RICE UNIVERSITY

Strontium Laser Cooling and Trapping Apparatus

by

Francisco Camargo

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

Master of Science

APPROVED, THESIS COMMITTEE:

Thomas G. Killian, Chair
Professor of Physics and Astronomy

Barry Dunning
Sam and Helen Worden Professor of Physics and Astronomy

José Omicic
Professor of Physics and Astronomy

Houston, Texas

March, 2015
Contents

1 Introduction 1

2 Doppler Cooling 3
  2.1 Scattering Force .................................................. 3
  2.2 Optical Molasses ................................................... 5
  2.3 Doppler Cooling Limit ............................................ 6
  2.4 Strontium Level Structure ....................................... 6

3 Apparatus Design 9
  3.1 Vacuum Chamber Overview ....................................... 9
  3.2 Strontium Oven Nozzle ........................................... 10
  3.3 2D-Collimator .................................................... 11
  3.4 Zeeman Slower .................................................... 12
  3.5 Magneto-Optical Trap ........................................... 15
  3.6 Magnetic Trap .................................................... 18

4 461nm Diode Laser System 21
  4.1 Optical Layout ................................................... 21
  4.2 Frequency Locking Scheme ..................................... 24

5 Measurements 27
  5.1 Atom Number ..................................................... 27
  5.2 Magnetic Trap Atom Loss ....................................... 28
  5.3 Zeeman Slower Optimization ................................... 31
  5.4 MOT Optimization ................................................. 32
  5.5 Loading Rate ..................................................... 35
  5.6 Temperature ....................................................... 37
  5.7 Conclusion ......................................................... 38
Appendices 39

A Vacuum Viewport AR Coatings 41

B Machine Drawings 43

C Oven Nozzle Assembly 53

D Obtaining Ultra-High Vacuum 55
List of Figures

2.1 Relevant energy levels for Doppler-cooling on broad strontium transition. .......................... 3
2.2 Photon scattering rate as a function of total detuning at different values of intensity. ............... 4
2.3 Damping coefficient as a function of laser detuning at different intensities in 3-D. ................. 5
2.4 Energy level spectrum of strontium. Decay rates are shown in addition to the wavelengths of the trapping and repumping beams. .......................................................... 7

3.1 Listed are the various vacuum chamber components of the apparatus: the oven nozzle (cyan), 2D-Collimator (red), differential pumping tube (green), Zeeman Slower (orange), MOT chamber (blue), anti-Helmholtz coils (pink), ion pumps (purple), non-evaporable getter (dark green). 9
3.2 Simplified strontium oven nozzle. Strontium (red) is housed beneath the nozzle head (orange), which is bolted down to the body (blue). Two heating elements are used; a Firerod (light-blue) behind the stontium and outside vacuum, and a 1.6Ω/ft. heating coil (pink) which is silver-soldered around the capillary tubes (green). The coils serve the essential role of keeping the capillary tubes hot enough such that strontium does not clog them. ............................... 10
3.3 Velocity distribution of a beam of strontium at different temperatures. Velocity is scaled by the capture velocity. .......................................................... 11
3.4 2D-Collimator optical path layout. The vacuum chamber walls are in red, the viewports in green, mirrors in light blue, and laser beam in dark blue. The atoms are centered in the chamber and travel into the page, the laser beam originates from the right-hand side and traverse the atoms four times. .......................................................... 12
3.5 Plotted is the force exerted by laser on an atom traveling along the center of the Zeeman Slower (blue) and along the $e^{-2}$ radius of the laser (orange), if kept on-resonance. The design parameter, $\eta$ (red), is chosen to be less than the force the laser can exert along the $e^{-2}$ radius. 13
3.6 Plot of calculated magnetic field given our choice of $\eta$ (black), and direct measurements of field (red). .......................................................... 14
3.7 Trajectories of atoms as they traverse the Zeeman Slower at different initial axial velocities via interpolation of the measured magnetic field. Solid is for an atom that travels along the axis of the Zeeman Slower, dashed is for an atom that travels along the waist of the Zeeman laser beam. That is, the intensity is reduced by \( \exp(-2) \). Position is scaled by the length of the Zeeman Slower, 0.41m, and the velocity is scaled by the capture velocity.

3.8 Schematic of MOT operation in 1-D on a \( J = 0 \rightarrow J = 1 \) transition. The field gradient results in a spatially dependent Zeeman shift which splits the excited state sub-levels. Two counter-propagating, \( \sigma^\pm \) polarized, red-detuned laser beams propagating in the \( \pm z \) direction are incident on the atoms. The spatially dependent energy shift in conjunction with selection rules result in an imbalanced force contribution from each laser. As atoms are pushed closer to the zero of the magnetic field, the force falls out of resonance.

3.9 Plotted are the results of a three-dimensional calculation of the magnetic field. (a) Axial magnetic field component as a function of axial position at different currents. At 40A, the axial component of the field gradient is 44G/cm. (b) Radial magnetic field component as a function of radial position at different currents. At 40A, the radial component of the field gradient is -22G/cm.

3.10 Magnetic trap potential energy for atoms in the \( m = 2, 3 \) \(^3\)P\(_2\) state.

4.1 Simplified optical layout. Made using image library from Alexander Franzen.

4.2 Saturated Absorption optical setup. To drive the \( \sigma^+ \) transition, the probe (pump) propagating parallel (anti-parallel) to the magnetic field must have right-handed (left-handed) circular polarization. Made using image library from Alexander Franzen.

4.3 Entry point of each laser beam. The MOT beams enter through three orthogonal directions and are each retro-reflected. The MOT coils are shown in pink. Also depicted are the Zeeman Slower beam, repumper, and imaging beam.

5.1 Sample false color image of an atom cloud of \(^{88}\)Sr in a MOT.

5.2 Sample fit to one dimensional slice through image of an atom cloud of \(^{88}\)Sr.

5.3 Timing diagram showing when each beam is on in addition to the Anti-Helmholtz coils.

5.4 Lifetime measurement of \(^{88}\)Sr with nozzle heating coil at 1.06A, coil temperature of 374C and a Firerod setpoint of 400C resulting in a decay time constant of \( 9.4 \pm 0.1 \)s.

5.5 Lifetime of \(^{88}\)Sr in the magnetic trap as a function of the oven nozzle temperature set to 1.06A through the heating coil and variable Firerod setpoint.

5.6 Atom number as a function of Zeeman Slower laser beam power.

5.7 Atom number as a function of Zeeman Slower currents through (a) 13AWG main coil, and (b) 13AWG tuning coil.
5.8 Atom number as a function of Zeeman Slower (a) laser beam power, (b) frequency detuning, (c) 13AWG main coil current, and (d) 13AWG tuning coil current. ............................................. 33
5.9 Trapped atom number as a function of axial Anti-Helmholtz magnetic field gradient. Find optimal number at 47G/cm (43A from the current supply). ................................. 34
5.10 Trapped atom number as a function of angle of half-wave plate used for power distribution between the vertical and horizontal arms of the MOT beams. Find peak when each horizontal arm has twice as much power as the vertical arm. .......................................................... 34
5.11 Trapped atom number as a function of total power in MOT beams. Peak atom number at total MOT power of 28mW. ................................................................. 35
5.12 Trapped atom number as a function of detuning of MOT beams. Peak atom number at 54MHz red-detuned from the transition. ...................................................... 35
5.13 Loading curves for $^{84}\text{Sr}$ of both the MOT, where the repumper is on during the load, and the magnetic trap, where the repumper is flashed on for 50ms after loading of the trap. ................................. 37
5.14 Measured and calculated MOT temperature as a function of detuning of $^{88}\text{Sr}$. The expected temperature depends weakly on small values of $I/I_{\text{Sat}}$. Plotted is the expected values at $I/I_{\text{Sat}} = 0$, which sets the minimum achievable temperature, and at $I/I_{\text{Sat}} = 0.1$ which corresponds to the intensity of the MOT. ...................................................... 38
A.1 Reflectance of vacuum viewports. Each viewport is AR coated for 461nm, 689nm, and 1064nm, with reflectances of 0.26%, 0.19%, and 0.14%, respectively. For reference, these wavelengths are demarked with vertical lines. ............................................. 42
A.2 Transmittance of vacuum viewports. The transmittances for 461nm, 689nm, and 1064nm are 98.4%, 99.9%, 99.3%, respectively. For reference, these wavelengths are demarked with vertical lines. ............................................. 42
B.1 Heat shield for oven nozzle, originally drawn by Tom Killian. ............................................. 43
B.2 Oven nozzle, originally drawn by Tom Killian. In red is the nozzle head which will house the capillary tubes. ................................................................. 45
B.3 Chamber section containing oven nozzle viewed from the side, originally drawn by Tom Killian. 46
B.4 Chamber section containing oven nozzle as well as the arms of the 2D-Collimator. Originally drawn by Tom Killian. ................................................................. 47
B.5 Drawing of differential pumping tube. A solid gasket is machined (orange) and used to hold the differential pumping tube in-between the 2D-Collimator and the start of the Zeeman Slower. 48
B.6 Zeeman slower design. Two separate currents were used, 5A and 20A, corresponding to two different square copper wire gauges, 13 AWG (orange), and 18 AWG (orange) respectively. In addition, the end segment, 13 AWG (purple), is made separately such that we can tune the tail-end of the magnetic field to control the final velocity of slowed atoms. 49
B.7 Drawing of MOT chamber body, viewed from the side. Part machined by Huntington Mechanical Labs. ................................................................. 50
B.8 Drawing of MOT chamber body, viewed from the top. Part machined by Huntington Mechanical Labs. ......................................................... 51
B.9 Drawing of MOT chamber flanges, viewed from the side. Parts machined by Huntington Mechanical Labs. ............................................... 51
B.10 Dimensions of each set of anti-Helmholtz coils. In pink are the coils used for the blue MOT, each coil consists of five radial layers and seven vertical layers made from S&W Wire Company .125SQ DPG/BARE wire. Additionally, the anti-Helmholtz coils that will be used for a narrow-line MOT are also shown in red, they consist of 10 radial layers and 2 vertical layers made from 13AWG square copper wire from MWS Wire Industries. ............................................. 52
C.1 (a) Photo of strontium pellets already loaded into the cavity of the oven nozzle. Also pictured is the cap with capillary tubes already inserted, and resistive heating wire silver-soldered on. (b) Heat shield enclosing most of the oven nozzle. Cut-outs of the material are made to accommodate feedthrough connections. (c) Capillary tubes viewed through the aperture of the heat shield. ................................................................. 54
D.1 Pressure versus time during bake of 100C for dominate partial pressures. ................. 56
List of Tables

2.1 Strontium $^1S_0 \rightarrow ^1P_1$ transition parameters. ........................................ 8

4.1 Legend of components on optical schematic. .................................................... 23
4.2 Frequency shift of first diffracted order for each AOM. .................................... 23
4.3 Frequencies of the various beams at currents chosen to trap each isotope. .......... 25

5.1 Summary of decay time constant measurements for each Bosonic isotope for heating coil
current of 1.06A, temperature of 390C, and Firerod setpoint of 430C. ..................... 30
5.2 Experimental parameters used for loading rate measurements. ......................... 36
5.3 Summary of trap loading results with the nozzle at 390C. ................................. 37
LIST OF TABLES
Abstract

Strontium Laser Cooling and Trapping Apparatus

Francisco Camargo

This work describes the assembly and use of an apparatus for laser cooling and trapping of atomic strontium in a broad-transition magneto-optical trap and magnetic trap. An all-diode 461nm laser system is used to drive the main cooling transition, $^1S_0 \rightarrow ^1P_1$. The lifetimes, loading rates, and temperatures of the trapped atoms are characterized.
Chapter 1

Introduction

Laser cooling and trapping has been instrumental in enabling the study of strongly interacting quantum systems such as BEC-BCS crossover [1], magnetic and optical Feshbach resonances [2, 3], Mott insulator-superfluid transition [4], and ultracold polar molecules [5]. Rydberg atoms have garnered significant interest in the last few years due to their large dipole moments which induce long-range, many-body interactions [6]. We aim to exploit these interactions via small admixtures of the Rydberg state [7, 8] in quantum degenerate gases of strontium in order to explore new phenomena, including three-dimensional solitons [9] and super-solids [10, 11].

Performing these experiments with strontium affords us the advantage of an enhanced lifetime compared to similar schemes using alkali atoms due to a long-lived intermediate state. This thesis reports on progress made towards the construction of a new apparatus for the production of quantum degenerate gases of strontium with the ability to excite and detect Rydberg atoms in the sample.

The centerpiece of this project is a magneto-optical trap (MOT) for strontium. A MOT is formed by a proper arrangement of near resonant laser fields and magnetic fields, and it provides a restoring force in position and velocity that provides a deep trapping potential on the order of one Kelvin, and cooling to a low temperature limit on the order of fractions of a mK in some cases. The first MOT was realized in 1987 [12], and has become the workhorse of ultracold atomic physics. It can in principle trap atoms from a room temperature source and cool them to the ultracold regime. In many situations a MOT works best when combined with precooled atoms in an atomic beam, as is the case in our experiment in which we employ a Zeeman Slower. A MOT can accumulate large numbers of atoms, which is a necessary starting point for forming high enough density samples to study interactions between atoms.

The first MOT of $^{88}$Sr was achieved in 1990 [13]. This was accomplished by utilizing the broad $^1S_0 \rightarrow ^3P_1$ transition at 461nm which constitutes the 'blue MOT'. The trap was limited to a short lifetime of 8ms due to optical pumping into the $^3P_2$ metastable state. To increase the number of atoms available for narrow-line cooling, a repumping transition can be employed to optically pump the magnetically trapped $^3P_2$ atoms.
back into the ground state [14]. A phase-space density of $10^{-2}$ was achieved by transferring into a MOT of the narrow $^1S_0 \rightarrow ^1P_1$ transition at 689nm [15]. With the ability to produce a sufficiently large number of atoms in this 'red MOT' at temperatures lower than the trap depths of optical dipole traps, all four isotopes have since been brought to quantum degeneracy [16, 17, 18, 19, 20] through evaporative cooling in different optical-dipole trap configurations.

We have successfully trapped each of the three bosonic isotopes in the blue MOT as well as in a magnetic trap made from the same magnetic fields used for the MOT. Lifetime, loading, and temperature measurements have been obtained for each boson, and are found to be comparable with results from other ultracold strontium experiments [14, 16, 17].
Chapter 2

Doppler Cooling

Doppler cooling is the basis for cooling and trapping through radiation pressure, and is applied throughout this work. In this chapter, a brief summary of the theory of two-level Doppler cooling is presented. The force exerted by a near-resonant laser beam on a free atom is velocity-dependent due to the Doppler effect. When two, counter-propagating lasers, each red-detuned with respect to atomic resonance, impinge on a gas of atoms, the sample experiences a velocity-damping force and is hence cooled.

2.1 Scattering Force

For a simple picture of laser-cooling, we can consider a two-level atomic system of transition wavelength \( \lambda \), and excited state decay rate \( \Gamma \). Begin by writing down the steady state population in the excited state, after
cooling light has been on for a time long compared to the lifetime of the excited state ($\Gamma^{-1}$) [21],

\[
f = \frac{\Omega^2/4}{\delta_0^2 + \Omega^2/2 + \Gamma^2/4},
\]

(2.1)

where $\Omega$ is the Rabi frequency, and $\delta_0$ is the total detuning. For large Rabi frequencies, the excited state population limits to $1/2$. To achieve a particular population in the excited state, atoms must scatter from the light field at a rate, $R_S$, sufficiently large enough to compensate for the spontaneous decay rate.

\[
\dot{f} = R_S - \Gamma f
\]

(2.2)

Considering again the steady state we obtain $R_S = \Gamma f$. When combined with Eq. 2.1 we obtain an expression for the scattering rate,

\[
R_S = \frac{\Gamma}{2} \frac{\Omega^2/2}{\delta_0^2 + \Omega^2/2 + \Gamma^2/4}.
\]

(2.3)

For large Rabi frequency, the scattering rate limits to a maximum of $R_{\text{Max}} \equiv \Gamma/2$. The Rabi frequency can be rewritten in terms of the ratio of laser beam intensity to saturation intensity [21],

\[
\frac{I}{I_{\text{Sat}}} = \frac{2\Omega^2}{\Gamma^2},
\]

(2.4)

\[
I_{\text{Sat}} \equiv \frac{2\pi^2 \hbar c}{3 \lambda^3},
\]

(2.5)

where $c$ is the speed of light, and $\hbar$ is the reduced Planck constant. Knowing how often a scattering event occurs, the average force a light field exerts on an atom can be expressed as $\hbar k R_S$, where $k$ is the photon wavenumber.

\[
F_S = \frac{\hbar k \Gamma}{2} \frac{I/I_{\text{Sat}}}{1 + I/I_{\text{Sat}} + 4\delta_0^2/\Gamma^2}.
\]

(2.6)

In the limit of large Rabi frequency and equivalently, high laser intensity, the scattering force approaches a maximum of, $F_{\text{Max}} \equiv \hbar k \Gamma/2$. 

Figure 2.2: Photon scattering rate as a function of total detuning at different values of intensity.
2.2 Optical Molasses

We now consider the average force exerted on an atom by two counter-propagating laser beams, which constitutes the force of optical molasses. The total detuning is now written in terms of the laser detuning, $\delta$, and the Doppler shift, $-k \cdot v$,

$$\delta_0 = \delta - k \cdot v. \quad (2.7)$$

Here, $k$ is the laser wave-vector and $v$ is the atom velocity. In one dimension, the force of optical molasses simplifies to

$$F_{OM} = F_S(\delta - kv) - F_S(\delta + kv). \quad (2.8)$$

For velocities much lower than the capture velocity, $v_C \equiv \Gamma/k$ (which sets the scale for the velocity range over which optical molasses is most effective), we make the approximation

$$F_{OM} \approx -\alpha v. \quad (2.9)$$

Where $\alpha$ is the damping coefficient defined as

$$\alpha \equiv -\frac{F_{Max}}{v_C} \frac{16I/I_{Sat} \delta/\Gamma}{[1 + 2NI/I_{Sat} + 4(\delta/\Gamma)^2]^2}. \quad (2.10)$$

This equation has been generalized for $N$ orthogonal dimensions (See Ref. [22] for details), where each dimension contains a pair of counter-propagating beams, by making the substitution

$$I/I_{Sat} \rightarrow 2NI/I_{Sat} \quad (2.11)$$

to the denominator of Eq. 2.6 to account for the increase in total field intensity. Note that in order to actually damp the motion, negative values of detuning are required, as can be seen in Fig. 2.3.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.3.png}
\caption{Damping coefficient as a function of laser detuning at different intensities in 3-D.}
\end{figure}
2.3 Doppler Cooling Limit

Next we consider the rate of change of kinetic energy, $E$, in optical molasses in order to calculate temperature (for a detailed derivation see Ref. [22]). The cooling rate is determined by taking the product of the force due to optical molasses and the atom velocity,

$$\left(\frac{dE}{dt}\right)_{\text{Cool}} = F_{\text{OM}} \cdot v.$$  \hspace{1cm} (2.12)

Utilizing Eq. 2.9 and rearranging, we arrive at

$$\left(\frac{dE}{dt}\right)_{\text{Cool}} = -\frac{E}{\tau_{\text{Cool}}},$$  \hspace{1cm} (2.13)

where $\tau_{\text{Cool}} \equiv \frac{M}{2\alpha}$ defines the cooling time constant. The average force exerted by optical molasses reduces an atom’s momentum to zero, however, individual absorption and emission events contribute to a random walk in momentum space, each of size $\hbar k$. The rate of change of the mean square momentum goes as the number of steps of absorption-emission, times $\hbar^2k^2$, times the total scattering rate, $2NR_S$. Again the substitution, Eq. 2.11 is made, this time in the denominator of $R_S$.

$$\frac{d(p^2)}{dt} = 4N\hbar^2k^2R_S$$  \hspace{1cm} (2.14)

Dividing by $2M$, we obtain an expression for the increase in kinetic energy,

$$\left(\frac{dE}{dt}\right)_{\text{Heat}} = 2N\hbar^2k^2R_S/M.$$  \hspace{1cm} (2.15)

At equilibrium, the cooling and heating rates are equal, such that,

$$\left(\frac{dE}{dt}\right)_{\text{Cool}} + \left(\frac{dE}{dt}\right)_{\text{Heat}} = 0.$$  \hspace{1cm} (2.16)

Taking temperature to be $Nk_B T/2 = M v^2/2$, where $k_B$ is Boltzmann’s constant, we arrive at an expression for the temperature of an atom in optical molasses in $N$ dimensions for red-detuned light,

$$k_B T = \frac{\hbar \Gamma}{2} \frac{1 + 2N I/I_{\text{Sat}} + (2\delta/\Gamma)^2}{4|\delta/\Gamma|}$$  \hspace{1cm} (2.17)

Taking the limit of zero intensity, the minimum of temperature is found at $\delta = -\Gamma/2$, resulting in the so-called, Doppler cooling limit

$$k_B T_D = \frac{\hbar \Gamma}{2}.$$  \hspace{1cm} (2.18)

2.4 Strontium Level Structure

The $(5s^2)\,^1S_0 \rightarrow (5s5p)^1P_1$ strontium transition at 461nm possesses a broad, $2\pi \times 30.5$MHz linewidth [23], which is used as the main cooling and trapping transition with a Doppler limit of 0.7mK. However, this is not a closed transition due to decay to the $(5s4d)^1D_2$ state with a branching ratio of $20 \times 10^{-6}$. From the $(5s4d)^1D_2$ state, approximately a third will decay to the magnetically trappable $(5s5p)^3P_2$ metastable state,
2.4. STRONTIUM LEVEL STRUCTURE

Figure 2.4: Energy level spectrum of strontium. Decay rates are shown in addition to the wavelengths of the trapping and repumping beams.

which constitutes the main loss mechanism [24, 25]. To recuperate these atoms back in the ground state, repumping via the doubly excited \((5s^2)^3P_2\) state [26] can be utilized.

Table 2.1 summarizes quantities related to the main cooling transition of strontium. The formulas for each of the calculated values not previously defined are as follows, recoil temperature: \(k_B T_r = \frac{\hbar^2 k^2}{M}\), recoil velocity: \(v_r = \hbar k / M\), and recoil frequency: \(\omega_r = \hbar k^2 / 2M\) [27]. These quantities are related to the scattering of a single photon. The recoil velocity represents the change in atom velocity and similarly for the recoil frequency. The recoil temperature is equivalent to the energy deposited on an atom after scattering. For the broad 461nm transition, the Doppler temperature is much higher by comparison such that it sets the scale for the minimum attainable temperature when optical molasses is employed for cooling.
Table 2.1: Strontium $^1S_0 \rightarrow ^1P_1$ transition parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>461</td>
<td>nm</td>
</tr>
<tr>
<td>Linewidth</td>
<td>$\Gamma/2\pi$</td>
<td>30.5</td>
<td>MHz</td>
</tr>
<tr>
<td>Saturation Intensity</td>
<td>$I_{Sat}$</td>
<td>40.5</td>
<td>mW/cm$^2$</td>
</tr>
<tr>
<td>Capture Velocity</td>
<td>$v_C$</td>
<td>14.1</td>
<td>mm/ms</td>
</tr>
<tr>
<td>Doppler Temperature</td>
<td>$T_D$</td>
<td>730</td>
<td>$\mu$K</td>
</tr>
<tr>
<td>Doppler Velocity</td>
<td>$v_D$</td>
<td>380</td>
<td>$\mu$m/ms</td>
</tr>
<tr>
<td>Recoil Temperature</td>
<td>$T_r$</td>
<td>534</td>
<td>nK</td>
</tr>
<tr>
<td>Recoil Velocity</td>
<td>$v_r$</td>
<td>10.3</td>
<td>$\mu$m/ms</td>
</tr>
<tr>
<td>Recoil Frequency</td>
<td>$\omega_r/2\pi$</td>
<td>11.2</td>
<td>kHz</td>
</tr>
</tbody>
</table>
Chapter 3

Apparatus Design

3.1 Vacuum Chamber Overview

There are four main components in the cooling and trapping apparatus. First, the nozzle, which houses strontium pellets which are heated to induce sublimation. Second is the 2D-Collimator section, through which a laser beam is recycled and retro-reflected to pass through the atoms 4 times in order to collimate the atoms into a beam. Third is the Zeeman Slower whose objective is to slow and cool the atomic beam along the direction of beam propagation. Lastly, with a sufficient flux of slow atoms we can load the magneto-optical trap (MOT). An overview of the final vacuum chamber is given in Figure 3.1.

Figure 3.1: Listed are the various vacuum chamber components of the apparatus: the oven nozzle (cyan), 2D-Collimator (red), differential pumping tube (green), Zeeman Slower (orange), MOT chamber (blue), anti-Helmholtz coils (pink), ion pumps (purple), non-evaporable getter (dark green).
3.2 Strontium Oven Nozzle

Strontium pellets are housed in a cavity at the end of the nozzle. Once heated, atomic strontium escapes through the capillary tubes that constitute the output of the nozzle. Machine drawings can found in Appendix B. Details of assembling the oven nozzle can be found in Appendix C.

Figure 3.2: Simplified strontium oven nozzle. Strontium (red) is housed beneath the nozzle head (orange), which is bolted down to the body (blue). Two heating elements are used; a Firerod (light-blue) behind the stontium and outside vacuum, and a 1.6Ω/ft. heating coil (pink) which is silver-soldered around the capillary tubes (green). The coils serve the essential role of keeping the capillary tubes hot enough such that strontium does not clog them.

The flux of an atomic beam has a velocity distribution of the form (Ref. [28])

\[
f(v) = \frac{1}{2} v^3 v^4 \exp \left( -\frac{2v^2}{v^2_{\text{RMS}}} \right),
\]

where the root-mean-squared velocity is given by \( v_{\text{RMS}} = 2\sqrt{k_B T/M} \). In addition, \( k_B \) is Boltzmann’s constant, \( T \) is temperature of the beam, and \( M \) is the mass of the atom. This distribution is plotted in Figure 3.3 with velocity scaled by the capture velocity, \( v_C = \Gamma/k \approx 14 \text{ m/s} \). It is important to note that because the distribution is normalized to unity it does not represent the absolute number of atoms in the beam. As such, insufficient trapped atom flux can be augmented by increasing the temperature of the source. However, this comes at the cost of increased background pressure in addition to the need to replenish the source more frequently.

In order to achieve the necessary temperatures, a Firerod\(^1\) and resistive heating coils\(^2\) are used to heat

\(^1\)Wattlow High-Temperature Firerod Cartridge Heaters: 120V 240W FIREROD 0423, SK7J-2953, 1.5cm OD.
\(^2\)ARI Industries, Inc. P/N 1HN063B-1.6
3.3 2D-COLLIMATOR

Figure 3.3: Velocity distribution of a beam of strontium at different temperatures. Velocity is scaled by the capture velocity.

the strontium pellets\textsuperscript{3}. There is also a thermocouple which is held by one of the bolts that connects the head of the nozzle to the body. Both the resistive heating coils and the thermocouple are connected through feedthroughs welded on the flange. Temperature measured at the nozzle head as a function of temperature in the Firerod with a constant 1.06A through the resistive coil follows the linear form

\[ T_{\text{Nozzle}} = 0.67 T_{\text{Firerod}} + 105 \, \text{C}. \]  

(3.2)

This is a fit to data taken of a range of Firerod temperatures of 250C to 500C, and is accurate to within ±2C.

3.3 2D-Collimator

The first stage of cooling, the 2D-Collimator\textsuperscript{29}, is a direct application of optical mollasses in which we aim to cool the atomic beam in the transverse direction resulting in a collimated atomic beam with increased flux in the trapping region. This is accomplished, as shown in Figure 3.4, by recycling and retroreflecting a laser beam at a detuning of \( -\Gamma/2 \) in order to cool to the Doppler limit. The viewports are AR coated\textsuperscript{4} and the flanges are located 12in away from the nozzle end to minimize buildup up of strontium on the glass. The mirrors used are anchored separately to the table to ensure vibrational stability. The laser beam is shaped to have a width of 0.5cm in a transverse direction to match the radius of the atomic beam, and a 1.0cm width along the axial direction to increase the interaction time.

After the 2D-Collimator, there is a tube of diameter 0.3in and length 2.4in which constitutes a differential pumping tube of conductance 0.8L/s. In addition, the Zeeman Slower’s geometry restricts the conductance

\textsuperscript{3}Sigma-Aldrich Strontium dendritic pieces, purified by distillation, 99.9% trace metals basis
\textsuperscript{4}All viewport were coated for for 461nm, 689nm, and 1064nm, see Appendix A.
CHAPTER 3. APPARATUS DESIGN

Figure 3.4: 2D-Collimator optical path layout. The vacuum chamber walls are in red, the viewports in green, mirrors in light blue, and laser beam in dark blue. The atoms are centered in the chamber and travel into the page, the laser beam originates from the right-hand side and traverse the atoms four times.

to 1.5L/s. Having these low conductance values compared to the pumping speed of the ion pumps and the non-evaporable getter, restricts the pressure contribution due to the heated nozzle in the region of the trapped atoms. Detailed drawings can be found in Appendix B.

3.4 Zeeman Slower

In between the 2D-Collimator and the atom trap we use a Zeeman Slower [30] to axially cool the atomic beam. We have chosen as a design objective to trap atoms with a velocity equal to or lesser than the most probable velocity, $v_{MP}$, of an atomic beam at 450C,

$$v_{MP} = \frac{\sqrt{3}}{2}v_{RMS} \approx 33v_C.$$  \hspace{1cm}(3.3)

A circularly polarized laser counter-propagating to the atomic beam will, averaging over many scattering events, reduce the axial velocity of the atomic beam. As the velocity dependent Doppler Shift changes, a position-varying magnetic field retains resonance as the atoms decelerate through the Zeeman Slower.

Assuming an atomic beam shape constrained by the vacuum chamber geometry, we choose a laser beam
profile to match. This means that the laser intensity will monotonically decrease along the atomic path as the atoms radially expand. In addition, because of the Gaussian laser beam shape, the force that can be exerted on the atoms, even on resonance, is diminished at the wings. With a 100mW beam, the expected scattering force is plotted in Figure 3.5. Because the Zeeman laser beam will overlap with the MOT, it is important to detune away from the resonance in order to minimize the force exerted on trapped atoms [15, 31]. Constrained by accessible frequency shifts via Acousto-Optical Modulators (AOMs) and reasonable magnetic field values, a detuning of -550MHz was chosen. Note that the choice of non-zero detuning results in a Zeeman Slower with a zero-crossing of the magnetic field.

Figure 3.5: Plotted is the force exerted by laser on an atom traveling along the center of the Zeeman Slower (blue) and along the $e^{-2}$ radius of the laser (orange), if kept on-resonance. The design parameter, $\eta$ (red), is chosen to be less than the force the laser can exert along the $e^{-2}$ radius.

To mitigate the effects of an imperfect magnetic field, Zeeman Slowers are commonly designed such that the force they exert on a test atom moving at $v_{MP}$, is lower than the force an on resonant laser could provide. And so, we define $\eta$, the design parameter, to be the ratio of the force we want to exert on the test atom to the maximum force. Compared to other designs, we chose a conservative value for the design parameter [31, 32],

$$\eta_1 = 0.3, \ 0 < z < z_{zero}$$
$$\eta_2 = 0.2, \ z_{zero} < z$$

(3.4)

Where $z_{zero}$ is the position at which the magnetic field crosses zero. With this choice of $\eta$ we can solve for the position dependent velocity of the test atom. Given the resonance condition,

$$\delta - \mathbf{k} \cdot \mathbf{v} - g \mu_B m B / \hbar = 0,$$

(3.5)
where we introduce the Zeeman shift due to the magnetic field, \( B \), where \( g \) is the Lendé \( g \)-factor, \( \mu_B \) is the Bohr magnaton, and \( m \) is the magnetic quantum number. We can get an expression for the spatially varying magnetic field needed to keep a circularly polarized laser on resonance with an atom entering the slower at the design velocity and decelerate by \( \eta_1 F_{\text{Max}} \) in region 1 and by \( \eta_2 F_{\text{Max}} \) in region 2:

\[
B = \begin{cases} 
B_0 + B_1 \sqrt{1 - z/z_1} & : 0 < z < z_{\text{zero}} \\
B_0 + B_2 \sqrt{1 - (z - z_{\text{zero}})/z_2} & : z_{\text{zero}} < z < z_{\text{zero}} + z_2
\end{cases}
\]

\[
B_0 = \hbar \delta/\mu_B \\
B_1 = \hbar k v_{\text{MP}}/\mu_B \\
z_1 = \frac{1}{2} M v_{\text{MP}}^2/\eta_1 F_{\text{Max}} \\
z_{\text{zero}} = z_1 [1 - (B_0/B_1)^2] \\
v_{\text{zero}} = v_{\text{MP}} \sqrt{1 - z_{\text{zero}}/z_1} \\
B_2 = \hbar k v_{\text{zero}}/\mu_B \\
z_2 = \frac{1}{2} M v_{\text{zero}}^2/\eta_2 F_{\text{Max}}
\]

Figure 3.6: Plot of calculated magnetic field given our choice of \( \eta \) (black), and direct measurements of field (red).

With positive field denoting direction parallel to the atomic beam propagation direction, left-handed circular polarization must be used to drive the \( \sigma^+ \) transition. Figure 3.7 shows calculated trajectories of atoms of various initial axial velocities. These trajectories are obtained by numerically solving

\[
M \ddot{z} = F_S(z, \dot{z}),
\]

(3.7)
where \( F_S \) is given by Eq. 2.3 under resonance condition Eq. 3.5. The measured magnetic field was interpolated and used in the numerical solution. Two paths are plotted for each initial velocity; one where the atom travels along the center of the Zeeman Slower where the light intensity is maximal, and when an atom travels along the waist of the laser beam. Even though there is a difference of \( \exp(-2) \) in intensity, the trajectories are remarkably similar. Upon reaching the end of the Zeeman Slower, atoms of low enough initial velocity experience a reversal of propagation direction. To have the flexibility to avoid this possibility, which would significantly degrade trap loading efficiency, the end of the Zeeman Slower coils are controlled separately. In essence, by tuning the magnetic field on the output of the Zeeman Slower, the output velocity can be changed to optimize atom trapping.

![Figure 3.7: Trajectories of atoms as they traverse the Zeeman Slower at different initial axial velocities via interpolation of the measured magnetic field. Solid is for an atom that travels along the axis of the Zeeman Slower, dashed is for an atom that travels along the waist of the Zeeman laser beam. That is, the intensity is reduced by \( \exp(-2) \). Position is scaled by the length of the Zeeman Slower, 0.41m, and the velocity is scaled by the capture velocity.](image)

### 3.5 Magneto-Optical Trap

The MOT creates a dissipative restoring force to provide cooling and trapping. Like the 2D-Collimator which cools via optical molasses in two dimensions, the MOT consists of three orthogonal laser beams which are then retro-reflected. The attractive component of the force results from the spatially dependent Zeeman Shift due to the inclusion of a quadropole magnetic field. In one dimension, the MOT can be modeled as two counter-propagating beams, each exerting a force (Eq. 2.8) under resonance condition Eq. 3.5. At the
center of the magnetic quadrupole, the magnetic field gradient is approximately linear such that \( B \approx \frac{\partial B}{\partial z} z \).

\[
F_{\text{MOT}} = F_{\sigma^+} (\delta - kv - \frac{\mu_B}{\hbar} \frac{\partial B}{\partial z} z) - F_{\sigma^-} (\delta + kv + \frac{\mu_B}{\hbar} \frac{\partial B}{\partial z} z).
\]  

(3.8)

The subscripts of each term have been changed to indicate the correct polarization required. Fig. 3.8 demonstrates how the MOT operates for a \( J = 0 \to J = 1 \) transition.

![Figure 3.8: Schematic of MOT operation in 1-D on a \( J = 0 \to J = 1 \) transition. The field gradient results in a spatially dependent Zeeman shift which splits the excited state sub-levels. Two counter-propagating, \( \sigma^\pm \) polarized, red-detuned laser beams propagating in the \( \pm z \) direction are incident on the atoms. The spatially dependent energy shift in conjunction with selection rules result in an imbalanced force contribution from each laser. As atoms are pushed closer to the zero of the magnetic field, the force falls out of resonance.](image)

Under the conditions, \( |kv/\Gamma| \ll 1 \), and \( |\frac{\mu_B}{\hbar} \frac{\partial B}{\partial z} z/\Gamma| \ll 1 \), we can make the approximation

\[
F_{\text{MOT}} \approx -2\zeta M \omega_0 v - M \omega_0^2 z.
\]  

(3.9)

The trapping frequency is given by,

\[
\omega_0 = \sqrt{\frac{\alpha \mu_B}{M \hbar^2} \frac{\partial B}{\partial z}}.
\]  

(3.10)

where \( \alpha \) is the damping coefficient given by Eq. 2.10. For intensity \( I/I_{\text{Sat}} = 0.1 \), detuning \( \delta/\Gamma = -2 \), and a field gradient \( \frac{\partial B}{\partial z} = 44 \text{G/cm} \), the trapping frequency is \( 2\pi \times 240 \text{Hz} \). The damping time is \( \tau_{\text{Damp}} = M/\alpha \).
such that the damping ratio is given by

\[ \zeta = \frac{1}{(2 \tau_{\text{Damp}} \omega_0)}. \] (3.11)

For the same parameters, the damping ratio is 0.3, meaning the MOT at this detuning is an underdamped oscillator.

Figure 3.9: Plotted are the results of a three-dimensional calculation of the magnetic field. (a) Axial magnetic field component as a function of axial position at different currents. At 40A, the axial component of the field gradient is 44G/cm. (b) Radial magnetic field component as a function of radial position at different currents. At 40A, the radial component of the field gradient is -22G/cm.
The quadrupole magnetic field is produced by a pair of coils in an anti-Helmholtz configuration. See Appendix B for a machine drawing of the coils. The wire\(^5\) used is hollow on the inside to allow for water cooling. The field gradient depends linearly on the current with a proportionality constant of \(1.1 \text{G/cm/A}\). In addition, an extra set of coils that will be utilized to create a MOT of the \(^1\text{S}_0 \rightarrow ^3\text{P}_1\) transition have also been installed. In addition, there are electrode plates inside the chamber to be used for selective field ionization and a multi-channel plate to detect electrons.

### 3.6 Magnetic Trap

When driving the 461nm transition most atoms spontaneously decay back to the ground state, but about 1 in \(50 \times 10^3\) will decay to the \(^1\text{D}_2\) state and subsequently either the \(^3\text{P}_1\) or \(^3\text{P}_2\) state [25], (Fig. 2.4). The lifetime of the latter is much longer than the loading time of the MOT, and as such, constitutes the largest source of atom loss. With increasing density, loss due to two-body light assisted collisions also become prevalent.

Because atoms in the \(^3\text{P}_J\) state have a magnetic dipole moment, the low field seeking magnetic sublevels are trapped by the MOT quadrupole magnetic field [25, 14]. Given that the divergence of magnetic fields is zero, near the center of the trap we can write an approximate expression for the potential energy, in cylindrical coordinates, as

\[
U = g \mu_B m \frac{\partial B}{\partial z} \sqrt{\frac{r^2}{4} + z^2},
\]

where \(\frac{\partial B}{\partial z}\) is the gradient along the axial coordinates of the anti-Helmholtz coils. Given a Lendé g-factor of \(3/2\) for the \(^3\text{P}_2\) state and an axial field gradient of \(44\text{G/cm}\) at \(40\text{A}\), the minimum trap depth, found along the radial direction, is \(m \times 7\text{mK}\). At low density, a prevalent loss-mechanism of the \(^3\text{P}_2\) state is due to blackbody radiation driving the \(^3\text{P}_2 \rightarrow ^3\text{D}_2\) transition, which at a temperature of 21\text{C} yields an estimated magnetic trap lifetime of 9s [33]. In order to reobtain these atoms in the ground state, the long lifetime of the \(^3\text{P}_2\) state must be circumvented. This is achieved by driving a repumping transition to the \((5\text{p}^2)^3\text{P}_2\) state with 481nm light. From there, one in three atoms decays to the \(^3\text{P}_1\) state, and subsequently decays again to the ground state.

By having 481nm light on during the loading of the MOT we greatly increase the maximum number of atoms that we can trap, however we would still be limited by the efficiency of continually repumping and recapturing, background gas collisions, and two-body light assisted collisions. Instead we choose to load for several seconds without the 481nm light such that we populate the \(^3\text{P}_2\) state and accumulate atoms in the magnetic trap. Only at the end of the load time do we flash 481nm light for 50ms to repump the atoms back to the ground state.

---

\(^{5}\text{S&W Wire Company .125SQ DPG/BARE}\)
Figure 3.10: Magnetic trap potential energy for atoms in the $m = 2$, $^3P_2$ state.
Chapter 4

461nm Diode Laser System

4.1 Optical Layout

The laser system consists of three blue diode lasers in a master-slave configuration (Fig 4.1 1a-c). The master is a 40mW external cavity, tunable laser\(^1\). The beam first goes through a -30dB optical isolator\(^2\) (OI), (2a), to prevent optical feedback. The profile of the master is bi-modal with nearly equal power distribution, we therefore separated the lobes with a pick-off mirror. One of these beams proceeds to an AOM\(^3\), (4a), of central frequency \(\Delta_{2S} = 2\pi \times 535\text{MHz}\). The zeroth order beam is sent to a cell for saturated absorption spectroscopy to generate the error signal needed to frequency lock the master to \(-\Gamma/2\) away from resonance.

The first order beam is detuned to attain light at the frequency need for the Zeeman Slower. The beam is then steered through the rejection port of a second OI\(^4\), (2b) such that the beam is reflected unto the first slave\(^5\), (1b). Once injection locked, 104mW of light is measured on the output of the OI, all of which is used to Zeeman slow atoms (11). The beam is expanded and refocused, (9a), beyond the strontium oven nozzle, (10), to match the expected profile of the counter-propagating atomic beam.

The second lobe of light from the master is used to injection lock the second slave laser\(^6\), (1c), via the rejection port of a third OI\(^7\), (2c). On the output of the OI we place a \(\Delta_{\text{MOT}} = 2\pi \times 40\text{MHz}\) AOM, (4c), to red detune such that the beam frequency is nearly \(-2\Gamma\). After expansion and collimation, (9b), the beam has a waist of 2.5cm and is subsequently split into the the three arms of the MOT, (3a) and (3b), using half-wave plates\(^8\) and polarizing beam splitting cubes\(^9\). We use another wave-plate cube pair, (3c), such that all

---

\(^1\text{NewFocus TLB-6802}\)
\(^2\text{Thorlabs IO-3-460-HP}\)
\(^3\text{All AOM’s were purchased from IntraAction Corp.}\)
\(^4\text{Thorlabs IO-3-460-HP}\)
\(^5\text{NewFocus TLB-6802-IJ-D}\)
\(^6\text{NewFocus TLB-6802-IJ-D}\)
\(^7\text{ConOptics 711C-3}\)
\(^8\text{All waveplates were custom made by Sinocera Photonics, Inc. for 461nm}\)
\(^9\text{All PBS cubes were custom made by Lambda Research Optics, Inc. for 461nm}\)
three MOT arms emerge as a transmission through a cube to ensure high polarization fidelity. Quarter wave plates are used to obtain circular polarization for each beam, (6c-e). Three additional quarter waveplates are used, (6f-h), such that upon reflection from mirrors, each arm is then circularly polarized with opposite polarization in order to satisfy Eq. 3.8 given the field produced by the Anti-Helmholtz coils, (12).

The zeroth order beam from (4c) is sent to a $\Delta_{\text{Im}_1} = 2\pi \times 85\text{MHz}$ AOM, (4d). The zeroth order is expanded and collimated into a cylindrical beam used as the 2D-Collimator beam. The waist along the axis of atom propagation is 1cm while the orthogonal axis has a waist of 0.5cm. The first order beam is blue detuned by $\Delta_{\text{Im}_2} = 2\pi \times 100\text{MHz}$ by another AOM, (4e). The emerging beam will be on resonance and after passing through collimation optics, it will be used for absorption imaging in conjunction with a CCD camera\textsuperscript{10}. Lastly, 481nm\textsuperscript{11} light is brought to the apparatus with an optical fiber from another optical table, (13). The light is frequency locked using the side of a Doppler broadened peak of a tellurium transition.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4_1}
\caption{Simplified optical layout. Made using image library from Alexander Franzen.}
\end{figure}

\textsuperscript{10}Andor Technology Luca-R EMCCD
\textsuperscript{11}Toptica Photonics DC-110
### 4.1. OPTICAL LAYOUT

#### Table 4.1: Legend of components on optical schematic.

<table>
<thead>
<tr>
<th>Label</th>
<th>Name</th>
<th>Label</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a-c</td>
<td>Laser Heads</td>
<td>9a-d</td>
<td>Expansion and collimation optics</td>
</tr>
<tr>
<td>2a-c</td>
<td>Optical Isolators</td>
<td>10</td>
<td>Oven nozzle</td>
</tr>
<tr>
<td>3a-c</td>
<td>Half-wave plate and PBS Power control</td>
<td>11</td>
<td>Zeeman Slower</td>
</tr>
<tr>
<td>4a-e</td>
<td>AOMs</td>
<td>12</td>
<td>Anti-Helmholtz coils</td>
</tr>
<tr>
<td>5</td>
<td>Beam splitter</td>
<td>13</td>
<td>481nm fiber coupler</td>
</tr>
<tr>
<td>6a-h</td>
<td>Quarter-wave plates</td>
<td>14a-d</td>
<td>Beam dumps</td>
</tr>
<tr>
<td>7</td>
<td>Saturated absorption cell</td>
<td>15</td>
<td>Camera</td>
</tr>
<tr>
<td>8</td>
<td>Balanced photodiode</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 4.2: Frequency shift of first diffracted order for each AOM.

<table>
<thead>
<tr>
<th>AOM</th>
<th>Shift (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a, $\Delta_{ZS}/2\pi$</td>
<td>-535</td>
</tr>
<tr>
<td>4b, $\Delta_{SA}/2\pi$</td>
<td>+260</td>
</tr>
<tr>
<td>4c, $\Delta_{MOT}/2\pi$</td>
<td>-40</td>
</tr>
<tr>
<td>4d, $\Delta_{Im_1}/2\pi$</td>
<td>-85</td>
</tr>
<tr>
<td>4e, $\Delta_{Im_2}/2\pi$</td>
<td>+100</td>
</tr>
</tbody>
</table>
4.2 Frequency Locking Scheme

The master laser tuning range spans resonance frequencies for all three stable isotopes of strontium. To trap any one isotope, the frequency is varied by Zeeman shifting the transition of atoms inside the saturated absorption cell, \(7\). The cell is heated to approximately 250°C, leading to approximately \(2\pi \times 1\) GHz of Doppler broadening. Doppler-free spectroscopy is used to generate an error signal from the Lamb dip. The setup can be seen in Fig. 4.2. The zeroth order diffracted beam from the \(-2\pi \times 535\) MHz AOM, (4a), in Figure. 4.1 is incident on a window, (5). The reflection and transmission constitute the probe and pump beams, respectively. Before entering the cell, the pump is up-shifted by \(\Delta \text{SA} = 2\pi \times 260\) MHz through an AOM, (4b). Bear in mind that the frequency of the probe is the same as the frequency of the master, \(\omega_M\). The pump frequency can be written as

\[
\omega_P = \omega_M + \Delta \text{SA}. 
\] (4.1)

The master laser is locked by utilizing the Lamb Dip signal produced by the \(^{88}\text{Sr} \ 1S_0 \rightarrow 1P_1\) transition due to its large isotope abundance. The laser frequencies are therefore expressed in terms of the natural transition frequency \(\omega_{ss}\),

\[
\omega_P = \omega_{ss} + kv - g\mu_B m_P uB 
\] (4.2)

\[
\omega_M = \omega_{ss} - kv - g\mu_B m_M B
\] (4.3)

where \(\omega_P\) and \(\omega_M\) are the laser frequencies of pump and master, respectively, and \(B\) is the magnetic field inside the cell. With both beams having opposite circular polarization handedness, both beams drive the \(\sigma^+\) transition. Solving for the frequency of the master,

\[
\omega_M = \omega_{ss} + \frac{g\mu_B B}{\hbar} - \Delta \text{SA}/2. 
\] (4.4)

The Zeeman shift as a function of current is determined empirically to be

\[
\frac{g\mu_B B}{\hbar} = (2\pi \times 26.1 \text{ MHz}/\text{A}) I. 
\] (4.5)
4.2. FREQUENCY LOCKING SCHEME

Given the shifts due to the AOMs used, the frequency of each beam is as follows:

\[
\begin{align*}
\omega_{\text{Coll}} &= \omega_M \\
\omega_{\text{ZS}} &= \omega_M + \Delta_{\text{ZS}} \\
\omega_{\text{MOT}} &= \omega_M + \Delta_{\text{MOT}} \\
\omega_{\text{Im}} &= \omega_M + \Delta_{\text{Im}} + \Delta_{\text{Im_2}}
\end{align*}
\]  

(4.6)

Where \( \omega_{\text{Coll}} \) is the frequency of the 2D-Collimator, \( \omega_{\text{ZS}} \) is the frequency of the Zeeman Slower, \( \omega_{\text{MOT}} \) is the frequency of the MOT beams, and \( \omega_{\text{Im}} \) is the imaging frequency. Figure 4.3 shows the configuration of each beam that enters the MOT vacuum chamber.

Table 4.3: Frequencies of the various beams at currents chosen to trap each isotope.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>I (A)</th>
<th>Master</th>
<th>2D-Collimator</th>
<th>Zeeman Slower</th>
<th>MOT</th>
<th>Imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{88}\text{Sr})</td>
<td>4.42</td>
<td>(\omega_{88} - 2\pi 15) MHz</td>
<td>(\omega_{88} - 2\pi 15) MHz</td>
<td>(\omega_{88} - 2\pi 550) MHz</td>
<td>(\omega_{88} - 2\pi 55) MHz</td>
<td>(\omega_{88})</td>
</tr>
<tr>
<td>(^{86}\text{Sr})</td>
<td>-0.37</td>
<td>(\omega_{86} - 2\pi 15) MHz</td>
<td>(\omega_{86} - 2\pi 15) MHz</td>
<td>(\omega_{86} - 2\pi 550) MHz</td>
<td>(\omega_{86} - 2\pi 55) MHz</td>
<td>(\omega_{86})</td>
</tr>
<tr>
<td>(^{84}\text{Sr})</td>
<td>-5.99</td>
<td>(\omega_{84} - 2\pi 15) MHz</td>
<td>(\omega_{84} - 2\pi 15) MHz</td>
<td>(\omega_{84} - 2\pi 550) MHz</td>
<td>(\omega_{84} - 2\pi 55) MHz</td>
<td>(\omega_{84})</td>
</tr>
</tbody>
</table>

Figure 4.3: Entry point of each laser beam. The MOT beams enter through three orthogonal directions and are each retro-reflected. The MOT coils are shown in pink. Also depicted are the Zeeman Slower beam, repumper, and imaging beam.
Chapter 5

Measurements

5.1 Atom Number

The Beer-Lambert law is used to calculate the number of atoms trapped, $N$. The law states that the attenuation of light through a medium depends exponentially on the optical depth of the medium, $OD$,

$$ I = I_0 \exp(-OD). \quad (5.1) $$

![Sample false color image of an atom cloud of $^{88}$Sr in a MOT.](image)

The $OD$ can be expressed as the product of the cross-section, $\sigma$, with the density, $n$, integrated along the direction of imaging beam propagation, $y$,

$$ OD = \sigma \int n \, dy. \quad (5.2) $$

$$ \sigma = \frac{3\lambda^2}{2\pi} \frac{1}{1 + I/I_{\text{Sat}} + (2\delta/\Gamma)^2} \quad (5.3) $$

At low intensity and zero detuning, the cross-section simplifies to

$$ \sigma = \frac{3\lambda^2}{2\pi}. \quad (5.4) $$

A three dimensional Gaussian density distribution is assumed,

$$ n = n_0 \exp \left( -\frac{x^2}{2\rho_x^2} - \frac{y^2}{2\rho_y^2} - \frac{z^2}{2\rho_z^2} \right). \quad (5.5) $$
Where $\rho_i$ is the radius of the cloud along the dimension $i$, and $n_0$ is the peak density,

$$n_0 = \frac{N}{(2\pi)^{3/2}\rho_x\rho_y\rho_z}. \quad (5.6)$$

The OD therefore takes the functional form

$$OD = \sigma N \frac{\rho_x\rho_y\rho_z}{2\rho_z} \exp\left( -\frac{x^2}{2\rho_x^2} - \frac{z^2}{2\rho_z^2} \right). \quad (5.7)$$

Images are converted to plots of $OD$ by via Eq. 5.1 where background images taken immediately after atoms have left the region of interest are used for $I_0$. The widths and atom number are fit parameters.

![Figure 5.2: Sample fit to one dimensional slice through image of an atom cloud of $^{88}$Sr.](image)

**5.2 Magnetic Trap Atom Loss**

The first set of measurements determined the one-body loss time constant in the magnetic trap. This serves as an indicator of the background pressure of the apparatus[14]. A measurement of a decay time much shorter than the contribution due to blackbody radiation can be attributed to collisions with background gas. Loss contributions due to light assisted collisions become significant with increased density, and are more prevalent with the isotopes of larger abundances. As such, to measure the one-body decay constant, we hold in each trap long enough to where one-body decay is the dominant loss mechanism.

Loading the MOT simultaneously loads the magnetic trap through continual decay of the $^1P_1$ state to the $^3P_1$ state for a time $t_L$ of order $1s$, (Fig. 5.3). When loading is complete, the Zeeman Slower laser beam and magnetic field is turned off in addition to the MOT laser beams. The time atoms are held in the magnetic trap, $t_H$, is then varied. The atoms are imaged by repumping back into the MOT for a time $t_R = 50ms$. Once the atoms have returned to the ground state, the camera is exposed to the imaging beam for absorption imaging for a time $t_1 = 15 \mu s$.

Figure 5.4 shows an example measurement of the decay time constant. The loading time is chosen to be short enough to maintain a low enough density such that two-body loss is not prevalent. As such, atom
5.2. MAGNETIC TRAP ATOM LOSS

Figure 5.3: Timing diagram showing when each beam is on in addition to the Anti-Helmholtz coils.

The number is fit to

\[ N = N_0 \exp(-t/\tau), \]  

(5.8)

where \( N_0 \) is the initial atom number, and \( \tau \) is the one-body decay constant. The same measurement is then repeated at various oven nozzle temperatures (Fig 5.5).

Figure 5.4: Lifetime measurement of \(^{88}\text{Sr}\) with nozzle heating coil at 1.06A, coil temperature of 374C and a Firerod setpoint of 400C resulting in a decay time constant of 9.4 ± 0.1s.

Below 300C, an approximately constant value of trap lifetime of 20s is observed, a value similar to previous measurements [34]. This roughly agrees with an estimate of trap lifetime limited by blackbody
radiation of the chamber at room temperature of 9 s [33]. The decrease in lifetime at higher temperatures can be attributed to an increased presence of background gas. However, operating at lower temperatures comes at the cost of atom flux, such that a compromise between loading rate and decay time is made. We discounted the possibility that the decrease in lifetime at increasing temperatures is due to collisions with the strontium atomic beam itself. This was done by trapping $^{86}$Sr and repeating the lifetime measurements while deflecting $^{88}$Sr away from the MOT with a beam of resonant light at the 2D-Collimator.

Lastly, the decay time for the different bosonic isotopes is measured at fixed oven nozzle parameters, (Table 5.1). The same value of one-body loss coefficient is expected; changing isotopes only changes the loading rate of the trap which has no bearing on the lifetime.

Table 5.1: Summary of decay time constant measurements for each Bosonic isotope for heating coil current of 1.06A, temperature of 390C, and Firerod setpoint of 430C.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\tau$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{88}$Sr</td>
<td>8.6 ± 0.4</td>
</tr>
<tr>
<td>$^{86}$Sr</td>
<td>8.0 ± 0.3</td>
</tr>
<tr>
<td>$^{84}$Sr</td>
<td>8.6 ± 0.1</td>
</tr>
</tbody>
</table>
5.3 Zeeman Slower Optimization

Next we optimized the performance of the Zeeman Slower and MOT such that for fixed loading times we maximized the number of atoms trapped. The following measurements were done by trapping $^{86}$Sr after a loading time of 1s with the nozzle temperature at 390C, heating coil current at 1.06A, and Firerod set to 425C. We see a monotonic increase in atom number with increasing Zeeman Slower laser power such that we are limited by the power output of the diode laser to about 104mW, (Fig. 5.6).

![Figure 5.6: Atom number as a function of Zeeman Slower laser beam power.](image)

Ideally, a Zeeman Slower magnetic field drops off sharply such that atoms cease to be slowed beyond the output of the slower. Although the direction of current to operate the Zeeman Slower is not unique, we find an increase in trapped atom number by a factor of two when the Zeeman Slower magnetic field destructively interferes with the MOT magnetic field at the output of the Zeeman Slower. In contrast, if the fields constructively interfered, atoms would experience a stronger slowing force beyond the region of the Zeeman Slower. This can result in an increase number of atoms experiencing a reversal of propagation direction or enough transverse scattering events such that atoms transversely move out of the trapping region of the MOT.

Next, we iteratively scanned the Zeeman Slower currents (Fig. 5.7) and find a sharp peak in atom number around 19.5A for the 13AWG coils, and at 3A for the tuning current. There is a weak dependence on the current through the 18AWG coils (not shown), which are kept at 5A, as was designed. Lastly, the laser beam detuning is also varied, Fig. 5.8.
CHAPTER 5. MEASUREMENTS

5.4 MOT Optimization

Having optimized the Zeeman Slower, we next vary MOT parameters. Starting with the magnetic field gradient, we find peak atom number at 43A resulting in an axial magnetic field gradient of 47G/cm, (Fig. 5.9).

Figure 5.7: Atom number as a function of Zeeman Slower currents through (a) 13AWG main coil, and (b) 13AWG tuning coil.
Next, we look at the power distribution between the vertical and horizontal arms of the trap, (Fig. 5.10). We find optimum loading with each horizontal arm having twice as much power as the vertical arm. With the relative powers set, the total power for all MOT beams is varied, (Fig. 5.11). From the peak atom number at 28mW in conjunction with the previous plot we determine that each horizontal arm has 11mW while the vertical arm has 6mW of power. Consequently, because the 2D-Collimator light is derived from the same diode, the 2D-Collimator power is set to 52mW. Lastly, we vary the current of the magnetic field in the saturated absorption cell to control the frequency of the MOT beams and find optimal trapping when detuned by -54MHz.
Figure 5.9: Trapped atom number as a function of axial Anti-Helmholtz magnetic field gradient. Find optimal number at 47G/cm (43A from the current supply).

Figure 5.10: Trapped atom number as a function of angle of half-wave plate used for power distribution between the vertical and horizontal arms of the MOT beams. Find peak when each horizontal arm has twice as much power as the vertical arm.
5.5. LOADING RATE

Figure 5.11: Trapped atom number as a function of total power in MOT beams. Peak atom number at total MOT power of 28mW.

Figure 5.12: Trapped atom number as a function of detuning of MOT beams. Peak atom number at 54MHz red-detuned from the transition.

5.5 Loading Rate

With our MOT working optimally, we measured the loading rate into both the MOT and the magnetic trap. Table 5.2 shows a summary of the experimental parameters used for trapping each isotope.

We assume both a constant loading rate $R$, and one-body loss processes. Trapped atom number therefore follows a rate equation of the form,

$$\dot{N} = R - N/\tau.$$  \hspace{1cm} (5.9)

With solution

$$N = N_S [1 - \exp(-t/\tau)],$$ \hspace{1cm} (5.10)

where $N_S = R\tau$ is the steady state number of atoms in the trap. To measure the loading of atoms we set
### Table 5.2: Experimental parameters used for loading rate measurements.

<table>
<thead>
<tr>
<th>Label</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firerod Setpoint</td>
<td>425</td>
<td>C</td>
</tr>
<tr>
<td>Heating Coil Current</td>
<td>1.06</td>
<td>A</td>
</tr>
<tr>
<td>Heating Coil Temperature</td>
<td>390</td>
<td>C</td>
</tr>
<tr>
<td>2D-Collimator Power</td>
<td>52</td>
<td>mW</td>
</tr>
<tr>
<td>2D-Collimator Detuning</td>
<td>$-2\pi \times 15$ MHz</td>
<td></td>
</tr>
<tr>
<td>Zeeman Slower Power</td>
<td>107</td>
<td>mW</td>
</tr>
<tr>
<td>Zeeman Slower Detuning</td>
<td>$-2\pi \times 560$ MHz</td>
<td></td>
</tr>
<tr>
<td>Zeeman Slower Main Coils Current</td>
<td>19.5</td>
<td>A</td>
</tr>
<tr>
<td>Zeeman Slower 18AWG Coils Current</td>
<td>5</td>
<td>A</td>
</tr>
<tr>
<td>Zeeman Slower Tuning Coils Current</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td>MOT Horizontal Arm Power</td>
<td>11</td>
<td>mW</td>
</tr>
<tr>
<td>MOT Vertical Arm Power</td>
<td>6</td>
<td>mW</td>
</tr>
<tr>
<td>MOT Detuning</td>
<td>$-2\pi \times 54$ MHz</td>
<td></td>
</tr>
<tr>
<td>MOT Current</td>
<td>43</td>
<td>A</td>
</tr>
<tr>
<td>Sat. Abs. Current for loading $^{88}$Sr</td>
<td>4.4</td>
<td>A</td>
</tr>
<tr>
<td>Sat. Abs. Current for loading $^{86}$Sr</td>
<td>-0.4</td>
<td>A</td>
</tr>
<tr>
<td>Sat. Abs. Current for loading $^{84}$Sr</td>
<td>-6.0</td>
<td>A</td>
</tr>
</tbody>
</table>
the hold time, $t_H$, to zero and vary the load time, $t_L$. Figure 5.13 shows loading curves of $^{84}$Sr into both the MOT and the magnetic trap. In the former, the repumper is kept on during the load. For the magnetic trap, we flash the repumper light for 50ms after the load has completed. Loading rate into the magnetic trap is slower compared to the MOT, a limit due to the fact that only two out the five sublevels of the $^3P_2$ are trappable by the magnetic trap. Loading rate into the MOT is faster compared to that of the magnetic trap across the three bosonic isotopes, Table 5.3.

![Figure 5.13: Loading curves for $^{84}$Sr of both the MOT, where the repumper is on during the load, and the magnetic trap, where the repumper is flashed on for 50ms after loading of the trap.](image)

Table 5.3: Summary of trap loading results with the nozzle at 390C.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Abundance</th>
<th>MOT $R$ (10$^6$/s)</th>
<th>MOT $\tau$ (s)</th>
<th>MOT $N_0$ (10$^6$)</th>
<th>Magnetic Trap $R$ (10$^6$/s)</th>
<th>Magnetic Trap $\tau$ (s)</th>
<th>Magnetic Trap $N_0$ (10$^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{88}$Sr</td>
<td>82.58%</td>
<td>1800 ± 100</td>
<td>0.31 ± 0.03</td>
<td>560 ± 60</td>
<td>930 ± 52</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$^{86}$Sr</td>
<td>9.86%</td>
<td>81 ± 20</td>
<td>1.1 ± 0.3</td>
<td>89 ± 33</td>
<td>60.7 ± 4.5</td>
<td>7.6 ± 1.4</td>
<td>460 ± 70</td>
</tr>
<tr>
<td>$^{84}$Sr</td>
<td>0.56%</td>
<td>15.7 ± 0.6</td>
<td>0.70 ± 0.03</td>
<td>11 ± 1</td>
<td>4.3 ± 0.1</td>
<td>10.7 ± 0.6</td>
<td>46 ± 3</td>
</tr>
</tbody>
</table>

5.6 Temperature

The temperature of a cloud of atoms is measured by looking at time of flight (TOF) images [35] and measuring the size of the cloud. The value of temperature is then extracted by fitting each dimension to

$$\sigma^2 = \sigma_0^2 + \frac{k_B T}{M} t^2.$$  \hspace{1cm} (5.11)
hen $\sigma_0$ and $\sigma$ are the initial width and the width after free-fall of duration $t$, respectively. Fig. 5.14 compares the measured temperatures to the values calculated from Doppler theory, Eq. 2.17. We observe a systemically higher temperature, by about a factor 2.

![Figure 5.14: Measured and calculated MOT temperature as a function of detuning of $^{88}$Sr. The expected temperature depends weakly on small values of $I/I_{\text{Sat}}$. Plotted is the expected values at $I/I_{\text{Sat}} = 0$, which sets the minimum achievable temperature, and at $I/I_{\text{Sat}} = 0.1$ which corresponds to the intensity of the MOT.]

5.7 Conclusion

The goal of this work has been to construct an apparatus capable of efficiently trapping and cooling the stable bosonic isotopes of strontium near the Doppler temperature limit via the broad $^1S_0 \rightarrow ^1P_1$ transition in anticipation of further cooling to quantum degeneracy. This will be accomplished by transferring to a $^1S_0 \rightarrow ^3P_1$ narrow line MOT and ultimately evaporative cooling in an optical dipole trap. The measured temperatures are within a factor of two from the Doppler limit. The loading of $^{84}$Sr is about half of that reported in Ref. [17], and the magnetic trap lifetime indicates adequately low background pressure which is crucial for evaporative cooling. However, magnetic trap lifetime over a factor of 2 higher are achievable [14], and would suggest that improvements could be made by increasing the vacuum pumping speed. Ideally, none of the laser diodes would have a double-lobe structure like the master laser does. Although we have utilized both lobes, it is far from ideal as careful alignment of the pick-off mirror is required. Any subsequent deviations in alignment over time will manifest themselves as diminishing injection locking capability of the slave lasers. We conclude that the apparatus in its current state is ready to begin the next stage of cooling and trapping on a narrow-line MOT of the $^1S_0 \rightarrow ^3P_1$ transition [15, 36].
Appendices
Appendix A

Vacuum Viewport AR Coatings

Uncoated\(^1\) viewports were anti-reflection (AR) coated for 461nm, 689nm, and 1064nm by Reynard Corporation. Though it is not necessary to AR coat all viewports for all three wavelengths, it was much more economical to do so given the number and sizes of viewports desired. This is because the cost depends on each individual coating run which may contain multiple substrates (as was the case); so long as there is enough space for the number of substrates desired in the same coating run, the price does not increase. This has the benefit of resulting in all viewports used, and any spares, are interchangeable with one another.

The following plots, Fig. A.1 and Fig. A.2, show reflectance and transmittance measurements with 1nm resolution performed by Reynard Corporation on a single viewport.

\(^1\)MDC Vacuum Products, LLC UHV Series Zero Profile 7056 Glass
Figure A.1: Reflectance of vacuum viewports. Each viewport is AR coated for 461nm, 689nm, and 1064nm, with reflectances of 0.26%, 0.19%, and 0.14%, respectively. For reference, these wavelengths are demarked with vertical lines.

Figure A.2: Transmittance of vacuum viewports. The transmittances for 461nm, 689nm, and 1064nm are 98.4%, 99.9%, 99.3%, respectively. For reference, these wavelengths are demarked with vertical lines.
Appendix B

Machine Drawings

In this section, machine drawings for the main components of the vacuum chamber are presented. As is standard for machine drawings in the US, imperial units are used.

Figure B.1: Heat shield for oven nozzle, originally drawn by Tom Killian.
Knowing the desired magnetic field, the coil arrangement is chosen, Figure B.6. Due to designing for 20A of current to flow on a large portion of the coils\(^1\), a significant amount of heat is generated. Excessive heating can damage the wires whose insulation is only rated to 180\(^\circ\)C and it could also compromise vacuum pressure by promoting outgassing from the chamber walls. Therefore, the Zeeman Slower is designed to incorporate cooling using circulating water. We accomplish this utilizing two concentric stainless steal tubes in order to pass water through the space between the two. The inner diameter of the tubes are 0.82in and 0.7in with a length of 19in, including the welded flanges on either end.

\(^1\)MWS Wire Industries: 13AWG and 18AWG square wire insulated with a rating of 180\(^\circ\)C.
Figure B.2: Oven nozzle, originally drawn by Tom Killian. In red is the nozzle head which will house the capillary tubes.
Figure B.3: Chamber section containing oven nozzle viewed from the side, originally drawn by Tom Killian.
Figure B.4: Chamber section containing oven nozzle as well as the arms of the 2D-Collimator. Originally drawn by Tom Killian.
Figure B.5: Drawing of differential pumping tube. A solid gasket is machined (orange) and used to hold the differential pumping tube in-between the 2D-Collimator and the start of the Zeeman Slower.
Figure B.6: Zeeman slower design. Two separate currents were used, 5A and 20A, corresponding to two different square copper wire gauges, 13 AWG (orange), and 18 AWG (orange) respectively. In addition, the end segment, 13 AWG (purple), is made separately such that we can tune the tail-end of the magnetic field to control the final velocity of slowed atoms.
Figure B.7: Drawing of MOT chamber body, viewed from the side. Part machined by Huntington Mechanical Labs.
Figure B.8: Drawing of MOT chamber body, viewed from the top. Part machined by Huntington Mechanical Labs.

Figure B.9: Drawing of MOT chamber flanges, viewed from the side. Parts machined by Huntington Mechanical Labs.
Figure B.10: Dimensions of each set of anti-Helmholtz coils. In pink are the coils used for the blue MOT, each coil consists of five radial layers and seven vertical layers made from S&W Wire Company .125SQ DPG/BARE wire. Additionally, the anti-Helmholtz coils that will be used for a narrow-line MOT are also shown in red, they consist of 10 radial layers and 2 vertical layers made from 13AWG square copper wire from MWS Wire Industries.
Appendix C

Oven Nozzle Assembly

After machining the oven nozzle, the resistive coil is silver soldered unto the head of the oven nozzle. The core of the free end of the wire is connected to a feedthrough while the other end is grounded at the nozzle head. The capillary tubes are hypodermic needles of size AWG-21. Each needle is cut to match the length of the oven nozzle head, and is held by friction. To ensure that the capillary tubes are tightly packed, smaller diameter needles are used to fill in excess space. Before attaching to the main vacuum chamber, the nozzle is baked on its own in a separate vacuum chamber at 250°C.

To load strontium, the nozzle body is held up-right as strontium pellets are dropped into the cavity. After bolting down the nozzle head, a thermocouple is held in place with a bolt in a spare tapped hole. Once the heating coil and the thermocouple are connected to their respective feedthroughs, the heat shield is attached to the flange, at which point the whole nozzle can be installed into the main vacuum chamber. Note that the process of loading strontium and attaching the nozzle to the vacuum chamber should take only a few minutes in order to minimize oxidation of the pellets.
Figure C.1: (a) Photo of strontium pellets already loaded into the cavity of the oven nozzle. Also pictured is the cap with capillary tubes already inserted, and resistive heating wire silver-soldered on. (b) Heat shield enclosing most of the oven nozzle. Cut-outs of the material are made to accommodate feedthrough connections. (c) Capillary tubes viewed through the aperture of the heat shield.
Appendix D

Obtaining Ultra-High Vacuum

The vacuum chamber is made of 304 stainless steel\textsuperscript{1}. Although not utilized at this time, we have installed electrodes to induce selective field ionization. As a result, we use alumina for electrical insulation. In addition, we have a multi-channel plate detector\textsuperscript{2} (MCP) for electron or ion detection. The MCP is electrically insulated with macor and sits inside a horizontally oriented half-nipple of inner-diameter 1.73cm and flange of outer-diameter 6.93cm. Before installing viewports we baked our chamber to 250C for multiple days. After final assembly we did a thorough helium leak check. We intended to use gold plated copper gaskets due to their temperature tolerance, however we found them to be prone to leaks. Once substitutions were made for standard copper gaskets we began a 100C bake, Figure D.1. During both bakes we used a turbo pump\textsuperscript{3}, backed by a dry scroll pump\textsuperscript{4}. We used an oil-free roughing pump in order to avoid the risk of coating the interior of our vacuum chamber with oil.

Ion pumps were installed on each side of the chamber\textsuperscript{5,6}. Due to their poor pumping speed of hydrogen, a Non-Evaporable Getter\textsuperscript{7} with an expected hydrogen pumping speed of 200L/s was also installed. To extend the lifetime of these components, they were utilized only after the bake-outs were complete and ultra-high vacuum was achieved. In addition, access to the turbo pump and residual gas analyzer\textsuperscript{8} was closed off by multiple vacuum valves. Although the ion gauges\textsuperscript{9} could still yield a measurement, we abstain from using them due to the outgassing caused upon turn-on. Instead we rely on the current measurement of the ion pumps, though they eventually bottom out at which point we no longer have a direct measure of pressure.

\textsuperscript{1}The MOT chamber was fabricated by Huntington Mechanical Labs
\textsuperscript{2}Photonis APD 2 MINITOF 8/6/5/12 D 60:1 EDR SE
\textsuperscript{3}Varian TV 81-T Pump
\textsuperscript{4}Varian SH-110
\textsuperscript{5}Varian REBG-VIP-75-
\textsuperscript{6}Gamma Vacuum 75S-CVX-6S-SC-N-N
\textsuperscript{7}SAES Group CapacitTorr D-200
\textsuperscript{8}SRS RGA 100
\textsuperscript{9}Varian T-NUDE-F
Figure D.1: Pressure versus time during bake of 100°C for dominate partial pressures.
Bibliography


