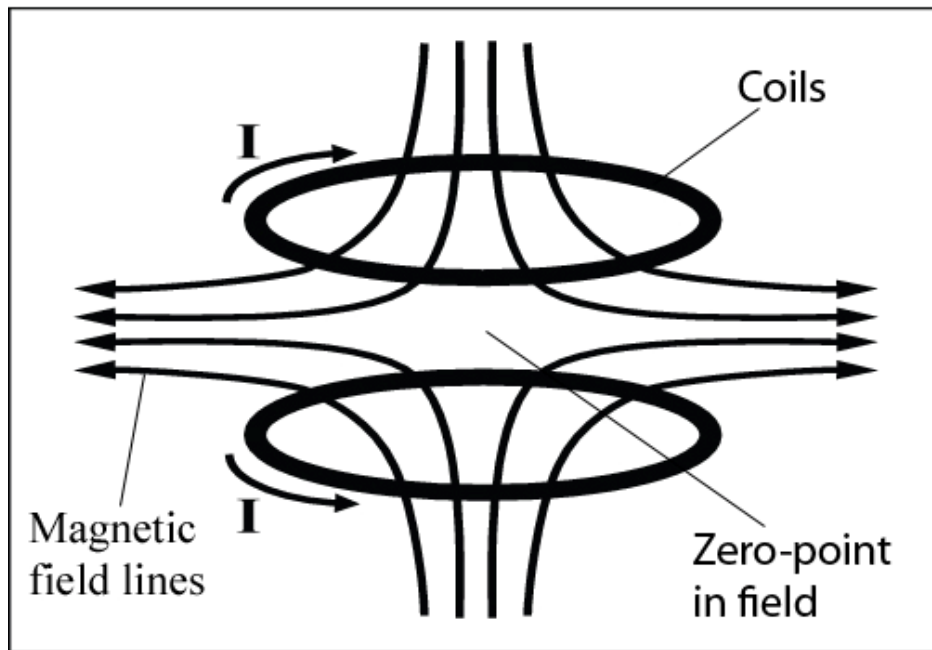dictates which photons the atoms will absorb depending on the atoms' velocities.

Figure 6 [5]: Quadrupole magnetic field.

III. Assembly of the MOT

    a.   The Laser System

The optical components of our MOT consist of two tunable diode lasers, designed at the Ohio State University, and a laser feedback system. A group of research students and I assembled the lasers at Cal Poly. The significant optical components required for each laser consist of a laser diode, lens, diffraction grating, and mirror (Figure 7).

The pins of the laser diode are wired to a combination laser diode and temperature controller. Light from the laser diode is focused by the lens, and the distance between the laser diode and the lens is adjusted until the focal point of the emitted laser light approaches infinity. At this point, the laser beam is said to be collimated. The collimated beam is then diffracted by the grating, reflected by the mirror, and sent out of the laser's protective box and into the experiment [6]. The frequency of the emitted light is dependent on the temperature of the laser cavity, the amount of current running through the laser diode, and the angle at which the laser light is incident upon the diffraction grating. Two adjustment screws are placed behind the hinged aluminum arm that holds the grating and mirror. Loosening or tightening these screws alters the angle at which laser light is incident upon the grating, which allows the laser beam to be tuned to very precise wavelengths. Adjustment of these screws can increase or decrease the wavelength of the emitted laser light by up to ~10 nm.

When the laser cavity is held at different temperatures, it produces light of different frequencies. Controlled heating and cooling of the lasers is extremely important because of the sensitivity of the trapped atoms to the frequency of the incident laser light. For this reason, two thermoelectric coolers (TEC coolers) are installed on each laser, along with a resistor that functions as a heater inside the baseplate of each laser (Figure 7). These heating and cooling elements allow us to keep temperature of the lasers extremely stable. A thermistor that acts as a temperature sensor is installed below each laser diode, which allows for the temperature of each laser to be monitored using a Thorlabs ITC 502 Laser Diode Combi Controller. Using this controller, we will be able to make extremely small adjustments to the temperature of each laser, increasing the likelihood that the frequency of the emitted light will remain stable. A heat sink is installed below the TEC coolers in order to carry away excess heat generated by the coolers. Coolant is pumped by a Thermo Scientific NESLAB RTE-7 Digital One refrigerated circulation bath through a series of hoses to the heat sink of each laser, dispersing excess heat.
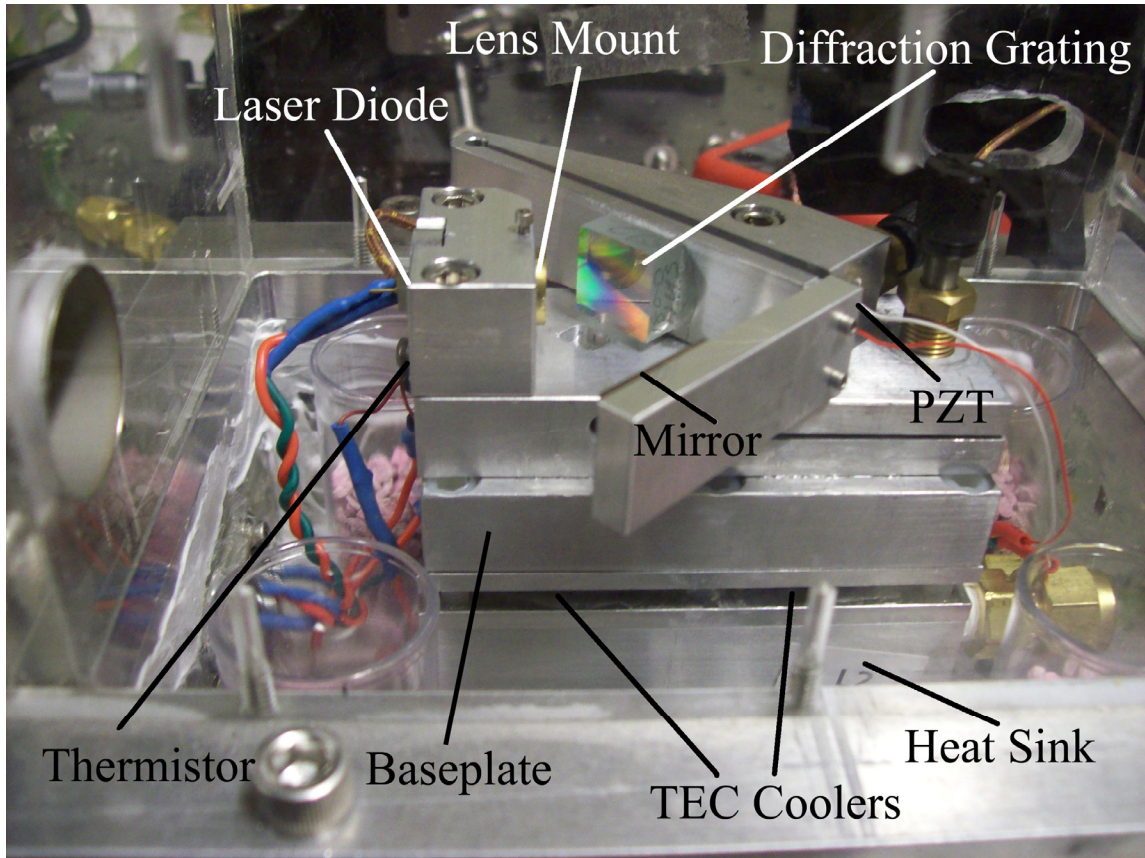
Figure 7: Completed trap laser.

The wavelength of the laser light is dependent not only on the temperature of the laser, but also on the angle at which the beam is incident upon the diffraction grating. To make tiny adjustments to this angle, a piezoelectric transducer (PZT) is installed in the hinge that holds the grating and mirror (Figure 7). Passing a voltage across the PZT causes its crystalline structure to expand, which changes the size of the PZT. The laser feedback system supplies tiny changes in voltage across the PZT, causing it to expand or contract, which alters the incident angle of the beam on the diffraction grating. Thus, we can make tiny adjustments to the frequency of the laser beams by supplying small voltages across the PZT.

The laser-locking feedback system we use is called a dichroic-atomic-vapor laser lock (DAVLL) [7]. The DAVLL (Figure 8) works by sending a linearly polarized laser beam through a cell of Rb^{87} vapor in the center of a solenoid. The beam then passes through a quarter-wave plate and polarizing beam-splitter, which splits the beam into two beams of equal intensity which are received by two photodetectors [5]. Each photodetector was constructed at Cal Poly and consists of a photodiode and an operational amplifier. The Zeeman-splitting of the energy levels of the atoms in the vapor cell, which is caused by the magnetic field of the solenoid, causes the signals from the two photodetectors to be shifted relative to each other [5]. These signals are electronically subtracted to create an error signal [5]. A laser lock box provides feedback to the PZT by increasing or decreasing the voltage across it depending on the error signal it receives (Figure 8). In this way, small adjustments in voltage across the PZT, which are essentially dictated by the error signal, have the potential to keep the frequency of the laser light extremely stable.
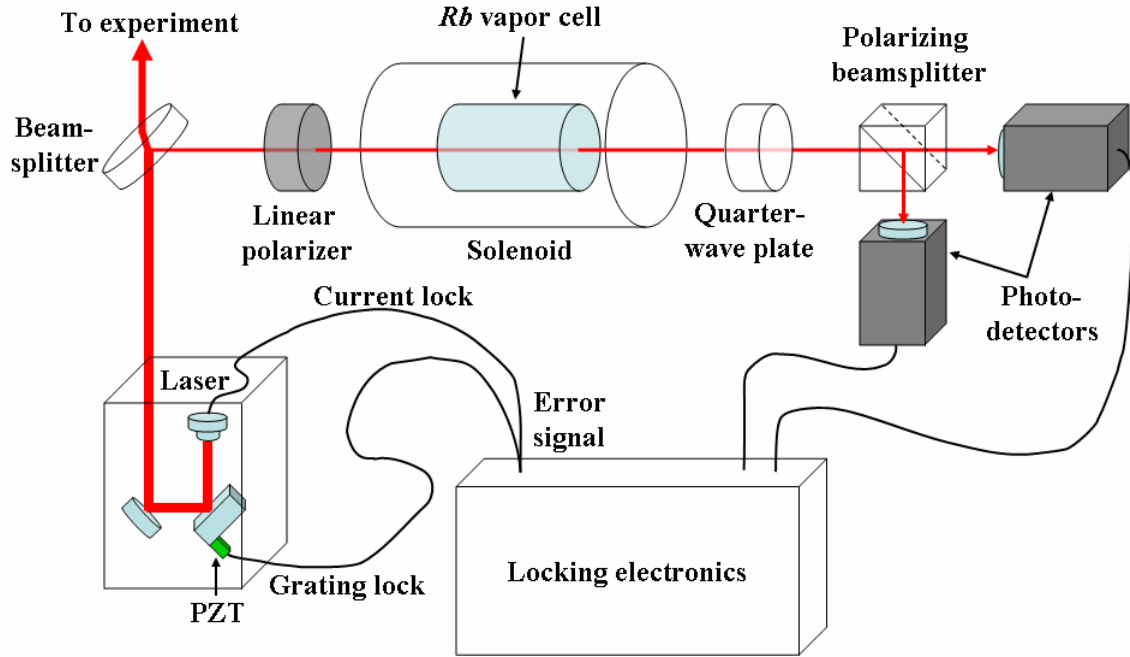
Figure 8 [5]: Dichroic atomic vapor laser lock.

After assembly of the lasers was completed, a protective Plexiglas box was designed to house each laser (Figure 9). The nearly airtight boxes thermally isolate the lasers from the outside environment and keep dust and other unwanted particles from settling on the optics inside the boxes. By thermally insulating the lasers with protective boxes, we improve the laser temperature control even further. Light exits the Plexiglas box through a window oriented at Brewster's angle, which insures that minimum laser beam power is lost due to reflection at the window of the box.
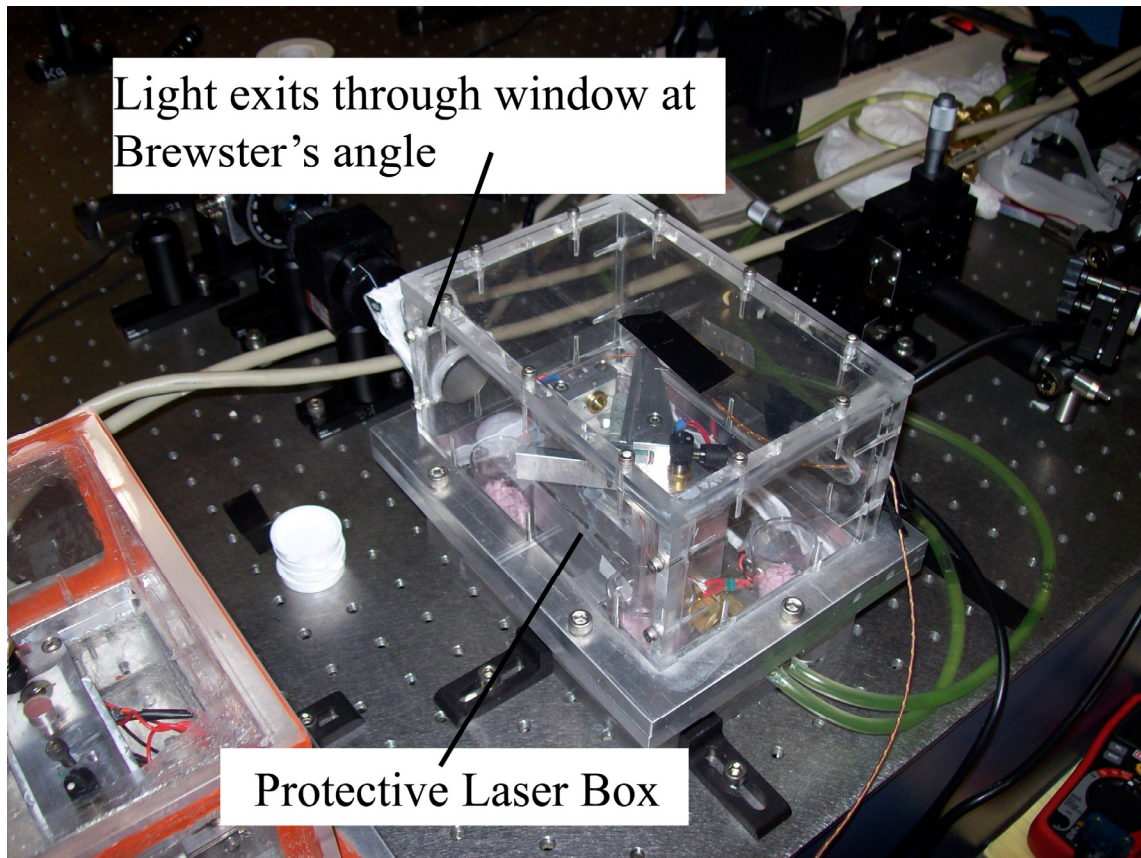
Figure 9: Plexiglas laser box.

b. The Magnetic Field

A magnetic field that increases in strength linearly with the distance from its central minimum point is called a quadrupole magnetic field. The most common way to produce a quadrupole magnetic field is by running a current through two spools of wire in the anti-Helmholtz configuration, where the current in one spool runs in the direction opposite to the current in the other. To provide this anti-Helmholtz current configuration, I designed two Plexiglas spools with an inner diameter of ~6.4 cm. I wound tight loops of 18-Gauge copper wire around the spools until each spool contained 20 layers of 20

loops of wire, or 400 loops of wire on each spool (Figure 10). To help insulate the wires from each other, a thin layer of Teflon was placed between about every 5 layers of wound wire. The layers of Teflon also prevent loops of tightly-wound wire from collapsing into the layers below them, which breaks the symmetry of the coils and the symmetry of the magnetic field produced by them. The spools are mounted on a 1.5 inch diameter optics post and will be placed just below and just above the vacuum chamber that houses the Rb^{87} atoms (Figure 11), which insures that the location of the minimum-strength point in the field occurs precisely where the atoms are to be trapped (Figure 12). During operation of the MOT, ~2 Amps of current will run through the wires on the spools, which is enough current to produce the desired magnetic field gradient of ~10 G/cm at the location of the trapped atoms between the spools. This magnetic field gradient produces enough Zeeman-splitting of the energy levels of the atoms in the trap to increase the likelihood that they will selectively absorb photons from either the σ_+ or σ_- laser beams.
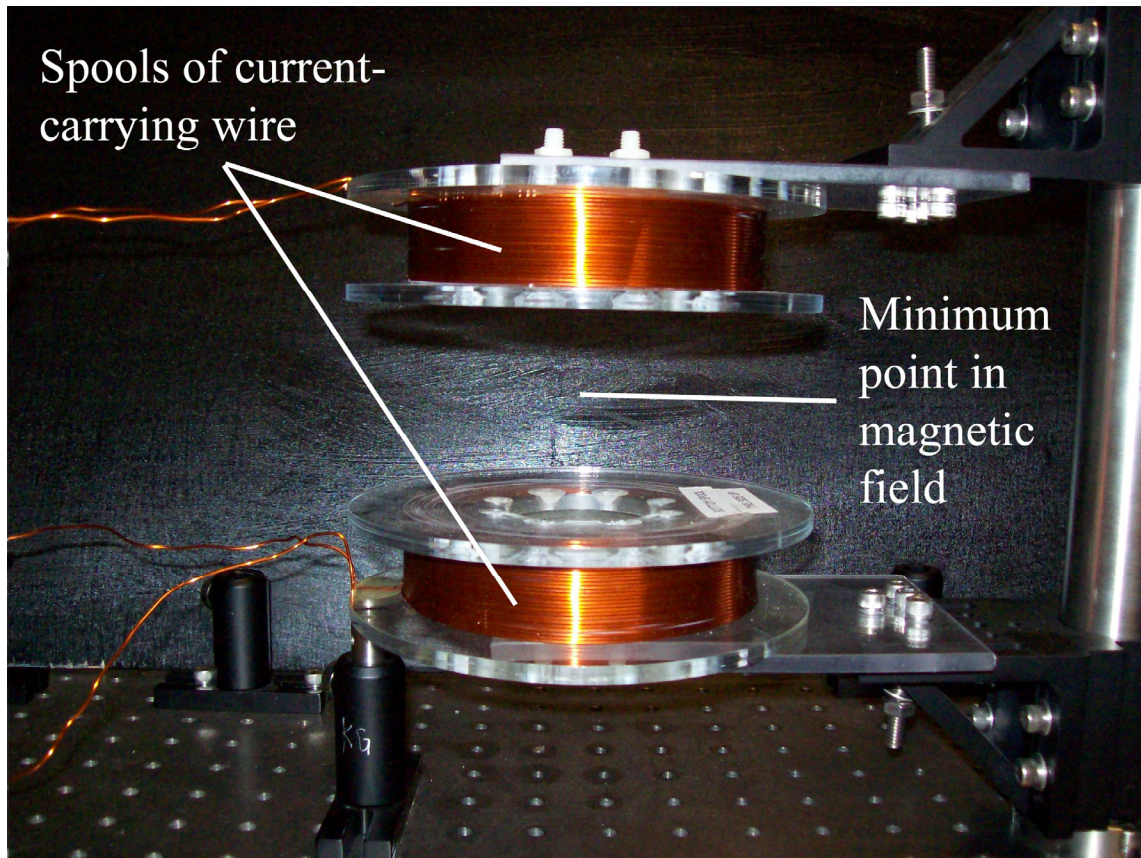
Figure 10: Current-carrying wire loops.

c. The Vacuum Chamber

The last component to be assembled for use in the MOT is the vacuum chamber that will hold the Rb^{87} atoms. It is a glass cylinder (Figure 11) that will be pumped down to pressures on the order of 10^{-9} Torr and baked to temperatures of ~300-350°C in a process called the "bake-out." Baking the chamber to such high temperatures while it is being pumped to low pressures ensures that loose particles, atoms, and molecules inside the vacuum chamber, including those stuck to its interior walls, will be expelled from the

chamber before the MOT becomes operational. Particles other than Rb^{87} atoms that are present inside the chamber when the MOT becomes operational will not respond to the laser light, which prevents them from being trapped. This means that high-velocity particles will be able to move around inside the chamber and potentially knock trapped Rb^{87} atoms out of the trap. For this reason, the bake-out is an essential process for pumping the vacuum chamber down to pressures as low as possible before the MOT can begin trapping. To pump the chamber down to extremely low pressures, a pumping station is attached to the end of the chamber with Quick Flanges. A roughing pump and turbo-molecular pump will pump down the chamber during the bake-out, while the high temperature helps to shake loose and expel any remaining particles inside. An ionization pump is turned on after the bake-out to insure that the pressure inside the chamber remains low.

In preparation of the bake-out, the vacuum chamber was covered with aluminum foil, then wrapped with heater tapes underneath another layer of aluminum foil, and was finally wrapped with multiple layers of thin sheets of fiberglass insulation. The fiberglass insulation was first baked piece by piece to ~400°C to allow for the off-gassing of byproducts that were added to it during its manufacture. The fiberglass insulation keeps the heat contained around the vacuum chamber where it is needed, and it also keeps the lab from heating up to a blistering 350°C.

Figure 11: Vacuum Chamber used for housing Rb^{87} atoms.

Upon completion of the bake-out of the vacuum chamber, the chamber will be mounted between the two current-carrying spools that produce the quadrupole magnetic field. After traveling through a system of auxiliary optics, the laser beams will be reflected by mirrors in a way that causes them to intersect perpendicularly inside the vacuum chamber from each direction in space, allowing them to trap the Rb^{87} atoms inside (Figure 12).
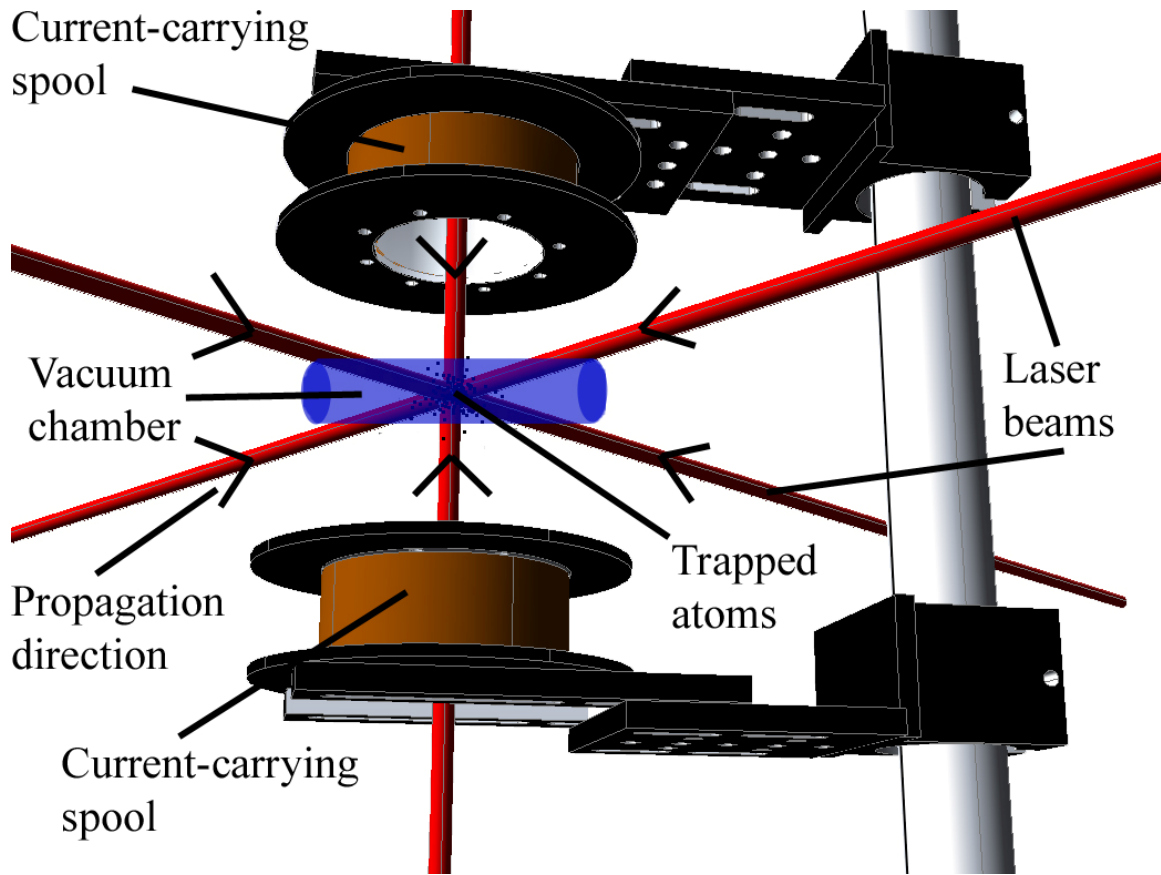
Figure 12: Rendering of completed MOT.

IV. Results

When I began construction of the MOT over two years ago, the lasers were incomplete or completely unassembled, the current loops for producing the magnetic field were nonexistent, and the vacuum chamber had no pumping station associated with it. Although successful trapping of atoms may take a few more months, the components of the MOT have been almost fully constructed and much progress has been made towards their completion.

I have completely assembled the optical components of the lasers and they are now fully operational. The laser locking system has not been completed, partly due to problems we have had with the photodetectors of the DAVLL. The chips in most of the photodetectors have been damaged, and even those that fully work usually transmit noisy signals that make it difficult to locate the characteristic signal of the atomic transitions on the oscilloscope. Once the DAVLL system has been successfully completed and tested, the only remaining problem with the laser system will be its temperature stability.

The PID settings on the Thorlabs Laser Diode Combi Controller must be appropriately adjusted to allow for maximum laser temperature stability. I created a LabVIEW program designed to read and record the laser temperature over extended periods of time. Using this program, I observed the fluctuations in laser temperature when different configurations of the PID settings were tested. The Thorlabs laser controller stabilizes the temperature of a laser by returning the temperature to its set value by way of a damped oscillation. According to the laser controller manual, adjustment of the P-share affects the speed of the temperature settling, I-share affects the acceleration of the temperature settling, and D-share affects the amplitude of the oscillations. However, we found experimentally that regardless of the D-share setting we employ on our laser controller, the amplitude of the oscillations generally remains constant. Thus, the laser temperature never reaches equilibrium. Because of this, the laser temperatures are not stable enough to produce consistent wavelengths within a few MHz of the Rb^{87} hyperfine transition that are needed to run the experiment. This is the last problem with the laser system that needs addressing before atoms can be trapped. In addition to the Thorlabs

temperature controllers, I installed a Thermo Scientific NESLAB RTE-7 Digital One refrigerated circulation bath that is supposed to keep temperatures stable to within ±.01°C. Once they are configured appropriately, the combination of the refrigeration bath and Thorlabs temperature controllers should keep the laser temperatures stable enough to successfully run the experiment.

The spools of wire that I designed and built over a year ago have been mounted on a 1.5 inch diameter optics post (Figure 10) and are ready to be positioned just above and below the vacuum chamber once the chamber is baked-out and pumped down to low enough pressures. The wires on the spools will be attached to a current source and ~2 amps of current will run through them, producing the appropriate quadrupole magnetic field.

The last major step in the process of completing the MOT is the bake-out of the vacuum chamber, in which the chamber is baked to temperatures near 350°C and pumped down to pressures near 10^{-9} Torr. As of the end of November 2009, the MOT was wrapped in heater tapes, aluminum foil, and fiberglass insulation in preparation for the bake-out. A LabVIEW program was designed to monitor the temperature of the vacuum chamber during the bake-out using thermal couples placed between the heater tapes and the vacuum chamber itself. The LabVIEW program was also designed to shut off power to the pumping station if the pressure inside it exceeds a certain limit. This is to prevent any damage to the pumps that can occur if the glass walls of the vacuum chamber break or if the system experiences a significant leak during the bake-out process.

The last problems that stand in the way of a successful bake-out involve the different circuits that the pumping station and heater tapes receive their electricity from, and a grounding issue with the relay box. The equipment used during the bake-out requires a large amount of power and without carefully distributing the load, it is possible to blow out one or more of the circuit breakers being used during the bake-out. For this reason, we distributed the equipment over multiple different circuits in the building. Before the last bake-out attempt, while we were testing the relay box used to shut off the equipment, it was found that a grounding issue with the relay box caused it to shut down when a light switch in an adjacent room was flipped. Before the bake-out can be attempted again, a better understanding of the electronics inside the relay box is needed. The problem is being further investigated and the exact grounding issue inside the box will soon be determined. After the problems with the electronics are solved, nothing significant will stand in the way of a successful bake-out and ultimately the successful trapping and cooling of atoms.

V. Conclusion

As the next step in creating smaller and more powerful computers, scientists are studying the possibility of producing practical quantum computers. In order to truly understand atomic properties and behaviors that are required for the realization of quantum computers, physicists must look at cold atom samples in which the interactions between atoms and light and atoms and other atoms can be more easily observed. The easiest way to trap and cool atoms down to the μK range is to employ a MOT. I have spent the last

three summers at Cal Poly helping to assemble and test the components of a MOT that will eventually be used to trap and cool Rb^{87} atoms. With some good fortune, this will be accomplished by the end of summer of 2010, at which point the atoms can be transferred to a light trap made by the diffraction pattern of a pinhole. Studying the atoms' behavior inside the diffraction-pattern light trap will help to determine the feasibility of creating a quantum computing system that uses light traps to store the atoms. Hopefully, one day quantum computers will be a practicality of modern civilization, and it is highly likely that magneto-optical traps will have a huge role in making this futuristic concept a useful reality.

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