Shedding Red Light on Ultra-Cold Strontium Gases

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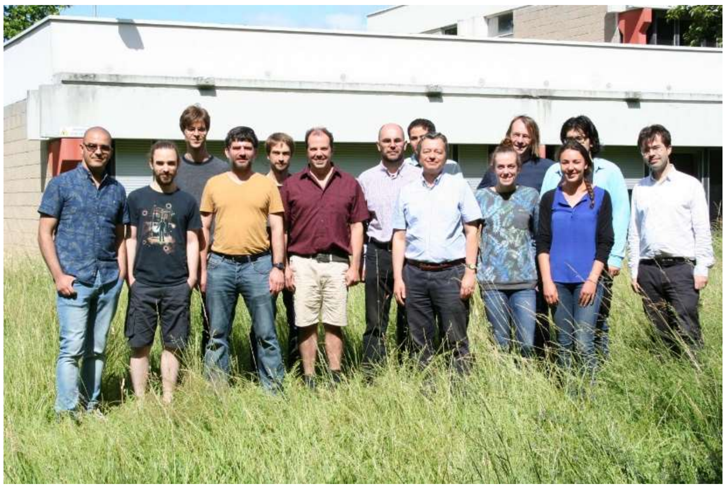

Abstract

One of the methods used to better understand the quantum world is studying ultracold gases at temperatures in the range of a few nanokelvin. This specific research study was dedicated to the ongoing construction of the system needed to obtain ultracold samples of strontium atoms in the Laboratoire de Physique des Lasers (LPL) at Université Paris 13. The atoms are cooled and trapped using lasers of very specific wavelengths that correspond to the atomic transitions between states of the atoms. After almost three years of construction, this summer, LPL produced its first laser cooled strontium gas with a temperature of about one millikelvin by exploiting a very wide atomic transition at 461 nm. In order to cool this gas even further, a much narrower transition must be targeted using a laser with a wavelength of 689 nm. The purpose of this summer research was to build this red laser system at 689 nm to cool the atoms to temperatures of a few nanokelvin. This process included measuring beam waists, placing optical lenses, optimizing six acousto-optical modulators (AOMs), injecting two different slave laser diodes, and aligning three beams into a Fabry-Perot cavity. The successes of this research project were the injections of the slave diodes (which was not guaranteed), the development of the red laser chain, and the creation of every wavelength needed to capture all the isotopes of strontium. This will now allow the LPL team to cool the strontium gas to a few hundred nanokelvin.

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1 Introduction

In order to gain a better understanding of the way the physical world works and how people can manipulate things to do exactly what is desired, an understanding of quantum mechanics is vital because its laws govern the basic building blocks of the world. Quantum mechanics particularly deviates from classical intuitions the nano-scale level. Quantum mechanical behavior already has important applications (transistors, lasers, etc.) and better understanding it can have an even greater impact in areas such as quantum computation, quantum simulation, condensed matter physics, high-energy physics, as well as the refinement of even more precise atomic clocks, which leads to increased precision in GPS locating. Recent methods, discovered in the late 1970s, of studying quantum behaviors which are simulated at the macroscopic scale are centered on ultracold gases: gases of atoms at sub-millikelvin temperatures which are cooled by lasers of coherent light as well as magnetic traps. This work studies the behavior of atoms at these ultracold temperatures because at this point, their behavior is modeled by the laws of quantum mechanics. The ideas behind this experiment involved Nobel Prizes in 1997, 2001, 2005, and other years.

The Laboratoire de Physique des Lasers (LPL) at Université Paris 13 located in Villetaneuse, France has four different experiments dedicated to the study of cold atoms, each studying a different element (rubidium, chromium, sodium, and now strontium). This particular research study funded jointly by Bloomsburg University of Pennsylvania's URSCA program and LPL took place in the strontium lab of LPL during the summer of 2017. It has been under construction for almost three years, and this past summer, the lab saw its first cloud of ultracold strontium gas. This gas was cooled and trapped using blue light at 461 nm. The cloud of atoms currently has a temperature of one millikelvin.

1.0.1 General Overview

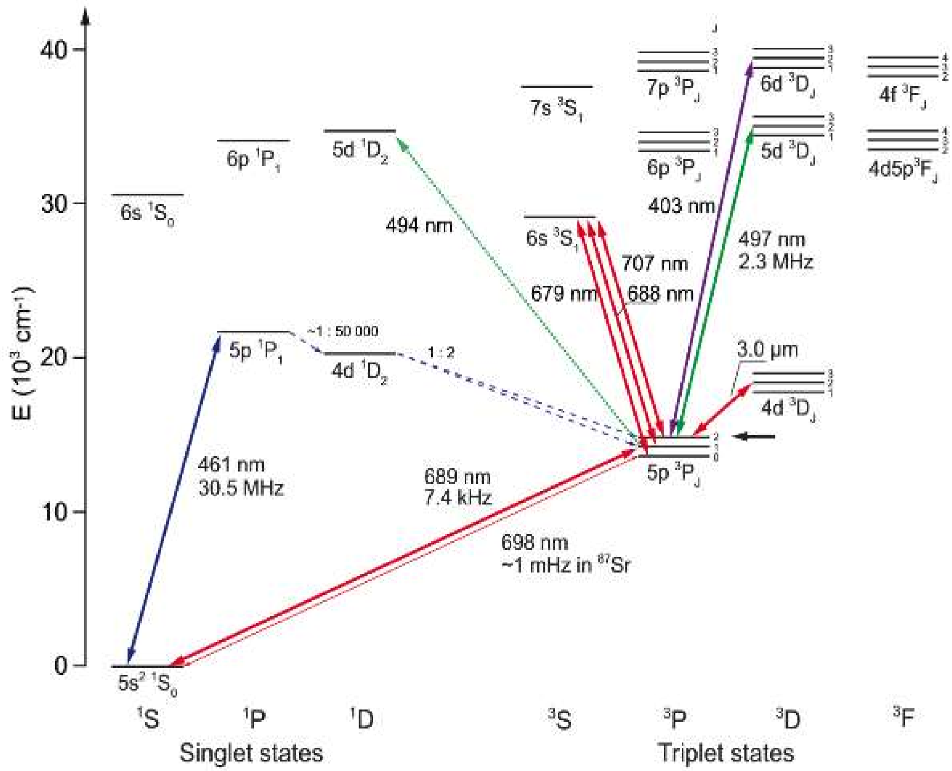

Figure 1: Level diagram of the internal structure of Strontium. The blue 461 nm transition was utilized to initially slow and trap the atoms. The red 689 nm will be utilized to further cool the atoms to create a degenerate Fermi gas.

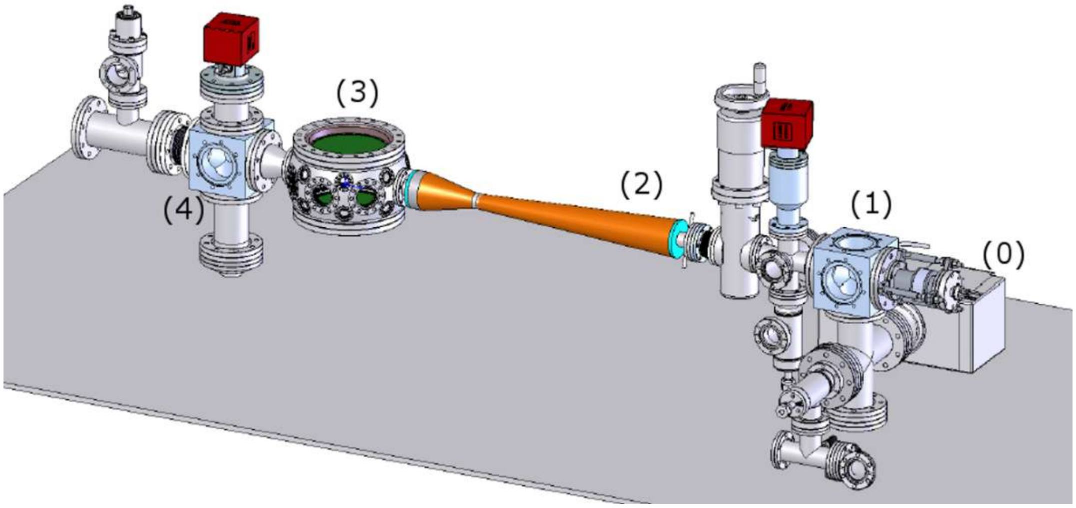

Figure 1: The machine used to slow and cool the atoms. (0) is the oven where the atoms are initially held and heated up into the gaseous state. In (1), the beam of atoms is cooled transversely and collimated by a laser beam intersecting it perpendicular to the main axis. (2) constitutes the inhomogeneous magnetic field that produces the Zeeman effect. (3) is the science cell where the atoms are trapped in the MOT.

The strontium atoms are initially held in an oven, represented by (0) in Figure 2. When the experiment is ready to begin, the atoms effuse out of the oven along an axis. They immediately encounter a counter-propagating laser beam at 461 nm, which corresponds to an atomic transition of strontium atoms (see Figure 1), along the same axis. The atoms travel through a spatially inhomogeneous magnetic field, which uses the Zeeman effect to shift the transitions of the atoms. This Zeeman shift counteracts the Doppler shift which is produced by the changing velocity of the atoms. Together, these two effects keep the atoms in resonance with the laser beam to maintain deceleration. The atoms absorb photons from the laser beam, and they re-emit photons with a higher energy, decreasing the kinetic energy, and thus the

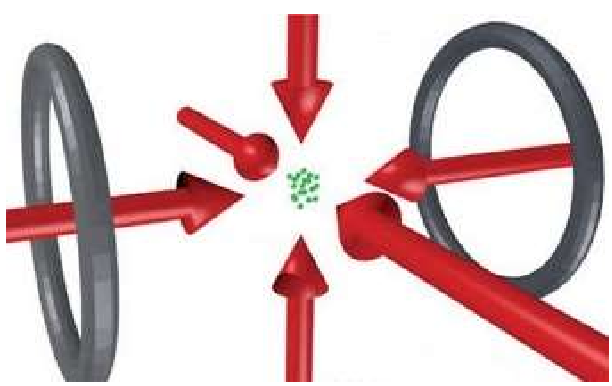

Figure 3: Magneto-Optical Trap (MOT) [1]

velocity of the atoms. Once they reach the other end of the machine about one meter away, they have been slowed from hundreds of meters per second to almost a complete stop. Here, they are trapped by a magneto-optical trap (MOT): six counter-propagating laser beams as well as a magnetic field gradient that trap and further cool the atoms at a point in space, displayed in Figure 3. This is where the atoms can be manipulated and studied.

The minimum temperature that the atoms can reach is governed by either the Doppler limit, or the recoil limit: whichever one is higher. The Doppler temperature is given by the equation

$$T_{Doppler} = \frac{\hbar\gamma}{2k_B},$$

where $\hbar = 1.055 * 10^{-34}\, J \cdot s$ (Planck's constant), $k_B = 1.380 * 10^{-23}\, \frac{J}{K}$ (Boltzmann's constant), and γ is the natural line width of the atom. The recoil limit is given by the equation

$$T_{recoil} = \frac{\hbar^2 k^2}{2k_B m},$$

where $k = \frac{2\pi}{\lambda}$ is the laser wavenumber, m is the mass of the atom, and λ is the laser wavelength.

The 461-nm transition is very efficient because of its large natural linewidth of 32 MHz and its consequent ability to capture a large number of atoms. That large natural linewidth unfortunately also causes the temperature to be Doppler limited to about 800 mK. The 689 nm atomic transition, on the other hand, is very capture-inefficient because it has a very narrow natural linewidth of 7.5 kHz, but it allows the atoms to reach temperatures much colder than that of the former because it is recoil limited to about 200 nK [6]. So, in order for the MOT to reach temperatures in the nanokelvin range, the 689 nm transition is exploited. This particular summer of research was dedicated to the development of the red laser chain at 689 nm in order to accomplish this.

Strontium has four isotopes, each with very different characteristics. ^{88}Sr is the most abundant with a natural abundance of about 82.58%, with good collision properties in its collisions with ^{87}Sr. ^{84}Sr only has an abundance of 0.56%, but it has the best collision properties in order to make a Bose-Einstein Condensate (BEC) quantum gas. ^{87}Sr has a natural abundance of 7.0% and also has very good collision properties for the creation of a degenerate Fermi gas. These three isotopes have been chosen to be exploited in this lab. This lab has chosen to leave out the fourth isotope, ^{86}Sr, because it does not have good collision properties, deeming it essentially useless for the purpose of experimentation. For each of these three isotopes, it is essential to maximize the number of atoms trapped in the MOT, and minimize the temperature of the atoms. The architecture of the lasers and the optics in order to exploit each one of these isotopes was the first step in the process of establishing the red laser system.

2 Methods and Materials

2.1 The Design

The beginning, and perhaps the most important part of constructing the red laser system, was the planning and design of it all. In order to address all three desired isotopes of strontium, five different laser frequencies were needed, and each of these frequencies needed to be allocated a certain amount of power in order to be effective. The master laser that drove the entire chain was a commercial extended-cavity Radiant Dyes diode laser at 689 nm. Six different acousto-optical modulators (AOMs) were used in order to change the frequency of the laser beam to address each isotope of strontium. Figure 4 is a frequency scale which shows the desired frequencies and their shifts from the frequency of the master laser. The master laser was a wavelength of 689 nm, which corresponds to "0" in Figure 4. Each of the frequency

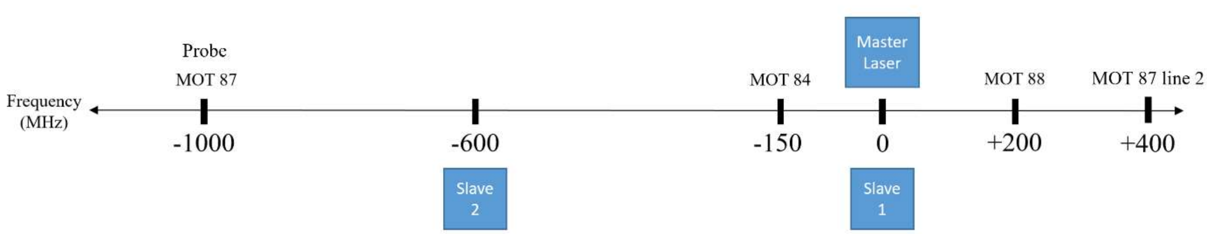

Figure 4: Frequency scale of strontium isotopes. Each isotope has a different frequency of laser light that corresponds to its atomic transition shown in Figure 1. ^{87}Sr actually requires two different frequencies. There is also a probe beam that will later be used to image the cloud of cold atoms.

shifts was accomplished by a different AOM. Figure 5 then shows the table setup decided on by the LPL team. This was a rough layout which had to be perfected and put into place during this research study.

Every AOM contains a crystal inside that vibrates based on the RF frequency given to it by the computer program. When the light enters the crystal, it is Bragg diffracted to a series of orders. The desired order of diffraction is separated from the others and that order is optimized. The order used depends on whether the frequency of the laser is being increased or decreased. The beam is then sent back through the AOM in the opposite direction, resulting in a frequency shift that is double that given by a single pass through the AOM. Each of the desired frequencies can be generated solely by AOMs, but the Radiant Dyes laser only outputs a power of about 30 mW; more power than that is needed for all of the beams to be effective in slowing, trapping, and cooling the isotopes. To acquire more power, two slave laser diodes are utilized. The computer program that controls the entire experiment was written by Etienne Marechal, a member of LPL, using LabView. This program, controlled by the user, sends a signal to a direct digital synthesizer (DDS) controller, whose signal is then sent through an amplifier and then to the AOM.

2.2 Laser Source: Master Laser

When the design was completed, the Radiant Dyes master laser was bolted to the table, and to protect the cords from being bumped, a small cage system was built around the laser because it hangs off the table. Directly out of the laser, the beam was very elliptically shaped, and the horizontal and vertical axes of the beam diverged at very different rates. The first task was to collimate this beam: make the beam round and minimize its divergence in the range of the distance that we are working with on the table. Lasers follow the laws of gaussian beam optics, and the Rayleigh length of a Gaussian beam is a parameter given to determine at what length the waist of the beam will double. The equation for the Rayleigh length is given by the equation

$$z_R = \frac{\pi {w_o}^2}{\lambda},$$

where w_0 is the beam waist. In collimating the beam, the goal is to maximize the Rayleigh length. To start, the waist of the beam was measured and recorded directly from the laser at multiple locations using a beam profiling camera (BladeCam) and a computer program called DataRay. Figure 6 displays the DataRay software with an image of the beam from the camera. The software does a fit of the horizontal and vertical directions, and gives the approximate diameter of the beam in each direction, shown by the red arrows in Figure 6. The waist of the beam is half the diameter, so the number displayed was divided by two and recorded in the lab notebook.Then, a gaussian fit was performed on this data using a program called IGOR to determine where the actual waist of the beam was in both the horizontal and vertical directions. A gaussian fit is performed according to the equation

$$w(z) = w_0\sqrt{1 + \left(\frac{(z-z_0)*10^4}{z_R}\right)^2},$$

where z_R is the Rayleigh length as referred to previously and λ is entered in μm. The user enters the data with the waist measurements in μm and the distances in cm. The 10^4 factor is added to convert the distances entered by the user to μm so that the units are consistent in μm throughout the equation. Figure 7 shows an example of a Gaussian fit of a set of data. The top set of data (blue) is the horizontal axis of the beam and the bottom set of data (green) is the vertical axis of the beam.

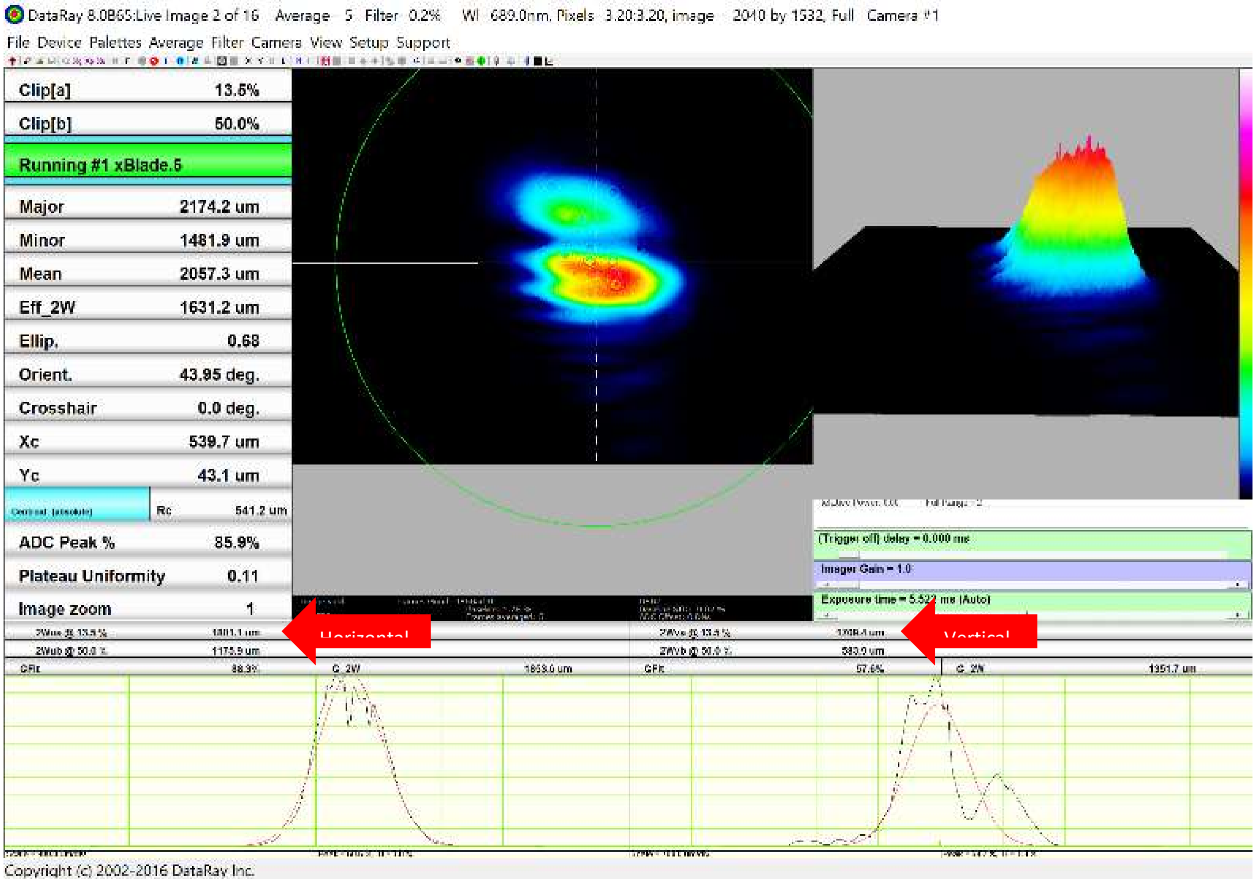

Figure 6: DataRay program used to measure beam waists. The red arrows point to the values of the diameters of the beam according to the gaussian fit performed. The left side is the horizontal diameter, and the right side is the vertical diameter.

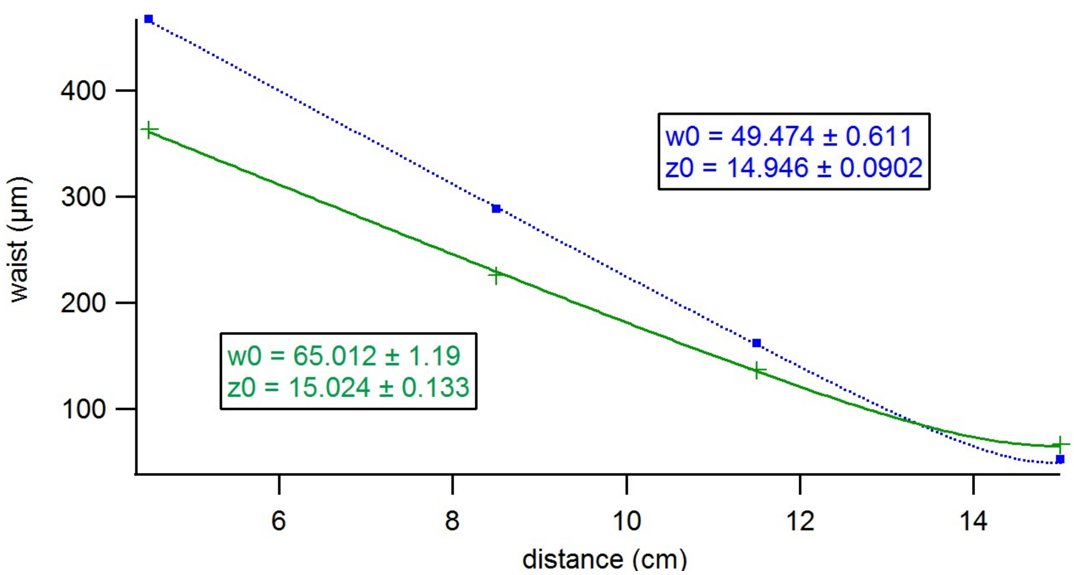

Figure 7: Example of a gaussian fit using IGOR

A program called Gaussian Beam simulates the propagation of a laser beam given the position and size of the waist of the incoming beam. It allows the placement of lenses with any focal length, mirrors, and other types of optics within the program, and it simulates the effect of the chosen optics on the size and shape of the beam, following the laws of gaussian optics. Figure 8 shows an example of a laser beam simulation in Gaussian Beam with two lenses placed on the beam. Using this software, the

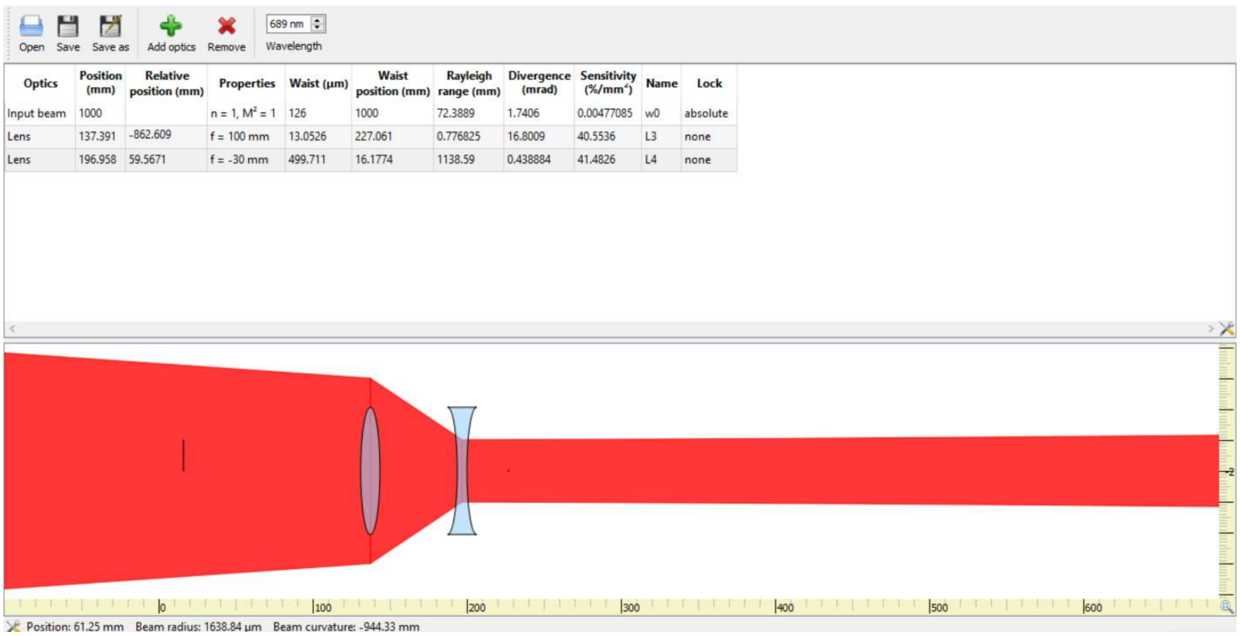

Figure 8: Gaussian Beam simulation software

lenses needed to collimate the beam coming from the Radiant Dyes laser were determined. Three lenses were used; the first was an f=-50 mm cylindrical lens which only affected the horizontal direction, the second was an f=100 mm spherical lens which effected both the horizontal and vertical directions, and the third was an f=-30 mm cylindrical lens which was positioned to only affect the vertical direction. The first two lenses together constituted a telescope for the horizontal direction. The first lens was placed as close to the laser as possible (0.5 cm), and the position of the second lens was changed in order to collimate the horizontal axis of the beam. Multiple different positions were tried until the beam was collimated as well as possible in the horizontal direction with a waist of around 500-600 µm. The final position of the second lens ended up being 7.4 cm from the first lens. The second and third lenses then constituted a second telescope for the vertical direction. The position of the third lens was changed until the vertical direction was collimated as well as possible with a beam waist at the same location as the horizontal direction. The third lens had a final distance of 4.1 cm from the second lens. In order to get a better idea of the locations of the waists, a small focal length lens was placed far from the laser and a Gaussian fit was performed on the waists in the horizontal and vertical directions just after the small lens.

Once the beam was collimated as well as possible, the next step was to put the beam through an isolator. The purpose of an isolator is to protect the diode of the laser. When light enters the isolator, it initially passes through a polarization beam-splitting (PBS). The polarization of the light is then rotated by 45 degrees when it passes through a medium surrounded by a magnet which produces the Faraday effect [5]. There is a second PBS cube at the other end of the isolator which only lets the light with the new polarization pass through. Any light that might reflect back is rotated by another 45 degrees when it passes through the medium in the opposite direction, so it is all reflected off of the first PBS cube because it does not have the correct polarization to pass through it. This protects the laser diode from receiving any feedback that might accidentally reflect off of an object and back towards the laser. Because the light needs to pass through the first PBS cube, it needs to have a specific polarization entering the isolator. In order to spare a waveplate, this isolator was optimized using the polarization of the beam as it was from the Radiant Dyes laser directly. Complete optimization of an isolator includes optimization of both the transmission and the isolation. The transmission is the percentage of light that passes through the isolator. The isolation is calculated from the amount of light that passes through when the isolator is placed backwards. The ideal transmission is 94%, and the ideal isolation is 40 dB. The isolation is calculated according to the equation

$$isolation(dB) = 10 * log_{10}\left(\frac{power\ out\ of\ isolator\ when\ reversed}{power\ into\ isolator}\right)$$

2.2.1 Optimization Procedure

The process of optimizing the isolator involves loosening the screws that hold the PBS cubes on either side in place, and removing their covers; the cubes can be rotated relative to each other. The transmission was first optimized. Then, when that was optimized as much as possible, the isolator was reversed and very fine adjustments were made to optimize the isolation. This process was repeated multiple times until both the transmission and the isolation were optimized together. When the final position was determined, the covers were replaced and the screws were tightened to keep the cubes in place. When working around the isolators, extreme caution must be taken; the magnetic field is very strong, and it heavily attracts any allen key or other metal piece that comes near the isolator.

2.3 Generating Frequencies: AOMs

After placing the isolator, the next step was to place a few optics to direct the beam to inject the first AOM: AOM 4. When the laser beam leaves the optical isolator, there are multiple different functions that the beam needs to fulfill. In order to turn this one beam into multiple beams with the same size and shape characteristics, PBS cubes were used. The light that is vertically (S) polarized skips off the cube and is redirected to whichever side the cube is facing. The fraction of light that is horizontally (P) polarized pierces straight through the cube. In this case, the beam coming from the optical isolator was split into one beam that continues straight through the cube, and one beam that would skip off the cube to the right. In order to control the fractions of light that went each direction through the cube, a $\lambda/2$ waveplate was placed just before the cube. This allowed the control of the polarization of the light that passed through it. Each of these PBS cubes and waveplates was specifically designed for optimal efficiency with light at 689 nm.

The light that skipped off of the first PBS cube then entered another cube with another waveplate to control what portion of light was transmitted. The first AOM that the light passed through was a 75

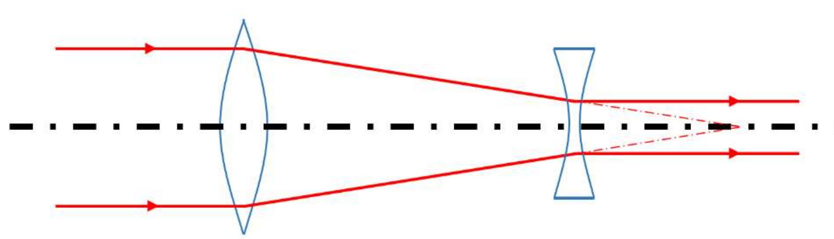

Figure 9: Ray diagram of Galilean telescope

MHz AOM. The required beam waist of this AOM, according to the specifications sheet, is about 400 μm. This was about half of the size of the beam's current waist. In order to decrease the size of the beam by half and still maintain its collimation, a Galilean telescope, displayed in Figure 9, was created using two lenses; one having half the focal length of the other. The first lens, the one with the larger focal length of the two, was converging, and the second lens was diverging, and the distance between the two lenses was equal to the sum of the focal lengths of the two lenses, one positive and one negative [2]. In order to inject this 75 MHz AOM, an f=100 mm lens and an f=-50 mm lens were used and they were placed 50 mm apart from each other to construct the Galilean telescope.

2.3.1 Optimization Procedure

In order to correctly place the lens and ensure that the beam passed directly through the center of the lens, an iris was placed at a far distance from the lenses before they were placed; then, when the lenses were placed, they were adjusted until the beam passed directly through the iris. The AOM was initially placed with the beam passing directly through the center of the entrance hole. With the AOM turned on using LabView, the -1 one order was separated from the other orders using an iris. With a power meter placed after the iris, the power of the -1 order was optimized using the AOM's adjustable rotating stage. Each AOM has an expected efficiency for the first order diffracted beam given by its specifications sheet.

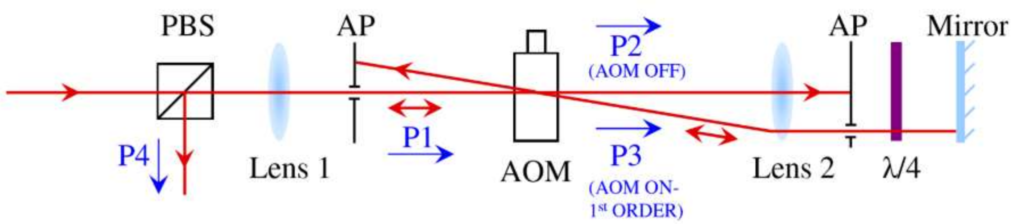

Figure 10: AOM double-pass scheme [3]

This 75 MHz has an optimal efficiency of 94% for the first order diffracted beam. The height of the AOM could also be adjusted in order to optimize the desired order. Once this first pass through the AOM was optimized, the beam had to be sent back through the AOM in the opposite direction. An f=100 mm lens was used for the double-pass scheme in the place of 'Lens 2' in Figure 10. The lens was placed exactly 100 mm from the center of the AOM, which is where the crystal is located. Then, a mirror was placed exactly 100 mm from the lens. Between the lens and the mirror, a pinhole, called 'AP' in Figure 10, was placed to isolate the -1 order from the rest of the diffracted beams because that is the only beam with the desired frequency. Then, at any point before the beam re-enters the AOM, a λ/4 waveplate was placed. When a beam passes through a λ/4 waveplate twice, it has the same effect on the polarization of the beam as a single pass through a λ/2 waveplate. The polarization was changed by 90 degrees by this waveplate, so the beam that initially skipped off the PBS cube to enter the AOM would now pierce through the same PBS cube after its double pass through the AOM. This double-pass scheme ensures that the beam has the exact same waist going through the AOM the second time as it did for the first pass, provides the highest efficiency for the double pass, and also ensures that the beam is angle-independent if the frequency of the AOM is changed amidst the experiment. After the beam passed through the PBS cube after the double pass, another iris was placed to separate the desired beam from the others; the -1 order was taken again. This order of diffraction fell back on the same exact path as the original beam with this 4f double pass scheme shown in Figure 10 [3]. Again, the power meter was placed after the second iris and the double pass was optimized using the mirror mount at the end of the double pass as well as by rotating the λ/4 waveplate.

The last step to optimizing the AOM double pass was ensuring that the double-passed beam was angle independent with changes in frequency of the AOM. This was done by making sure the position of the beam after the double pass did not change with a change in frequency of the AOM. In the future, the beams from these AOMs will be injected into polarization-maintaining fibers in order to bring the light from the optical table onto the main experimental table. The entrance of one of these fibers is extremely small, and the injections are very sensitive; any movement in the position of the beam could cause the beam to not pass through the fiber. The frequency of the beams will need to be changed in the midst of the experiment as part of the sequence of events to capture the largest number of atoms in the MOT. In order to ensure this position does not change, the BladeCam camera was placed after the second iris. Using the LabView program, the frequency of the AOM was programmed to blink between two different frequencies with a range of 50 MHz between them. As the AOM blinked between frequencies, the DataRay program was used to detect any change in position of the beam. The position of the lens in the double pass scheme was then changed by tiny amounts until the beam's position did not change with the change in frequency of the AOM.

This was the same process that was used for AOM 3 at 300 MHz, as well. There were only two differences for this AOM. First, the AOM used was actually an AOM with an optimal frequency of 350 MHz, but it was used at 300 MHz. Any frequency can be given to the AOM using the LabView program, but because the desired frequency was not the optimal functioning frequency, the expected efficiencies given by the specifications sheet were not quite accurate. This was just something to keep in mind while optimizing the AOM. Second, the beam waist required for this AOM, given by the specifications sheet, is 70 μm. For this case, one single lens was used. Using the Gaussian Beam software for simulation, the correct lens was chosen to obtain the desired waist. After the lens was placed, the beam waist was measured using the camera and the DataRay program, a Gaussian fit was performed using IGOR, and the actual size and position of the beam waist was determined for both the horizontal and vertical directions. The AOM was to be placed at the position of the waist in order to obtain the correct waist going into the AOM and to optimize the double pass scheme efficiency. Because the locations of the horizontal and vertical waists were never exactly the same, the position of the AOM had to be changed a few times until the optimum efficiency was obtained.

2.4 Power: Slave Lasers

The next step was to inject the slave laser diodes in order to gain more power. A slave laser diode is a laser that is highly multi-modal over a span that includes the desired frequency, but has more power than what is available from the master laser which has the desired frequency. The goal is to try to force the slave laser to output its light at the desired frequency by injecting into it a very small portion of the beam from the master laser, which has the desired frequency. This forces the slave to lase at this frequency by choosing that as the preferred frequency over all the others [4]. This is not always possible and is dictated by the chip that is used in the slave diode. In this portion of the research project, the aim was to determine whether or not the slaves were able to be injected, and if they were, determine at what current and temperature the slaves lasers had to be operating.

The first step in the process of the slave laser injection was to collimate the beam coming directly from the slave. Slave 1 itself houses an f=4.03 mm lens with position adjustment capabilities. The beam was first collimated in the vertical direction using only this lens. The same process was used as for the collimation of the main laser's beam. The beam waist was measured with the beam profiling camera, and a Gaussian fit was performed. The lens was then adjusted to collimate only the vertical direction, and the fit was performed again; the horizontal direction was ignored. After the vertical direction was collimated as well as possible, the cover was secured over the lens to ensure it did not move again.

The horizontal direction was then collimated relative to the vertical direction. A Gaussian fit was performed on the horizontal axis of the beam and from there, the Gaussian Beam software was used to determine what size telescope could be used to collimate the horizontal direction of the beam and also establish the horizontal and vertical waists of approximately the same size. The two cylindrical lenses that were used were an f=100 mm and an f=-75 mm lens. They were first placed 25 mm apart, in accordance with the definition of a Galilean telescope, but the position of the second lens relative to the first lens was adjusted many times by very small amounts until the horizontal axis of the beam was both collimated and the correct size based on the fits performed.

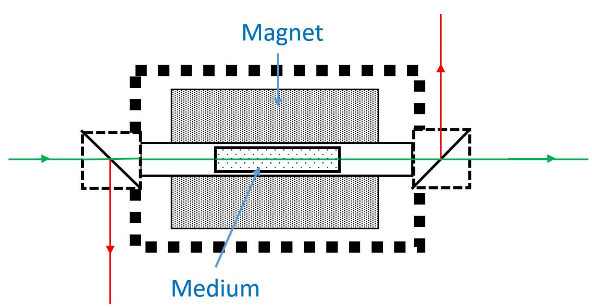

Figure 11: Top view of an optical isolator

When the slave laser beam passes through the optical isolator, the transmission efficiency is never 100%. A very small portion of the light skips off of the two PBS cubes within the isolator; this is shown by the red beams in Figure 11. The PBS cubes are typically covered to prevent these rejected beams from reflecting off of any objects and into somebody's eyes. If the covers are carefully removed, though, the injection beam can enter into the side of the isolator through the side of the second PBS cube, as shown by the red beam on the right side in Figure 11. The injection beam then travels the opposite direction through the isolator and enters the slave diode. This beam is able to travel the opposite direction through the isolator, contrary to what was stated previously, because the injection beam coming in has a polarization that is rotated 90 degrees relative to the beam coming out of the isolator. The beam coming out of the isolator from the slave is P-polarized, allowing it to pass straight through the cube. The injection beam light is S-polarized, allowing it to skip off of the PBS cube and travel the opposite direction through the isolator. When the injection beam passes through the medium surrounded by the magnet, the Faraday effect rotates the polarization in the same direction, so the injection beam is rotated 90 degrees, ending up P-polarized so that it is able to pass through the first PBS cube and enter the slave diode. For this purpose, the second PBS cube of the isolator must be perfectly horizontal to allow the injection beam to enter. The second PBS cube was held in place horizontally while the first cube was rotated to optimize both the transmission and the isolation of the optical isolator using the same process as described previously. For this case, a λ/2 waveplate was placed just before the isolator to ensure the light from the slave entered with the correct polarization to pass through.

Once the isolator was placed, the next step was to determine the size of the injection beam needed for a successful injection of the slave diode. The beam from the slave and the injection beam must match in size for optimal efficiency. The beam used to inject the slave was the beam coming from the 300 MHz

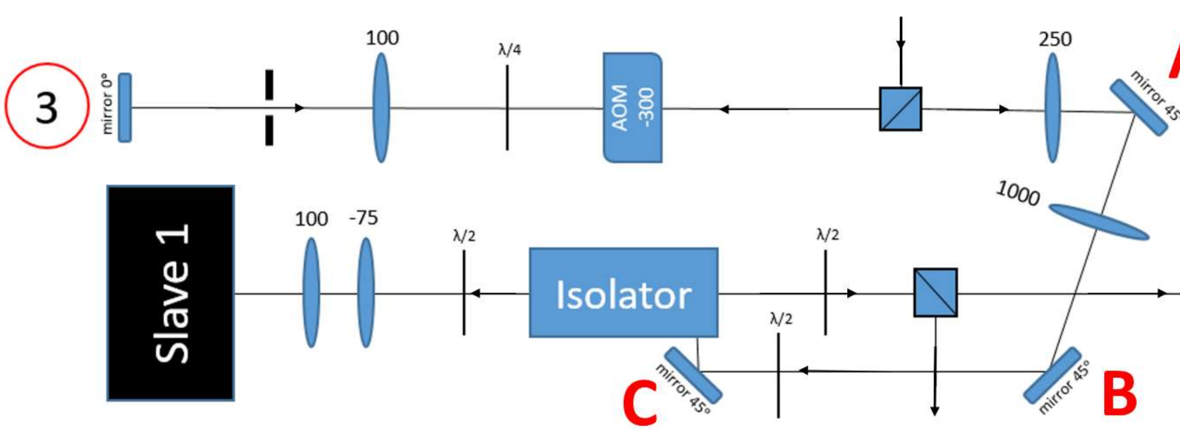

Figure 12: Scheme for the injection of Slave 1. The beam entering from the top is coming from the master laser. The beam exiting on the right is a very small portion of the slave laser that goes to the Fabry-Perot cavity, while the majority of the slave's power goes to the bottom where it is injected into two other AOMs (see Figure

AOM. The beam coming from the Radiant Dyes laser was a collimated beam, and an f=250 mm lens was used to focus the beam entering the 300 MHz AOM double pass. The double pass efficiency was optimized with the AOM placed 257 mm from the lens. According to the 4f double pass scheme, the beam should come out of the AOM after the second pass with the same exact beam characteristics as when it entered [3]. For this reason, if another f=250 mm lens is placed 257 mm after the exit of the AOM, the original collimation of the beam should be restored, but with the new frequency due to the AOM. An f=250 mm lens was placed at about that distance from the exit from the AOM to re-collimate.

Next, the slave beam and the injection beam were aligned along the same path. The cover of the second PBS cube was removed allowing the rejected beam from this cube to be visible. With the injection beam from the AOM blocked, the rejected beam was traced backwards, and three mirrors were placed in order to direct it toward the injection beam coming from the AOM. Once this beam was approximately on the path of the injection beam, the injection beam was unblocked and the two beams were aligned more accurately. Both beams coming from each direction are visible through a single piece of paper. When a paper was placed at point C, the position of the injection beam was adjusted using the mirror at point A to match the beam from the slave laser. Then, the paper was placed at point A, and the slave beam was adjusted to match the path of the injection beam using the mirror at point C. Once these two points were optimized after repeating those two steps many times, a $\lambda/2$ waveplate was placed along the path of the injection beam and was adjusted to ensure that all of the light that entered the PBS cube of the isolator skipped off the cube and entered the slave diode. The paper was then placed just in front of the slave. The two beams were aligned at this location using the mirror at point B. This alignment process was repeated multiple times until the beams were exactly along the same path.

Next, a wavemeter was used to measure the wavelength of the beam coming from the slave to ensure it was injected. In order to find the injection, the current to the slave laser diode had to be adjusted along with the temperature of the diode, and critically, the size of the injection beam had to match the size of the slave's beam; all three of these variables had to be right at the same time to achieve a successful injection. It was hypothesized that the size of the injection beam was too large, so in an attempt to fix that, an f=1000 mm lens was placed arbitrarily along the path of the injection beam between points A and B (see Figure 12), and the injection was obtained by changing the current to the slave diode. This injection process was completed using a wavemeter, but it would later obtain a much more accurate injection when the slave laser beam was injected into a Fabry-Perot cavity.

Using the beam from the slave laser, AOMs 1 and 2 were injected and optimized in a double pass scheme. Both AOMs 1 and 2 were the same 200 MHz AOM, which requires a beam waist of 100 μm. Because they both needed the same beam waist, the beam was passed through a single lens and was then split by a PBS cube so that single lens could be used to inject both AOMs. The double passes were optimized for both, and the position change after the double pass with a change in frequency was eliminated as well.

The next step was to repeat the slave injection for slave 2. The same process was used as for slave 1. The beam coming from the slave was collimated in the vertical direction by adjusting the small lens within the diode, and then a telescope of lenses was used to collimate the horizontal direction. The injection beam for this slave was coming directly from the Radiant Dyes master laser, so the beam was already collimated, and no additional lenses were needed to match the sizes of the beams. This diode was, again, injected through the side of the isolator. The using the wavemeter by adjusting the current and the temperature of the slave diode.

When both slave diodes were in place, there was a problem with their temperature controls. When the temperature of one slave was changed, the temperature of the other slave would change as well. When the error signals of both temperature controllers were connected to an oscilloscope, though, it was found that this was not really the case. The display of the temperature controller was changing, but the actual temperature was not. For this reason, the digital displays of the temperature controllers cannot be considered completely reliable, so the temperatures of the slave diodes were reported as the values of the resistances on the temperature controllers rather than the temperatures shown on the digital displays.

2.5 Ensuring Stable Frequencies: Fabry-Perot Cavity

In order to ensure that the frequency of each of the lasers was extremely precise and extremely stable, each of the three beams coming directly from the lasers (the main Radiant Dyes laser as well as the two slave lasers) was injected onto a Fabry-Perot cavity. A Fabry-Perot cavity, shown in Figure 13, is a cavity consisting of two mirrors facing each other with a very precisely set distance between them. Depending on the type of cavity, the two mirrors can both be flat, they can both be round, or there can be one of each. The light enters one end of the cavity through the back of one mirror. The light then reflects off of the mirrors and bounces back and forth between them. Behind the second mirror is a photodiode that detects the transmitted beams. The length of the cavity is an integral number of quarter-wavelengths of the laser being used, and as a result of the precision of the length of the cavity, the only light that is transmitted through the second mirror is the light with the correct wavelength. When the wavelength of the light is correct, the signal on the photodiode shows a sharp peak because at that point, the light is transmitted. Light with the wrong wavelength will remain inside the cavity, continuing to reflect between the two mirrors.

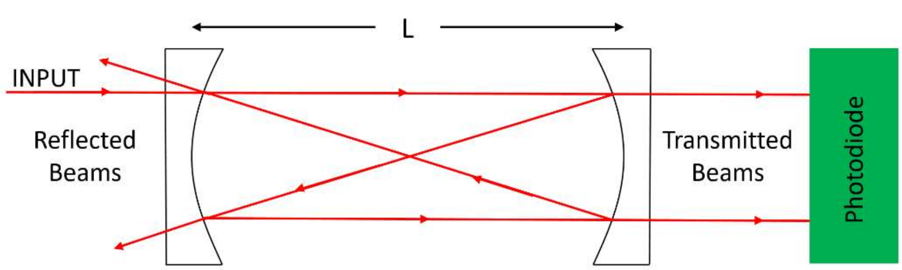

Figure 13: Fabry-Perot Cavity

For the purpose of this experiment, a commercial Fabry-Perot cavity was purchased from Thorlabs. This cavity was specifically built for light at 689 nm, so the length of the cavity never had to be adjusted, and the two mirrors inside were both confocal mirrors. The signal from the photodiode was connected to an oscilloscope, and all three beams directly from the lasers were combined using PBS cubes each preceded by $\lambda/2$ waveplates to control the light's polarization. They were aligned directly into the cavity using adjustments on the mirror just before the entrance of the cavity as well as the adjustments on the mount of the cavity. One of the mirrors inside the cavity is attached to piezoelectric transducers which, when fed a voltage, move the mirror back and forth by very small amounts to scan different lengths of the cavity. This ramping was seen on the oscilloscope along with the signal of the photodiode. When the spacing between the mirrors became equal to an integral number of quarter-wavelengths of the laser light, then the light was transmitted and the signal on the photodiode increased.

3 Results/Outcomes

There were two major successes of this research project: the completion of the setup of the 689-nm red laser chain and the successful injection of two slave-laser diodes. The final schematic of the laser chain, including lens focal lengths as well as distances, was made after the setup was complete (see Figure 14).

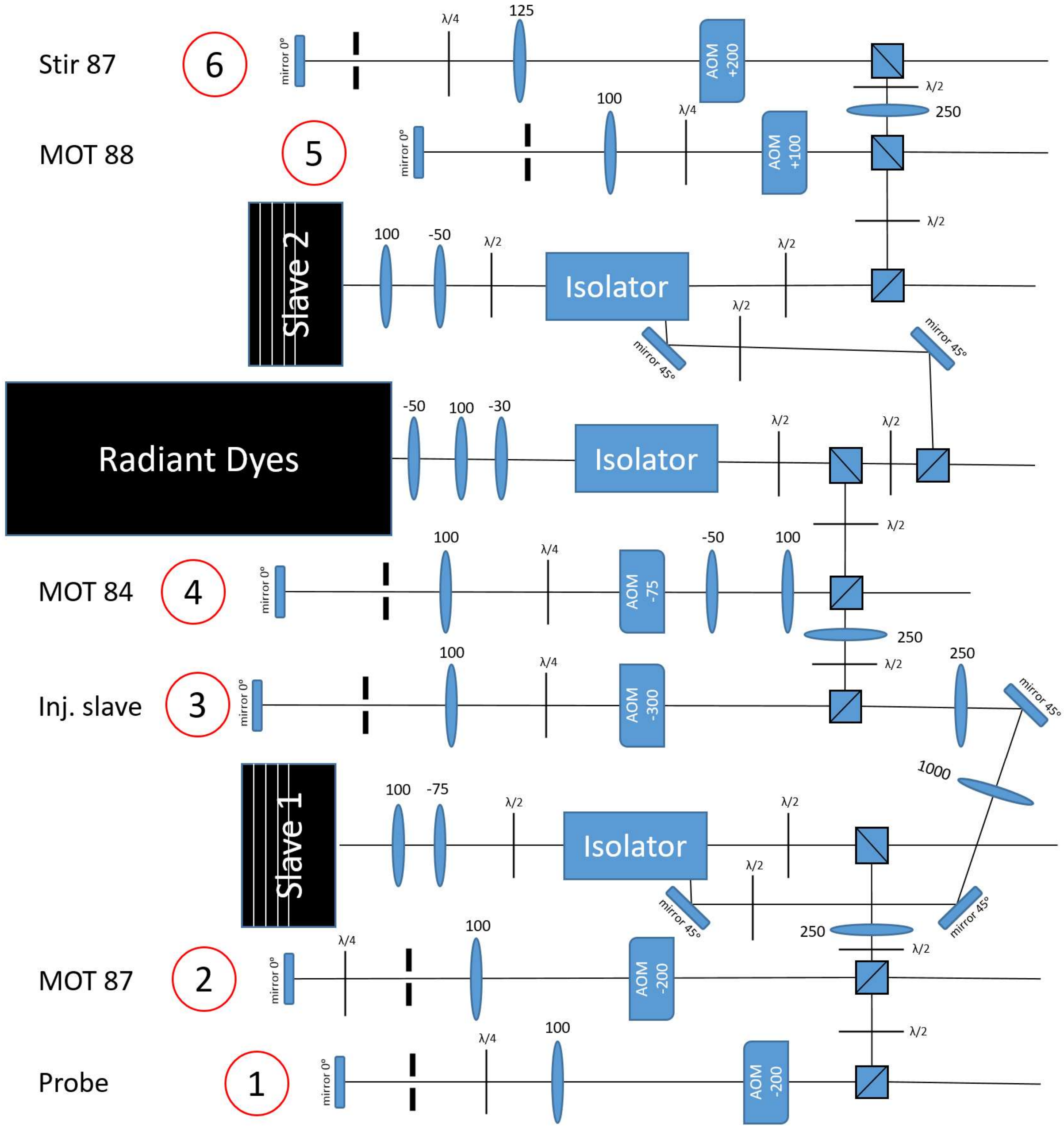

Figure 14: The final schematic of the red laser chain after the setup was complete. The beams from the Radiant Dyes, slave 1, and slave 2, were all injected into the Fabry-Perot cavity. Lines 2, 4, 5, and 6 will be combined and injected into polarization-maintaining fibers to bring the light over to the main experimental table and build the red MOT. Line 1, the probe, will also be injected into a polarization-maintaining fiber and used for imaging of the cloud of atoms.

Because the injection of a slave diode is dependent on the chip inside the laser, there is no guarantee that any given slave laser will be able to be successfully injected and lase at a single stable frequency. Slave lasers are high output-power lasers that are typically unable to perform with low noise; they output a signal that ranges over a span of frequencies. The injection beam is intended to force the chip to lase at a single specific frequency by choosing the frequency of the injection beam as the preferred frequency over every other.

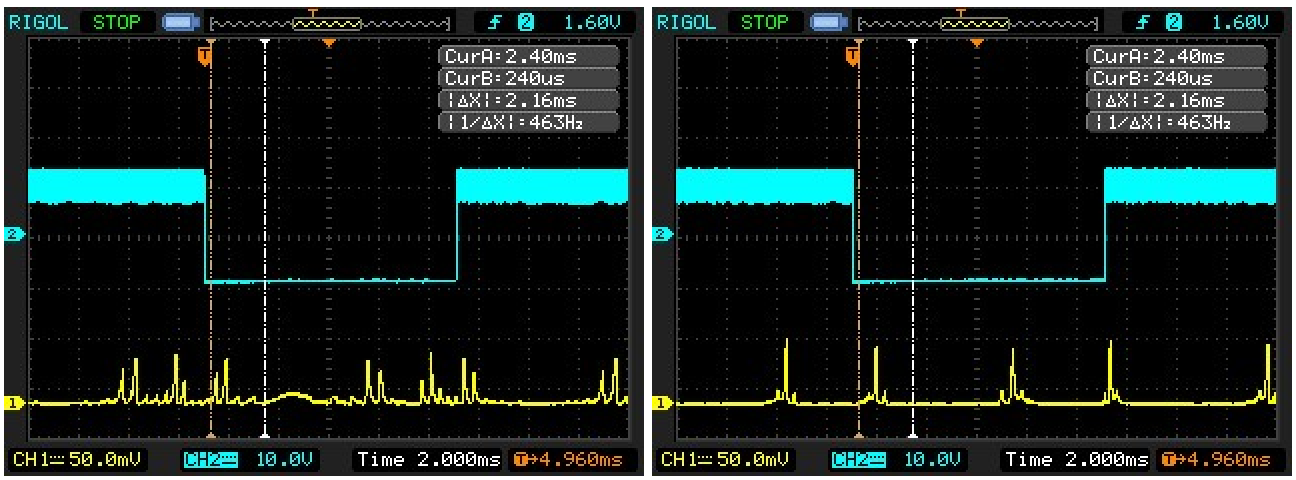

Figure 15: Slave laser output displayed as a signal from the photodiode on the Fabry-Perot cavity. The left is showing when the slave is multi-mode, and the right is showing when the slave is mono-mode. The blue signal is the ramping of the piezo which scans a range of lengths of the cavity.

Both slave lasers on this 689-nm laser chain were successful within in specific ranges of currents of the slave lasers. Slave 1 was injected first. It was found that the injection was only successful when the slave itself was multi-mode. As the current of the slave was adjusted, it was observed that there were ranges where the slave was mono-mode, and outside of those ranges, it was multi-mode. When the beam from the slave was injected into the Fabry-Perot cavity, these ranges were easily visible. The output of the photodiode on the Fabry-Perot cavity was connected to an oscilloscope so that it was very clear when the slave was multi- or mono-modal (see Figure 15). In the range that the slave was mono-mode, the frequency that it was lasing at was not the desired frequency for this experiment. In order to force the slave diode to lase at the desired frequency, the slave itself had to be multi-mode. Figure 16 displays the

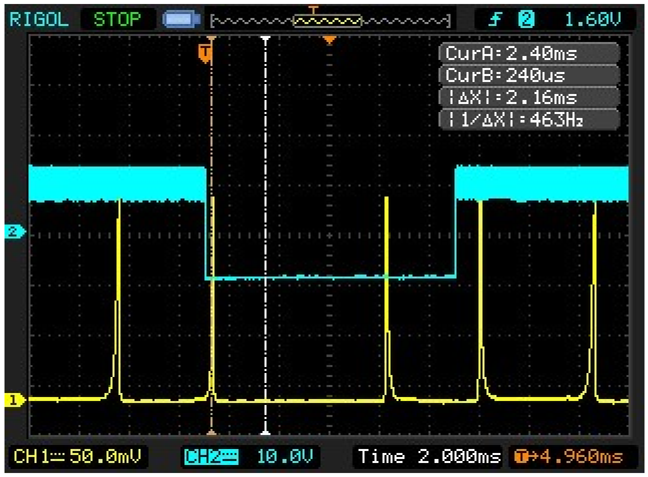

Figure 16: Signal from the photodiode of the Fabry-Perot when the slave laser diode is successfully injected.

signal of the Fabry-Perot when the slave was successfully injected. The peak, in this case, was much higher, sharper, and narrower compared to when the slave was lasing mono-modally without injection. The injection of slave 1 was successful when the master laser had 140.3 mA of current, and the piezo was set at 200, the injection beam going into the isolator was 0.58 mW, the slave had 105.1 mA of current, and the resistance of the temperature control of the slave diode was 72 kΩ.

Slave 2 was also later successfully injected in the same manner. This injection required 1.40 mW of power in the injection beam going into the isolator, 114.3mA of current going into the slave, and a resistance of 72 kΩ on the temperature control of the slave diode. When all three beams were injected on the Fabry-Perot cavity and they were all stabilized, the signal on the photodiode was shown in Figure 17.

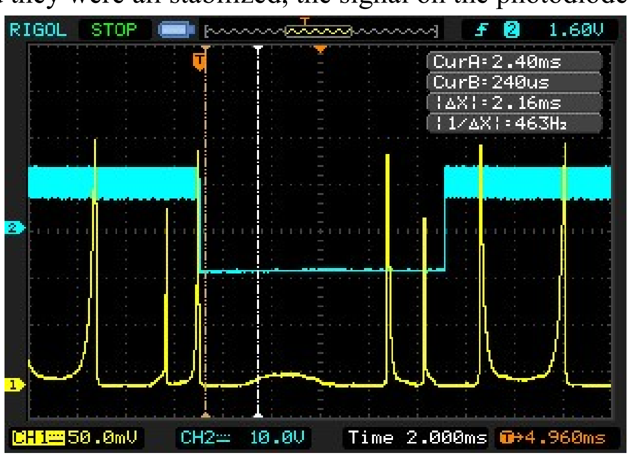

Figure 17: Signal from the photodiode of the Fabry-Perot cavity when all three laser beams were successfully injected on the cavity, the master laser was stabilized, and both slave lasers were successfully injected to lase at the desired frequency.

4 Outlook

Following this particular research project, the LPL team will continue the setup of this cold atoms machine. With regard to the red laser system that was built on this project this summer, each of the five beams with different frequencies will be injected into polarization-maintaining fibers. The four beams to be used for the MOT (MOT 84, MOT 87, MOT 87 line 2, and MOT 88) will be combined using PBS cubes and then split evenly between three different fibers. The output of these three fibers will be then set up for the MOT. The three beams will be retro-reflected back on each other to form the six beams of the MOT, as displayed in Figure 3. The output of the fibers will then bring the light over to the main experimental table, where the red 689-nm light will be used to create a red MOT. The team plans to have the red MOT completed in fall 2017, and they plan to reach degeneracy with the atoms in 2018. Once the setup of the machine is complete, the team will be able to manipulate the atoms in different ways, and that is where a lot of the new science and discovery will happen.

5 The Experience

Along with the work we did in the lab every day, there were different members of LPL that gave talks to our group about once a week, on average. Conveniently for me, the majority of these talks were given in English. Each person who presented chose a topic or a specific paper to focus on. Each of the topics was a topic in physics today that is very controversial or is being talked about a lot currently. Because my level of physics knowledge is lower than most people working in LPL, I probably never understood more than half of any given presentation, sometimes no more than ten percent, but these talks were still important to my experience. They allowed me to see what kinds of things are being actively studied in the physics world today, and what topics are popular currently. One major thing that I took away from this part of the experience is that the physics community is very close-knit. People are constantly working together with other labs and building off of other people's methods and results. For example, the machine being built in the Strontium lab of LPL that I spent the summer working on, is designed following guidelines inspired by Simon Stellmer in his Ph.D. thesis, “Degenerate quantum gases of strontium” [6].

Ever since I graduated high school, my plan for school has been to get my bachelor’s degree in physics in and then proceed to work for my master’s degree in engineering. This experience has had a huge impact on my thoughts about what path I want to follow in my education. In order to obtain a full-time position in a lab like LPL, you must have a Ph.D. As a student, I have never really known all of the options that a Ph.D. in physics can provide. This opened my eyes to some options, and also gave me the opportunity to experience what it is like first-hand. I have enjoyed being given the opportunity to work very hands-on in the lab rather than a lot of typical internships where you are stuck at a desk. I enjoyed working in the lab, and this experience has given me a lot to think about with regard to what path I want to pursue with my education.

Aside from the educational aspect of this experience, this summer has really helped me grow as a person. I was able to work with an amazing group of people who were so welcoming and willing to answer any question I might have had. I learned so much from each person I came in contact with this summer. This was my first experience traveling abroad by myself, and to make it even more challenging, I was thrown into a country where I did not speak the same language as most people, so everyday communication was difficult. At first it was extremely intimidating and scary, but over time, I learned a little bit more of the language, and I learned a little bit more of the culture, and I became much more comfortable. The ability for me to adapt to such a strange situation on my own was something that, when I arrived in Paris, I was not sure I was ever going to be able to do. I have learned so much about myself and I have become a lot more comfortable with myself as a person and my abilities. Besides the research aspect of this experience, the life experience that I gained from this opportunity really opened my eyes to the world and gave me so much confidence in myself and my ability to overcome any obstacle. I am extremely grateful to Dr. John Huckans for setting me up with this opportunity, the entire LPL team at Université Paris 13 for taking me on and being so welcoming, and to URSCA for making it all possible.

Appendix: Data

Table 1: Beam Waists

	Horizontal				Vertical			
Location	w_0 (μm)	±	z_0 (cm)	±	w_0 (μm)	±	z_0 (cm)	±
coming from Radiant Dyes, after first 3 lenses	806.54	6.7	64.162	17.6	778.16	40.4	57.572	99.7
after 250 mm lens, entering AOM 3	63.932	0.469	25.57	0.112	77.575	5.33	26.661	1.1
coming from slave 1, after 2 lenses	573.43	26.6	49.356	47.8	483.7	15.2	16.42	13.4
after 250 mm lens, entering AOMs 1 and 2	94.8	4.93	25.887	0.69	106.38	3.58	23.819	0.387
coming from slave2, after 2 lenses	399.04	45.6	-10.239	6.27	477.17	4.46	57.21	4.01
after 250 mm lens, entering AOM 6	113.24	29.6	15.37	1.79	93.96	5.7	14.66	0.255

Table 2: Isolator Efficiencies

	Expected		Experimental	
Isolator	Efficiency (%)	Isolation (dB)	Efficiency (%)	Isolation (dB)
Slave 1	94%	40	91.5	41
Radiant Dyes	94%	40	94	38.2
Slave 2	94%	40	91.8	37.8

Table 3: AOM Efficiencies

		Frequency	Expected Efficiency	First Pass Efficiency	Second Pass Efficiency	Double Pass Efficiency
1	Tomographie	-200	90%	78.60%	84.60%	66.50%
2	MOT 87	-200	90%	78%	83%	64.74%
3	Inj. Slave 1	-300	85% @350 MHz	62%	76%	47.12%
4	MOT 84	-75	94%	82%	80%	65.60%
5	MOT 88	100	95%	82.8%	86%	71.21%
6	Touille 87	200	90%	69%	88%	60.72%

Table 4: AOM Channels and Optimal Powers

		Frequency	DDS type	DDS channel #	amplifier	optimum RF power (W)	Max RF Power (W)
1	Tomographie	-200	9852	6	6	A58	2.2
2	MOT 87	-200	9852	5	5	A42	2.2
3	Inj. Slave 1	-300	9858	11	1	(attenuator)	1.3
4	MOT 84	-75	9852	2	2	A42	2.2
5	MOT 88	100	9852	[6]	4	A26	2.2
6	Touille 87	200	9852	[5]	[5]	A42	2.2

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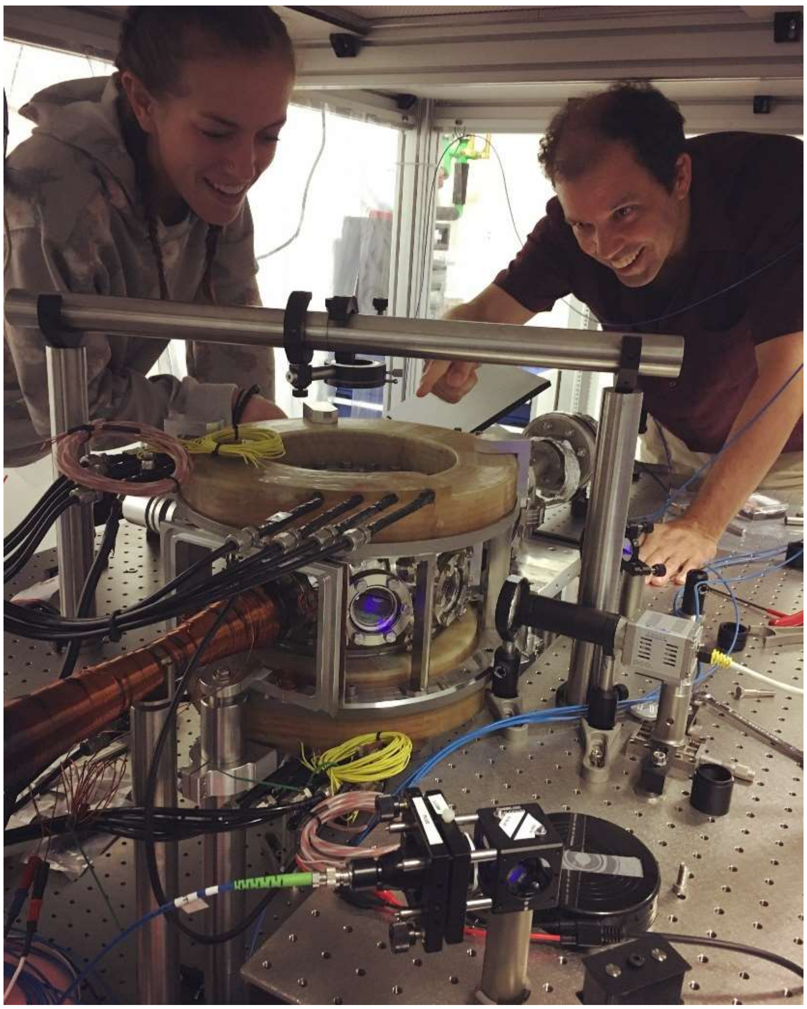
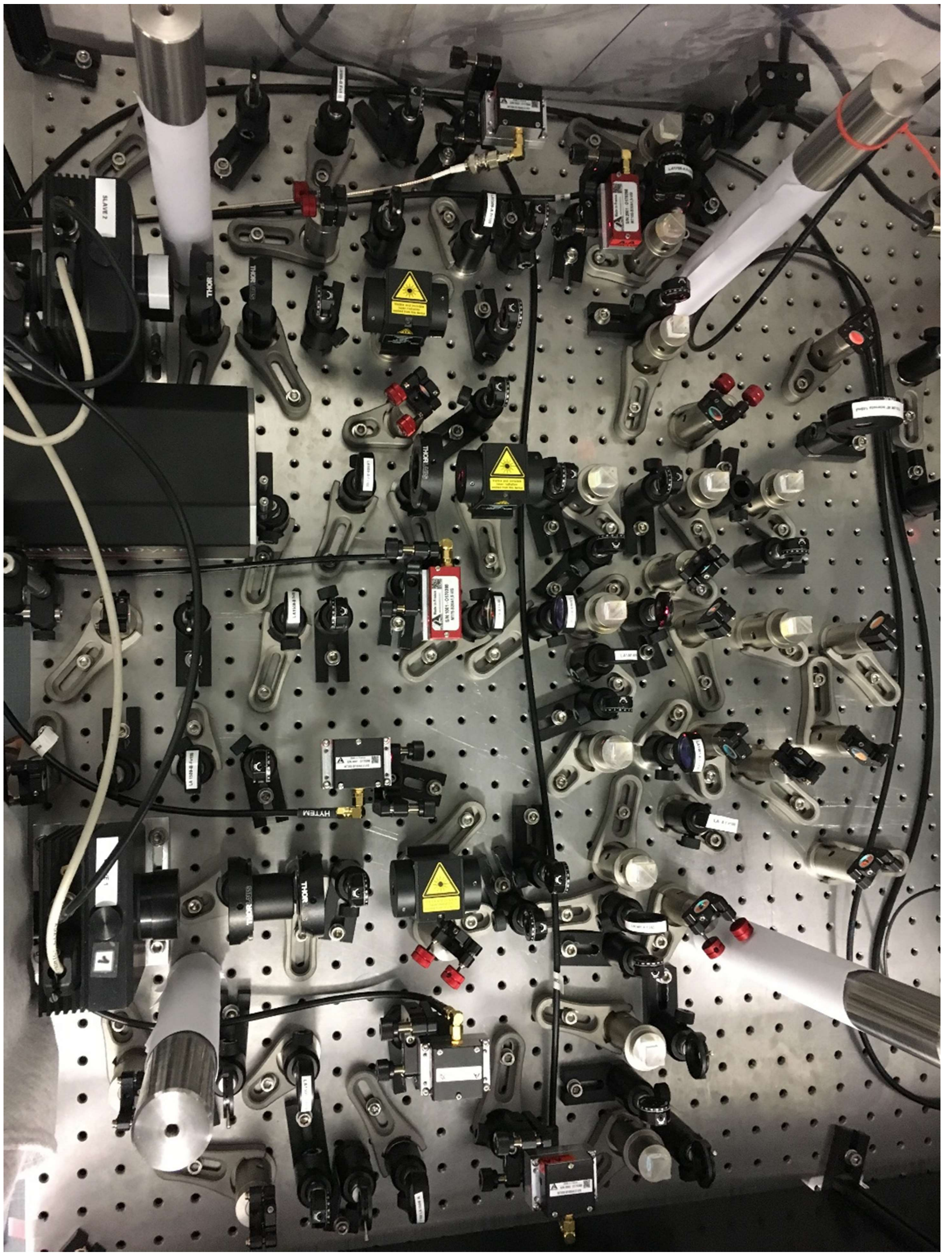
Illustrations



Rachel Yenney and Dr. John Huckans looking at the cloud of Strontium atoms trapped in the blue MOT.



Actual version of Figure 14 with optics and lasers on the table.