ABSTRACT

BUILDING AND DETECTING AN OPTICAL LATTICE

by Samuel Gerard Bish

The purpose of this thesis is to trap $^{85}\text{Rb}$ atoms in an optical lattice (a series of light-shifted optical potentials), and then verify the existence of a lattice through the use of Bragg scattering. An optical lattice requires the use of a magneto-optical trap to first collect the rubidium atoms and cool them to the Doppler limit ($143 \, \mu\text{K}$ for $^{85}\text{Rb}$), the optical lattice is capable of cooling atoms far below the Doppler cooling limit ($\sim 10 \, \mu\text{K}$). For this project we decided to start from scratch with an all new vacuum chamber, which required the construction of new magnetic coils (to cancel the Earth’s magnetic field and to apply a magnetic gradient to the chamber necessary for the magneto-optical trap), as well as the use of a new method of leaking rubidium into the chamber. When we started it was necessary to overhaul the entire vacuum system and the lasers necessary to trap the atom. This thesis describes the progress achieved toward building the optical lattice.
BUILDING AND DETECTING AN OPTICAL LATTICE

A THESIS

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Dedicated to my mom

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Chapter 1

Introduction

Laser cooling and trapping is becoming quite a popular and heavily researched field, as evidenced by the recent Nobel laureates in laser trapping. Laser cooling and trapping has a vast number of possibilities such as, but not limited to: observation of atomic motion with an emphasis on Brownian motion, Levy flights and walks; quantum computation, the eventual goal of creating a real quantum computer, etc.

Some of the coldest atoms in the universe are currently being cooled in optical lattices, which are periodic–light shifted optical potentials. With an optical lattice you can specify the structure of the lattice and the density (or number of sites occupied) by atoms, you can essentially create your own crystal. The primary cooling mechanism behind optical lattices is Sisyphus cooling, where the atom loses energy (over many cycles) through transitions from well to well.

Before atoms can be cooled in an optical lattice, they must first be cooled and collected in a magneto–optical trap (MOT). The MOT is actually a combination of two previous cooling trapping methods: the optical molasses and the magnetic trap. The primary purpose of an optical molasses is to cool atoms through the use of Doppler cooling. By illuminating an atom with six laser beams, tuned to resonance, the atom will absorb and spontaneously emit photons. Since the emission of photons is random, they will average out to zero over several cycles. This leaves the primary force on the atom being the absorption of photons from the light, meaning that the atom has an overall loss in momentum and kinetic energy. Since kinetic energy is directly related to the temperature of the atom, the atom cools as it slows down. The magnetic gradient applies a position dependent force on the atom through interactions between the splitting of the magnetic sublevels of the atom and the incident lasers.

It is very important to distinguish the differences between and optical lattice and a MOT: not only does the optical lattice cool the atoms much lower than the MOT can (143 $\mu$K in the MOT for $^{85}$Rb and $\sim$ 10 $\mu$K for the lattice) but also the atoms in a MOT are disordered and atoms in a lattice are arranged in a crystal–like structure. This crystal–like structure allows us to use the classic method of Bragg scattering to probe the lattice and make determinations as to the presence of a lattice as well as the relative density of atoms in the lattice (number of sites filled).
Part I

Theoretical Background
Chapter 2

Laser Cooling and Trapping

The impetus behind laser cooling is that because there is a direct relationship between the velocity of an atom and the temperature, we can cool an atom by slowing it down. Cooling atoms is accomplished with an optical molasses, which makes use of Doppler cooling. The atoms are collected by applying a magnetic gradient across the trap region. The combination of an optical molasses and a magnetic gradient is called a magneto–optical trap.

2.1 Optical Bloch Equations

The optical Bloch equations are the basis for the theory behind laser cooling and trapping. Assume we have a simple two–level atom with excited and ground states, \( |e\rangle \) and \( |g\rangle \), respectively. Quantum mechanically, we can calculate the probability of the atom being in the ground or excited state (or population densities) by taking the outer product of \( |e\rangle \) and \( |g\rangle \),

\[
\rho_{ee} = |e><e| \quad \text{(2.1)}
\]

or

\[
\rho_{gg} = |g><g|. \quad \text{(2.2)}
\]

The outer product, \( \rho \), is usually referred to as the atomic density operator and can alternatively be represented as the multiplication of the probabilities of the two states,

\[
\rho_{ee} = |e><e| = c_e^*c_e \quad \text{(2.3)}
\]

\[
\rho_{gg} = |g><g| = c_g^*c_g. \quad \text{(2.4)}
\]

We can now calculate the off diagonal elements of the density matrix, giving the coherence of the atomic state. We can now form our density matrix for a two level atom,
\[ \rho = \begin{pmatrix} \rho_{ee} & \rho_{eg} \\ \rho_{ge} & \rho_{gg} \end{pmatrix} \]  \hspace{1cm} (2.5) \\
\[ = \begin{pmatrix} c_e^* c_e & c_g^* c_e \\ c_g^* c_g & c_e^* c_g \end{pmatrix} \]  \hspace{1cm} (2.6)

By taking the time derivative of each element in the density matrix and using Schrödinger equations for \( c_g \) and \( c_e \), we can calculate the transition rates (for \( \rho_{eg} \) and \( \rho_{ge} \)) as well as the time–dependent populations (\( \rho_{ee} \) and \( \rho_{gg} \))[5],

\[ \frac{d\rho_{gg}}{dt} = \gamma \rho_{ee} + \frac{i}{2}(\Omega^* \rho_{eg} - \Omega \rho_{ge}) \]  \hspace{1cm} (2.7) \\
\[ \frac{d\rho_{ee}}{dt} = -\gamma \rho_{gg} + \frac{i}{2}(\Omega \rho_{ge} - \Omega^* \rho_{eg}) \]  \hspace{1cm} (2.8) \\
\[ \frac{d\rho_{ge}}{dt} = -\left(\frac{\gamma}{2} + i\Delta\right) \rho_{eg} + \frac{i}{2} \Omega^*(\rho_{ee} - \rho_{gg}) \]  \hspace{1cm} (2.9) \\
\[ \frac{d\rho_{eg}}{dt} = -\left(\frac{\gamma}{2} - i\Delta\right) \rho_{eg} + \frac{i}{2} \Omega(\rho_{gg} - \rho_{ee}) \]  \hspace{1cm} (2.10)

Where \( \tilde{\rho}_{ij} = \rho_{ij} e^{-i\Delta t} \), and \( \Delta \) is the detuning from resonance (\( \Delta = \omega_{\text{laser}} - \omega_o \)). \( \Omega \) is the Rabi frequency (\( \Omega \equiv -\vec{d} \cdot \vec{E}/\hbar = -\frac{eE_o}{\hbar} < e|\tau|g > \)), or the transition frequency between states. The Rabi frequency arises from the atomic dipole interaction with the laser. \( \gamma \) is the spontaneous emission rate. An important note at this point is that for a closed system \( \rho_{ee} + \rho_{gg} = 1 \), in other words, the total population for the system remains constant. Equations 2.7–2.10 are known as the optical Bloch equations.

### 2.2 Doppler Cooling

Cooling a moving atom requires that you detune your laser from resonance, because the frequency will be Doppler shifted. In our case, we want an atom to absorb more photons from a laser that it is moving against, thus we detune our lasers to the red. Once an atom absorbs a photon, it spontaneously emits another photon. The net force felt by the atom, also known as the Doppler cooling force, is[2]

\[ F = \hbar k \frac{\gamma}{2} \frac{s_o}{1 + s_o + (2\Delta/\gamma)^2} \]  \hspace{1cm} (2.11)

Where \( s_o \) is the on–resonance saturation parameter, \( s_o = 2|\Omega|^2/\gamma = I/I_s[2] \); and the saturation intensity is given by \( I_s = \pi \hbar c/3\lambda^3 \tau \), where \( \tau \) is the mean decay time \( \tau = 1/\gamma \). When \( s_o \) is much less than 1, the majority of the atoms are in the ground state; as the saturation increases, the population in the excited state approaches 1/2.

If we now illuminate the atom from opposite directions with red detuned lasers, the atom will feel a velocity dependent damping force
\[
F = -\beta v 
\]
\[
= -\frac{8\hbar k^2 s_0 (\Delta/\gamma)}{(1 + (2\Delta/\gamma)^2)^2} v 
\]

Where \( \beta \) is the damping coefficient. Expanding this model again to three dimensions (essentially a 1–D example in the \( x, y \) and \( z \) directions), we create what is called an optical molasses. The purpose of an optical molasses is to cool the atoms to near the Doppler cooling limit (see section 2.3), an optical molasses is not by itself an atom trap because there is no position–dependent restoring force to collect the atoms (see section 2.4).

### 2.3 Doppler Cooling Limit

There is a heating rate and a cooling rate related to the emission and absorption of photons, respectively. When an atom absorbs a photon, the atom loses velocity so it cools down. When the atom spontaneously emits a photon, the velocity of the atom increases giving rise to a heating rate. When the heating rate and cooling rate reach a steady state equilibrium, you have the minimum possible temperature achievable through Doppler cooling.

When an atom of mass \( m \) absorbs a photon with momentum \( \hbar k \), the velocity at which the atom recoils is

\[
v_{\text{recoil}} = \frac{\hbar k}{m} 
\]

For a monatomic, ideal gas we can relate the temperature of the gas to the velocity through the kinetic energy:

\[
\frac{1}{2}mv^2 = \frac{1}{2}k_B T 
\]

\[
T = \frac{mv^2}{k_b} 
\]

By plugging the recoil velocity in to equation 2.16, we can get the temperature associated with the recoil velocity. We can also deduce a cooling rate for our atom:

\[
\left( \frac{dE}{dt} \right)_{\text{cool}} = Fv 
\]

\[
= -\beta v^2 
\]

\[
= -\beta k_B T \frac{m}{m} 
\]

Where \( F \) is the Doppler cooling force (equation 2.11). This is the cooling rate associated with the force applied by an absorbed photon. There is also a heating rate which arises from the re–emission of a photon. Assuming the emitted photon has a momentum of \( \hbar k \),
\[ \Delta E = \frac{(\Delta p)^2}{2m} \]  
\[ = \frac{2(\hbar k)^2}{m} \]  
\[ (2.20) \]

The rate at which the photons are emitted depends on the spontaneous emission rate \( (\gamma) \) and the population density of the excited state \( (\rho_{ee}) \),

\[ \left( \frac{dE}{dt} \right)_{\text{heat}} = \gamma \rho_{ee} \frac{2(\hbar k)^2}{m} \]  
\[ (2.22) \]

This is known as the heating rate. Once the heating rate and cooling rates reach a steady state, we can equate them and after some algebra we arrive at the minimum temperature possible through Doppler cooling\[1\],

\[ T_{\text{min}} = \frac{\hbar \gamma}{2k_B} \]  
\[ (2.23) \]

Since \(^{85}\text{Rb}\) is the most abundant isotope of rubidium (72%), that is the isotope that we choose to trap. Plugging in the spontaneous emission rate for \(^{85}\text{Rb}\) (3.75516 MHz\[2\]), the Doppler limit can be calculated to be 143 \( \mu \)K.

### 2.4 Magneto–Optical Trap

The purpose of an optical molasses is to cool the atoms through the use of a velocity dependent force. A MOT, however, seeks to collect those atoms by imparting a position dependent restoring force on them. To develop the theory behind magnetic trapping, we first consider a simple two–level atom with a ground state and an excited state, having total angular momentums of \( J = 0 \) and \( J = 1 \) respectively (see figure 2.1 for an energy level diagram). By applying a magnetic field across the atom, the magnetic sublevels of the excited state split into \( m = -1, 0, +1 \). If we use an inhomogeneous magnetic field, or magnetic gradient, the magnetic sublevel shifts become position dependent. As the magnetic field becomes more positive, the \( \Delta m = -1 \) transition frequency becomes lower, and vice–versa for when the magnetic field becomes more negative, the \( \Delta m = +1 \) transition frequency becomes lower.

Now, if we apply two circularly polarized, oppositely–handed, counter–propagating beams to the atom, we can induce a position dependent force. A \( \sigma^+ \) beam can only trigger a \( \Delta m = +1 \) transition. If we send a \( \sigma^+ \) beam in from the right (see figure 2.1), then the \( \Delta m = +1 \) transition requires a lower excitation voltage. Thus the farther the atom is displaced to the right, the larger the restoring force it feels towards the origin. This idea also applies for when an atom moves to the left, the \( \Delta m = -1 \) transition requires less energy, and since we are conveniently sending in a \( \sigma^- \) beam from the left, the atom feels a restoring force towards the origin.

In order to expand this idea to three dimensions, we need to examine Maxwell’s equations. Looking at Maxwell’s equation for the divergence of a magnetic field (also known as Gauss’ law for magnetism\[6\]),
\[ \vec{\nabla} \cdot \vec{B} = 0 \quad (2.24) \]
\[ \frac{\partial B}{\partial x} + \frac{\partial B}{\partial y} + \frac{\partial B}{\partial z} = 0 \quad (2.25) \]

If the \( x \)-direction is along the axis of the coils (see figure 2.2), then we can solve equation 2.25 for \( x \),

\[ \frac{\partial B}{\partial x} = -\left( \frac{\partial B}{\partial y} + \frac{\partial B}{\partial z} \right) \quad (2.26) \]

This tells us that when we apply a magnetic gradient across the chamber, the magnitude of the gradient in the \( x \)-direction will be double the gradient in either the \( y \) or \( z \) directions. Also, the gradient in the \( x \)-direction will be in the opposite direction of the gradient in the \( y \) and \( z \) axes (see figure 2.3). Great care must be taken experimentally to assure that the polarizations and gradients are arranged as shown in figure 2.3 (see section 7.2 for explanation on how to arrange this setup).

Figure 2.1: Energy level diagram for a MOT.
Figure 2.2: Diagram of a MOT showing polarizations of incident beams and magnetic coils.

Figure 2.3: The gradients are opposite for the $x$ and the $y,z$ directions, giving rise to differences in polarizations.
Chapter 3

Cooling Beyond the Doppler Limit

In order to cool beyond the Doppler limit, we must use a very complicated yet clever way of cooling atoms. The most common apparatus for cooling beyond the Doppler limit is an optical lattice, which is an ordered series of light shifted optical potentials. Optical lattices can be in one, two or three dimensions. The actual cooling mechanism behind optical lattices is Sisyphus cooling.

3.1 Sisyphus Cooling

In Greek mythology, Sisyphus was a king who was punished by the gods to roll a boulder up a hill for eternity. In an optical lattice, an atom is constantly climbing a never ending optical potential. Sisyphus cooling is the primary mechanism used to cool atoms below the Doppler limit. There are three main components to Sisyphus cooling: a polarization gradient, optical pumping, and light shifts.

3.1.1 Polarization Gradient

Assume we have two counter propagating linearly polarized beams, with orthogonal polarizations and a $\pi$ phase difference (also known as a “lin⊥ lin” configuration, see figure 3.1). The interference pattern of the two beams is a wave which alternates polarizations from linear to circular every $\lambda/8$. The circular polarizations alternate between left and right–handed every $\lambda/4$.

3.1.2 Light Shifts

When an atom is in the presence of a magnetic field, the magnetic sublevels of the atom split, this is known as the Zeeman effect. In the simple case of an atom with a ground and excited state, the total angular momentum shifts to $J_g = -\frac{1}{2}, +\frac{1}{2}$ and the excited state shifts to $J_e = -\frac{3}{2}, -\frac{1}{2}, +\frac{1}{2}, +\frac{3}{2}$ (see figure 3.2). The only allowed excitations are ones where $\Delta m = \pm 1$, and the only allowed spontaneous emissions are ones where $\Delta m = 0, \pm 1$.

The Stark shift is analogous to Zeeman shifts, however the Stark shift relies on incident electric fields. If we use a laser beam as our electric field, the atomic shifts are dependent
Figure 3.1: Diagram of polarization gradient[1] and diagram of Sisyphus cooling.

Figure 3.2: Energy level diagram for a two-level atom, with its excited and ground states Zeeman shifted.
upon how close the frequency of the beam is to certain atomic transitions of the atom[1],
and the energy is shifted by:

\[ E_{e,g} = \frac{\hbar}{2}(-\Delta \mp \Omega') \quad (3.1) \]

Where \( \Omega' \) is the generalized Rabi frequency \( (\Omega' = \sqrt{\Omega^2 + \Delta^2}) \). Relating this to the
polarization gradient established by lin\(\perp\)lin setup, in a \( \sigma^+ \) well the magnetic sublevel of the
ground state is is shifted to both \( m_g = -\frac{1}{2}, +\frac{1}{2} \) however the shift to the \( m_g = +\frac{1}{2} \) is about
three times larger in magnitude than the shift to the \( m_g = -\frac{1}{2} \) sublevel[2]. Similarly for
a \( \sigma^- \) well, the magnetic sublevel is shifted to both \( m_g = -\frac{1}{2}, +\frac{1}{2} \), however the shift to the
\( m_g = -\frac{1}{2} \) has the larger magnitude of the two shifts. Thus, the majority of the atoms in an
optical well will be shifted according to the circular polarization of the well.

### 3.1.3 Optical Pumping

Assume we already have a two-level atom, with its excited and ground states shifted as
described in the previous section. Examining an ground state atom that is initially in a \( \sigma^+ \)
well, the atom will most likely be split into the \( J_g = +\frac{1}{2} \) ground state. An atom in the
\( J_g = +\frac{1}{2} \) ground state can only make two possible transitions: \( J_g = +\frac{1}{2} \rightarrow J_e = +\frac{3}{2} \) or
\( J_g = +\frac{1}{2} \rightarrow J_e = -\frac{1}{2} \). Since the atom is in a \( \sigma^+ \) well, the atom will make the transition to
\( J_e = +\frac{3}{2} \). An atom decaying from an excited state must obey the selection rule \( \Delta m = 0, \pm 1 \),
since the only ground state the atom can legally drop down to is \( J_g = +\frac{1}{2} \) then that is
where it goes. Thus the cycle continues for an atom in the \( \sigma^+ \) well. An atom in a \( \sigma^- \) well
will behave exactly the same, except that the most probably state it will be excited to is
\( J_g = -\frac{1}{2} \rightarrow J_e = -\frac{3}{2} \). Thus atoms in \( \sigma^+ \) wells are pumped into the \( J_g = +\frac{1}{2} \) ground state,
and atoms in \( \sigma^- \) wells are pumped into the \( J_g = -\frac{1}{2} \) ground state.

### 3.2 Cooling

In an optical lattice the atom is cooled by losing energy after falling from an excited state to
a lower ground state than it was excited from. Examining figure 3.1, we will start off with an
atom that is initially in the \( J_g = -\frac{1}{2} \) ground state and the atom is in a \( \sigma^- \) well. As the atom
climbs out of the well, the polarization changes form \( \sigma^- \) to \( \sigma^+ \), thus the atom undergoes the
transition \( J_g = -\frac{1}{2} \rightarrow J_e = +\frac{1}{2} \). At this point the atom can legally decay to either ground
state, however atoms usually decay to the lowest ground state possible (\( J_g = +\frac{1}{2} \)). So after
several cycles the majority of the transitions will be to the \( J_g = +\frac{1}{2} \) state, thus the atom has
a net loss in energy after it climbed out of the \( \sigma^- \) well.

The atom may absorb a photon and jump to the excited state at any point, but it is
most likely to make a transition when the polarization is completely circular. Also, the atom
could indeed drop down to the same ground state it was excited from (in the example above,
for instance, the atom would have decayed to \( J_g = -\frac{1}{2} \)), however it is more like the atom
would decay to the lowest possible ground state (i.e. \( J_g = +\frac{1}{2} \)).
3.3 Optical Lattice

An example of a 1–D optical lattice is the conventional lin⊥lin configuration described above. Optical lattices can be created in two and three dimensions, where atoms are Sisyphus cooled along more than one axis. Unlike an optical molasses, you do not need six beams to trap atoms in a lattice, a 3–D lattice can be achieved by only using 4 beams. A 4 beam, three dimensional lattice is usually referred to as an “umbrella” or “Paris” style lattice. A Paris lattice consists of 4 linearly polarized beams with the same polarization and phase difference sent into the trap region. Two of the beams propagate in a horizontal plane and make an angle $2\theta_1$ with each other (see figure 3.3), the beams are also polarized perpendicular to the plane they propagate in. The other two beams propagate in the vertical plane and make an angle $2\theta_2$ with each other, and they are polarized perpendicular to the plane they propagate in. By varying the geometrical angles of the incident beams, we can change the structure of the lattice[7]. In general when $\theta_1 = \theta_2$ the lattice will be a type of body–centered tetragonal; when $\theta_1 \neq \theta_2$ then an asymmetry is introduced to the structure. We aim to reproduce the lattice described in a 1996 Aspect paper[8], in which they used incident angles of $\theta_1 = \theta_2 = 20^\circ$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.3.png}
\caption{Diagram of a Paris optical lattice[2].}
\end{figure}
Chapter 4

Detection of an Optical Lattice

It is very important to be able to distinguish between disordered atoms trapped in a MOT and ordered atoms trapped in a lattice. Since a lattice will establish a crystal-like structure of atoms, it is natural to probe the crystal using Bragg scattering.

Bragg Scattering A beam scattered off of a crystal will have increases in reflectance for certain combinations of incident angle, wavelength and atom spacing, this is known as Bragg scattering. Reflected waves will constructively interfere when the Bragg condition is satisfied

\[ 2d \sin \theta = m \lambda \]  

Where \( d \) is distance between adjacent atoms, \( \theta \) is the incident angle, \( \lambda \) is the wavelength of the incident beam and \( m \) is the order of the diffracted beam (see figure 4.1). Waves leave the crystal in phase and with their original polarizations.

A crystal can be modelled as a series of planes determined by the constituent atoms of the crystal, these planes are known as Bragg planes (see figure 4.2).

4.1 Bragg Scattering off an Optical Crystal

A 1995 Bill Phillips PRL[4] outlines how to conduct Bragg scattering detection of an optical lattice and what the expected results are. In that paper, they a Paris style lattice but they used different geometries than us (the angle between the incident lasers was \( 2\theta = 90^\circ \)). They chose this geometry because it makes their experimental setup more simple. It turns out that if you send in a probe beam counter propagating against one of the lattice beams, the Bragg scattered beam coincides with the other beam in that plane (see figure 4.3).

To collect Bragg scattering data, the group turned off the lattice and almost immediately (\( \sim 100 \) ns) and sent the probe into the trap region. They varied the detuning of the probe beam from 8 line widths below resonance to 4 line widths above resonance. The Bragg condition was satisfied during the entire range of data, we calculated the change in angle per line width to be less than a micro radian.

What they found was that a peak developed near the resonant frequency (at zero detuning). At other places where the laser was less resonant, there was very little signal. This
Figure 4.1: Diagram of Bragg scattering.

Figure 4.2: Diagram of possible Bragg planes inside a body-centered cubic[3].
is because the atoms in the lattice interact more with photons that are on resonance than other photons. Thus, a signal is only seen near resonance. Figure 4.4 is, essentially, a plot of the absorption profile of the atoms (for low densities).

As the density of atoms increased (more lattice sites filled), the spike in reflectance continued to increase, but a dip near resonance developed (see figure 4.4). This dip becomes more pronounced when the lattice contains more and more atoms (the lattice becomes “optically thick”). When a photon enters the lattice which is optically thick, the photon cannot probe as deeply into the lattice because more of the lattice sites are filled, slowing the progression of the photon into the lattice. Thus, if the photons cannot go as deeply into the lattice, there will not be as much Bragg scattering and the reflectivity will decrease.

The results from this paper layout what one needs to look for when doing Bragg scattering experiments on an optical lattice. At low densities, a peak in reflectance will appear near resonance. At high densities a dip within a peak will develop near resonance. Using this technique it is possible to not only determine the existence of a lattice, but also the relative density of atoms within the lattice.
Figure 4.4: Data from 1995 Phillips paper[4]. The curves with higher reflectance represent lattices with higher densities. The inset data plot shows theoretical values.
Part II

Experimental Apparatus
Chapter 5

Vacuum System

The entire vacuum system is made up by two main parts: the vacuum pumps and the vacuum chamber. Our system is capable of reaching an ultimate vacuum of $10^{-10}$ Torr.

5.1 Pumps

There are three pumps being used in our system: a mechanical roughing pump, a turbo pump and an ion pump.

5.1.1 Roughing Pump

We use a Varian SD-40 double vane mechanical pump with a an NW 16 KF (kwik flange). It is meant to be started at atmosphere and can pump a system down to about $10^{-2}$ Torr, the lowest pressure the pump has ever pulled a system down to is $3.2 \times 10^{-2}$ Torr. The pressure is monitored by placing a thermocouple in the hose connecting the mechanical pump to the turbo pump (see section 5.1.4 for more information on the thermocouple). The roughing pump is very robust and needs little maintenance throughout its lifetime.

5.1.2 Turbo Pump

We use a Varian V-60 turbo pump, it has an NW 16 KF input and 4.5” conflat flange on the other end. This pump is meant to pump down the system from about a miliTorr to a $\mu$Torr. The lowest pressure the turbo has been able to pull a system down to is $2 \times 10^{-5}$ Torr. The pressure must be monitored by an ion gauge. This pump must be run once every 8 months to avoid failure of bearings because they cannot be replaced. Care must be taken with the turbo pump because there is little maintenance that can be performed on it except for cleaning it.

To clean the turbo, first create a bath made up of Liquinox (or another solvent) and distilled water. Disconnect the pump, remove any flanges and gaskets, then remove the screen (accomplished with a common pocket knife). Turn the pump upside down and dunk it in the solvent, and lift it up and down several times; the pump should not be lowered in farther than about 85 cm (or the vent valve). Repeat with fresh cleaning solution 2 to 3 times.
5.1.3 Ion Pump
Using a 200 L/s Physical Electronics ion pump, we are able to go from about a $\mu$Torr down to 0.1 nanoTorr. The ion pump can start working in the milliTorr range, but for the best performance and product reliability, the system should be pumped down as low as possible before the ion pump is turned on. The ion pump is controlled by a Digitel Multi-Pump Controller (MPC). The pressure displayed on the MPC is calculated from the current applied to the ion pump (see section 5.1.4). One other note is that the maximum baking temperature is 300° C, above that temperature the magnets’ intensity and strength will be irreversibly changed.

5.1.4 Gauges
In our vacuum system we use multiple gauges, each with its own caveats.

**Thermocouple** The thermocouple we use is connected between the mechanical pump and the turbo. The pressure is displayed on a Varian Multi Gauge (VMG). here are 4 thermocouples attached to the VMG, but we usually use the one labeled TC2 because it is the most accurate of the 4. The thermocouple can measure pressures anywhere from atmosphere down to $1 \times 10^{-3}$ Torr. However, TC2 is not calibrated correctly, so the lowest pressure it will display is $2.8 \times 10^{-2}$ Torr, which should be taken as being a milliTorr. The thermocouple does not give accurate pressure readings once the other pumps become active; thus an ion gauge must be placed further upstream, preferably as close to the vacuum chamber as possible.

**Ion Pump** The ion pump is its own ion gauge. A pressure reading is calculated from the current applied to the pump and displayed on the MPC. According to the ion pump, our ultimate pressure is $1 \times 10^{-10}$ Torr.

**Ion Gauge** There is about 5 ft of hose between the ion pump and the vacuum chamber, so to get a more accurate reading of the pressure inside the chamber, we place an ion gauge as close to the chamber as possible. We use a “nude” ion gauge purchased from Varian, the gauge is referred to as “nude” because the actual innards are completely exposed and need to be covered/shielded by the user. The pressure measured by the ion gauge is read by the same controller used for the thermocouple. Our ion gauge can read pressures from 1 milliTorr to 0.01 nanoTorr. The ion gauge is very delicate, however it is safe to leave it on for extended periods of time with no negative effect on the gauge’s life. The ion gauge always reads a pressure which is about 10 times higher than what ion pump claims, this is due to the fact that we have not calibrated the ion gauge. As such, the ultimate pressure measured at the ion gauge is less than $1 \times 10^{-9}$ Torr.
5.2 Vacuum Chamber

Our vacuum chamber was built by Kimball Physics (an “Extended Octagon” MCF800–E020080.16), it has a total of 26 ports (all conflat flanges): $2 \times 8''$, $8 \times 2^{3/4}''$, $16 \times 1^{1/3}''$. The flanges are arranged in a “wagon wheel” or “pancake” configuration. The chamber is connected by the bottom $2^{3/4}''$ flange to a six-way cross, which will be used for time–of–flight measurements. The six–way cross is clamped to a custom built base made by 80/20 parts. The height of the geometric center of the chamber is 12.5” from the table.

All the flanges were covered with glass viewports which were made by Larson Electronic Glass, and were made using 3056 glass. All the viewports were coated by ZC&R Coatings, and they all have a nominally centered “V–coating” centered at 780 nm (the percent reflectance at 780 nm is about 0.07%, and the reflectance increases to 4% by about 710 nm). The only flanges which do not have viewports are the flanges being used for the connection of: the vacuum system ($1 \times 2.75''$ flange), the six–way cross ($1 \times 2.75''$ flange), and the rubidium dispenser ($1 \times 1.33''$ flange).

It is apparent that we have a pressure gradient in our system as evidenced by the fact that the ion pump measures a pressure in the 0.1 nanoTorr range and the ion gauge measures pressures in the nanoTorr range. This is most likely due to the fact that there is about 5 feet of hose between the ion pump and the chamber; the ion gauge is only about 1 foot away from the chamber, thus it gives a much more accurate reading of the pressure inside the chamber.

We have leak checked all the flanges by spraying them with methanol and watching the ion gauge for increases in pressure and have not found any leaks. We also valved all the pumps out of the system and watched the pressure rise from ultimate vacuum; after about 3 minutes, the pressure fell from $2.3 \times 10^{-9}$ Torr to $6.4 \times 10^{-8}$ Torr.

In order to align the lasers with the geometric center of the chamber we use several “alignment tools” to do the job (see section 7.2).

5.3 Rubidium Dispenser

In order to fill our chamber with rubidium gas, we used a rubidium dispenser. The actual rubidium getters were purchased from SAES, and the voltage feed through was purchased from Kurt J. Lesker Company. The current feed through is model number EFT0084032, it is made of molybdenum, uses a 1.33” flange, has 8 pins and a maximum voltage of 500V. The rubidium getters are only sold in factors of ten, so for 2 pairs of pins we had to use 4 getters each pair of pins and we used the remaining 2 getters for one pair of pins, there was one pair of pins that were unused (see table 5.1 for list of pin connections and figure 5.1 for an image of the feed through).

The rubidium dispenser is connected to a Sorenson DLM 60–10, capable of providing 60 V or 10 A. We usually set the power supply at 3 A (connected to pins 4 and 5), in order to leak enough rubidium into the chamber for trapping, but not so much that we cannot cool the atoms. To investigate operation of the dispenser, I sent a probe beam into the chamber. The probe beam was on resonance, and it was going straight through the chamber, through two 2.75” flanges. When I was applying 3 A of current, the probe beam was faintly visible;
Table 5.1: List of pin connections for rubidium dispenser. Where pin 1 is the closest pin to the 2.75” flange at the top the chamber, and the other pins are numbered in a clockwise fashion from there.

<table>
<thead>
<tr>
<th>pins</th>
<th>getters</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–3</td>
<td>4</td>
</tr>
<tr>
<td>4–5</td>
<td>2</td>
</tr>
<tr>
<td>6–7</td>
<td>4</td>
</tr>
<tr>
<td>1,center</td>
<td>N/C</td>
</tr>
</tbody>
</table>

Figure 5.1: Image of the high voltage feed through with pins label.
at 4 A, the beam was strongly visible and the getters were glowing red (in both cases the
probe beam was visible throughout the entire chamber, from window to window). At 4 A,
there are too many atoms leaving the dispenser and they are moving too fast, which is why
3 A is a much better current setting.
Chapter 6

Magnetic Coils

We use a total of 4 pairs of coils: 3 to cancel the Earth’s magnetic field, and 1 to apply the necessary magnetic field gradient in the vacuum chamber to create a MOT.

6.1 Cancelling the Earth’s Magnetic Field

We employ 6 coils, each connected to its own power supply, to cancel the Earth’s magnetic field. The coils are setup such that the field produced by two pairs of coils (any two that are parallel) is uniform over the trap region. We attached a power supply to each coil to give ourselves greater control over the magnetic field in the chamber. We attached an MPJA HY1802D power supply to all but one coil, which uses an Elenco XP–603 (connected to the $z_-$ coil). Each coil is made up of a parallel ribbon cable wrapped 12 times around a square frame made of delrin. The inner width of the delrin frame is $24\frac{7}{8}$", each coil has a resistance of about 140 Ω. Before we closed the vacuum chamber, we placed a three–dimensional Hall probe (an F. W. Bell Sypris 7030) in the chamber and verified that the field was zeroed to within $\pm 0.008$ G at a distance of 5mm away from the center in all directions (see figure 6.1).

For a list of the voltages applied to each coil see table 6.1, and for a diagram of the coordinate system used to label the coils see figure 6.2.

<table>
<thead>
<tr>
<th>coil</th>
<th>voltage applied (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_-$</td>
<td>7.8</td>
</tr>
<tr>
<td>$x_+$</td>
<td>8.8</td>
</tr>
<tr>
<td>$y_-$</td>
<td>5.6</td>
</tr>
<tr>
<td>$y_+$</td>
<td>5.1</td>
</tr>
<tr>
<td>$z_-$</td>
<td>5</td>
</tr>
<tr>
<td>$z_+$</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 6.1: List of voltages applied to open chamber to produce almost no magnetic field (note that these voltages will change every day, use this list as a starting point). (*)Also note that the $z_-$ coil has a different power supply than the other coils.
Figure 6.1: Data showing the Earth’s magnetic field is cancelled to within ± 0.008 G

Figure 6.2: This is the coordinate system used to label the cancellation coils (standing in the lab with your back facing Spring st., looking directly at the chamber). This coordinate system is only used to label the coils.
6.2 Gradient Coils

To apply a magnetic ramp, we setup two coils in an anti–Helmholtz configuration – the magnetic fields created by the two coils point in opposite directions, so instead of creating uniform field, a magnetic gradient arises. We used 10 AWG wire insulated with enamel. We wrapped the wire around a circular delrin frame (which had an inner diameter of $7\frac{5}{16}$”). Each coil has 108 turns and a resistance of about 0.35 Ω. Originally, we assumed that the coils would butt right up against the 8” windows (giving a separation of 14 cm, or 5.5”). However, due to the fact that there are screw heads sticking out of the window, and we need space to slide the alignment tool over the window, the coils are now separated by $7\frac{1}{16}$”. Our calculated gradient was 0.739 G/mm and our measured was 0.791 G/mm (measurement and calculation for separation of 14 mm, and only for direction perpendicular to the face of the coils, see figure 6.3). In order to make sure that the same current is applied to both coils, we attached the coils in series with each other and a single power supply. Using a Sorenson DLM 20–30 (capable of providing 20 V or 30 A), we applied 10 A to the coils and recorded the magnetic gradient in the $x$, $y$, and $z$ directions.

![MOT coil gradients](image)

Figure 6.3: Graph of magnetic gradients produced in the $x$, $y$, and $z$ directions. Where $x$ is along the axis of the coils.

Gauss’ law for magnetism is $\nabla \cdot B = 0$, solving for the $x$ component gives $\frac{\partial B}{\partial x} = -\left(\frac{\partial B}{\partial y} + \frac{\partial B}{\partial z}\right)$. Taking the $x$–direction to be along the axis of the coils, the gradient should be twice as large in the $x$–direction than in the $y$ and $z$–directions, and the gradient in the $x$–direction should also have an opposite sign than the $y$ and $z$–directions. Our measured gradients in the $x$, $y$, and $z$ directions were (respectively): 0.7913 G/mm, -0.385 G/mm, and -0.386 G/mm. So our magnetic gradient satisfies Maxwell’s equation for the divergence of a magnetic field.
Chapter 7

MOT Laser

For the optical molasses we are using a home-built extended cavity diode laser (ECDL)[9], with a Sharp GH0781JA2C diode. There are two output laser beams that exit the ECDL: a weaker beam which is used for a saturated absorption experiment, and the stronger one is used as the MOT laser.

7.1 Saturated Absorption

We use the common technique of saturated absorption to determine whether the laser is on resonance by sending one of the beams leaving the ECDL through an enclosed cell full of rubidium [9]. In order to detune our laser from resonance, we put an acousto-optic modulator (AOM) in the path of the laser. In an AOM (we use an Isomet 1205C), a transducer applies an acoustic wave perpendicular to the path of the laser, resulting in diffraction of the beam. The beam is diffracted into a higher and a lower order beam (the frequency is shifted up or down, respectively). The shift in output frequency is linear with the voltage applied (3 MHz/V), and the voltage ranges for the AOM are from 4 to 17 V. In our setup, the AOM shifts the laser to the +1 order, meaning that the strong beam coming out of the laser, used for the trap, will be detuned to the red.

7.2 Preparing the Trap Beam

The next step in our setup is an anamorphic prism pair (APP) in order to circularize the laser. The beam leaving the laser is spatially elliptical, which is not desirable for most components in our experiment. An APP effectively circularizes the beam with a minimum loss in power. We used a commercial APP, a New Focus APP model 5414.

Faraday Optical Isolator  In an optical system, back-reflections are undesirable because they can destabilize the frequency of the laser or possibly even damage the laser. To avoid back-reflections, the next component is a Faraday isolator[10], also known as an optical diode. The Faraday isolator consists of three components: two polarizers and a optical Faraday rotator (OFR). Through the use of the Faraday effect[10], an OFR will rotate the polarization by 45 degrees. By placing a polarizer before and after the OFR (with a 45
degree difference in polarizations, light is allowed to pass through. Light going through the isolator in the wrong direction will be rotated to a polarization of 90 degrees, with respect to the polarizer closest to the source laser, thus it will not escape the isolator.

**Telescope**  After the isolator, we need to telescope the beam to a diameter of 15 mm. The best way to do this is to put our beam into a fiber and then telescope the beam. While you will lose around 50% of your power, you end up with a beam that is gaussian. We tried a new, to us, method of using aspheric lenses which were attached directly to the fiber such that the focal point of the lens was at the end of the fiber. In theory this is a much simpler setup, however it proved not to be the case in practice. We eventually had to scrub the entire fiber setup and just send the beam straight into the telescope. We did use a microscope objective and a 15 mm pin hole, to make the beam as clean as possible, but our beam still is not as pure as if we had used a fiber.

**Beam Splitters**  Next we must split the beam into the $x$, $y$, and $z$ components. To do this, we will use a polarizing and a non–polarizing cube beam splitter (see figure 7.1). The difference between a polarizing cube beam splitter (PCBS) and non polarizing cube beam splitter (NPCBS) is that the NPCBS always splits the beam 50/50, while the PCBS splits the beam according to the beam’s polarization. The advantage to a PCBS is that when you place $\lambda/2$ wave plate before it, you can rotate the polarization of the beam and change where the light exits the beam splitter. In our setup we send 20% of the power along the $x$–axis (the axis perpendicular to the face of the gradient coils) and 40% along both the $y$ and $z$–axis'.

**Quarter Wave Plates**  An optical molasses requires circularly polarized beams, so to convert our linearly polarized beams to circularly polarized beams we put the beams through $\lambda/4$ wave plates. Because the gradient in the $x$ direction is opposite that in the $y$ and $z$ directions, the $\lambda/4$ placed in the path of the beam moving in the $x$ direction must be rotated 45° from the orientation of the other two input plates. On the other side of a chamber is another $\lambda/4$ plate (set at an arbitrary orientation) and a mirror, thus the beam going back into the chamber is opposite (see figure 2.3 and 7.2). The polarizations and magnetic fields only have one orientation that works (see figures 2.3 and 2.2)

To correctly set the orientations of the $\lambda/4$ plates, it required the use of three $\lambda/4$ plates, 2 polarizers and a wave meter (an ILX Lightwave OMM6810B). I first setup the two polarizers and set them at 90° to each other by putting the wave meter after them and minimizing the power. Then I set two $\lambda/4$ plates in between the polarizers and tried to maximize the power at the wave meter. $\lambda/4$ plates can rotate a polarized beam by a maximum of 45°, thus two $\lambda/4$ plates set rotate a wave by 45°, in the same direction, will rotate the wave by a total of 90°. Then I replaced one of the $\lambda/4$ plates with another plate and tried to minimize the power. When one $\lambda/4$ plate is aligned at $+45°$ and the other is oriented to $-45°$, then there is no net effect on the polarization because the two $\lambda/4$ plates cancel each other out (see figure 7.2). The $\lambda/4$ plates on the other side of the chamber can be at any rotation.
Figure 7.1: Diagram of the setup for the beam splitters (viewed from above). Where $x$ is along the axis of the coils.

Figure 7.2: Diagram of the orientations of the $\lambda/4$ plates used to circularize the polarizations of the MOT lasers.
Beam Alignment  In order to align all our beams through the windows of the chamber, we used various alignment tools. To send beams through the center of the 2.75” viewports, we cover the port with a plastic cap (these are the caps that usually cover new vacuum equipment when it is shipped from the manufacturer). In order to align the beams going through the 8” windows, we had a special alignment tool made by the department’s machinist, Michael Eldridge. It is a plexiglass cover that goes on over the 8” window, and has a vertical and a horizontal row of dimples forming a cross hair at the center of the window. The diameter of each dimple is 0.2”. Since the dimples are placed end to end, the distance between the centers of adjacent dimples is also 0.2”. The angular displacement of each hole (with the magnetic coils in place) is $2.17^\circ$, giving a total angular displacement of $62.44^\circ$ across the entire diameter of the window.

After each component in the system, we placed a wave meter to measure the power loss (see table 7.1).

<table>
<thead>
<tr>
<th>component</th>
<th>power (mW)</th>
<th>% transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>laser</td>
<td>24.75</td>
<td>100</td>
</tr>
<tr>
<td>APP</td>
<td>24.20</td>
<td>97.8</td>
</tr>
<tr>
<td>Periscope</td>
<td>22.43</td>
<td>92.7</td>
</tr>
<tr>
<td>Faraday isolator</td>
<td>16.12</td>
<td>71.9</td>
</tr>
<tr>
<td>Telescope</td>
<td>5.60</td>
<td>2.89</td>
</tr>
</tbody>
</table>

Table 7.1: Insertion loss for each component in the setup for our MOT laser.

Repumping Laser  The repumping laser is left on continuously throughout the experiment. The main purpose of the laser is to pump the atoms $^{85}$Rb atoms from the $F = 3$ state to the $F = 4$ state. However, the setup of the repumping laser is not as critical as the other aspects of this experiment. The beam only needs to be circularized (spatially) and then sent into the chamber through the trap region. It is not necessary to put an optical Faraday isolator in the repumper setup, it is possible to just misalign all the retro–reflections so that they are not propagating back into the laser. After that the laser must be sent through the trap region, which can be accomplished through several methods. One clever method is to send it through the PCBS so that the trap laser and repumping laser coincide (see figure 7.1).
The setup for our lattice beams mimics the setup for the MOT lasers, until the telescope. In the setup for the lattice beams, did send the beam through a fiber, and then through a 30 cm lens to telescope the beam to a diameter of 10 cm. After that we need split the single lattice beam into 4, and the polarizations, phases and intensities must all be the same. We accomplished this using 3 non–polarizing cube beam splitters.

The lattice we wish to create is the same as the one made in the 1995 Aspect paper[8], in which their lattice was a Paris style lattice with a total of 40° between each pair of incident beams.
Chapter 9

Bragg Scattering Experiment

There are two main components to the Bragg scattering experiment: knowing what type of lattice you have, experimental procedure for loading atoms and taking data.

9.1 Lattice Type

As outlined in a 1994 by Grynberg[7], it is possible to determine what type structure you can expect for a given lattice type. However, we did not have enough time to work through the theory of that paper. As such, this step will be left up to future graduate students and is a future outlook.

9.2 Procedure

(see figure 9.1) The repumping laser is left on continuously throughout the entire experiment. Initially, both the lattice beams and the MOT beams are on, however the lattice beams are near resonance and have far lower intensities than the MOT lasers, thus the MOT lasers dominate.

First the MOT must be loaded with atoms, which should take about 2 ms. Then the magnetic gradient is turned off (this switch should be done in about 1 ms to avoid Eddy currents; however all other switching should be done as fast as possible, preferably on sub millisecond time scales), leaving only the optical molasses beams to cool the atoms (see figure 9.1 for a diagram of entire schedule). The atoms cool in the optical molasses for 1 ms, then the molasses beams are turned off and the atoms are allowed to equilibrate in the lattice for 1 ms. Next the lattice beams are turned off and the probe beam is sent in, you should wait at least 100 ns which gives you enough time to make sure the lattice is extinguished, but it is not long enough for the atoms to leave their locations[4]. The probe beam is sent in for 0.5 µs. After this the lattice beams and probe beams can be alternated to take many data points, and so that the atoms are at about the same point spatially for each data point.
Figure 9.1: Timing sequence for trapping/probing cycle for the Bragg scattering experiment.
Chapter 10

Conclusion and Future Outlook

First the MOT must be finished, the beams still need to be aligned through the chamber and the path differences of the lasers must be relatively the same. Also, the $\lambda/4$ wave plates must be installed and oriented properly to circularize the polarization of the beams. After the MOT is installed and working, time–of–flight and intensity correlation measurements can take place.

The next major step after that would be to align the lattice beams and attempt to trap atoms in an optical lattice. There are several major details that must be worked out in order for this to happen: a switching circuit must be made to switch off the MOT lasers and coils in a suitable amount of time, the beams must be positioned correctly and aligned such that they are going through the chamber correctly, etc.

The final step would be to collect Bragg scattering data from the lattice. This itself has several major steps yet to be taken: we need to calculate the cubic structure we expect to see with our geometries, this would give rise to the geometry of the Bragg scattering experiment, we would need yet another timing circuit (or one large timing circuit) to shut off the lattice and then apply the probe beam, etc.

Also, once we have verified the existence of a lattice, we can conduct intensity correlation measurements on the trapped atoms. This would give us information on the motion of the atoms within the optical wells, and how the atoms move between wells (Brownian motion).
Bibliography


Part III
Appendices
## Appendix A

### Notational Definitions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>$-\frac{eE_0}{\hbar} \langle e</td>
<td>r</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$\sqrt{\Omega^2 + \Delta^2}$</td>
<td>Rabi frequency</td>
</tr>
<tr>
<td>$\Omega'$</td>
<td>$\sqrt{\Omega^2 + \Delta^2}$</td>
<td>generalized Rabi frequency</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$\omega_{\text{las}} - \omega_o$</td>
<td>spontaneous emission rate</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>$\omega_{\text{las}} - \omega_o$</td>
<td>detuning from resonance</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$\frac{8\hbar k^2 s_o (\Delta/\gamma)^3}{(1+(2\Delta/\gamma)^2)^2}$</td>
<td>damping coefficient</td>
</tr>
<tr>
<td>$s_o$</td>
<td>$\frac{2\Omega^2}{\lambda^2} = \frac{I}{I_o}$</td>
<td>on–resonance saturation parameter</td>
</tr>
</tbody>
</table>

Table A.1: List of notions and conventions used in this paper
Appendix B

Vacuum System Pump Down

The mechanical pump must pump the system down in stages before the other pumps can be used:

1. Close all valves and turn on roughing pump, the pressure should drop down to a milliTorr within 5 minutes. The pressure should be measured by TC2, connected between the mechanical and turbo pumps. TC2 can measure atmospheric pressure down to a milliTorr at the high and low ends, respectively. However, our thermocouple is not calibrated correctly so the lowest pressure it can measure is $2.8 \times 10^{-2}$ Torr.

2. Open the first valve so that the mechanical pump is roughing the ion pump. The pressure should drop to tens of milliTorr within 5–10 minutes.

3. Open the last valve, the pressure should again jump up to atmosphere and then gradually fall back down to tens of milliTorr within 10 minutes.

4. Turn on the turbo pump, it should take about a minute for the turbo to spin up to 70 krpm (its operating speed). The roughing pump must continue running for the turbo to work effectively. The thermocouple that was originally used to measure the pressure can no longer be used for 2 reasons: 1.) the lowest pressure it can measure is a milliTorr 2.) at its location between the roughing and turbo pumps, it is not going to measure an accurate pressure because it is behind where the turbo creates its vacuum. Thus, an ion gauge must be placed somewhere in the system between the chamber and the turbo, preferably as close to the chamber as possible. All of our ion gauges read a maximum of 1 milliTorr and a minimum pressure of $1 \times 10^{-11}$ Torr. The ion gauge can be left on for long periods of time without any threat of damage or negative effects on the gauge’s lifetime. The turbo should take the system down to tens of $\mu$Torr within 10–20 minutes. The lowest pressure seen at this stage is $7.1 \times 10^{-6}$ Torr.

5. Once that happens the ion pump may be turned on. To turn on the ion pump flip on the Digitel MPC. Push “9” to switch to high voltage operation, push “Display Select” next to the screen for supply 1, then hit “enter” to activate the pump. The LED display should show the voltage being applied to the ion pump, if not push “Display Select” until the voltage is displayed on the screen. Once the voltage rises above 700V, the turbo and roughing pumps should be valved off from the system. If the ion pump
begins to stall (as evidenced by a drop in voltage), the roughing pumps should be
valved back into the system to assist the ion pump.

6. Once the ion pump reaches 3 kV, you can switch the display over to pressure by hitting
the “Display Select” button until the pressure is displayed. The pressure displayed is
calculated from the amount of current passing through the ion pump, the ion pump
is essentially its own ion gauge. The system pressure should drop down to nanoTorr
within 10 minutes. The optimal voltage is 7 kV, this represents the highest pumping
speed.

7. At this point the mechanical and turbo pumps can be turned off, as they serve no
purpose and their vibrations will interfere with the optics.

8. The ion gauge attached to the system should agree with the pressure reading on the
Digitel MPC. If it does not, the ion gauge must be degassed until its pressure meets
the pressure of the ion pump.
Appendix C

Ion Pump Maintenance/Cleaning

C.1 Troubleshooting

There are troubleshooting steps you can take before you attempt to disassemble the ion pump:

1. If the voltage across the pump doesn’t go higher than a few hundred volts, then you have a problem with either the ion pump or the Multi-Pump Controller (MPC).

2. To test the MPC, turn it off and disconnect it from the ion pump. Then turn on the MPC, the voltage should go straight up to 7 kV. If not, there is a problem with your MPC unit.

3. To test whether there are any leaks at your flanges, spray each flange individually with methanol, if there is a leak the pressure will jump up dramatically and then gradually fall. Make sure that the ion pump is running and has achieved its lowest possible pressure. This test works best at or below the $\mu\text{Torr}$ range. **IMPORTANT:** Do not forget to test the high voltage feed through (the wire that connects the MPC and the ion pump), the high voltage feed through has a 1.33" conflat gasket inside to create a seal.

4. Otherwise there is a short somewhere inside the pump. This means that there are flakes or something else inside the elements which allows for electron arcing. Alternatively, one or more elements could be bad and need replacement. But elements should be very durable.

5. To test whether there is current leaking from one or more of the elements, use an external ion gauge to test whether the pressure reading from the MPC is accurate or not.

6. To test each element individually, open the pump and connect a Ohmmeter to each element individually and to ground. Each element should have a resistance greater than 150 MΩ. Any elements that are less than that should be paid special attention to.
7. Each element in our system consists of a bank of open cylinders with a plate on the top and the bottom. There should be sputtering craters on these plates, if the ions have sputtered clean through either of the plates leaving you with one or more holes, that element must be replaced.

C.2 Cleaning Materials

Make sure you have plenty of table space set aside for your parts. Cover all table space with aluminum foil. You can use store bought aluminum foil, but be aware that it usually has some sort of peanut oil or other grease on it so just clean it with acetone or methanol. Latex gloves alone are not enough, you need something that will cover your entire arm because you could drop lint or hairs inside the pump. I recommend putting on butchers gloves, and then latex gloves on top of them (when dealing with vacuum systems, always double bag it).

Summary of necessary materials:

- Butchers gloves and latex gloves (powder free)
- Steel brush (if bought from hardware store clean first to get rid of any loose fibers and grease)
- Table space covered with aluminum foil (if store bought foil, clean first with methanol to get rid of any oils)
- Air Duster (any type of air will work as long as it is high pressure, dry and oil free)
- Wrenches of sizes:
  - 23/64
  - 17/64
  - 13/64

C.3 Cleaning Instructions

1. Open port of ion pump and remove the braid that connects the high voltage feed through to the 4 elements, then remove the 4 standoffs from each of the elements.

2. Next, remove the anode/cathode elements (the elements themselves are the banks of cylinders on the sides of the ion pump, there should be 4 elements). Each element consists of a bank of hollow cylinders with a plate above and below those cylinders. Note:

- The bank of cylinders is the actual anode, made of ceramic. The plates above and below the cylinders are the cathodes, one plate is made of titanium and the other made of tantalum
- The elements are completely interchangeable. So if you forget which element went in which well, don’t worry it will be ok.
• DO NOT disassemble the elements (do not remove the cathodes from the anodes)
• DO NOT use an ultra sonic cleaner on the elements
• DO NOT use any chemicals or liquid cleaners on the elements
• If the elements have a blue/purple color to them that means that the ion pump was started at too high of a pressure, the ion pump should not be started until at least $10^{-5}$ Torr. The solution to this is to let the turbo pump suck on the ion pump (with the ion pump off) for a couple of hours.

3. The only cleaning you can do to the elements is blow out any flakes from the elements with the airduster. It is not necessary to scrub the outside of the elements with a steel brush, the flakes inside the element should be your main concern.

4. Clean out the wells that the elements sit in, scrub them with the steel brush to get any rubidium flakes off that have really been caked on there.

5. With a vacuum hose, suck out the remaining titanium flakes and other particulate that has accumulated at the bottom of the pump (cover the entire hose with aluminum and then poke a small hole in the end for the vacuum to use, make sure you clean the foil with methanol or acetone before introducing it into the pump).

6. It is not necessary to clean the elements with methanol/acetone or other chemical, unless you know you have touched the element with an exposed finger and gotten oil on it. Same goes for the inside of the ion pump, it should already be oil free and should not need to be hit with methanol unless you know you got oil on something.

7. Replace the elements, standoffs, braid and then close pump.

8. Bake out pump (see appendix D)

C.4 Contacts

C.4.1 Gamma Vacuum

(952)-445-4841
Supplies pumps to Physical Electronics. They also service and rebuild pumps. Excellent source of information

C.4.2 Physical Electronics (PHI)

(800)-922-4744
At one time sold and serviced ion pumps and still offers technical support for legacy pumps, but no longer services pumps. This is the company that originally built our pump
C.4.3 Pascal Technologies

(800)-367-2919
This is the company that we purchased our ion pump from, not a great source of information nor do they ship quickly or is their online inventory up to date.
Appendix D

Bake Out

When baking out the system, it is best to cover the entire system (chamber, hoses and ion pump) in a layer of foil, a layer of fiber glass, then finally wrap with heating tape, and another layer of foil. Heating of the chamber and ion pump are most effective if you use 2 or more heat tapes on each (the roughing and turbo pumps do not need to be baked because they will be damaged if their temperature rises above 120°C). To achieve high bake temperatures, it is best to use one variac per heat tape, unless you have a method for connecting heat tapes in parallel so that they have the same voltage drop. The ion pump and chamber should not go above 300°C, the hose (especially the valves because they have rubber gaskets and grease inside) should not go above 200°C, and the vacuum chamber and glass viewports should not go above 450°C. The longer the system is baked, the better; but it should be baked at a minimum of 2-3 days after being exposed to atmosphere. While baking the pressure should come down to $10^{-7}$ or $10^{-8}$ Torr. When the pressure stops dropping, then baking any longer will have little positive effect on the system. Once baking ceases, the pressure should drop straight down to a nanoTorr or lower.

It is recommended that you let the turbo and roughing pumps pump the system while baking, that way you can completely disconnect the ion pump to avoid damaging its wires. However, you may use the ion pump to pump the system while baking but care needs to be taken with the connection wires.

One final note, it is impossible to remove the magnets from our ion pump. Many people recommend removing the magnets prior to baking because you can bake at a higher temperature. While this is true, by removing the magnets you no longer are baking the magnets, so the entire baking process will have no positive effect on the system. Also, on our pump the magnets are welded on to the chassis of the actual pump, so they cannot be removed.
Appendix E

New Focus Commercial Laser, quick user guide

E.1 Information

Model: 6013
\[ \lambda = 710 - 800 \text{nm} \]
\[ P_{\text{max}} = 70 \text{mW} \]

Ramping
\[ V_{\text{max}} = \pm 4.5V \]
\[ Z_{\text{input}} = 5k\Omega \]
\[ F = DC - 3.5kHz \]

E.2 Operation

1. Connect serial cable between laser and laser power supply
2. Turn on power supply (turn key). Wait 20 minutes while laser temperature is stabilized
3. Press ”power” button to send power to laser (button flashes 4 times before putting out light)

The laser is normally operated in constant current mode (90 mA), while frequency modulation is done by adjusting the voltage applied to the piezo. If the “set” button next to the knob is lit, then the knob will control the voltage; if the button it not lit, just push it.

E.3 Ramping

A function generator should be connected to back of the laser supply at the “frequency modulation” input. The usual frequency and amplitude we applied is:
\[ F \approx 10\text{Hz} \quad \text{(E.1)} \]
\[ A \approx 100mV_{pp} \quad \text{(E.2)} \]

The limits for the input signal are:

\[ V_{max} = \pm 4.5V \quad \text{(E.3)} \]
\[ Z_{\text{input}} = 5k\Omega \quad \text{(E.4)} \]
\[ F = DC - 3.5kHz \quad \text{(E.5)} \]
Appendix F

Current to Voltage Converter

F.1 First Op Amp

We use current to voltage converters to convert the current signals produced by the photodiodes in our saturated absorption setups into voltage signals. The output voltage can be varied between 6.95 and -6.95V through the use of an LM399 precision reference, an LM356 operational amplifier, and a 20K POT. $V_{out}$ can be simply derived after using the following observations of the circuit elements (see figure F.1).

\[
\frac{V_{in} - V_1}{R_3} = I_3 = \frac{V_1 - V_{out}}{R_1} \quad (F.1)
\]

\[
\frac{V_{in} - 0}{R_7} = I_7 \quad (F.2)
\]

\[
\frac{V_{in} - V_1}{R} = I_7 \quad (F.3)
\]

Using equation F.1 we can relate $V_{out}$ to $V_{in}$

\[
V_{out} = V_1 \left( \frac{R_1 + R_3}{R_3} \right) - V_{in} \frac{R_1}{R_3} \quad (F.4)
\]

Equating F.2 and F.3, we can relate $V_1$ to $V_{in}$

\[
V_1 = V_{in} \left( \frac{R_7 - R}{R_7} \right) \quad (F.5)
\]

Plugging our value for $V_1$ back into equation F.4 we can find the ratio of $V_{out}$ to $V_{in}$

\[
\frac{V_{out}}{V_{in}} = 1 - \frac{R}{R_7} \left( 1 + \frac{R_1}{R_3} \right) \quad (F.6)
\]

In our circuit, we are using: $R_7 = R_3 = R_1 = 20k\Omega$. Since our POT can be varied between $0\Omega$ and $20k\Omega$.

<table>
<thead>
<tr>
<th>$R(\Omega)$</th>
<th>$V_{out}/V_{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>20k</td>
<td>-1</td>
</tr>
</tbody>
</table>
These voltages seen on the output would be 6.95V when the POT is set to maximum resistance, and -6.95V when the POT has minimum resistance.

F.2 Second Op Amp

The second Op Amp is used to determine the gain of the circuit. The gain is controlled by:

$$G = \frac{R_5}{R_4} \quad (F.7)$$

In the default configuration, $R_4 = 100K\Omega$ and $R_5 = 10M\Omega$. 