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# Achieving a Stable Magneto-Optical Trap

Chasen S. Himeda
*Loyola Marymount University*, chimeda@lion.lmu.edu

# Achieving a Stable Magneto-Optical Trap

by

Chasen Himeda

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**THESIS COMMITTEE APPROVAL**

of a thesis submitted by

Chasen Himeda

This thesis has been read by each member of the following thesis committee and by majority vote has been found to be satisfactory.

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| ______________ Date | ______________________________ Dr. David Berube, Advisor<br>Department of Physics |
| ______________ Date | ______________________________ Dr. Jeffrey Phillips<br>Department of Physics |
| ______________ Date | ______________________________ Anatol Hoemke<br>Department of Physics |

## ABSTRACT

The utilization of the *Magneto-Optical Trap* (MOT) as a method for cooling and confining atoms is a recent development in the field of modern optical physics. Producing an effective MOT relies on a constant magnetic field throughout the trapping region and successful laser cooling, a technique used to achieve optical molasses by slowing particles using a three-dimensional intersection of laser beams. A successful MOT occurs when the trapped atoms slow down to approximately 30 cm/s at a temperature in the microkelvin range and is observable when a small bright orb of atoms is located in the center of the chamber. In this endeavor, the experimental setup for achieving a stable MOT was established using an array of infrared lasers provided by MogLabs. Future work on this project should seek to capture an image of trapped rubidium atoms using the ColdQuanta MiniMOT using the kit's black and white CCD camera. Successfully establishing this MOT allows for further testing to optimize its effectiveness and can be applied in future experiments aimed at achieving Bose-Einstein Condensation.

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## ACKNOWLEDGEMENTS

I would like to extend my deepest gratitude toward my entire family for your continuous love and support in everything that I do. Also, thank you to the LMU physics faculty and staff for your guidance and support with this project.

# CHAPTER 1: INTRODUCTION

Optical physics is a branch of physics whose growth is constantly increasing, both in its concepts and its applications. Studying the behavior of light in optics laboratories all around the world has led to many advances in other related fields, such as quantum physics and biophysics (see [1] and [2], for example). In an effort to better understand and experience the recent successes and challenges in modern optics, I took on the challenge of establishing a Magneto-Optical Trap (MOT) in the Loyola Marymount University (LMU) physics laboratory.

The LMU physics department purchased the equipment used in my experiment in order to introduce this project into future modern physics courses. The goal of my work was to utilize this newly acquired equipment to demonstrate that acquiring a stable MOT was possible in the physics laboratory. Throughout the experimentation process, I recorded meticulous notes of my procedure and findings, such that it could be referred to in the future in setting this experiment up again. This work seeks to provide the conceptual background of the MOT, provide methodologies to explain all procedural steps used, and discuss the outcome and current state of the experiment.

# CHAPTER 2: BACKGROUND

The development of the MOT is a relatively recent breakthrough in modern optical physics. As recipients of the 1997 Nobel Prize in Physics, physicists Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips were credited for developing the methods of successful trapping of gaseous atoms within a MOT [3]. The methods considered in their version of the MOT in the late 1980s and early 1990s are very much comparable to both simple and complex vapor atom trapping systems used today. Figure 1 represents the schematic drawing of the vacuum chamber used by Dr. Chu's Doppler

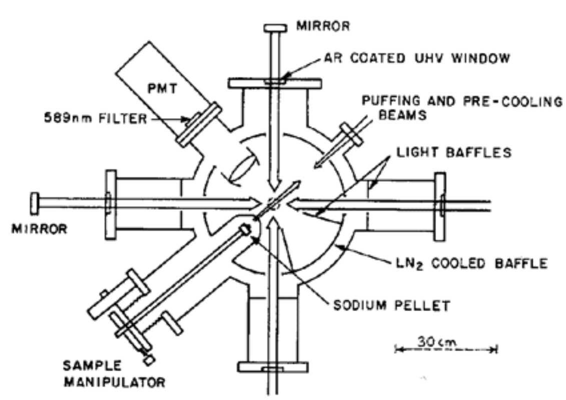


Figure 1. Schematic Drawing of Dr. Steven Chu's Vacuum Chamber [3]. Orthogonal lasers enter the chamber through the UHV windows and intersect at the center, where the gas sample is introduced via the sample manipulator.

Cooling Experiment in 1984, which illustrates many similarities to the apparatuses utilized in the construction of my MOT setup [3].

The physical operation of the MOT relies on two phenomena in order to control gaseous atoms' velocity and position within its chamber: laser cooling and magnetic trapping. The goal of laser cooling is to reduce the velocity of atoms or particles through the use of lasers, subsequently resulting in a reduction of kinetic energy and temperature of these particles. In a one-dimensional case, imagine a laser beam directed toward an atom that is travelling in the opposite direction (toward the source of the beam). If the atom were to absorb an incoming photon, it would experience a momentum kick in a direction opposite of the direction it was originally travelling. In a three-dimensional case, six orthogonal laser beams (± x, ± y, ± z directions) are aimed directly at the center of the MOT. Subsequently, an atom that travels away from the center of the MOT will absorb a photon from the opposing beams and will drive it back toward the center of the MOT.

After absorbing the initial photon that transitions it to a higher energy level, the atom must decay to a lower energy level via the emission of another photon. In this process, the atom will once again experience another momentum kick, but this time in a random direction. When considering the many emissions of photons, which results in random momentum kicks by all energized atoms transitioning from a particular high energy state down to a lower one, the average magnitude of the change in the atom's momentum will always be less than the magnitude of the momentum kick experienced initially by the absorbed photon (with direction toward center of trap) [4]. For this reason, although individual atoms experience two momentum kicks from the absorbed and emitted photons, the net change in momentum of the atom will always be directed toward the center of the MOT.

The term "quantum" in quantum theory explains that atoms can only gain or lose energy if their final energy after the transition is at very specific (quantized) energy levels. Therefore, in order for gas atoms in the MOT to absorb photons and excite them to a higher energy level, the gained energy from the photon absorption must be equivalent to the precise energy value between the initial and final energy states.

Laser cooling is often referred to as "Doppler Cooling" due to the importance of the Doppler Effect in this interaction between atom and photon; the Doppler Effect is a phenomenon that causes the frequency of particles or light waves to increase or decrease as they travel with a high velocity toward or away from an "observer". In this experiment, the "observer" is an atom that is moving away from the center of the trap. Since the atom has a velocity directed toward the photon beam, the atom will observe the frequency of the oncoming photon to be higher than the actual frequency of the light used. Therefore, when tuning the laser to the frequency required for energy transitioning during photon absorption, this "actual" frequency should be offset to a lower frequency (also referred to as red-shifting) such that the atom experiencing the Doppler effect will absorb the photon. The Doppler Effect will have more of an effect on particles with higher velocities toward the source of the photons compared to those with lower velocities; it is for this reason that atoms will very rarely ever absorb photons from the laser beam behind it [5]. Therefore, the effectiveness of laser cooling on atoms travelling away from the center of the trap is dependent on the velocity of the atom [6]. Over the

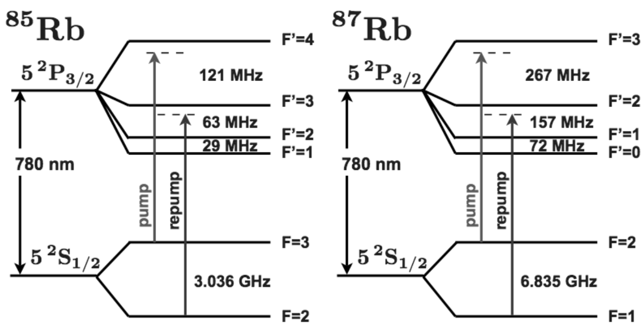


Figure 2. Energy Transition Levels for Rubidium [7]. Note that the MOT is this experiment will trap rubidium-85 atoms with energy transitions depicted on the left.

course of many of these atom-photon interactions, the atoms' loss of kinetic energy from these collisions results in an overall reduction of velocity and temperature of atoms within the chamber.

Quantum theory also dictates that the excitation and decay of an atom are restricted to only certain allowable energy transitions. As depicted in Figure 2, rubidium-85 atoms in the lower energy F=3 state can be excited by a photon that results in the atom occupying the higher energy F'=4 state [7]. Note that the "pump" arrow does not actually reach the F'=4 energy state- this is due to the red-shifted detuning of the laser that is required due to the Doppler effect. When this atom emits a photon and it decays back to a lower energy level, it is allowed to return to the lower energy F=2 state, but not the lower energy F=3 state. This restriction is undesirable because atoms in the lower energy F=2 state cannot be re-excited by the same "pump" laser beam used to excite it the first time from the F=3 state. Therefore, a second beam, called the "repump" laser beam, must be used to excite the atom from the lower energy F=2 state to the higher energy F'=3 state. It is from this higher energy F'=3 state that the atom is now allowed to decay back to the original lower energy F=3 state. This “optical loop” is created by the pump and repump lasers, causing atoms to experience this continuous cycle of energy transitions within the MOT.

In addition to the orthogonal lasers used in the laser cooling process, two coaxial current-carrying coils located below and above the rubidium chamber produce a magnetic field within the chamber. The goal of the magnetic trap is to introduce a magnetic field throughout the region in which the rubidium chamber is located such that gaseous atoms experiencing the effects of laser cooling will be confined to a very small area of observation within the chamber. By setting the current in each of the coils equal in magnitude but flowing in opposite directions, Ampere’s Law (or, the “Right-Hand Rule”) dictates that the resulting magnetic field from both coils is subsequently zero at the location directly between the two coils [8]. In addition, the magnitude of the magnetic field increases as the displacement away from the center of the trap increases. A phenomenon called the Zeeman effect occurs to the rubidium atoms due to this magnetic field. The Zeeman effect splits each quantized energy level into more spaced out components, which effectively increases the chances of an atom becoming excited to that energy level. Therefore, placing the chamber of atoms precisely in between the two coils allows the position-dependent field to increase the occurrence of photon absorption from atoms located further away from the center of the trap, which confines and “traps” the atoms into a tighter region of space [9].

The ultimate result of the MOT is a unique force that restricts a ball of atoms into a confined position and reduced velocity. This force, which is created due to the combination of laser cooling and the magnetic field, can be modeled with (1),

$$\vec{F} = -\beta\vec{v} - k\vec{z} \tag{1}$$

where $\beta$ and $k$ are constants [6]. The first term in (1) is due to laser cooling and depends linearly on the atom's velocity $\vec{v}$ with a proportionality constant $\beta$ corresponding to the effect of Doppler shifting on moving particles. This dependency is similar to forces of friction (i.e. air or drag) and is the primary reason laser-cooled atoms are often referred to as "optical molasses". The second term in (1) is due to the magnetic field, whose magnitude relates to directly to the displacement of the atom from the center of trap due to the Zeeman effect. Due to the force's dependency on displacement $\vec{z}$, the resulting effect of the particle due to the magnetic field resembles one of an object on a spring with spring constant $k$. Previous studies have experimentally determined the value of $k$ to be on the order of $10^{-19}$ N/m [9]. Furthermore, the overall force will be a negative value,

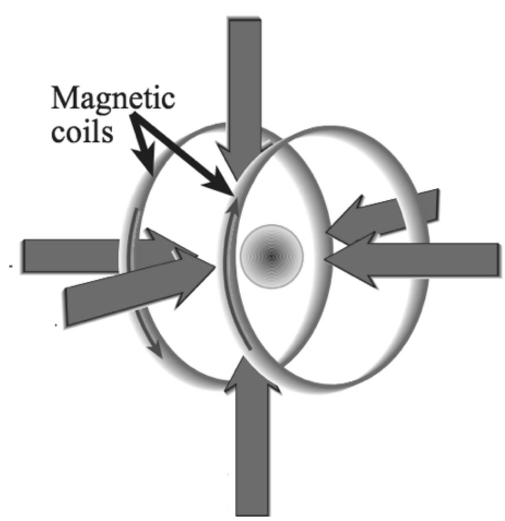


Figure 3. Configuration of Orthogonal Laser Beams and Magnetic Coils [10].

verifying that regardless of the atom's movement, it will always experience a restoring force that returns it to the center of the MOT.

Figure 3 summarizes the above ideas with three orthogonal laser beams responsible for controlling the atoms' velocity via laser cooling and simultaneously, and two coaxial coils introducing a magnetic field responsible for confining atoms into a dense ball at the center of the contraption [10]. Figure 4 summarizes the relationship between the two essential concepts in the MOT: laser cooling and magnetic trapping. Recall that the goal is for atoms in the MOT to absorb photons in order to redirect back to the center of the trap, which can only happen when the correct amount of energy is transferred to the atom. Atoms absorb the photon when the frequency required for the specific energy excitation is equal to the sum of the frequency of the photons and Doppler shift (i.e. when the sum of the arrows lands in the dashed higher energy level box). The Doppler effect (length of arrow) and Zeeman effect (height of box) increase as the velocity and displacement of the atom increase, respectively.

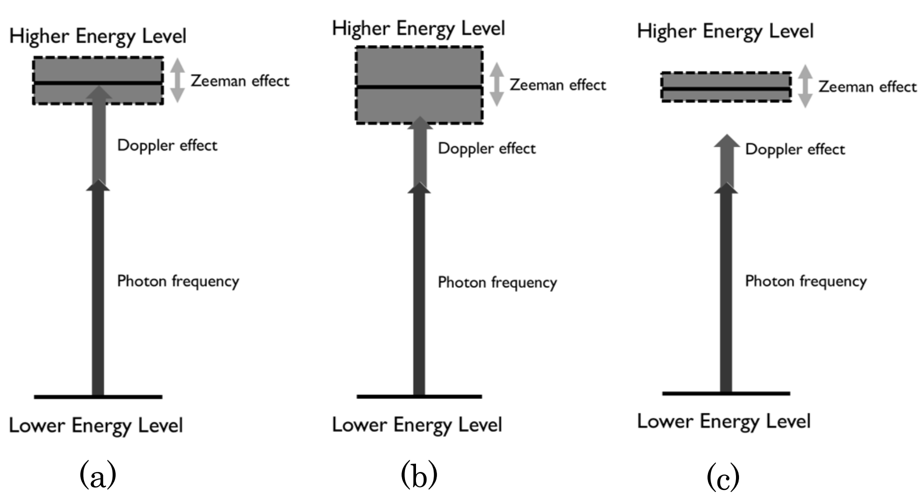


Figure 4. MOT Concepts Resulting in Photon Absorption. (a) Atoms will absorb the photon. (b) Atoms at lower velocity, but larger displacement can still absorb photon. (c) Atoms confined in the MOT with a low velocity and small displacement will not absorb photon.

# CHAPTER 3: METHODOLOGY

The complete construction of the MOT setup requires two distinct sets of apparatus: The MogLabs lasers and associated equipment, and the ColdQuanta MiniMOT kit. The MogLabs equipment primarily consists of two infrared lasers (of power and wavelength ranges, 200 mW & 250 mW and 770 – 810 nm & 750 – 810 nm, respectively), two diode laser controllers (DLC) (one for each laser), and a DC locking feedback circuit. The purpose of each feedback circuit is to provide visibility and control of the frequency of each laser as they pass through a sample vapor cell containing rubidium gas [11]. The output of each feedback circuit is a single laser beam, tuned at the appropriate frequency necessary for laser cooling. The two laser beams must then be coupled into one beam using a series of beamsplitters and will then enter the ColdQuanta MiniMOT kit. Refer to Figure 5 for the schematic trajectory of each laser beam.

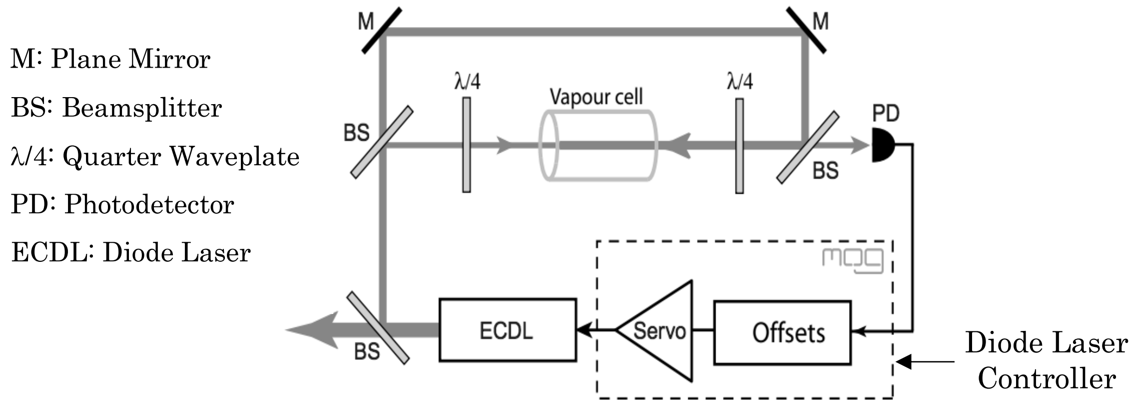


Figure 5. DC Feedback Loop Schematic [12]. The feedback loop is responsible for providing the means to lock the frequency of light prior to the beam entering the MiniMOT kit.

The second apparatus used for the experiment, the ColdQuanta MiniMOT kit, is comprised of two components: First is the optics kit, which is a collection of periscopes, beamsplitters, and mirrors used for receiving the incoming laser beam and then splitting them into three identical beams. After proper alignment of mirrors located at the center of the MiniMOT kit, the three beams should intersect at the precise location of the second ColdQuanta component: the MiniMOT itself. The MiniMOT consists of the glass chamber filled with rubidium-85 gas and two coils used for establishing the necessary magnetic field. Once all apparatuses above are aligned and installed properly and precisely, current can be pumped through the coils to produce the magnetic field, and a MOT can be observed in the center of the glass chamber and recordable via a black and white CCD camera.

The intended outcome of the experiment can only be achieved when each stage of the setup process is performed accurately; thus, it is essential that each step of the methodology is completed with great attention to detail to ensure a successful operation of the entire system. Failure to complete any step accurately can cause human injury and/or harm to hardware, and will ultimately result in the inability to obtain a stable MOT.

The following five steps represent the individual stages that shall be completed for a successful recording of a stable MOT. Subsequent sections will describe each stage in further detail.

A. Verify and adjust settings for MogLabs lasers via controllers
B. Build and align feedback loops for laser frequency locking
C. Couple beams into MiniMOT kit
D. Adjust optics apparatus on MiniMOT kit
E. Install MOT and record observations

## 3.1 VERIFY AND ADJUST SETTINGS FOR MOGLABS LASERS VIA CONTROLLERS

The first of the three components of hardware necessary for obtaining a stable MOT is the MogLabs Extended Cavity Diode Laser (ECDL) and DLC. The utilization of two diode lasers and their corresponding controllers allowed for manual control of the operation of each laser individually and precisely. In order to properly produce two laser beams using the MogLabs lasers, adjustments to the laser diodes' settings via each laser's corresponding controller box was required. Optimal settings for temperature and current should be verified during power up procedures to maximize the longevity of hardware.

Each MogLabs EDCL was connected to its corresponding DLC via a DB9 cable. Due to the specific power outputs of each laser, the DLC that produces a higher optimal current should be connected to the DLC of higher power output. Similarly, the DLC that produces a lower optimal current should be connected to the lower power laser. Prior to arriving at the LMU laboratory, MogLabs individually tested each pair of EDCL and DLC to ensure product quality, as well as to provide the optimum current and temperature values to be used in experimentation.

Two documents provided by MogLabs were used as the foundation for powering up the MogLabs lasers: the product test results mentioned above, and the Diode Laser Controller User's Manual (UM). The DLC UM should be referenced for basic procedural steps in powering up the DLC (page 25). For this experiment, the instructions for the simplest configuration was utilized. As the DLC UM refers to temperature and current values that should be set on the controller, input the values indicated by the product test results to ensure optimal operation of equipment. Before powering up equipment, ensure that all individuals within the vicinity of the apparatus are wearing IR-protective eyewear. In this experiment, an IR viewing card was used to test the output beam presence and strength.

## 3.2 BUILD AND ALIGN FEEDBACK LOOPS FOR LASER FREQUENCY LOCKING

After each laser beam exited the EDCL and prior to entering the MiniMOT kit, each beam was closely analyzed in order to determine its frequency and polarization. Since the success of achieving a rubidium MOT requires two lasers of very specific frequency, each beam was directed into a feedback loop prior to entering the MiniMOT kit. There are two primary purposes of the feedback loop. First, within the feedback loop are two quarter-wave plates, which are responsible for converting linearly polarized light from the EDCL to a circularly polarized beam. The second function of the feedback loop is to send a beam through a rubidium cell to analyze the frequency and wavelength of light. By analyzing the behavior of the rubidium atoms in the vapor cell, the wavelength of light can be tuned to optimize the amount of desired energy transitions. This is accomplished by reflecting the beam through a series of plane mirrors and beam splitters (BS), which ultimately is received by a photodetector (PD) and relayed to the DLC. Refer to Figure 5 for a schematic for each laser beam as shown in the DLC UM (page 29), in the section *Locking to an Atomic Transition*. Note that since two EDCL beams was used, the pictured setup was duplicated for a second EDCL. The various optics equipment that were utilized in directing the beams also included adjustable optics stands and holders. For simplicity, the DC schematic setup, rather than the AC schematic, was utilized for this experiment. Once the beams in each feedback loop were aligned (i.e. two beams travelling in opposite directions overlap, pass through the vapor cell, and strike one of the two photodetector inputs), the beam was analyzed using an oscilloscope and further controlled by the DLC to lock the laser at a particular frequency for the energy transitions of rubidium. Please refer to Chapter 4 for the results of the frequency locking process.

## 3.3 COUPLE BEAMS INTO MINIMOT KIT

Prior to directing the two laser beams into the ColdQuanta MiniMOT kit, the beams should be coupled together and aimed appropriately into the input of the kit. Recall that the purpose of coupling the two laser beams is to achieve laser cooling, which is the interaction of fast-moving atoms with photons travelling in the opposite direction. Each of the two feedback loops outputted one primary beam, indicated by the thick arrow at the bottom-left edge of Figure 5. Two primary beams, each of which originates from a corresponding MogLabs EDCL, exit their respective feedback loop parallel to one other. The first primary laser beam, located farthest away from the MiniMOT kit, is then reflected toward the MiniMOT kit using a plane mirror. The second primary laser beam, located closest to the MiniMOT kit, encounters a beamsplitter, which also partially reflects the beam toward the MiniMOT kit. The location of this beamsplitter is exactly at the intersection of the first reflected beam and the second primary beam, such that part of the first reflected beam passes through the beamsplitter, and the resulting beam in the direction of the MiniMOT kit is a coupling of two reflected beams. Refer to Figure 6 for a diagram of the beam-coupling process.

Not depicted in either figure above is a potential obstacle: the incompatibility of beam heights. Due to the fact that the equipment utilized (MogLabs lasers, various optical equipment, ColdQuanta MiniMOT) originated from different manufacturers, the height of the required beam at each stage of setup could potentially vary. For inconsistent heights between the ECDLs and the optics equipment in the feedback loop, the ECDLs were raised off the breadboard by aluminum stilts of an appropriate height. Further

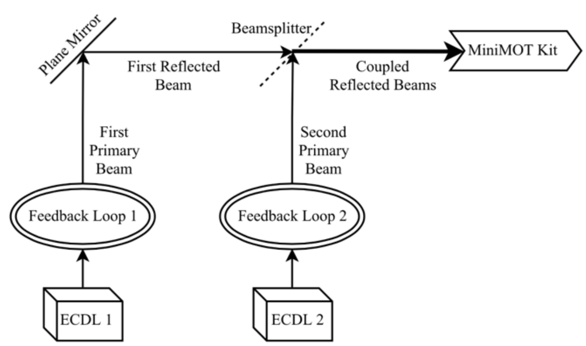


Figure 6. Diagram of Beam-Splitting Process

adjustments within the limitations of the optics equipment were made to the stands of the optics equipment to accommodate the laser beam passing through or reflecting from them. The next step required an adjustment of ColdQuanta MiniMOT kit to match the height of the coupled beam. Similar to the raising of the laser, this can be accomplished by raising the MiniMOT kit with additional aluminum stilts to the appropriate height such that the coupled beam enters the kit at the correct location.

## 3.4 ADJUST OPTICS APPARATUS ON MINIMOT KIT

The process for aligning the beam on the ColdQuanta MiniMOT kit begins without the MiniMOT apparatus installed on the breadboard. The coupled beams entering the MiniMOT kit enters through the bottom aperture called the periscope plate beam input. Using the IR viewing card, the beam is tracked as it entered the periscope plate beam input to verify initial alignment of the input beam. The periscope plate splits the beam into three outputs, each of which is directed toward the center of the MiniMOT kit. The power of each of the three outputted beams is to be measured visually to one-third of the input beam power using an IR viewing card, and adjusted using the first and second half-waveplates located at the bottom output.

The circular polarization of the outputted beams shall be adjusted appropriately to achieve a stable MOT. The mirrors in the center of the MiniMOT kit are responsible for controlling the left- and right-handedness of the circular polarization of the beam once it is reflected. Therefore, to ensure proper polarization, the polarization of the outputted beams shall be individually measured and adjusted to the identical polarization using a polarization tester at the beam output. To accomplish this, each quarter waveplate can be turned to an amount such that the beam is extinguished on the polarization tester.

To align the optics equipment at the center of the MiniMOT kit, the position of the pedestal holding each optics apparatus should not need to be moved. Adjustment of the beams requires the use of screws located on the back of each mount such that the beams intersect at the MOT location. The outgoing beams (i.e. beams that exited the MOT chamber) shall be reflected such that they align with the incoming beams (i.e. beams directed toward the MOT chamber) and are traced back to the output aperture. The importance of these alignment steps on the MiniMOT kit is crucial in assuring that laser cooling is achieved within the gas chamber. As previously mentioned, the beams entering the MOT must be exactly orthogonal in order for the rubidium atoms to effectively slow its velocity. Only after this had been verified shall the MiniMOT be installed onto the breadboard.

### 3.5 INSTALL MOT AND RECORD OBSERVATIONS

The MiniMOT shall be installed on the breadboard such that the three beams prepared in the prior procedural steps intersect at the location of the glass chamber containing the rubidium gas. This step introduces the glass chamber of rubidium gas where the lasers intersect and also introduce the magnetic field to the system. Installation of the MiniMOT begins by securing the apparatus to the breadboard using screws and connecting the power cable to the rear panel of the MiniMOT. An LED display and switch located on the rear panel allow the user to read the coil current or the dispenser current. Additional switches and dials can be used to control the status and value of the coil and dispenser currents.

To activate the MOT, a switch controlling the ion pump shall be turned on. LEDs located on the rear of the panel should be green to indicate that the pressure within the chamber are within operable levels. If a red light appears above the ion pump, turn off the dispenser current to allow the unit to achieve a lower normal pressure. Note that the unit requires a “warm-up” period of approximately 20 minutes during which the ion pump and dispenser current is on. During this time, the dispenser current LED will be red until the optimal pressure is reached.

A CCD camera is located on the MiniMOT breadboard and facing into the rubidium glass chamber. The purpose of the CCD camera is to observe and record the stable MOT once it has been achieved. The camera should be connected to a display such that the user can observe for fluorescence once the MOT is operating. By adjusting the direction of the coil current, a fluorescent trap of rubidium gas should be present in the chamber. If the unit had sufficient time to warm up and a MOT is not observed in the chamber, verify the polarization, alignment of optics apparatus, coil direction, beam output powers, and laser frequencies.

# CHAPTER 4: EXPERIMENTATION

The previous chapter outlines the general steps that were taken in developing the experimental setup needed for establishing a MOT. This chapter presents a more detailed explanation of the steps that were taken in the laboratory, specific values (current, frequency, temperature, etc.) used in setting up the laser beams, and the current outcome of the experiment.

With the directions provided by the ECDL and DLC manuals, a procedure for turning on the infrared laser beam was determined and is detailed in Appendix A. This procedure involves adjusting the settings for each laser using the DLC. Table 1 below indicates the specific values used for powering up each laser. *ECDL Max. Power* refers to the maximum output power of the ECDL and is indicated in writing on the back of each ECDL. *Temperature Set* is the desired temperature of the ECDL during operation, maintained by the DLC. *Max. Allowable Current* is a setting that defines the upper limit to the amount of current that is allowed to be delivered to the ECDL. *Min. Current for Turn On* is the minimum experimental current value at which the infrared beam is viewable using the IR viewing card. Lastly, *Actual Current Used* refers to the experimental current value at which the DLC was set.

| ECDL Max. Power (mW) | Temperature Set (°C) | Max. Allowable Current (mA) | Min. Current for Turn On (mA) | Actual Current Used (mA) |
|---|---|---|---|---|
| 200 | 16.15 | 200 | 78 | 178.65 |
| 250 | 25.04 | 250 | 144 | 173.8 |

Table 1. DLC Values for ECDL Power Up

The final experimental setup very closely follows the methodologies illustrated by Figures 5 and 6 above. Figure 7 is a bird's eye view of the breadboard, which carries the two infrared ECDLs, two identical feedback loops, additional optical equipment used for coupling beams, and the MiniMOT and MiniMOT kit. Note that within each feedback loop, there was an additional component between the two closest beamsplitters to the ECDL. This component, called an optical isolator, was responsible for allowing the beam

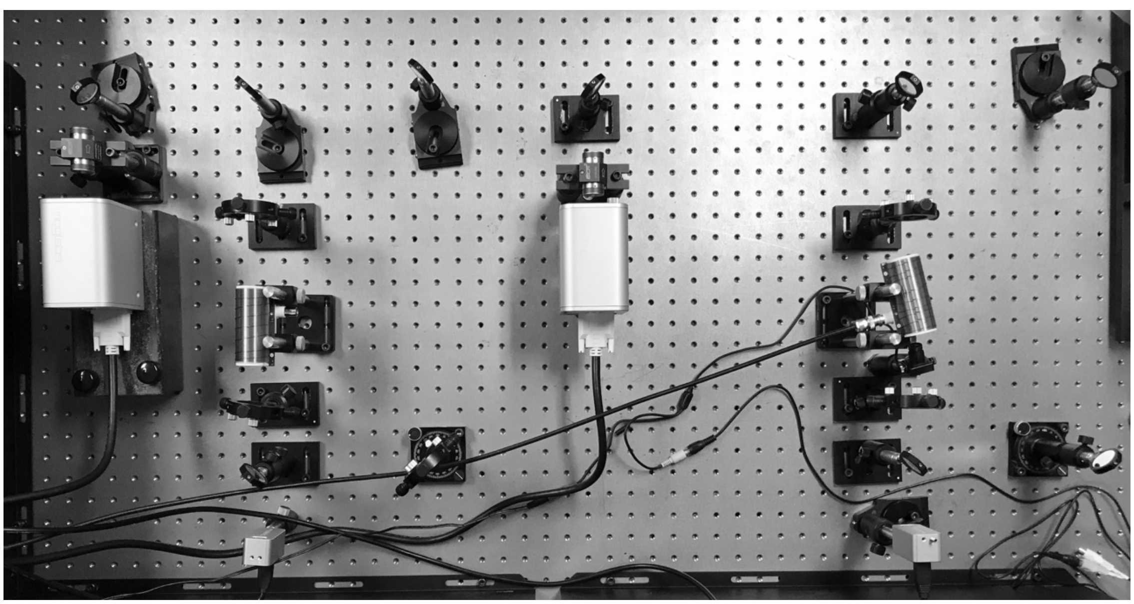

Figure 7. Bird's Eye View of Experimental Setup. The rectangular boxes are the pump and repump ECDLs with their corresponding feedback loop to the right of each.

to pass through in one direction, but not the other. It was utilized in the feedback loop due to the path of a reflected beam around the loop – without this isolator, the reflected beam would trace the path of the incoming beam, shining directly back into the ECDL and potentially causing damage to hardware.

Once each feedback loop was constructed and the beam was aligned precisely through the vapor cell, the photodetector was connected to the DLC. By connecting Channel A and B to Channels 1 and 2 of an oscilloscope respectively, and the Trigger output of the DLC to the Trigger input of the oscilloscope, the sawtooth-shaped pulses of the EDCL and the photodetector reading were displayed on the oscilloscope. Refer to Figure 8 for images of the oscilloscope screen.

The top trace of Figure 8 is the measurement of the voltage output of the ECDL, while the bottom trace of Figure 8 represents the voltage measurement performed by the

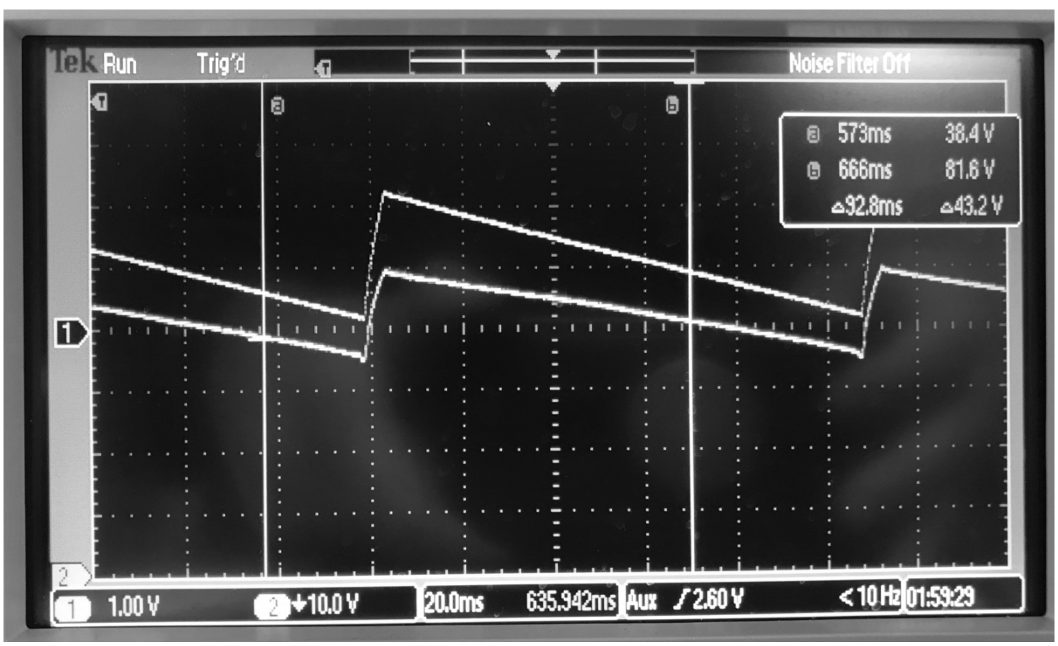


Figure 8. Image of the Oscilloscope Used for Laser Spectroscopy. The top trace displays the sweep of the frequency of the laser to find absorption spectrum for rubidium atoms. The bottom trace displays the signal received by the photodetector.

photodetector. As the voltage of the laser “sweeps” from high to low, the laser frequency sweeps over a range of frequencies. In theory, as the laser sweeps over the frequencies at which the rubidium atoms are likely to absorb photons, one would expect to observe dips in the bottom trace representing frequencies at which the atom-photon interactions are occurring. Despite meticulous efforts, this step has not yet been successfully achieved thus far and serves as the next step in progressing this project.

# CHAPTER 5: SIGNIFICANCE

The completion of the MOT setup procedure marks the beginning of future experiments to be conducted utilizing this apparatus. My work on developing this MOT has both short-term and long-term benefits. When a MOT is successfully achieved using this equipment, it will provide evidence that this equipment that was purchased for the use of the LMU Physics Department is capable of producing a stable MOT. With the notes and procedures that were recorded throughout the process of setting up the system, users of the equipment can continue this endeavor in achieving the MOT. Furthermore, if the use of the equipment is intended as teaching material for various courses, my documented work ensures that the entire setup can constructed, and then later carefully deconstructed and stored, if necessary, while maintaining confidence that it can be recreated using the same parts and procedure in the future.

In planning for the long-term uses of this particular MOT apparatus, one could turn to the modern physics experiments that have been recently conducted utilizing the MOT. As a relatively new and emergent apparatus in the fields of modern optical physics and quantum theory, the MOT is at the forefront of many of today's recent publications in these fields, which should serve as the inspiration toward future steps taken utilizing a stable MOT produced in this experiment. For example, in the immediate years after the concept of the MOT was introduced, physicists began experimentation on the MOT using various types of gaseous atoms in the glass chamber, such as sodium [13]. As a first step in advancing this experiment, one could attempt trapping rubidium-87, rather than the rubidium-85 atoms that were intended to be trapped in my endeavor. Conducting an experiment using different gases may pose a challenge with the ColdQuanta MiniMOT itself (which has been configured strictly for rubidium atoms); however, if this obstacle can be hurdled, much of the procedural steps and foundational concepts are identical between these experiments, mainly differing only in the frequency of light used for laser cooling purposes.

Rather than reconfiguring the MOT to test with various atoms and isotopes, one could continue experimentation using the same MOT stabilized in my experiment and investigate further into the behavior of the atoms trapped at the center of the chamber. For example, a better understanding between the dependence of magnetic field strength and laser intensity on the MOT's overall stability, temperature, and atom density could be achieved by adjustments made on the current MOT setup [9]. Due to the MOT's ability to slow and cool atoms down to ultra-low temperatures, modern MOTs are currently being used to study quantum phenomena. Examples of this include the creation of Bose-Einstein condensates, which are atoms that have been cooled to near absolute zero temperatures such that they exist in low quantum states [14]. Studying atom behavior

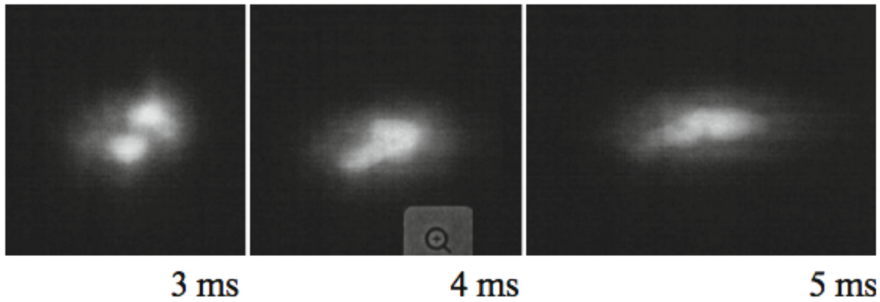


Figure 9. Images of Cold Atom Cloud Dispersion Using ColdQuanta MiniMOT [15]. Within the matter of milliseconds, cooled atoms begin to regain kinetic energy and disperse from the center of the MOT.

such as this is possible with a simple ColdQuanta MiniMOT – scientists have used this same apparatus to analyze the dispersion behavior of cooled atom clouds once the MOT is instantaneously removed [15]. Utilizing the same CCD camera available on the MOT setup used in my experiment, Russian physicists were able to capture atom cloud dispersion images, as displayed in Figure 9 [15]. Experiments such as these can be recreated or adapted using our available MOT, and serve as directions for how the MOT setup can be best utilized in the future to learn more about this advancing field of physics.

## APPENDIX A: SETUP OF MOGLABS DLC

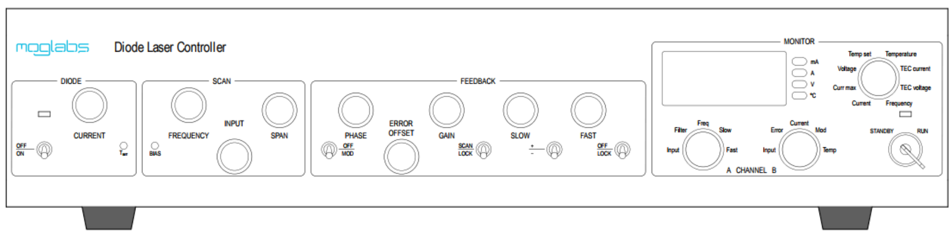


Figure 10. Front Panel of MogLabs (DLC) [12].

The following instructions describe the procedural steps that should be taken to power up and configure the MogLabs DLC.

**Power Up:**

1) Ensure that the correct ECDL is connected to the correct DLC by matching the power output of the laser to the power specifications of the controller.
2) Initialize all DLC settings.
   - Power switch back of DLC is OFF
   - Key on STANDYBY mode on front of DLC
   - Slide screen on ECDL closed
   - Diode switch OFF

- Diode current dial turned completely counterclockwise

3) Connect the power cable to the back of the DLC.
4) Switch the power to ON at the back of the DLC. The STANDBY/RUN LED will turn orange. For initial power up troubleshooting, ensure the red fuse box in DLC is arranged correctly. For further troubleshooting, refer to DLC manual, Appendix B, page 49.
5) Insert Interlock key into back of DLC.
6) Turn key to RUN on front of DLC. LED will turn green.
7) Adjust temperature setpoint: Select *Temp set* using Monitor dial. Using a small flathead screwdriver, (slowly) adjust the small Tset trimpot in the diode box at front of DLC until desired diode temperature is reached on monitor screen (~16.14°C and ~25.03°C).
8) Turn the Monitor dial to Temperature. Wait until the desired temperature is reached.
9) Adjust current setpoint: Select *Curr max* on the Monitor dial. Desired maximum current values should read -200mA and -250mA. (If necessary) Use a small flathead screwdriver to slowly adjust the small Igain trimpot on the rear of the DLC until the monitor reads the desired value. Turn back Monitor dial to read current.
10) Open slide screen on ECDL. Ensure that you are wearing IR goggles or other IR eye protection prior to powering up lasers.
11) Turn the Diode Switch to the ON position. LED should switch from orange to green. LED on the back of ECDL should be ON.

12) Increase Diode current dial clockwise to at least ~78mA and ~144mA until a beam is visible using an IR viewing card.

**Power Down:**

1) Turn back current dial completely counterclockwise to near zero current.
2) Turn Diode Switch to OFF position.
3) Turn STANDBY/RUN key to STANDBY.
4) Turn power switch at back of DLC to OFF.
5) Slide laser screen closed.

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