

# Zeeman Tunable Saturated Absorption Spectroscopy Cell for Locking Laser Frequency to the Strontium $^1S_0$ - $^1P_1$ Transition

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## Abstract

We present an analysis of a saturated absorption spectroscopy cell designed to lock a blue (461 nm) diode laser to  $^1S_0$ - $^1P_1$  transitions of strontium. The cell is tuned by Zeeman shift, allowing us to lock the laser over a wide range of frequencies and cool all isotopes of strontium. Included are a model of the cells temperature as a function of heater and Zeeman solenoid currents, measurements of Zeeman splitting in the strontium-88 transition induced by the cells solenoid, and measurements of the bandwidth of the solenoid. We also address the underlying science of frequency modulation spectroscopy.

# Introduction

Laser cooling is a technique in which lasers are used to cool samples of atoms to micro Kelvin temperatures. To do this, three pairs of orthogonal, counterpropagating beams are pointed at a vaporous sample of atoms. The beams are slightly red-detuned from an atomic transition of the sample atoms, in this case the  $^1S_0$ - $^1P_1$ , 461 nm transition of strontium. As an atom moves opposite the direction of a laser beam, the beam becomes blueshifted to the transition frequency in the frame of the atom, and the atom absorbs a photon. The atom then reemits the absorbed photon in a random direction, starts to move with a new random velocity, and proceeds to absorb more blueshifted photons. Over time, the random velocities average out to zero, and the sample of atoms becomes cooled as the average thermal velocity decreases.

Since laser cooling is a process that takes advantage of atomic transitions, the trap lasers must remain at the exact red-detuned frequencies with little variation. Diode lasers, which we use in our lab to cool atoms, are generally not stable enough on their own to be used for laser cooling [1]. We are able to counteract this instability by locking the frequency of the laser to an atomic transition. This is typically done by creating an atomic spectrum of the atom in question and then locking the laser to the peak in the spectrum corresponding to the transition of interest.

Normally, atomic spectra are created by shining a laser through a vaporous sample of atoms and sweeping the laser frequency across a set interval. As the laser approaches a transition frequency, the absorption of the beam increases, creating an absorption profile. For room temperature vaporous atoms, this method produces narrow absorption peaks that are good references for locking a laser. However, making a strontium spectrum using this method has some added difficulty. Strontium must be heated to very high temperatures in order to reach its vaporous form. These high temperatures cause the thermal velocity of the sample atoms to increase, which in turn causes the absorption profiles to become wider due to Doppler broadening. Absorption profiles that are created by this method of spectroscopy are simply too broad to be used for laser locking; the error signals of these broad peaks are too shallow for the lock-in amplifier to establish a good lock.

We thus use a Doppler-free spectroscopy method called saturated absorption spectroscopy to create an atomic spectrum for strontium. In saturated absorption spectroscopy, a laser beam is split into two weak beams and one strong beam. The two weaker “probe” beams are sent through a cell containing a sample of vaporous strontium in one direction, and a stronger “pump” beam is sent through the cell in the opposite direction. The pump beam is oriented so that it crosses paths with one of the probe beams within the cell. The probe

beam that does not intersect the pump beam produces a normal spectrum with Doppler-broadened absorption profiles at atomic transition frequencies. The spectrum produced by the other probe beam is slightly different. If there are atoms at the intersection point of the beams that have no velocity with respect to either the probe or the pump beam, then these atoms will be excited by the stronger pump beam. The probe beam, unable to be absorbed by these atoms, passes through the cell unabsorbed, creating a spike in the absorption profile exactly at the atomic transition. This spike, known as the Lamb Dip, is a Doppler-free transition profile and can be used as a reference point to lock the laser [2]. An illustration of saturated absorption spectroscopy can be seen in Figure 1.

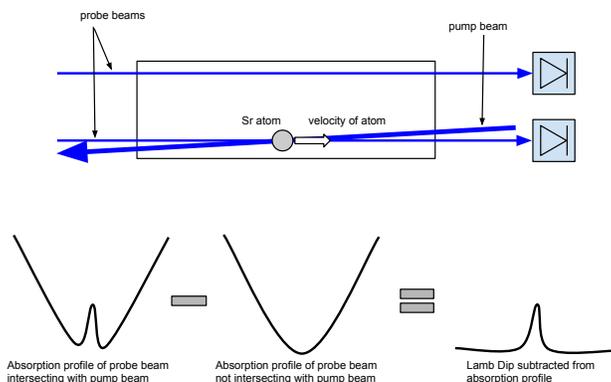


Figure 1: The basics of saturated absorption spectroscopy. Atoms at the intersection of the two beams with zero velocity with respect to either of the beams will absorb the pump beam, allowing the probe beam to pass through unabsorbed at the transition frequency. The probes then impinge on photodiodes, which send the electrical signals to a differential op amp. The op amp can subtract the signal of the unperturbed probe beam from the signal of the intersected beam, leaving just the Lamb Dip behind.

The Lamb Dip cannot be used on its own to lock the laser. Instead, we must lock the laser to the error signal of the Lamb Dip. The error signal is created by dithering the laser frequency sinusoidally. Doing this causes a change in laser intensity measured by the photodiode, which we can multiply by the modulation input. To first order, this product is actually the first derivative of the Lamb Dip, since it shows the change in amplitude of the Lamb Dip as a function of frequency. Thus, because the error signal is the first derivative of the Lamb Dip, the peak of the Lamb Dip is represented as a zero crossing in the error signal. The error signal serves as a much better feedback mechanism to correct laser drift than the Lamb Dip does [3]. One major flaw of using the Lamb Dip as a feedback mechanism is that both positive and negative frequency drifts are seen as a decrease in amplitude, meaning that the lock does not know in which direction it should shift the laser frequency should

the laser drift. With the error signal, on the other hand, decreases in frequency are seen as increases in amplitude, while increases in frequency are seen as decreases in amplitude. Thus, the lock is able to correct drift in either direction. Illustrations of the Lamb Dip and error signal can be seen in Figure 2.

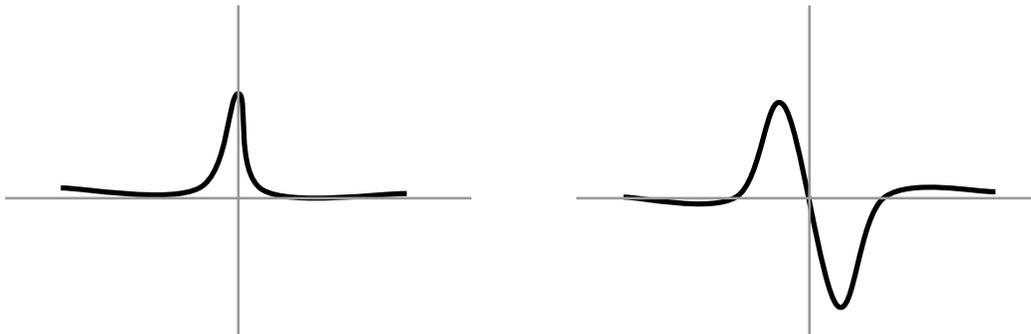


Figure 2: On the left is an illustration of the Lamb Dip, and on the right is an illustration of the error signal. Notice how the maximum of the Lamb Dip corresponds to a zero crossing of the error signal. We can lock our laser to this zero crossing.

In many cases, physicists want their saturated absorption cells to do more than lock to just one frequency. In our case, strontium has four naturally occurring isotopes (88-Sr, 87-Sr, 86-Sr, and 84-Sr). Each of these isotopes has different excitation frequencies for the  $^1S_0$ - $^1P_1$  transition. If we want to trap all of these isotopes, we need to oscillate our locking frequency between all of these excitation frequencies quickly. Tuning can be done with external hardware such as acousto-optical modulators (AOM's), but these components are prohibitively expensive. Instead, we are able to tune our locking frequency using the Zeeman Effect, a quantum mechanical effect which causes the  $^1S_0$ - $^1P_1$  Lamb Dip to split into three distinct peaks when an external magnetic field is applied to the vaporous strontium sample. Zeeman Effect tuning allows us to adjust the locking frequency quickly and is very cost effective compared to using an AOM. More on how Zeeman tuning works will be discussed later.

In this paper, we examine a Zeeman tunable strontium saturated absorption cell designed and built by Michael Peron, a former undergraduate in the Killian Research Group. We present general operating guidelines for using the cell, such as how to maintain the cell's temperature, how much Zeeman shift you can induce in the cell, and how quickly you can modulate the locking frequency. We also explain some of the physics behind the cell's operation.

# Experimental Setup

## Cell Specifications

The saturated absorption cell discussed in this paper was made by Michael Peron in 2012, and more detailed schematics may be found in his undergraduate thesis, *Development and Use of a Saturated Absorption Spectroscopy Cell for Tuning the Frequency of the Atom-Cooling Laser* (2012). A picture of the cell can be found in Figure 3. The main body of the cell is a one foot long stainless steel tube with flanges and vacuum tight windows at each end. Heating cable is tightly wound around the steel tube to provide heat to vaporize the strontium inside. The main tube and heating wire are covered with fiberglass insulation, and the insulation is enclosed with stainless steel semi-tubes. Three layers of magnet wire are wrapped around the steel tube to provide Zeeman splitting. The wire in the innermost and middle layers is sleeved with fiberglass insulation, while the wire in the outermost layer is bare. The layers of magnet wire are covered in epoxy to hold them in place as well as more fiberglass insulation. The cell is finished off with a few layers of aluminum foil. Figure 4 gives an illustration of each of these layers. The temperature of the strontium vapor is monitored via a thermocouple wire brazed to the heating wire [4].

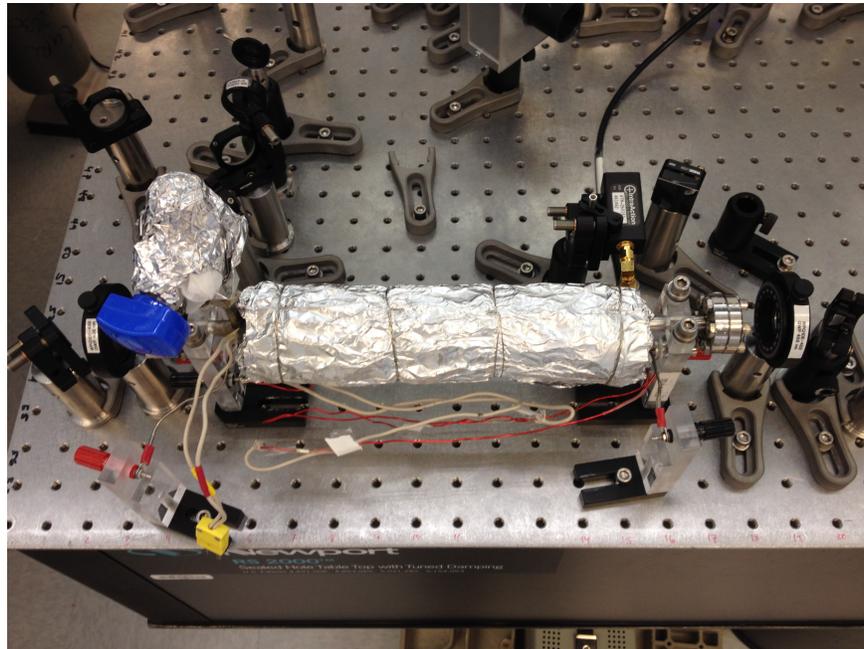


Figure 3: The saturated absorption cell.

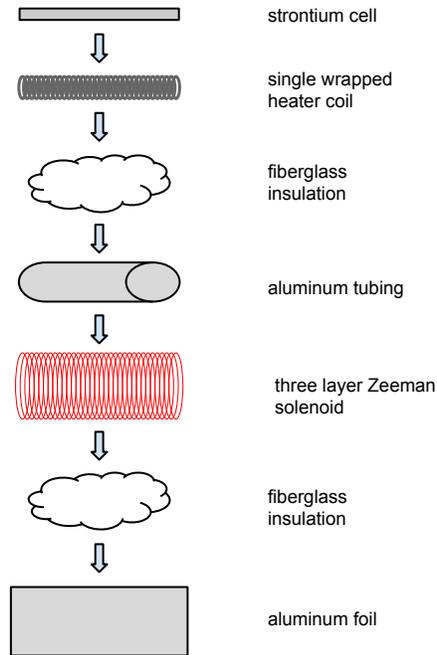


Figure 4: Layer-by-layer illustration of the strontium saturated absorption cell.

## Displaying the Lamb Dip

Figure 5 gives an illustration of the setup we use to display the Lamb Dip. The laser in our setup is a New Focus Vortex Plus TLB 6800 external cavity diode laser. The beam is sent to a beam splitter, where it is split into two weaker probe beams and one stronger pump beam. The probe and pump beams enter the strontium vapor cell on opposite sides, and the pump beam is aligned to intersect one of the probe beams inside the cell. After traveling through the vapor cell, both probe beams impinge upon photodiodes, and the resulting electrical signals are sent to a differential op amp. The op amp subtracts the signal of the unperturbed probe beam from the signal of the probe beam that intersected the pump, leaving just the Lamb Dip. The Lamb Dip is then sent to an oscilloscope to be displayed.

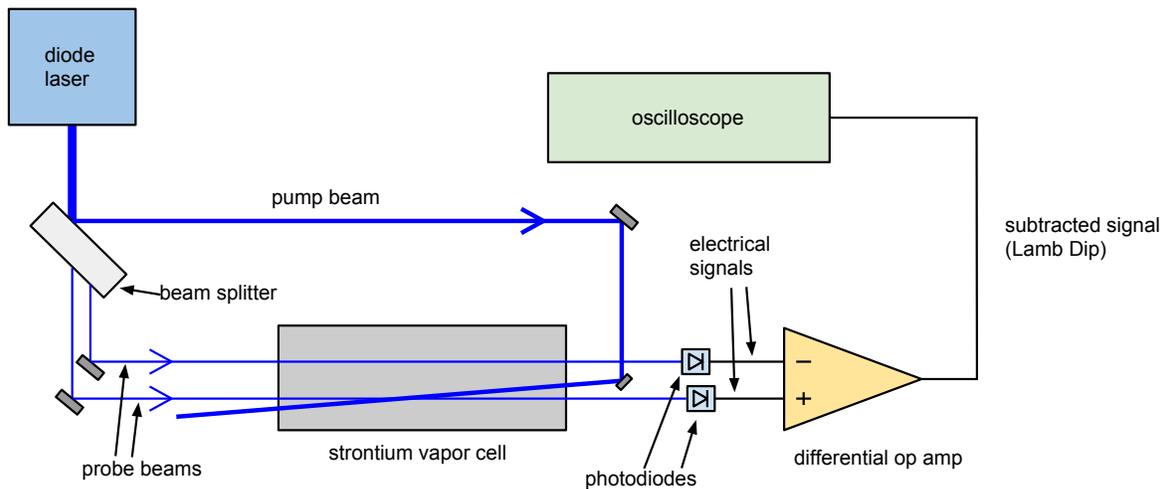


Figure 5: Diagram of experimental setup, from the laser to the oscilloscope displaying the Lamb Dip.

## Generating an Error Signal and Locking the Laser

The frequency dithering required to make an error signal is done by sending an alternating current through the heater coil. This induces an alternating magnetic field throughout the cell, which then causes the Lamb Dip to move around. This movement of the Lamb Dip is what creates the error signal. Upon its creation, the error signal is sent to a lock-in amplifier. The lock-in amplifier itself is connected to the external cavity of the laser. Inside the cavity is a mirror attached to a piezoelectric transducer (PZT). When the amplifier locks the laser, it sends an electrical signal to the PZT. The PZT then changes its shape and adjusts the position of the mirror until the standing wave in the cavity is the lock wavelength. The laser we are locking in this setup is not actually the laser used for the MOT. Instead, the laser we are locking is a master laser, and the MOT laser is a slave laser attached to the master. Once the frequency of the master has been locked, the frequency of the slave will follow suit. An illustration of the error signal and lock setup can be seen in Figure 6.

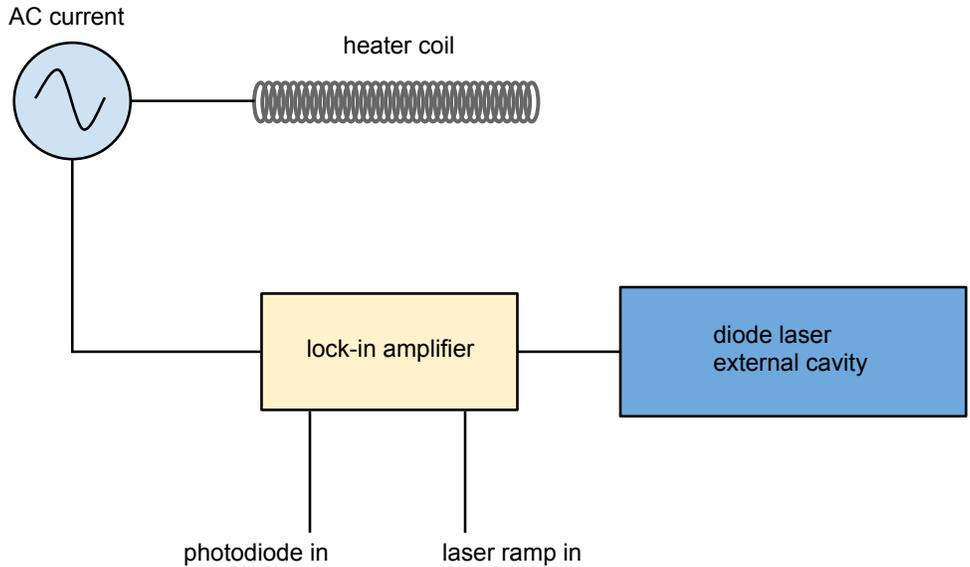


Figure 6: Diagram of error signal generation and laser lock.

## Maintaining Temperature

Monitoring the temperature of the strontium is one of the most important aspects of operating the cell. If the temperature is too low, the strontium will not vaporize, and there will be no absorption profiles. On the other hand, if the temperature is too high, the absorption profiles become much too broad, and the strontium vapor will absorb all the laser light passing through. In an extreme case, if the temperature is exceedingly high, the heat can wind up blacking out the windows on the cell. The cell operates best when the strontium is at around 50% absorption, which is in the neighborhood of 270-280°C.

The cell's primary heating element is the aforementioned heating wire wrapped around the main steel tube. Ideally, the heating wire would be the only source of heat for the cell, but the solenoid wires add a small but significant amount of heat to the cell as well. Additionally, the solenoid wires are separated from the main cell body with fiberglass insulation, so the heat produced by the solenoid must first permeate the insulation before it can begin warming the cell. This can cause the cell's temperature to take a long time to stabilize.

In an effort to eliminate guesswork and save future experimenter's time, we set out to create a model of the cell's temperature as a function of both the heater current and the solenoid current. To do this, the heater and solenoid currents were set to varying levels, and the temperature of the cell was recorded at each of these levels. Then, operating under

the assumption that power output of a electric wire does not depend on the direction of the current, we stated that the temperature of the cell would be the same for all possible polarity combinations of the heater and solenoid currents, effectively quadrupling the number of data points and ensuring that the fit surface would be symmetric about the origin. Since temperature is directly proportional to power output, and since power output and current are related by  $P = I^2R$ , we expected the temperature of the cell to be given by a paraboloid of the form  $T_{cell} = c_1I_{heater}^2 + c_2I_{solenoid}^2 + T_0$ , where  $c_1$ ,  $c_2$ , and  $T_0$  are constants. The fit function for the data points was created using the curve fitting tool in MATLAB, with the restriction that the fit function be a second degree polynomial of both  $I_{heater}$  and  $I_{solenoid}$ .

$c_1$ [ $^{\circ}\text{C}/\text{A}^2$ ]	$c_2$ [ $^{\circ}\text{C}/\text{A}^2$ ]	$T_0$ [ $^{\circ}\text{C}$ ]
301	4.202	25.97

Table 1: Coefficients for temperature fit surface.

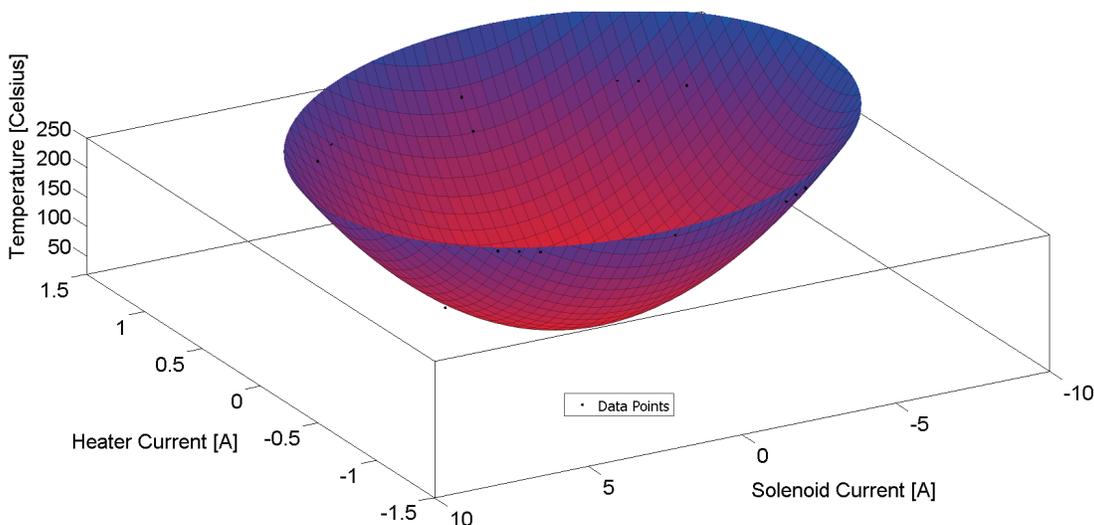


Figure 7: Paraboloid for predicting the temperature of the cell given the heater and solenoid currents.

Figure 7 is an image of the fit surface created in MATLAB. As predicted, the equation of the fit surface is of the form  $T_{cell} = c_1I_{heater}^2 + c_2I_{solenoid}^2 + T_0$ , with the values of the coefficients given in Table 1. MATLAB also returned coefficients for the first order terms as well as an  $I_{heater}I_{solenoid}$  term, but these terms are of order  $10^{-13}$  and can be ignored. With this paraboloid, one can now determine what the heater current should be if they want to run the Zeeman coil at a certain direct or RMS current while keeping the temperature at a

certain value. For example, Figure 8 is at cross section of the fit surface at  $T_{cell} = 270^\circ\text{C}$ . If one wants to run the solenoid at a certain current while maintaining the temperature of the cell at  $270^\circ\text{C}$ , one simply has to rearrange the fit equation in the following form:

$$I_{heater}^2 = \frac{270^\circ\text{C} - (c_2 I_{solenoid}^2 + T_0)}{c_1}$$

One can easily calculate the two possible heater currents from here.

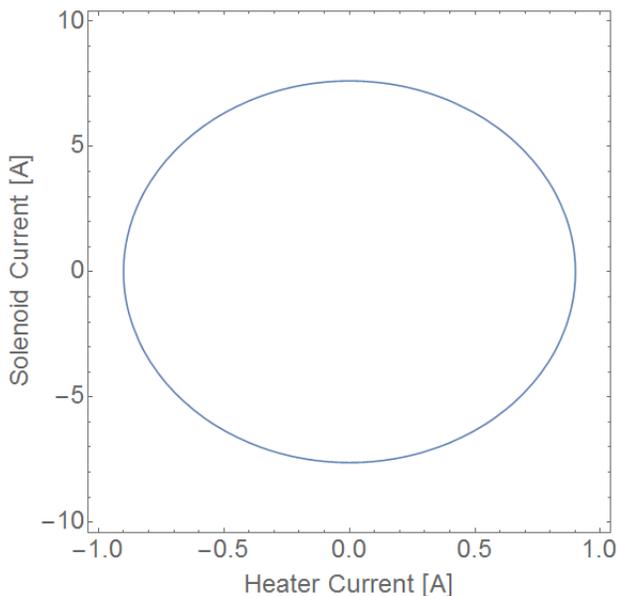


Figure 8: Isotherm of Figure 7 at  $T = 270^\circ\text{C}$ .

## Zeeman Splitting

Zeeman splitting is a quantum mechanical effect that occurs in the presence of a magnetic field. Suppose we are driving an atomic transition, and one or both of the states involved has a nonzero angular momentum quantum number. If so, then the state(s) will split into a distinct number of energy levels upon exposure to a magnetic field. The number of new energy levels that a state will split into is the state's number of nonzero magnetic quantum numbers. For instance, if a state has an angular momentum quantum  $\ell = 2$ , the state will split into four new lines for  $m_\ell = \pm 1$  and  $\pm 2$ . In the strontium  $^1S_0$ - $^1P_1$  transition, the  $^1S_0$  has an angular momentum number of 0 and does not undergo Zeeman splitting. The  $^1P_1$  transition has an angular momentum quantum number of 1, so this state splits

into two new energy levels. Since the energy levels have been shifted from the original value, the excitation frequencies of the Zeeman shifted peaks have also been shifted. The formula for Zeeman shifting as a function of magnetic field strength is given by the equation  $\Delta f = \frac{m_\ell \mu_B B}{\hbar}$ , where  $B$  is the magnitude of the magnetic field doing the shifting and  $m_\ell$  is the magnetic quantum number of the state.

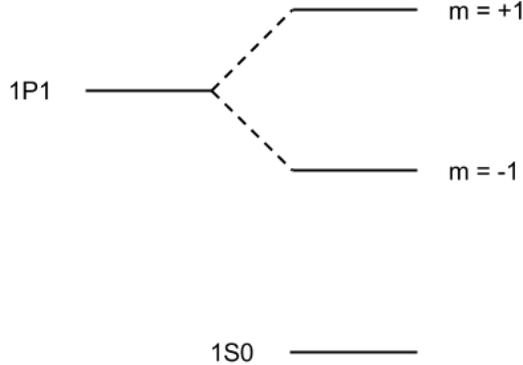


Figure 9: Splitting of energy levels in the  $^1S_0$ - $^1P_1$  transition.

We expect the  $^1S_0$ - $^1P_1$  transition to split into two peaks upon exposure to a magnetic field. However, we see three peaks on the oscilloscope, but only the two outer peaks are Zeeman-shifted Lamb Dips. The third, center peak is known as the crossover resonance, and it appears when two absorption profiles are separated by less than a Doppler width and overlap. In more mathematical terms, consider a saturated absorption cell as in Figure 1. Any atoms in the cell that lie at the intersection of the probe and pump beam will have a velocity with respect to the direction of both of those beams. Let  $f_L$  be the frequency of the pump and probe beams, and let  $f_0$  be the excitation frequency of our sample (in our case, it is the excitation frequency of strontium-88). Additionally, let  $\vec{v}$  be the velocity of an atom in the direction of the two laser beams. Thus, due to Doppler shift from the atom's velocity, the atom is excited by the probe beam when the probe beam has a frequency of  $f_1 = f_L - \vec{k} \cdot \vec{v}$ ; meanwhile, the atom is excited by the pump beam when the pump beam has a frequency of  $f_2 = f_L + \vec{k} \cdot \vec{v}$ . However, the Lamb Dip forms at resonance, or when the atoms at the intersection of the beams have zero velocity with respect to either of the beams. Therefore, at resonance,  $\vec{v} = 0$ , and the atoms are excited when both the probe and pump lasers are at the frequency  $f_L = f_0$ .

If an external magnetic field  $\vec{B}$  is subsequently applied to the sample of atoms, the one strontium-88 excitation frequency will split into two excitation frequencies:  $f_+ = f_0 + \frac{\mu_B B}{\hbar}$

and  $f_- = f_0 - \frac{\mu_B B}{h}$ . We mentioned earlier that a crossover resonance occurs if the absorption profiles of the two resonant peaks are separated by less than the Doppler widths of the peaks. The Doppler width of an absorption profile is given by:

$$\Delta f = \sqrt{\frac{8kT \ln(2)}{mc^2}} f_0$$

In this equation,  $m$  is the mass of a strontium atom, and  $T$  is the absolute temperature of the sample. The frequency of the strontium-88 transition is known to be  $6.51 \times 10^{14}$  Hz. In comparison, the amount of Zeeman shifting done by the magnetic field is on the order of 200 MHz. This is considerably smaller than the frequency of strontium-88, so  $f_- \approx f_+ \approx f_0$ . Thus, the Doppler width of the three peaks at 270 °C is approximately:

$$\begin{aligned} \Delta f &= \sqrt{\frac{8k(543 \text{ K}) \ln(2)}{m_{Sr} c^2}} (6.51 \times 10^{14} \text{ Hz}) \\ &= 1135 \text{ MHz} \end{aligned}$$

In order for a crossover resonance to appear, the two peaks must be separated by less than 1135 MHz. We have not yet induced this much peak separation in the lab, which explains why we have always seen crossover resonances. It is also unwise to try to induce 1135 MHz of peak separation, as the amount of current required to do that will likely damage the solenoid.

We now turn our attention to measuring Zeeman splitting as a function of solenoid current. In his senior thesis, Michael Peron calculated the Zeeman shift of the solenoid per amp. He did this by first calculating the magnetic field per amp produced by the solenoid using the equation  $B = \mu_0 n I$ , where  $n$  is the number of turns per length of the solenoid and  $I$  is the current. Once he calculated the magnetic field per amp, he inserted that value into the equation  $\Delta f = \frac{m \mu_B B}{h}$  to find the Zeeman shift per amp, which he found to be 24 MHz/A. However, this calculation assumes that the solenoid is infinite, and our solenoid is most definitely finite. This calculation also assumes that the magnetic field is exactly parallel to the laser's propagation, which may not be exactly true. Thus, we set out to measure the Zeeman shift as a function of solenoid current.

To measure Zeeman shift, various currents were applied to the solenoid, creating a magnetic field and splitting the Lamb Dip into three peaks. At each of these current values, we took oscilloscope data of both the three Lamb Dips and the peakless backgrounds. We then subtracted each background from each corresponding set of peaks in MATLAB (Figure 10 shows two sets of background subtracted peaks). Finally, we used MATLAB to fit three

Lorentzian functions to each of the three peaks to determine their exact location in time. We used the known frequency shift between strontium-88 and strontium-86 (Figure 11) to convert the time measurements to frequency measurements. By setting the middle peak at 0 MHz, we were then able to measure the magnitude of the Zeeman frequency shift. We plotted the positive and negative frequency shifts of the peaks as a function of current and set a linear fit to these data points to determine the Zeeman shift of the peaks per amp through the solenoid (Figure 12).

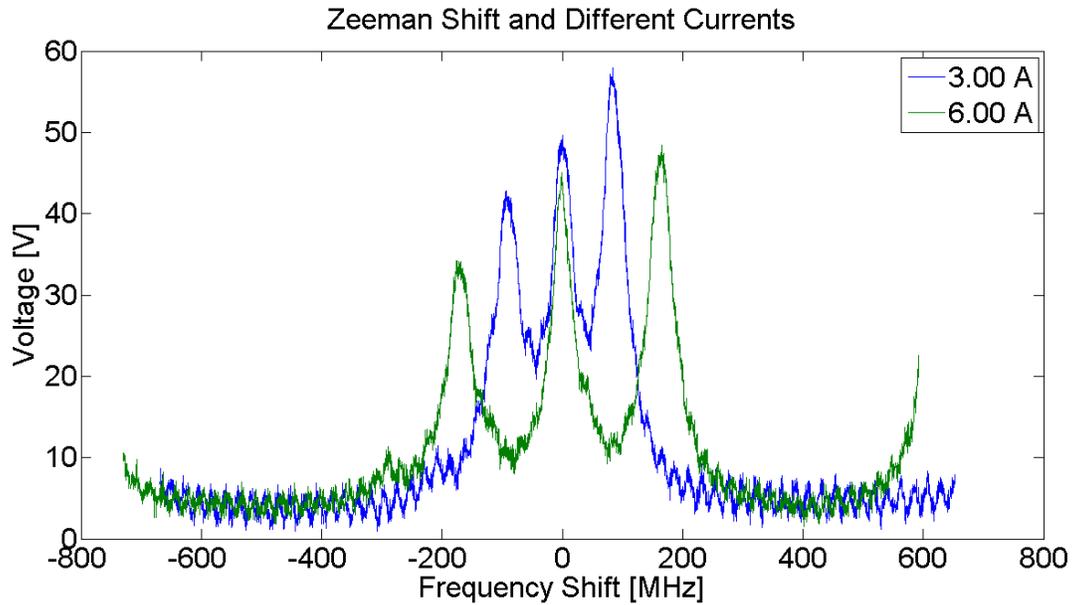


Figure 10: Zeeman shifting of the Lamb Dip at 3.00 A and 6.00 A.

Solenoid Current [A]	Negative Frequency Shift [MHz]	Positive Frequency Shift [MHz]
0	-	-
2.50	-79.85	70.33
3.00	-93.07	85.93
3.50	-105.76	100.47
4.00	-118.45	112.90
4.50	-131.14	124.80
5.00	-144.10	137.23
5.50	-157.85	149.92
6.00	-171.34	164.46

Table 2: Megahertz shifts of left and right Zeeman peaks at different solenoid currents.

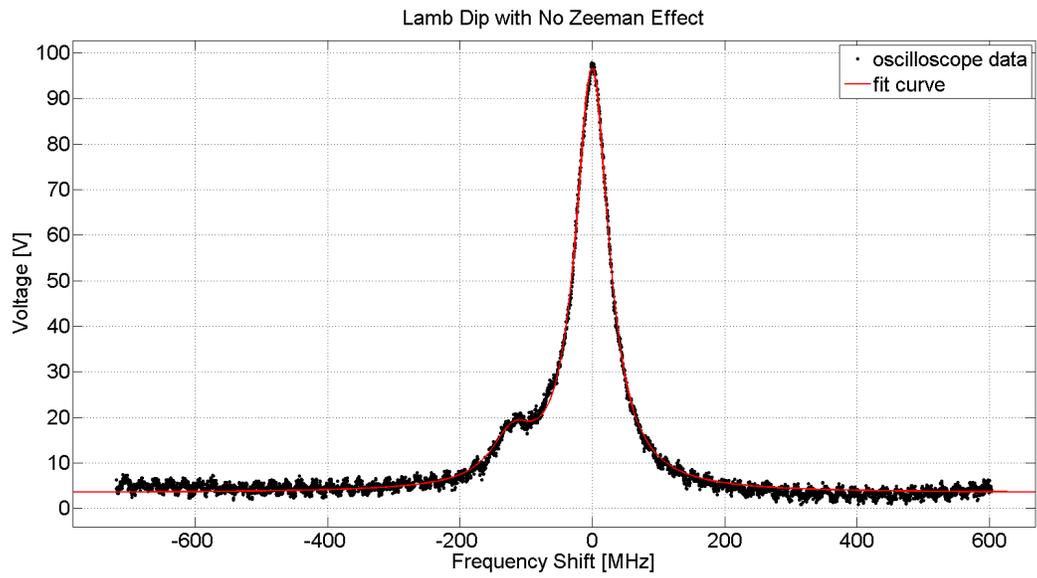


Figure 11: Lamb Dip with no Zeeman shift and fit function. The strontium-88 and strontium-86 transitions are visible in this spectrum.

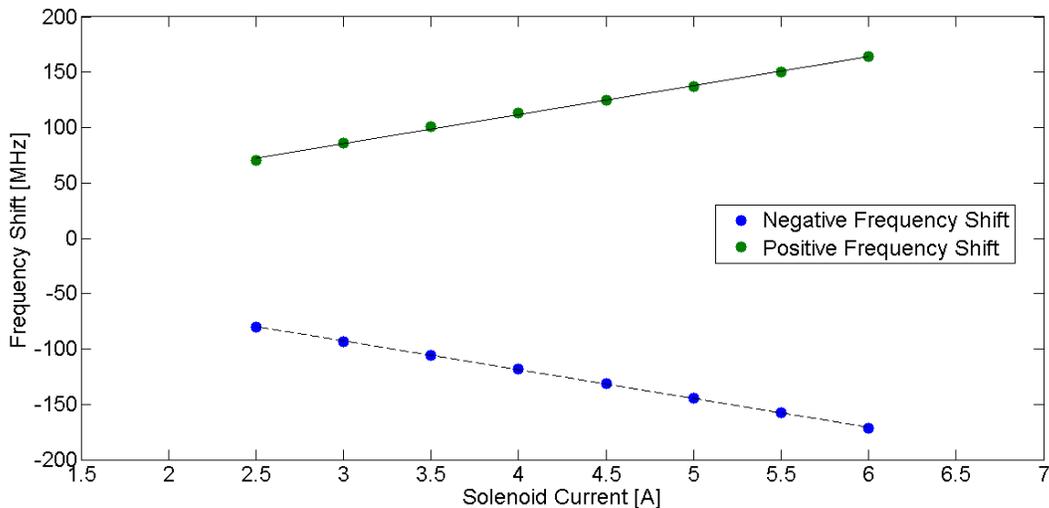


Figure 12: Zeeman shifting of both the decreasing frequency and increasing frequency peaks.

A least squares linear fit of the frequency-increasing peaks gives a Zeeman shift of  $26.21 \pm 0.42$  MHz/A. Likewise, a least squares linear fit of the frequency-decreasing peaks yields a Zeeman shift of  $26 \pm 0.14$  MHz/A. Averaged together, we get a Zeeman shift of  $26.11 \pm 0.22$  MHz/A. This is slightly higher than the predicted Zeeman shift of 24 MHz/A; the discrepancy may be due to errors such as not accounting for the finiteness of the solenoid.

It should be noted that the heater coil can also cause some Zeeman splitting if a direct current is sent through it. However, we send an alternating current through the heater to dither the Lamb Dip and create the error signal. The alternating current is centered at zero, so on average any Zeeman shifting induced by the heater cancels out. There is also a small amount of shifting due to the Earth's magnetic field, but this shifting is on the order of 1 MHz and is negligible.

## Polarization of Probe and Pump Beams

As stated earlier, this particular saturated absorption cell is Zeeman tunable. What this means is that, once locked, the frequency of the laser can be adjusted simply by changing the current through the solenoid. This method requires that only one peak be present for the laser to lock to, yet the  $^1S_0$ - $^1P_1$  transition of strontium splits into three peaks when exposed to a uniform external magnetic field. To overcome this problem, one can add quarter-wave plates in the paths of both the probe and pump beams just before either one enters the cell, causing only one Lamb Dip to appear in the spectrum. How this works is explained below.

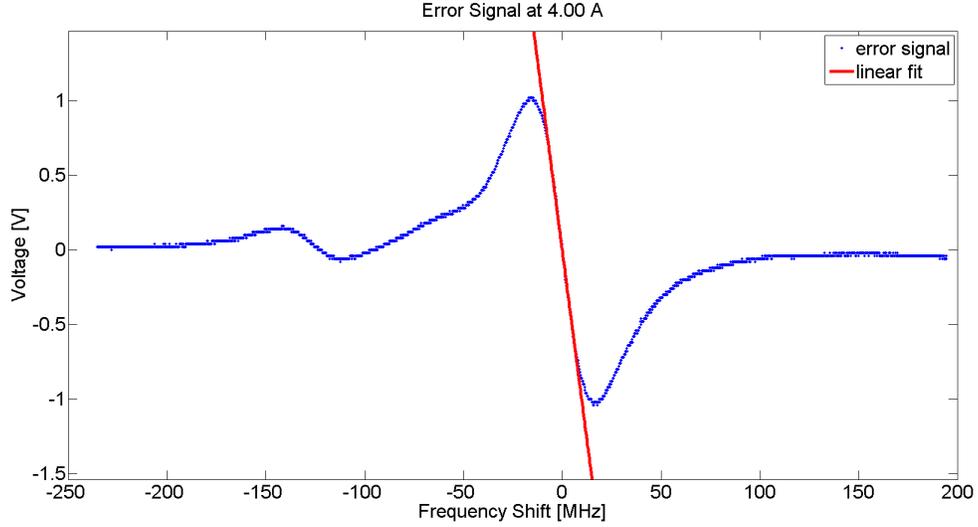
Upon exposure to an external magnetic field, the  $^1S_0$ - $^1P_1$  transition of strontium splits

into three peaks, with the two outside peaks corresponding to a magnetic quantum number ( $m_\ell$ ) value of -1 or +1. Additionally,  $m = +1$  is driven by  $\sigma^+$  polarized light and not  $\sigma^-$  polarized light; likewise,  $m = -1$  is driven by  $\sigma^-$  polarized beams and not  $\sigma^+$ . We can therefore use quarter-wave plates to set the probe and pump beams to the same circular polarization, be it  $\sigma^+$  or  $\sigma^-$ . When both beams have the same circular polarization, one of the  $m = \pm 1$  transitions will not be excited. This eliminates one of the Zeeman shifted peaks, and it also eliminates the crossover resonance since there is no overlap of absorption profiles. As a result, only one peak out of the original three remains.

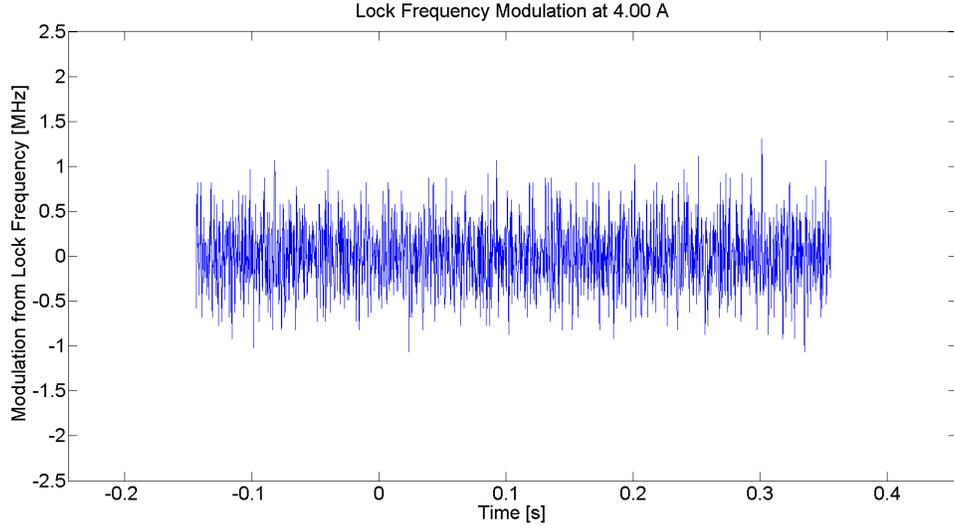
The end result is immensely powerful, for we can now lock our laser to this single peak. Since the one remaining peak is Zeeman-shifted, we can change its frequency simply by modifying the solenoid current. Additionally, since only one Lamb Dip is present in the spectrum, there will only be one error signal for the lock-in circuit to lock to. It is also worth mentioning that this method of lock tuning is much more cost effective than tuning the lock via an AOM. An AOM costs in the neighborhood of \$1100, whereas the cost of supplies you need to make a Zeeman tunable lock (two quarter-wave plates, copper wire, and a power source) is well under \$1000.

## Stability of Laser Lock

Even after being locked to an atomic transition, the frequency of a laser will drift around the transition frequency. A lock is considered “good” if the amplitude of the frequency oscillation is small compared to the natural linewidth of the transition. To measure the “goodness” of our lock, we locked the laser to the atomic transition at various Zeeman currents, examined the lock frequency on an oscilloscope, and measured the RMS voltage deviation. We then took oscilloscope data of the unlocked error signal. For each of these error signals, we set linear fits to the strontium-88 zero crossing to determine the voltage-to-frequency conversion factor (Figure 13 shows an example of this for a solenoid current of 4.00 A). With the conversion factor, we then calculated the RMS frequency deviation of the lock.



(a) Unlocked error signal



(b) Deviation from lock frequency

Figure 13: Figure 13(a) is the error signal before being locked, with a linear fit at the strontium-88  $^1S_0-^1P_1$  zero crossing to determine the voltage-to-frequency conversion. Figure 13(b) is the modulation of the locked laser's frequency, with frequency deviation from the lock frequency as the y-axis. The y-axis was calibrated with the voltage-to-frequency conversion.

We find that the average RMS frequency deviation of the locked laser is  $0.296 \pm 0.030$  MHz. The natural linewidth of the 88-Sr  $^1S_0-^1P_1$  transition by comparison is about 30 MHz, so the RMS frequency deviation of the lock is about 1/100 of the natural linewidth. In other words, our lock is very good.

Solenoid Current [A]	RMS Voltage Deviation [V]	Conversion Factor [MHz/V]	RMS Frequency Deviation [MHz]
-4.00	0.028480	10.6297	0.30273
-3.00	0.029550	12.0885	0.35721
-2.00	0.031405	9.58782	0.301102
0.00	0.033728	8.05619	0.271715
2.00	0.034671	8.38301	0.290656
3.00	0.031311	8.89581	0.278539
4.00	0.028311	9.45573	0.267705

Table 3: Lock RMS frequency deviations for various solenoid currents.

## Bandwidth of Lock

We mentioned earlier that the Zeeman tunability of the cell allows us to change the lock frequency of the laser by changing the current through the Zeeman solenoid, and that we can sweep the lock frequency across a certain range by sending an alternating current through the solenoid. This is useful because, if we can alternate the lock frequency quickly enough, we will be able to trap all isotopes of strontium in our MOT. In an ideal setup, we could oscillate the Zeeman alternating current at any frequency, and the lock circuit would be able to keep up with these fast oscillations. However, in the real setup, the PZT moving the mirror in the cavity cannot keep up with the Zeeman current at high frequencies. We created gain and phase Bode plots, as seen in Figure 14, of the PZT to determine how the PZT’s responsiveness reacted as the frequency of the Zeeman current increased. Note that the “gain” in the gain plot is the logarithm of the ratio of the peak-to-peak voltage across the PZT over the peak-to-peak voltage of the signal going into the lock circuit. This ratio has been normalized so that the gain is zero at low frequencies.

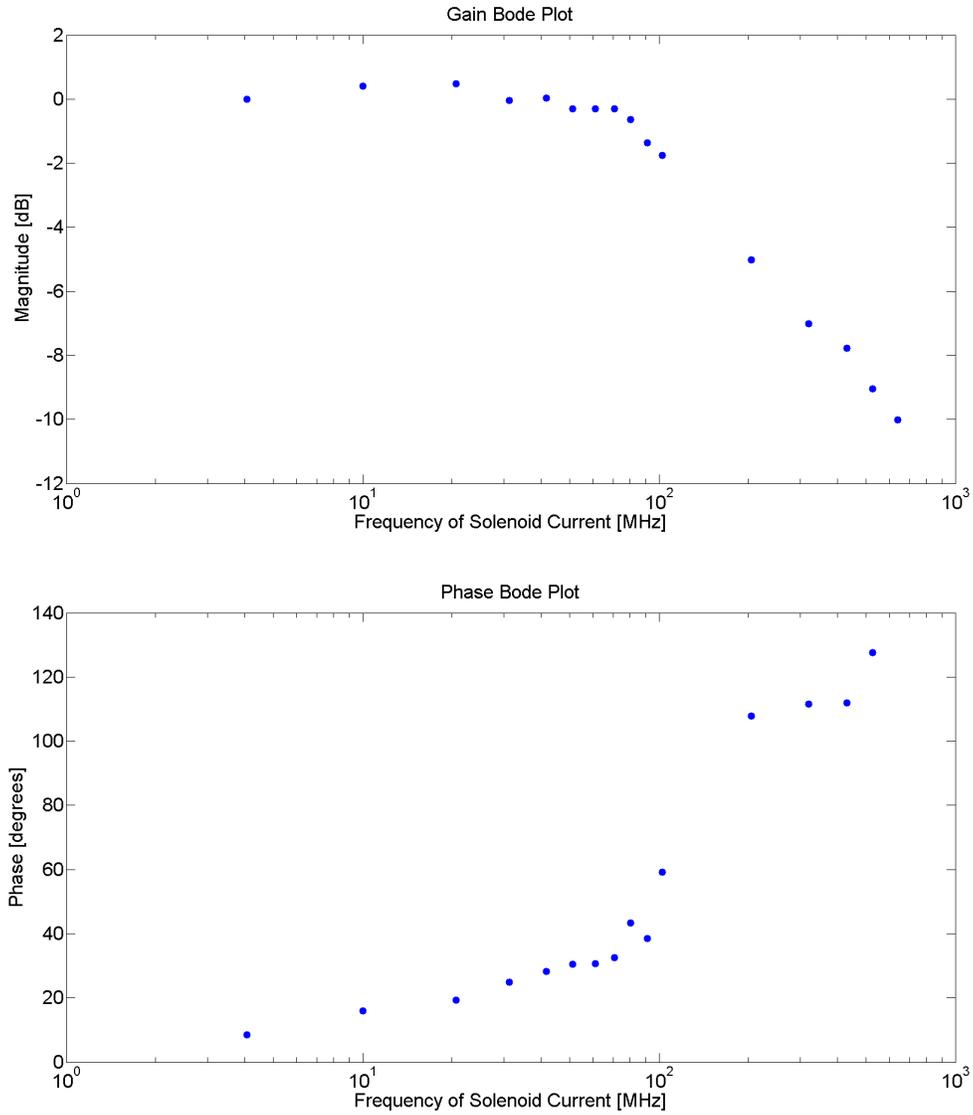


Figure 14: Bode plots for the PZT in the laser cavity.

We can see from the Bode plots that the gain starts to roll off once the frequency of the Zeeman current reaches approximately 100 Hz. At higher frequencies, the PZT can no longer adjust the cavity mirror quickly enough to keep up with the solenoid current. Thus, when cooling atoms, the lock frequency should not be swept at a rate faster than 100 Hz.

## Conclusion

We find that the saturated absorption cell and lock circuit work very well. The RMS frequency deviation of the lock frequency is  $0.296 \pm 0.030$  MHz, which is small compared to the 88-Sr  $^1S_0$ - $^1P_1$  transition's natural linewidth of 30 MHz. We are also able to modulate the lock frequency without using expensive external components, and the lock is stable enough that we can begin cooling atoms. We also find that the experimentally determined Zeeman splitting as a function of current is  $26.21 \pm 0.42$  MHz/A; this is slightly higher than the theoretically predicted value, though this may be due to the nonideal nature of our solenoid and is ultimately not a major concern.

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