Investigation of Optical Dipole Traps for Trapping Neutral Atoms for Quantum Computing

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the Requirements for the Degree
Bachelor of Science

by
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1 Introduction

The ability to trap and manipulate atoms with laser light has been a large interest in many fields of physics. The first experimental success of trapping atoms in a light trap occurred in 1986 by trapping sodium atoms with a strongly focused Gaussian laser beam [1]. The magneto-optical trap (MOT) has become a commonly used approach for cooling neutral atoms, such as Rubidium and Cesium, to ~100’s of micro-Kelvin.* After a cloud of neutral atoms is cooled in a MOT, the atoms can be further confined in a light trap. These light traps, or optical dipole traps, use laser light to induce an electric dipole moment in the atoms and trap them in potential energy wells with a trapping depth on the order of several mK. In particular, cooling and trapping neutral atoms has influenced the study of: Bose-Einstein condensates in light traps [2], the observation of long decay times for atoms in their ground state [3], and the study of trapping other atomic species or molecules [4]. For this report, we will focus on trapping neutral atoms in optical dipole traps for quantum computing applications.

Quantum computers exploit the quantum mechanical phenomena of entanglement and superposition of states, which allows solving certain problems exponentially faster than classical computers. Neutral atoms are of particular interest in the field of quantum information because they do not interact strongly with the environment in their ground state, which results in a long time until the state decays in a spontaneous uncontrolled manner, also known as a long decoherence time. Trapping and manipulating neutral atoms in an optical dipole trap has been experimentally shown to be a feasible technique for quantum computing. By exploiting the atom’s motional or electronic states as the so-called quantum bit (qubit), we can perform quantum manipulations such as initialization, read out, single qubit gates, and two qubit gates [5]. One remaining difficulty for using neutral atoms for quantum computing is the ability to create a scalable array of trapped atoms such that individual atoms can be addressed.

Neutral atoms can be trapped in localized dark spots (if the laser frequency exceeds the resonance of the atom, “blue-detuned”) or localized bright spots (for laser frequencies less than resonance, “red-detuned”). In this paper, we discuss the diffraction pattern that occurs from laser light incident on a pinhole, or circular aperture, which creates localized intensity minima and maxima feasible for trapping cooled neutral atoms [6]. The blue detuned localized dark spots allow for low intensity laser light and small laser detuning in order to trap the atoms. On the other hand, using red detuned laser light, the localized bright spots are also feasible for trapping neutral atoms with a large detuning. Gillen-Christandl et al. have shown computationally that this diffraction pattern is suitable for creating a two-dimensional (2D) array of trapped atoms such that individual atoms can be addressed for quantum manipulation. This 2D array of trapped atoms also allows for pairs of atoms to be brought together and apart by exploiting the light-polarization dependence of the atoms in their magnetic substates.

*We specify the average kinetic energy, $K$, of the atoms as a temperature using $K = \frac{3}{2} k_B T$, where $k_B$ is the Boltzmann constant and $T$ is temperature (Kelvin units).
The experiment presented in this paper measures the diffraction pattern created from laser light incident on a pinhole at angles from 0° to 30°. Chapter 2 will discuss the theoretical background of trapping atoms in optical dipole traps, the use of neutral atoms for quantum computing, and the computational results for the diffraction pattern that occurs directly behind a pinhole. Chapter 3 will describe the experimental apparatus we use to measure the diffraction pattern at normal incidence (0°) and at an angle. Chapter 4 discusses the procedure to modify the incident beam at normal incidence, to make setup adjustments for measuring the diffraction pattern for an incident angle, and the use of Mathematica for creating plots to compare to computational results. Chapter 5 summarizes the experimental results for measuring the diffraction pattern behind a pinhole.

2 Theoretical Background of Trapping Neutral Atoms

2.1 Theory of Optical Dipole Traps

In the presence of an electric field, the positive and negative charges in a neutral atom experience opposing forces. The resulting charge separation constitutes an induced electric dipole moment. Laser light has an oscillating electric field, $E$, that induces a dipole moment, $p$, on a neutral atom. The relationship between the electric field and the induced dipole moment is

$$p = \alpha E,$$

(1)

where $\alpha$ is the complex polarizability due to the damped oscillation of the electron when considering the atom as a simple oscillator. Note that the following equations were adapted from [7]. The interaction between the electric field and the induced dipole moment creates a dipole potential energy of

$$U_{dip} = -p \cdot E.$$  

(2)

By expressing this in terms of laser intensity, we get

$$U_{dip} = -\frac{1}{2\epsilon_0 c} \text{Re}(\alpha) I,$$

(3)

where $\epsilon_0$ is the permittivity of free space, $c$ is the speed of light, and $I$ represents the intensity of the electric field, which is proportional to $|E|^2$, and the factor of $\frac{1}{2}$ indicates that the dipole moment is not permanent but rather induced. The resulting force due to the induced dipole moment is found by applying the gradient to the dipole potential energy as follows

$$F_{dip} = -\nabla U_{dip}(r) = \frac{1}{2\epsilon_0 c} \text{Re}(\alpha) \nabla I(r),$$

(4)

where $\nabla I(r)$ represents the intensity gradient of the electric field.

In an optical dipole trap, the main decoherence mechanism for a trapped atom is photon scattering from trap photons. For quantum computing applications, this scattering rate needs to be as small as possible. Therefore, we need to determine the relation of the potential energy and the photon scattering rate in terms of laser detuning and laser intensity. The dipole potential energy, $U_{dip}$, and the photon scattering rate, $\Gamma_{sc}$, can be expressed as
In equation (5) and equation (6) $\omega_0$ is the resonant frequency of the atom, $\Gamma$ is the damping rate that corresponds to the spontaneous decay rate from the excited state, $I(r)$ is the position dependent light intensity, and $\Delta = \omega - \omega_0$ is the laser detuning. Note that equation (5) and equation (6) were derived from equation (4) by assuming the laser has a large detuning and assuming the light intensity is low compared to the saturation intensity of the atom.

The detuning is an important factor when determining if the atom will be trapped in a high or low intensity region of laser light. For the case when the detuning is negative ($\Delta<0$), the laser is below atomic resonance and by referring to equation (5) the dipole potential energy would be negative as well. Therefore, the potential energy minimum occurs at the light intensity maximum, so atoms are attracted to intensity maxima. This case, when the detuning is negative, is called red-detuned. On the other hand, for the blue-detuned case, the detuning is positive ($\Delta>0$), which corresponds to the laser frequency being above the atom’s resonant frequency. For positive detuning the dipole potential energy is also positive, which causes the atoms to repel from high intensity laser light. Therefore, the atom will be attracted to the potential energy minimum that occurs where the light intensity is at a minimum. In summary, when $\Delta<0$ or red detuned, then we trap the atoms in regions of high intensity laser light or bright spots. When $\Delta>0$ or blue detuned, then we trap the atoms in regions of low intensity laser light or dark spots. Any light pattern with localized bright or dark spots can be feasible for optical dipole trapping. Grimm et al. [7] express examples for trapping atoms in red-detuned or blue-detuned laser light. Examples for red-detuned optical dipole traps include focused laser beam traps, standing wave traps, crossed-beam traps, and lattices; for blue-detuned traps examples include light-sheet traps, hollow-beam traps, evanescent-wave traps, and lattices.

### 2.2 Optical Dipole Traps for Neutral Atom Quantum Computing

The ability to trap neutral atoms in a confined region of light that is dependent on the detuning has many advantageous applications. However, for our type of light trap we are exploring the feasibility for neutral atom quantum computing. Neutral atom quantum computing is a promising approach to creating a quantum computer. The qubits are formed by the motional or electronic states of the neutral atoms. An intrinsic characteristic of using neutral atoms is their weak interaction with the environment, which can result in long coherence times. One aspect of neutral atom quantum computing that has caused difficulty is the ability to create a scalable system of qubits such that each qubit can be addressed individually. For instance, a common trapping pattern used in neutral atom quantum computing is the optical lattice. A three-dimensional (3D) optical lattice that consists of three pairs of counter propagating laser beams that create an array of potential energy minima for the atoms. Due to the 3D structure of the lattice, it is difficult to address each atom individually without disturbing a neighboring atom in the
lattice. Other light traps have been explored by creating a 2D array of trapping regions, including: microlenses [8,9], spatial light modulators (SLMs) [10,11], mirrors [12,13], Fresnel lenses [14], metamaterial lenses [15], and other diffraction patterns [16,17].

Initialization and readout of each qubit, single qubit gates, and two qubit gates have been experimentally demonstrated by the neutral atom quantum computing community [18-21].

Our approach explores the light pattern that occurs directly behind a pinhole from incident laser light. There exist localized light traps that have the ability to manipulate the position of an atom by tilting the incident laser beam. Two atoms can be brought together and apart by tilting two opposite circularly polarized incident laser beams. Therefore, two qubits can be brought into close proximity to facilitate two qubit gates. By creating a 2D array of pinholes, this approach can be scaled into a 2D array of individually accessible atoms for quantum computations. The next section discusses the diffraction pattern behind a pinhole in more detail.

2.3 Computational Results for the Diffraction Pattern Behind a Pinhole

2.3.1 Dipole Traps Formed in the Diffraction Pattern Behind a Pinhole

The region of interest of the diffraction pattern that results from incident laser light on a pinhole appears before the near-field (Fresnel) and far-field (Fraunhofer) diffraction regions. When the pinhole radius is larger than the wavelength of the incident laser light such that the pinhole radius to wavelength ratios are greater than 1, then localized maximum and minimum intensities occur directly behind the pinhole [22]. Previous work [22] shows that these high and low intensity regions can operate as dipole traps for our neutral atoms depending on the laser detuning. Moderate laser powers (~100 W/cm²) and small laser detunings (~10⁻³-10⁻⁴ linewidths) allow for potential energy wells that are deep enough to trap atoms and facilitate quantum computations. The potential energy wells have trap depths of ~1mK. Therefore, these localized maximum and minimum intensity regions of the diffraction pattern can create optical dipole traps viable for qubit storage for quantum manipulations.

The pattern consists of many localized bright and dark spots that are all possible dipole traps, but the trapping sites closer to the pinhole may be more difficult address. The regions we explored occur at the second to last bright region and the last dark region. For a 780nm laser and a 25µm diameter pinhole these locations occur at 67µm and 100µm behind the pinhole. Figure 1 shows the computed Y-X potential energy profile for the red detuned example (Z=67µm) and the blue-detuned example (Z=100µm), along with the corresponding Y-Z profile for one incident laser beam for both cases. From the previous section, detuning of the laser light determines if an atom will be trapped in a bright or dark spot. For blue-detuned light, the atoms will be trapped in a region of low intensity or the dark spots. For red-detuned light, the atoms will be trapped in regions of high intensity or the bright spots. It then follows that the dark spot at Z=100µm corresponds to a possible trapping region for blue-detuned light. Similarly, for red-detuned light, the neutral atom will be trapped in the bright spot at Z=67µm.
2.3.2 Bringing Atoms Together and Apart

Varying the tilting angle of the incident beam on the pinhole can move a trapped atom in either a bright or dark spot. By tilting two beams incident on a pinhole, we can bring two atoms in separate trapping sites together and apart. One problem that may occur is the atoms can get kicked out of the traps due to the potential energy barriers from the other atom’s trap or they could tunnel from one trap site to another; however, this can be avoided by exploiting the circular polarization dependence of the different magnetic substates of the atom. It can be shown that atoms in different magnetic substates can be manipulated by different polarizations of light. Two atoms in different magnetic substates see different potential energies for the same light pattern. For instance, an atom in the F=1, m_F=+1 substate sees a higher trapping potential energy from left circularly polarized light (σ-) and a trapped atom in the F=1, m_F=−1 substate sees a higher trapping potential energy from right circularly polarized light (σ+). The basic setup is shown in figure 2. The computational results for the polarization dependence of the magnetic substates are shown in figure 3. We can use two opposite circularly polarized beams to bring two atoms in different substates together and apart without the atoms getting knocked out of the traps or losses due to tunneling.

One of the advantages of our optical dipole traps is the ability to confine atoms with blue-detuned light in the dark spots or red-detuned light in the bright spots simply...
by changing the laser frequency. Referring to equation (5), one can see for high laser intensities, \( I(r) \), the dipole potential energy becomes large; however, referring to equation (6) the scattering rate also increases by the same factor. The detuning is squared in the denominator for photon scattering; therefore, we want a detuning large enough to reduce the photon scattering, but small enough the create a deep potential energy well. For blue detuned traps, the atoms are trapped in areas of low intensity light, and then a small detuning can be used in combination with low intensity laser light to create a deep enough potential well to trap the atoms. One consequence of the blue-detuned case is that when bringing two atoms together into the same trap, the potential energy barrier between the atoms may cause the atom to move, which can create a disturbance to quantum manipulations. We need to make this disturbance negligible; otherwise red-detuned traps may be more beneficial. Red-detuned traps are commonly used in trapping atoms when high laser power is attainable because then the traps will have deep potential energy wells and a low photon scattering rate in combination with a larger detuning.

![Figure 3](image)

**Figure 3:** Computational results of the trapping potential energy diffraction patterns (mK) for different magnetic substates \( m_F = -1, m_F = 0, \) and \( m_F = +1 \) of \( ^{87}\text{Rb} \). [6].

### 2.3.3 Creating a 2D Array of Trapping Sites

For neutral atom quantum computing we want to generate a large 2D array in which individual atoms can be addressed and manipulated for quantum computations. We can create a large 2D array of pinholes with two large incident laser beams of opposite circular polarization. Then a pair of atoms can be trapped behind each pinhole by their preferable circularly polarized beam. By tilting the incident laser beams, pairs of atoms can be brought together and apart for quantum applications, and we can further tilt the beams such that atoms can be brought together with atoms in neighboring pinhole traps. This paper will investigate the limits of these traps by exploring the diffraction pattern and the trapping sites for large tilting angles.

### 3 Basic Setup for Measuring the Diffraction Pattern Behind a Pinhole

#### 3.1 Overview of Experimental Apparatus

We designed and constructed an experimental setup that can directly measure the intensity pattern behind a pinhole for angles of incidence ranging from 0° to 30°. The experimental setup is shown in figure 4 and figure 5. The apparatus uses a 780nm diode
laser in TEM\textsubscript{00} mode that is temperature controlled to avoid any laser fluctuations due to room temperature changes. The temperature of the diode laser is stabilized with a heat sink system and two thermoelectric coolers (TECs). The current of the laser and the TECs are managed with a Thorlabs ITC-502 laser controller. The parameters used by the laser controller for this experiment is a current of 100.0mA and a temperature of 12.493k\textdegree\;C (13.241°C). Two mirrors are used to maneuver the incident laser light to be vertically level with the pinhole to avoid any unintentional vertical angles. The first mirror, called \textit{m1}, is 1-inch in diameter and placed such that it is directly in front of the laser and the beam strikes the center of the mirror. The second mirror, called \textit{m2}, is 2 inches in diameter and is placed on a stage that can be moved on a horizontal rail, which will be important when taking scans for various incident angles. Both mirrors are mounted in a kinematic mount that can vary the reflected beam vertically and horizontally, which will be discussed in more detail in the later sections. A 100\textmu m diameter pinhole is glued to a customized c-shaped mount in order to avoid blocking of the incident laser light for large angles. Mechanical engineering student and fellow researcher Bert Copsey and I designed and machined this c-mount. The c-mount is attached to a post, which is further attached to a manually adjustable 3D translation stage. The post is shaved down so that the photodiode can be directly behind the pinhole.

Behind the pinhole is a photodiode, which is attached to a 3D translation stage that moves in three dimensions of space (X, Y, and Z). The photodiode is a UDT-555D photodiode from OSI Optoelectronics that is highly sensitive and has a low noise operational amplifier. The 3D translation stage has a range of 50mm in all three directions and can be controlled manually using the joystick on the individual Thorlabs TDC001 Servo Motor Driver Cubes or by inputting the desired position of each motor using a LabVIEW program provided by Thorlabs. A 5\textmu m diameter pinhole is mounted on the photodiode to increase the spatial resolution of the intensity measurements. In order to allow for long scan times (~2 weeks), the photodiode is powered by a wall plug instead of batteries with no observable effects from the 60Hz noise. The photodiode is connected to the 3D translation stage with various posts and clamps such that the center of the X and Y range of the motors puts the photodiode in a position that is approximately at the center of the pinhole. We adjust the zero position of the Z motor such that it is about where the pinhole would be. The following sections give detailed instructions for further assembling the apparatus for scans at normal incidence and at an angle, and the programs used to take the scans and visualize the intensity readings.
3.2 Mounting the Pinhole to the C-Mount

First, we cleaned the c-mount, tweezers, and the pinhole (if necessary) with methanol. The Melles-Griot 04 PIP 015 pinhole was previously manufactured using a high-powered laser that makes a 100µm diameter circular aperture in a thin piece of foil. We used a microscope to determine which side of the foil we want to mount facing away from the incident laser beam in our setup to avoid adverse effects of imperfections on our diffraction pattern. We observe ejecta on one side of the foil around the pinhole, and then we label this side with a dot on the foil far from the pinhole. This side will be the surface
that we mount facing away from the incident laser beam and towards the photodiode. When mounting the pinhole on the c-mount, place a small drop of super glue on the edge of a toothpick. Then, apply a thin layer of the adhesive to the edge of the c-mount that will be facing towards the photodiode and where the thin foil of the pinhole will be touching the c-mount. Use the clean tweezers to place the labeled side of the aluminum foil facing away from the thin layer of super glue. Then, use a clean toothpick to apply pressure to the edges of the foil to create a flat and secure surface for the pinhole. Let the adhesive completely dry over night and then check to verify the pinhole surface is visibly flat and secured to the c-mount. The next step is to set up the apparatus to take measurements of the diffraction pattern.

### 3.3 The Basic Setup for Normal Incidence

Begin by attaching the shaved post to the c-mount as seen in figure 6. Then, screw the post to the 3D translation stage such that the pinhole is facing towards the photodiode and is completely flat. Manually adjust the stage in order for the pinhole to be approximately above a hole of the bolt pattern in the optics table. When setting up the normal incidence scans adjust \( m2 \) on the horizontal rail in a position that places the center of the mirror in direct alignment with the bolt pattern on which the pinhole was placed. We use the bolt pattern to give a rough estimate that the reflected beam from \( m2 \) is not at a horizontal angle to the pinhole. Place a screw in the bolt pattern close to \( m2 \) (close screw) and another in front of the pinhole (far screw), and both screws should be on the same line of the bolt pattern. Then, adjust an iris such that its center is at the same height as the pinhole. Place the iris at the far screw and adjust the horizontal and/or vertical screws of \( m2 \) in order to get the laser beam at the center of the iris. Then, place the iris at the close screw and adjust the horizontal and/or vertical screws of \( m1 \) in order to get the laser beam, again, at the center of the iris. Repeat this procedure until the beam is at the center of the iris at both the close screw and the far screw.

Move the photodiode away from the pinhole by manually adjusting the Z-motor or by using the LabVIEW program that will be discussed in section 3.4.1. Place the photodiode far enough away from the pinhole in order to place a note card behind (~15mm) and adjust an infrared (IR) camera to face the note card. See figure 7 for a picture of this setup. Next, alter the vertical and horizontal knobs of the manually adjustable 3D translation stage until a spot on the note card appears from laser light shining through the pinhole. Continue to adjust the horizontal and vertical knobs until the spot on the note card is brightest. Note that for this step, we lowered the current of the laser to avoid saturation of the camera during fine adjustment of the pinhole position to the precise center of the laser beam.

Next, we adjust the photodiode until it is directly behind the pinhole. Use a flashlight to shine light between the photodiode and the pinhole to observe the distance when the light is no longer visible. In the next sections we will discuss the LabVIEW program’s ability to control the X, Y, and Z motors, take intensity measurements at each
Z position, save the information in a text file, read in that file and create an X-Y profile for each scan, and save the information as a matrix that can be interpreted by Mathematica.

Figure 7: Setup for using an IR camera and note card to see the spot behind the pinhole in order to adjust the pinhole at normal incidence (section 3.3) or to adjust the incident beam at angle (section 4.2).

3.4 Overview of LabVIEW Programs

3.4.1 Movement and Data Read

There are two LabVIEW programs that are used to read the diffraction pattern information from the photodiode into interpretable data. The first program that is used to measure the pattern is called “MovementandDataRead,” which controls the three motors, the channel used, and the file path for the intensity data received by the photodiode. Figure 8 shows the front panel of “MovementandDataRead.” Figure 18 in the appendix shows the LabVIEW block diagram for “MovementandDataRead.” Before taking any scans verify the channel being used by the program, in the “channel (0)” drop down menu, is the same as the channel the photodiode is attached to on the DAQ board attached to the computer. The photodiode signal was attached to Channel 0 on the DAQ board for this experiment. The photodiode reads a voltage that can be interpreted as a power reading per area (of the 5µm pinhole), which gives an intensity reading for each step. The diffraction pattern is measured by taking power readings for a row of X steps for every Y step to create a 2D matrix. Then, the photodiode repeats the sequence for each Z step, which results in a 3D matrix. When taking a scan there are three parameters that manipulate the position of the photodiode in relation to the diffraction pattern. The Iterations refers to the number of steps the photodiode moves and the Step Size (SS) refers to the distance the photodiode moves per step. The Home Position (HP) is the starting position of the photodiode.

After the basic setup for normal incidence is complete, we take a low-resolution scan of the X-Y profile in order to get a basic idea where the pattern is located. The low-resolution scan is a 4mm by 4mm scan in the X-Y plane, and consists of parameters: 40 Iterations in the X and Y directions, 0.1 mm SS in the X and Y directions, 1 Iterations in the Z direction, 0 mm SS in the Z direction, and an arbitrary starting home position (-2,-
See Table I for an outline of the parameters used for a low-resolution scan to determine the home position. Before running the LabVIEW program make sure to update the path and file name, and make sure the file name has a “.txt” ending. Run “MovementandDataRead” and the next section discusses the second program used to interpret the saved data.

![Figure 8: Labeled front panel of LabVIEW program “MovementandDataRead.”](image)

**Table 1:** The scanning parameters for normal incidence at a) low-resolution, b) medium-resolution, and c) high-resolution.

<table>
<thead>
<tr>
<th>a) low-resolution scan for normal incidence</th>
<th>b) medium-resolution scan for normal incidence</th>
<th>c) high-resolution scan for normal incidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Iterations 40</td>
<td>SS X 0.1</td>
<td>X HP -2</td>
</tr>
<tr>
<td>Y Iterations 40</td>
<td>SS Y 0.1</td>
<td>Y HP -2</td>
</tr>
<tr>
<td>Z Iterations 1</td>
<td>SS Z 0</td>
<td>Z HP 0</td>
</tr>
</tbody>
</table>

### 3.4.2 Automated Read

Once the scan is finished, the second LabVIEW program, named “AutomatedRead,” is needed to read in the previously saved information and create a new text file that creates a 2D array of power readings for every Z iteration and saves it as “z is #u.txt,” where # stands for the Z position in microns of the X-Y slice saved here. Figure 9 shows the front panel for “AutomatedRead.” Figure 19 in the appendix shows the LabVIEW block diagram for “AutomatedRead.” We input the same filename used in “MovementandDataRead” in the box indicated by “Read file path,” and input a filename
for the new matrix data to be saved in the box named “Main File Path.” We found it is helpful to save the data from both LabVIEW programs in the same folder. In order to create a matrix of the appropriate size, we input the parameters used in “MovementandDataRead” into the suitable boxes in “AutomatedRead.” For example, to read in the low-resolution scan, we input “40” into the “X Iterations” and “Y-Iterations” boxes, “1” into the “Z Iterations” box, “0” into the “starting Z value” and “Z iteration size.” Calculate the product of the X Iterations and Y Iterations (40 x-iterations * 40 y-iterations = 1600) and input that value in the “Product of X and Y iterations” box. “AutomatedRead” also shows an image of the X-Y profile intensity pattern for each Z-iteration. Run the program and an Intensity Graph will appear as seen similar to figure 9. In the near future, we plan to streamline this process by saving the parameters from “MovementandDataRead” in the header of the saved file and read them in automatically so no manual input besides the file name will be needed.

![Image](image-url)

**Figure 9:** Front panel of LabVIEW program “AutomatedRead” for low-resolution, medium-resolution, and high-resolution scans at normal incidence.

### 3.4.3 Determining the Home Position

The next step is to adjust the home position in “MovementandDataRead” such that the diffraction pattern at Z=0mm is in the center of the Intensity Graph for our complete scan of the entire diffraction pattern. The low-resolution scan results in an Intensity Graph as seen in figure 9. If there is no visible “dot,” then you need to repeat the previous two sections with a new arbitrary home position. From the low-resolution Intensity Graph, we want to alter the home position such that the “dot” is at the lower left corner of the Intensity Graph. We approximate the number of steps needed to move in the X and/or Y direction of the Intensity Graph, and then multiply that value by the SS to determine the values needed to add or subtract to our previously assumed home position. For instance, as shown in the low-resolution scan in figure 9, the “dot” is approximately 30 steps to the right and 33 steps up. Then we multiply those values to the SS, 0.1 mm, and our result is 3mm in the X-direction and 3.3mm in the Y-direction. Since we want the
“dot” to be in the lower left corner, this corresponds to moving the Intensity Graph up and to the right, or “+X” and “+Y” as indicated in figure 10. Therefore, we add both our X and Y values to their respective previous HP, (-2,-2,0), which results in our new home position to be (1,1.3,0).

Repeat the procedure discussed in sections 3.4.1 and 3.4.2 with the medium-resolution scan with parameters outlined in table I(b), and repeat the above procedure until the “dot” is in the bottom left corner of the Intensity Graph. Next, do a high-resolution scan with parameters outlined in table I(c), which should result in a visible X-Y profile of the diffraction pattern at Z=0mm. Adjust the home position until the pattern is approximately at the center of the Intensity Graph. The next chapter describes the procedure to correct for beam movement at normal incidence and how to take scans at an angle.

Figure 10: The Intensity Graph in “Automated Read” and how to interpret adding (+X or +Y) or subtracting (-X or -Y) to the home position. Determine the correct home position by adjusting the dot to be in the bottom left corner.

4 Measuring and Visualizing the Diffraction Pattern

4.1 Setup Adjustments for Normal Incidence

For normal incidence, we want to verify the incident laser beam through the pinhole is not at any angle. We can do this by taking two X-Y profile beam scans at Z=0mm and Z=3mm, then adjusting the horizontal and/or vertical screws on m1 and m2. Note that Z=3mm is the maximum z-value used because the localized bright and dark spots for a 100µm pinhole all occur within 3mm. Use the medium-resolution scan parameters shown in table II(a). If the beam profile does shift in the X and/or Y direction then we adjust the horizontal and/or vertical screws of m1 and m2. Before altering the mirrors, place and modify an iris in front of the c-mount (as close as possible) as done previously in section 3.3. This allows us to modify the incident beam angle with out altering the home position; however, minor adjustments may be necessary to the home position to ensure the diffraction pattern is at the center of the Intensity Graph. Table III outlines the method used to adjust the mirrors properly to correct for any beam shift. For instance, if diffraction pattern at Z=0mm is in the lower left corner of the Intensity Graph and the pattern shifted right at Z=3mm, then turn the horizontal screw on m1 clockwise
approximately 2 turns and turn the horizontal screw on \( m_2 \) counterclockwise until the incident beam is at the original position, or the center of the iris. Then, repeat the table II(a) parameters until the beam does not shift from \( Z=0 \text{mm} \) to \( Z=3 \text{mm} \). The next step is to take a high-resolution scan with parameters shown in table II(b), and verify that the diffraction pattern is at the center of the Intensity Graph at \( Z=0 \text{mm} \) and \( Z=3 \text{mm} \) for the calculated home position.

Lastly, take a scan of the entire diffraction pattern using the parameters indicated in table II(c). These scans take approximately 2.5 weeks, but you can pause the program and use “AutomatedRead” to verify the pattern is on the right track and there are no significant problems. Some possible problems that may occur are power outages, laser beam interruption, and most recently the 100\( \mu \text{m} \) pinhole seems to be damaged due to an unknown cause. After completing the scan at normal incidence, we began taking scans for various angles to determine any pattern changes and the largest possible angle.

<table>
<thead>
<tr>
<th>a) medium-resolution scan for beam shift</th>
<th>b) high-resolution scan for beam shift</th>
<th>c) complete scan for normal incidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Iterations</td>
<td>SS X</td>
<td>X HP</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>**</td>
</tr>
<tr>
<td>Y Iterations</td>
<td>SS Y</td>
<td>Y HP</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>**</td>
</tr>
<tr>
<td>Z Iterations</td>
<td>SS Z</td>
<td>Z HP</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Table II: The scanning parameters to verify the beam does not shift at normal incidence for a) medium-resolution and b) high-resolution. Part c) gives the scanning parameters for measuring the complete diffraction pattern behind a pinhole at normal incidence.

<table>
<thead>
<tr>
<th>Pattern Shift</th>
<th>( m_1 ) screw</th>
<th>( m_2 ) screw</th>
</tr>
</thead>
<tbody>
<tr>
<td>left</td>
<td>horizontal CCW</td>
<td>horizontal CW</td>
</tr>
<tr>
<td>right</td>
<td>horizontal CW</td>
<td>horizontal CCW</td>
</tr>
<tr>
<td>up</td>
<td>vertical CCW</td>
<td>vertical CW</td>
</tr>
<tr>
<td>left</td>
<td>vertical CW</td>
<td>vertical CCW</td>
</tr>
</tbody>
</table>

Table III: The adjustments to \( m_1 \) and \( m_2 \) for different pattern shifts from \( Z=0 \text{mm} \) to \( Z=3 \text{mm} \). CW stands for clockwise and CCW stands for counterclockwise.

### 4.2 Setup for Scans at an Angle

When changing the apparatus for various angles, we alter the position of \( m_2 \) by adjusting the stage on the horizontal rail. As seen in figure 11, the angle is determined by measuring \( d_1 \), the pinhole to \( m_2 \) distance at normal incidence, and \( d_2 \), the distance \( m_2 \) is moved on the horizontal rail. We measured \( d_1 \) by placing one end of a string on the edge of the pinhole post (closest to the photodiode) and the other end of the string at the beam intersection point, and then measure the string with a ruler. When measuring \( d_2 \), we
marked the position of $m_2$’s stage at normal incidence and again the position for measurement at an angle, and then measured the distance between the marks with a ruler. The angle is calculated by the geometric expression $\tan \theta = \frac{d_2}{d_1}$.

To ensure that the beam is properly incident on the pinhole, a similar procedure is used as discussed earlier for normal incidence. As seen in figure 7, move the photodiode away from the pinhole and place a note card with an IR camera facing it, and then adjust $m_2$ horizontally such that the dot on the note card is brightest. Note that after normal incidence you do not need to adjust the vertical screws on $m_1$ nor $m_2$, otherwise you will have to repeat the previous procedure to ensure the beam is not at any vertical angle. The next step is to determine the home position of the diffraction pattern similarly as before for normal incidence. Repeat the procedure outlined in sections 3.4.1, 3.4.2, and 3.4.3 to determine the home position, then the next section outlines the procedure to determine the re-home parameter for an angle to avoid very long scan times for high-resolution scans.

![Figure 11](image)

**Figure 11:** The experimental setup for taking scans at angle $\theta$ such that $d_1$ is measured with a string from the shaved post to the laser beam and $d_2$ is measured as the distance the mirror stage moves from its normal incidence position on the horizontal rail.

### 4.3 Determining the Re-Home Parameter for Scans at an Angle

When taking scans at an angle, we added a re-homing parameter to the LabVIEW program in order to make the scans high-resolution without taking additional time to complete a scan. The added re-home parameter adjusts the home position of X for each Z-iteration. This re-home parameter, called “X Re-Home (mm),” allows the X-Y beam profile to be the same size and resolution as normal incidence without the cost of time and blank space.

Once the home position at $Z=0$mm is established for a certain angle, we determine the re-home parameter. The re-home parameter is the distance in the x-direction that the beam shifts per Z iteration. We measure the re-home parameter by taking a medium-
resolution scan at Z=0mm and at Z=3mm, then we calculate the distance in the X direction the center of the pattern has shifted per 3mm Z-iteration. Note that the re-home parameter in LabVIEW has units of millimeters. For example, if the center of the diffraction pattern for Z=0mm is at step 5 and the center of the pattern for Z=3mm is at step 10, then the beam shifted 0.25mm [(10-5 steps)*0.05 step-size]. Add this value into the “X Re-Home (mm)” and continue taking scans at Z=0mm and Z=3mm at medium-resolution until the beam does not shift in the X direction. Again, repeat this procedure with the parameters for high-resolution scans at Z=0mm and Z=3mm until the center of the pattern is not shifting in the x-direction. Table IV(a,b) outlines the parameters used for medium-resolution and high-resolution for determining the re-home parameter. Once the pattern does not shift from Z=0mm and Z=3mm, then we have established the re-home parameter for that specific angle. We need to adjust the re-home parameter for a complete scan because the step size in the Z direction is different. Since the high-resolution scan has 0.02mm steps in the Z direction, then we adjust the re-home parameter by multiplying by 0.00666 (0.02mm/3mm). Then, take a complete scan of the pattern at high-resolution after calculating the necessary re-home parameter for the new step size. Table IV(c) outlines the parameters used for a long, high-resolution scan at an angle. The next section discusses the Mathematica code created to visualize the diffraction pattern.

<table>
<thead>
<tr>
<th>X Iterations</th>
<th>Y Iterations</th>
<th>Z Iterations</th>
<th>X-Home SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.05</td>
<td>3</td>
<td>**</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Table IV: The scanning parameters used to determine the re-home parameter (**) for an angle with a) medium-resolution or b) high-resolution. Part c) gives the scanning parameters for measuring the complete diffraction pattern behind a pinhole at angle.

### 4.4 Data Visualization for Scans

The data from “AutomatedRead” is saved as text files for each Z iteration. We use Mathematica to read in the data and create an array that can be visualized as density plots in 2D. See appendix figure 16 for the code and various visualization techniques. For normal incidence scans each Z iteration text file is read in and added to a larger array. By using the ListDensityPlot command we create X-Y density plots and X-Z density plots. For scans at an angle, an extra step is needed to add zeros to each Z-iteration to compensate for the re-home parameter. See appendix figure 17 for the Mathematica code for scans at an angle. The large array created causes a longer evaluation time, but all data can be interpreted in the same manner as with the normal incidence scan.
5 Experimental Results for the Diffraction Pattern Behind a Pinhole

The initial goal of this experiment was to determine the largest angle possible that ensures the bright and dark spots of the diffraction pattern are still feasible for atom trapping and quantum computations. We took scans for normal incidence and various angles, then we found the bright and dark spots by analyzing the X-Y density plots and choosing the second to last bright region and the last dark region respectively that is consistent with the computational results [6]. The angles we measured the diffraction pattern for are 6.7°, 16.9°, 27.2°, and 31.0°. Table V and table VI summarize the parameters used for each angle and the file path of the saved data for each angle measured, respectively. The Y-X intensity profiles of the bright spots are shown in figure 12. Similarly, the Y-X intensity profiles for the dark spots are shown in figure 13. The resulting X-Z plots are shown in figure 14. At approximately 35° we began to have light scattering at nearly the same intensity as the diffraction pattern as shown in figure 15. This may be due to the spacing between the 5µm pinhole and the photodiode sensor, or possibly light scattered from the c-mount into the photodiode.

We have the computational results for small angles as seen in section 2.3.1. Fellow researcher, Travis Frazer, is currently calculating the diffraction pattern behind a pinhole at large incident angles. We qualitatively compared our experimental results with our computational results. We found similarities in the features of both the experimental and computational intensity patterns for small and large angles. In the future we plan to do a full numerical comparison of our experimental results with computations and determine up to which angle the trapping sites are feasible for trapping and manipulating neutral atoms for quantum computations.
Figure 12: Experimental results for the bright spots that occur for an incident angle of 0°, 6.7°, 16.9°, 27.2°, and 31.0° using a 780nm laser and a 100µm diameter pinhole. Intensity scales are arbitrary.

Figure 13: Experimental results for the dark spots that occur for an incident angle of 0°, 6.7°, 16.9°, 27.2°, and 31.0° using a 780nm laser and a 100µm pinhole. Intensity scales are arbitrary.
Figure 14: Experimental results for the X-Z plots that occur for an incident angle of 0°, 6.7°, 16.9°, 27.2°, and 31.0° using a 780nm laser and a 100µm pinhole. Intensity scales are arbitrary.

Figure 15: The light scattering that occurs for an incident angle of 35°. Intensity scales are arbitrary.
6 Conclusion

Trapping neutral atoms in optical dipole traps from detuned laser light has been previously shown to be a feasible approach for quantum computing. We plan to trap atoms in the diffraction pattern from laser light incident on a pinhole. The bright and dark spots, depending on if the laser is red or blue detuned, have been computed to have potential energy wells that are deep enough for trapping neutral atoms and manipulating them for quantum computing. In particular, pairs of trapped atoms can be brought together and apart by tilting the incident laser beams.

The goal of this study was to determine the largest angle for which the atoms can be confined in these traps. We successfully designed and built an experimental apparatus that can measure the intensity pattern directly behind a pinhole for incident angles up to 35°. We found features similar to our computational results for small angles and full analysis is underway for large angles.
References


Appendix
Figure 16: Mathematica code for normal incidence (0°).

```mathematica
(*input scanning parameters*)
angle0xstart = 0;
angle0xstepsize = 40;
angle0xmax = 2960;
angle0xsteps = 150;
angle0ysteps = 150;
angle0xsteps = 75;

(*Read in each x-slice and create a 3D array of each set of x-
slice's per y-slice and each set of y-slice's per x-
slice and the entire set of x-slice's in a new array called "normArray".*)
SetDirectory["C:\Danil\SCANS2012\NormInc"]
normArray = {};
For[i = angle0xstart, i <= angle0xmax, i = i + angle0xstepsize,
    angle0xslice = StringJoin["C:\Danil\SCANS2012\NormInc\s is ",
       ToString[angle0xstart], ",\ u.txt"];
    angle0xslice = ReadList[angle0xslice, Real, WordSeparators -> {"\t"},
       RecordLists -> True];
    AppendTo[normArray, angle0xslice]];

C:\Danil\SCANS2012\NormInc
angle0xScan = {};
For[j = 1, j <= angle0ysteps, j = j + 1,
    AppendTo[angle0xScan, normArray[[j, 70]]]];
angle0xImage = ListDensityPlot[angle0xScan, ColorFunction -> GrayLevel]

Export["C:\Danil\IMAGES/XPLOTS/NormInc_70xstep.jpg", angle0xImage]
C:\Danil\IMAGES/XPLOTS/NormInc_70xstep.jpg
```

22
In[20]:=
angle0xyImage = ListDensityPlot[
Table[normArray[[10, i]], {i, 1, angle0xsteps}], ColorFunction -> GrayLevel]

Export["C:/Dani/IMAGES/XYPLOTS/NormInc/Angle2_10steps.jpg", angle0xyImage]
Out[20]= C:/Dani/IMAGES/XYPLOTS/NormInc/Angle2_10steps.jpg

In[34]:=
Manipulate[ListDensityPlot[Table[normArray[[u, i]], {i, 1, angle0xsteps}],
ColorFunction -> GrayLevel], {u, 1, angle0xsteps, 1}]
Figure 17: Mathematica code for angle 2 (27.2°).

```mathematica
(*input scanning parameters for angle 2*)
angle2xstart = 0;
angle2xstepsize = 20;
angle2xmax = 2980;
angle2xsteps = 150;
angle2ystart = 0;
angle2ystepsize = 20;
angle2ymin = 27.2;
(*Added parameter for angle scans*)
age2xhome = 10;
age2xmax = angle2xsteps * angle2xhome;

(*Read in each z-slice and create a 3D array of each set of x-slice's per y-slice and each set of y-slice's per z-slice and the entire set of z-slice's in a new array called "angle2array")*
SetDirectory["C:\Danni\SCANS2012\Angle 2"]
angle2array = {};
For[j = angle2xstart, angle2xstart = angle2xstart + angle2xstepsize, angle2readzslice = StringJoin["C:\Danni\SCANS2012\Angle 2\z\", ToString[angle2xstart], ",\n.txt"];
    angle2zslice = ReadList[angle2readzslice, Real, WordSeparators -> {"\t"}, RecordLists -> True];
    AppendTo[angle2array, angle2zslice];

(*Add zero's to create the appropriate array for the angle*)
angle2position = 0;
age2tablezslice = {};
For[k = 1, k <= angle2xsteps, k++,
    For[i = 1, i <= angle2xsteps, i++,
        angle2tablebefore = Table[0, {a, 1, angle2position}];
        angle2tableafter = Table[0, {a, 1, angle2xmax - angle2position}];
        angle2tablexslice = Join[angle2tablebefore, angle2array[{k, i}], angle2tableafter];
        AppendTo[angle2tablezslice, angle2tablexslice];
    ];
    angle2position = angle2position + angle2xstepsize;
]
age2mainTable = Partition[angle2tablezslice, angle2xsteps];
```

2 | MathematicaCodeAngle2_1182012.nb

(*Create 2D plot of xy plane for a specified z-slice called "angle2z")
angle2z = 43;
age2xyImage = ListDensityPlot[Table[angle2array[angle2z, i], {i, 1, angle2xsteps}],
    ColorFunction -> GrayLevel, PlotLabel -> StringJoin["27.2 degrees: X vs Y plot at ", 
    ToString[angle2z + angle2xstepsize], " microns"], FrameTicks -> False]

27.2 degrees: X vs Y plot at 860 microns
In[78]:= (*Create 2D plot of xy plane for a specified x-slice called "angle2x"*)
(*Determine angle2x by estimating the center of the pattern in the xy plot and manually enter*)
angle2x = 60;
angle2xScan = {};
For[j = 1, j <= angle2xsteps, j = j + 1,
  AppendTo[angle2xScan, angle2mainTable[[j, angle2x]]]];
angle2xImage = ListDensityPlot[angle2xScan, ColorFunction -> GrayLevel,
  PlotLabel -> StringJoin["27.2 degrees; Z vs X plot at ",
  ToString[angle2x], " X steps"], FrameTicks -> False]

27.2 degrees; Z vs X plot at 60 X steps

Out[78]=

In[81]:= Export["C:/Dani/IMAGES/DataImages/Angle2_XPlot_60xstep.jpg", angle2xImage]

Out[81]= C:/Dani/IMAGES/DataImages/Angle2_XPlot_60xstep.jpg

In[82]:= Export["C:/Dani/IMAGES/DataImages/Angle2_XPlot_43steps_BrightSpot.jpg", angle2xImage]

Out[82]= C:/Dani/IMAGES/DataImages/Angle2_XPlot_43steps_BrightSpot.jpg

(*Manipulate the x-slice to determine basic range of bright and dark spots*)
Manipulate[ListDensityPlot[Table[angle2array[[u, l]], {u, 1, angle2xsteps}],
  ColorFunction -> GrayLevel], {l, 1, angle2xsteps, 1}]

Out[84]=

25
Figure 18: Block diagram for LabVIEW "C:/Data/Dani/MovementandDataRead_11-18-2012.vi."
Figure 19: Block diagram for “C:/Data/Dani/AutomatedRead_11-18-2012.vi.”
Table V: The scanning parameters for each angle and the zstep of each angle’s bright and dark spots.

<table>
<thead>
<tr>
<th>Angle (degrees)</th>
<th>Date</th>
<th>X/Y steps</th>
<th>X/Y iter (mm)</th>
<th>Z steps</th>
<th>Z iter (mm)</th>
<th>X-ReHome (mm)</th>
<th>Bright Spot (zstep)</th>
<th>Dark Spot (zstep)</th>
</tr>
</thead>
<tbody>
<tr>
<td>normInc / 0</td>
<td>4/2/12</td>
<td>150/150</td>
<td>0.001</td>
<td>75</td>
<td>0.04</td>
<td>0</td>
<td>26</td>
<td>38</td>
</tr>
<tr>
<td>Angle3 / 6.7</td>
<td>6/20/12</td>
<td>150/150</td>
<td>0.001</td>
<td>150</td>
<td>0.02</td>
<td>0.0024</td>
<td>53</td>
<td>77</td>
</tr>
<tr>
<td>Angle1 / 16.9</td>
<td>1/20/12</td>
<td>100/100</td>
<td>0.0015</td>
<td>50</td>
<td>0.05</td>
<td>0.0145</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>Angle2 / 27.2</td>
<td>5/17/12</td>
<td>150/150</td>
<td>0.001</td>
<td>150</td>
<td>0.02</td>
<td>0.01</td>
<td>43</td>
<td>61</td>
</tr>
<tr>
<td>Angle5 / 31.0</td>
<td>8/5/12</td>
<td>200/150</td>
<td>0.001</td>
<td>90</td>
<td>0.04</td>
<td>0.024</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Angle7_1 / 35</td>
<td>9/5/12</td>
<td>100/200</td>
<td>0.01</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Angle7_2 / 35</td>
<td>9/5/12</td>
<td>150/150</td>
<td>0.001</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Table VI: The file location of the saved data for each scan.

<table>
<thead>
<tr>
<th>Angle (degrees)</th>
<th>File name</th>
</tr>
</thead>
<tbody>
<tr>
<td>normInc / 0</td>
<td>C:\Data\Dani\Dani_Fall12\SCANS\NormInc</td>
</tr>
<tr>
<td>Angle3 / 6.7</td>
<td>C:\Data\Dani\Dani_Fall12\SCANS\Angle 3</td>
</tr>
<tr>
<td>Angle1 / 16.9</td>
<td>C:\Data\Dani\Dani_Fall12\SCANS\Angle 1\REHOME</td>
</tr>
<tr>
<td>Angle2 / 27.2</td>
<td>C:\Data\Dani\Dani_Fall12\SCANS\Angle 2</td>
</tr>
<tr>
<td>Angle5 / 31.0</td>
<td>C:\Data\Dani\Dani_Fall12\SCANS\Angle 5</td>
</tr>
<tr>
<td>Angle7_1 / 35</td>
<td>C:\Data\Dani\Dani_Fall12\SCANS\Angle 6\1</td>
</tr>
<tr>
<td>Angle7_2 / 35</td>
<td>C:\Data\Dani\Dani_Fall12\SCANS\Angle 6\2</td>
</tr>
</tbody>
</table>