Towards 405nm Manipulation of $^{40}\text{K}$

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Abstract

This document describes the work done during the summer of 2009 on the Toptica DL100 405nm laser and the optical setup it feeds to. It begins with a discussion of relevant background material, most notably the concept of a modulation-transfer saturation spectroscopy lock, and touches on the early work done on cavity resonators. This is followed by a detailed description of both the electronics built to move towards a working lock setup and of the setup itself. Spectroscopic measurements are discussed, along with the relevant characteristics of the vapour cell, the AOMs, and the AOM drivers. The troubles experienced in attempting to use previously built electronics are discussed, with both specific and general proposals put forward for future work.
# Contents

1 Acknowledgments 4  
2 Introduction 4  
3 Background 4  
   3.1 Confocal Cavity Resonators 4  
   3.2 Saturated Vapour Spectroscopy 6  
   3.3 AOMs and Modulation Transfer 7  
   3.4 Locking 8  
4 The Toptica DL100 Diode Laser and DC110 Control Rack 10  
   4.1 Description, Tuning, and Repair 10  
   4.2 Modification for Feedback 11  
5 The Cavity 12  
6 Saturation Spectroscopy 13  
   6.1 The $^{39}$K Vapour Cell 13  
   6.2 The Setup 14  
   6.3 Results 15  
7 The Electronics Marathon 16  
   7.1 AOM Driver Boxes 16  
   7.2 Power Supply 17  
   7.3 Subtractor 17  
8 The Electronics Fiasco 17  
   8.1 Lock Box 17  
   8.2 Lock-In Amplifier 19  
9 An In-House Solution 20  
10 Conclusions, Comments, and Future Work 20  

# List of Figures  
1 A confocal cavity 5  
2 Saturation Spectroscopy Schematic 6  
3 Saturated Spectroscopic Profiles 7  
4 Acousto-Optical Modulator 8  
5 An Error Signal 8  
6 The DC110 Laser Rack 10  
7 Toptica DL110 threshold 11  
8 The cavity resonator 12  
9 Confocal cavity transmission 12
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>The $^{39}$K Vapour Cell</td>
<td>13</td>
</tr>
<tr>
<td>11</td>
<td>Percent absorption vs. optical power</td>
<td>13</td>
</tr>
<tr>
<td>12</td>
<td>Percent absorption vs. temperature</td>
<td>14</td>
</tr>
<tr>
<td>13</td>
<td>Saturated absorption spectroscopy setup</td>
<td>14</td>
</tr>
<tr>
<td>14</td>
<td>Results of saturated spectroscopy</td>
<td>15</td>
</tr>
<tr>
<td>15</td>
<td>Potassium-41 Hyperfine structure</td>
<td>16</td>
</tr>
<tr>
<td>16</td>
<td>An AOM driver control box</td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td>The power supply</td>
<td>17</td>
</tr>
<tr>
<td>18</td>
<td>The subtractor circuit</td>
<td>18</td>
</tr>
<tr>
<td>19</td>
<td>Lock Box Error Signal</td>
<td>18</td>
</tr>
<tr>
<td>20</td>
<td>Lock-in Amp Error Signal</td>
<td>19</td>
</tr>
<tr>
<td>21</td>
<td>A Homemade Lock Box</td>
<td>20</td>
</tr>
</tbody>
</table>
1 Acknowledgments

At one point or another during the summer, I needed the help of every person in the UCAL and I truly appreciate the patience displayed in showing me, for example, how a certain piece of equipment works, how to properly clean a mirror, and so forth. I must however reserve special thanks for Jason, whose magic oscilloscope hands and vast array of knowledge I frequently took advantage of, and for Dave who has guided me through this summer with a seemingly endless supply of patience. Specific thanks should also go to Joseph, not only for his continual trust that I probably wouldn’t destroy his laser, but for his thoughtful comments and suggestions whenever a wall of uncertainty was hit. My time at UofT has been an eye-opening experience, and I have deeply enjoyed simply being surrounded by interesting ideas and intelligent people, day in, day out.

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2 Introduction

The initial purpose of this summer project was the design of a high finesse reference cavity. As time progressed throughout the first four weeks, concerns shifted fairly seamlessly from a cavity lock to basic frequency stabilization, as the latter presented a more direct path to the possibility of quickly integrating the setup with the main lattice apparatus. This led directly to the need for a saturation spectroscopy lock, which in turn led to the need for the electronics that was subsequently built.

3 Background

This section describes background material that is relevant or quasi-relevant to the discussions that follow.

3.1 Confocal Cavity Resonators

The discussion here follows [1, Chp. 6]. Many details are omitted, and can be found in any standard reference such as [2, Chp. 14].

Cavity resonators are comprised of a space with uniform refractive index bounded by two mirrors, in which electromagnetic standing waves of certain frequencies are permitted to exist should they fulfill a resonance condition.

In the paraxial wave approximation, the electric field inside the cavity satisfies

\[
\Delta^2 \epsilon_0 + 2ik \frac{\partial \epsilon_0}{\partial z} = 0
\]
where $\epsilon_0$ is defined by $\epsilon(x, y, z) = \epsilon_0(x, y, z)e^{ikz}$. This PDE admits eigen-mode solutions of the form

$$
\epsilon_{mn}(x, y, z) = \frac{A\epsilon_0}{w(z)} H_m\left(\frac{\sqrt{2}x}{w(z)}\right) H_n\left(\frac{\sqrt{2}y}{w(z)}\right) e^{i(kz-(m+n+1)\tan^{-1}(z)/z_0)} e^{i\frac{2\pi}{\lambda}(x^2+y^2)}/2R(z) e^{-(x^2+y^2)/w^2(z)}
$$

with $m, n \in \mathbb{N}_0$ and

$$w(z) = w_0\sqrt{1 + \left(\frac{z}{z_0}\right)^2}, \quad R(z) = z + \frac{z^2}{2}, \quad z_0 = \frac{\pi w_0^2}{\lambda}$$

For this beam profile to be a mode of the cavity, we must have curvature matching between the beam and the mirrors, as in Figure 1. This line of thought leads directly to a condition on the round trip phase difference of the beam, namely

$$\Delta \theta = \frac{2\pi fd}{c} - (m + n + 1)\cos^{-1}\sqrt{g_1g_2} = q\pi$$

where $g_1, g_2$ are the standard cavity stability parameters, and $q \in \mathbb{N}_0$. For the same mode, the frequency difference between resonances clearly satisfies $\Delta f = c/2d$ where $d$ is $L$ in Figure 1, independent of the type of cavity under consideration. For the confocal cavity condition, $g_1 = g_2 = 0$ and $\cos^{-1}\sqrt{g_1g_2} = \pi/2$, yielding

$$\Delta f = \frac{c}{2d} \left(1 + \frac{1}{2} \Delta m + \Delta q\right)$$

The minimum $\Delta f$ is then clearly $c/4d$, half that of a standard Fabry-Perot cavity. A typical parameter used to describe the performance of a given cavity is the finesse, which in the case of identical mirrors is given by $F = \pi \sqrt{R}/(1 - R)$.
where $R$ is the reflectivity of one of the cavity mirrors. The finesse is related to $\Delta f$ (the free spectral range) and the linewidth of the transmission line via

$$\mathcal{F} = \frac{\Delta f}{\text{linewidth}}$$

### 3.2 Saturated Vapour Spectroscopy

Saturated Vapour Spectroscopy provides a method of examining atomic hyperfine structure due to the elimination of Doppler broadening. We give a cursory description of the process, and refer the reader to [5] for a more detailed examination. In this discussion, we deal with a two level atom characterized by ground state $|g\rangle$ and excited state $|e\rangle$ separated by energy $\hbar \omega_0$. Consider the situation depicted in Figure 2, in which the pump and probe are derived from the same source beam, and first remove the pump beam.

![Figure 2: Counter-propagating beams through a heated atomic vapour cell. The angle between the beams is exaggerated for clarity. [3, pg. 2]](image)

Due to the Maxwell-Boltzmann distribution of atomic velocities, an incident beam at frequency $\omega_0$ will appear red-shifted to atoms moving to the right, and blue-shifted to atoms moving to the left. As the laser frequency is scanned across $\omega_0$, different velocity classes of atoms will see the beam as being on resonance as $\omega(t)$ varies. This causes an effective broadening of the natural linewidth of the transition, referred to as Doppler broadening. At room temperature, this Doppler width is typically two orders of magnitude larger than the natural linewidth [3].

Now, consider Figure 2 with the pump added back in. The pump beam is on the order of 10 times more intense than the probe beam, and ideally the pump is intense enough such that it "saturates" the atomic sample in that close to half the population of some velocity class of atoms are in the excited state, for a corresponding detuning of the beam. Take the case when the beam is red-detuned. A velocity class of atoms moving to the left will see the probe as on resonance, but will not be able to see the pump due to its even more severe Doppler-induced red-detuning. The same argument can be applied to a blue
detuned beam.

The magic of saturation spectroscopy occurs when the beam is not significantly detuned from $\omega_0$. The pump beam will then saturate a velocity class of atoms that is approximately stationary. This velocity class of atoms can also see the probe, but there simply aren’t very many of the atoms left in $|g\rangle$ for the probe to excite. This is characterized by a marked decrease in absorption of the probe beam, and a corresponding increase in probe transmission, producing a narrow peak about $\omega_0$. This process is shown schematically in Figure 3.

![Saturation spectroscopy profiles for a two level system.](image)

Figure 3: Saturation spectroscopy profiles for a two level system. [3, pg. 3]

The concept of a cross-over absorption peak is also relevant for our purposes. An excellent discussion of this can be found at [5, pg. 159].

### 3.3 AOMs and Modulation Transfer

Acousto-Optical Modulators (AOMs), within our context, are used for modulating and dithering the frequency of a laser beam. A typical AOM is depicted in Figure 4.

The frequency shifting of the beam as it passes through the AOM is a consequence of conservation laws as the photons interact with the vibration phonons which propagate through the AOM. A special optics configuration referred to as the “cats-eye” configuration allows us to take advantage of this frequency modulation while cancelling the spatial modulation that comes along with it [9].

Let us reconsider the saturation spectroscopy setup from Section 3.2. For a fixed laser frequency $\omega$, using an AOM we can now 'dither' the pump frequency at, say, 100kHz. This dithering corresponds to a dithering of the ground state depletion caused by the pump, and the received probe transmission will then also be dithered at this frequency. We have thus transferred the frequency modulation of the beam to an amplitude modulation of the probe transmission.
which is easily detectable via a photodiode.

Figure 3: Typical AOM operation. [6]

3.4 Locking

In our context, locking refers to frequency stabilization of a diode laser via feedback control. In order to stabilize the laser to a particular frequency (say, an atomic transition), we must first have a way of determining whether we are currently above or below the desired frequency. A glance at Figure 3 indicates that we cannot simply look at the raw saturation spectroscopy signal due to its symmetry. However, the derivative of this signal, shown in Figure 5, has the asymmetry we desire.

Figure 4: Typical AOM operation. [6]

Figure 5: The derivative of a Gaussian, a typical error signal.

We can combine our modulation transfer from Section 3.3 with a device known as a lock-in amplifier to generate just such a signal. Since the frequency
of the laser varies as $\omega + \Delta \omega \cos(\Omega t)$, the voltage signal on our photodiode will in turn vary as

$$V(\omega') = V(\omega) = \frac{dV}{d\omega'}(\omega' - \omega) + \cdots$$  \hspace{1cm} (1)

$$= V(\omega) + \frac{dV}{d\omega'} \Delta \omega \cos(\Omega t) + \cdots$$  \hspace{1cm} (2)

The lock-in amplifier then mixes and averages this signal with a reference signal at frequency $\Omega$, giving an output that is proportional to the desired derivative.

Now that we have the desired error signal, we can use it to send information back to the diode piezo and current control to modify the laser frequency for localizing about the atomic resonance. This is typically achieved using an analog PID controller. The reader is deferred to any available control book for a discussion of PID controllers, such as [7]. Both current and piezo feedback are typically needed to reject noise over a large bandwidth, as piezos are unable to respond faster than a few kHz.
The Toptica DL100 Diode Laser and DC110 Control Rack

4.1 Description, Tuning, and Repair

Details regarding the diode laser and controller can be found in the respective manuals located beside the controller. The controller manual is particularly useful, and contains a large amount of information on the different modules. The DC110 rack contains three main modules, which respectively control the cavity piezo, diode temperature, and diode current.

The Piezo SC110 Scanning Control (large left module in Figure 6) can provide both a DC bias (0-150V in HV mode) to the cavity piezo and a scanning ramp. Full control is available over the ramp amplitude, frequency, and symmetry. A two-pole switch controls whether the ramp is triggered externally or internally, with the corresponding input/output going through the trigger BNC. The feed-forward option on the module allows the current to be scanned along with the piezo, in an effort to improve the mode hop free scanning range. The feed forward trim pot provides continuous adjustment of the proportionality between these two scans.

Upon initial investigation, the threshold current was found to be roughly 36.8mA (Figure 7). This exceeds the manufacturer listed threshold current of 34mA\(^1\). During the initial tuning of the laser to the desired frequency (741091.1GHz), the beam was sent into the Wavemeter, whose dip switches had been changed to allow lower, near UV wavelengths\(^2\). It was found that the easiest way to reach the desired frequency was to raise the temperature of the diode, and then work ones way back to the desired frequency using the piezo and current, while avoiding mode hops as best as possible. The temperature set point has since been at 31 Celsius. Feed forward was used liberally in achieving a mode hop

\(^1\)This, along with the consistently poor beam shape of the laser, likely indicates wear and tear on the diode

\(^2\)Although the Wavemeter is not designed for such wavelengths, changing the dip switches seems to produce the desired functionality. For more information, consult the Wavemeter manual
free scanning range.

![Graph](image.png)

**Figure 7:** Optical power, measured after the isolator, as a function of diode current. May 15th, 2009.

At one point during the summer, the laser controller stopped functioning completely. Upon consulting with Toptica support, the problem was diagnosed as a shorted voltage regulator, and was remedied in-house. Details of this can be found in Reference [8].

### 4.2 Modification for Feedback

The small panel on the left side of Figure 6 is the DCB 110 backplane connector. Through dip-switch configurations on the removable modules, the DCB110 input BNC can be routed to any module to externally control any relevant parameter. To configure this port for piezo feedback, Remote DIP-2 was set to 'on' on the SC110, and the BNC connector was routed to pin 25 on the DCB board. When using external feedback, the internal scanning ramp should be turned off and the piezo scanned externally. This is most easily accomplished by flipping the 'trigger' switch on the SC110 to external, and turning the scanning amplitude to zero. The output applied to the cavity piezo is then calculated as 15 times the remote signal, plus the remaining DC bias. Appropriate diagrams can be found in the DC110 manual.
5 The Cavity

The objective of the work done on the cavity (Figure 8) was simply to determine its finesse and linewidth.

A beam was taken directly from the laser, through an optical isolator, and subsequently coupled into the cavity. The old mirrors were then replaced with special 405nm mirrors ordered by Dave, and a finesse of approximately 500 was then measured (Figure 9). Using the measured length of the cavity of 5.0cm to determine the free spectral range, the transmission linewidth was then calculated to be 2.8MHz.

Figure 8: A simple cavity resonator

Figure 9: Transmission lines for the confocal cavity.

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3The threaded tube into which the adjustable mirror screws is not quite precise, leading to the possibility of the mirror wobbling in the socket, compromising the confocal condition.
6 Saturation Spectroscopy

6.1 The $^{39}$K Vapour Cell

The vapour cell (Figure 10) in use this past summer was built by David McKay, and only slight modifications of it were performed during the past 16 weeks. Heating of the enclosed $^{39}$K sample is accomplished via heater wire wrapped around the glass cell. The wrapping is concentrated near the ends to prevent accumulation of potassium on the cell windows. A K-type thermocouple is affixed firmly at one of cell for temperature monitoring, and the cell is, to some extent, thermally isolated from the metal that supports it via fiberglass tape.

Although the wire is rated to 200 Celsius, it was empirically found that running the cell continuously at a measured temperature of 120 Celsius severely compromised the heater wire. One possible explanation for this is that the temperature probe cannot measure exactly between the tightly wrapped wire, and thus the temperature in those small regions may be significantly higher. In any case, one should be wary when running the cell at temperatures in this range. Figures 11 and 12 respectively show the dependence of absorption on optical power and cell temperature.

![Figure 10: The $^{39}$K Vapour Cell](image)

![Figure 11: Percent absorption as a function of optical power.](image)
6.2 The Setup

Figure 13 shows a reduced\(^4\) schematic of the optical configuration used for saturation spectroscopy. The angle between the pump and probe is again exaggerated for clarity.

\(^{4}\)The schematic is reduced in the sense that it omits components in the setup that are irrelevant to the spectroscopy/locking at hand.

A 110MHz Crystal Tech AOM was used in the cat’s eye configuration. An
FM DC control signal of roughly 8V was used to set the center frequency of the AOM at 110MHz, and an AM DC control signal of roughly 0.3V was found by trial and error to maximize the diffraction efficiency\(^5\). It should be noted that the maximum RF output power for the AOM drivers can be adjusted either externally via the \(V_{alc}\) input or using the trim pot positioned on the front of the driver. This was not experimented with during the past 16 weeks.

### 6.3 Results

Traces obtained from the photodiode in the above setup are shown in Figure 14. Figure 14a primarily displays the Doppler broadening associated with the \(4S_{1/2} \rightarrow 5P_{3/2}\) transition of \(^{39}\text{K}\). Using the known splitting of the ground state hyperfine structure from [4] of 461.72MHz, the Doppler width can be calculated as 1.8GHz.

![Figure 14](image.png)

**Figure 14:** Results of saturated spectroscopy.

Figure 14b displays the previously mentioned hyperfine structure, a detailed account of which can be found in [4]. From left to right, the peaks are the \(F = 2\) state, the crossover, and the \(F = 1\). Again, using the known ground state splitting of \(^{39}\text{K}\) the linewidth of these transitions are found to be roughly 12MHz.

Curiously, the hyperfine structure of residual \(^{41}\text{K}\) in the sample was also visible, as shown in Figure 15. The isotope shift between \(^{39}\text{K}\) and \(^{41}\text{K}\) for the \(4S_{1/2} \rightarrow 5P_{3/2}\) transition is then readily measured to be 540MHz.

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\(^5\)The diffraction efficiency could unfortunately not be made to exceed roughly 60%. Minimum spec for the device is 75% at 633nm.
Figure 15: $F = 1$ Potassium-39 peak followed by the Potassium-41 ground state hyperfine structure

7 The Electronics Marathon

With the saturation spectroscopy firmly in place, concerns moved quickly to the prospect of locking and the work that would need to be done to achieve lock. This section catalogs the electronics built for this purpose.

7.1 AOM Driver Boxes

Four AOM Driver Boxes (Figure 16) were built, and were based completely off the designs of Stefan Myrskog, for which Eagle documents can be found here. Each box constitutes a steering wheel for its respective AOM, allowing remote and local (potentiometer) control of DC values for the FM and AM AOM driver inputs, along with an appropriate routing of an applied dither signal. The local FM (resp. AM) DC output can be varied from approximately 0 to 15V (resp. 0 to 2.5V). One must be careful however not to over drive the AM driver input, as the accompanying documentation for it lists the acceptable input range from 0 to 1V. The dither signal is DC blocked within the box, so any offset is irrelevant.
7.2 Power Supply

The AOM Driver Boxes require a ±24V supply, along with a +28V supply for each respectively controlled driver. With this in mind, a power supply (Figure 17) was built\(^6\) which contains both a PowerOne ±24V supply rated for 2A and a Condor +28V supply rated for 4A. Each supply was given five outputs, although more could be added in principle. The supply is fused with a 3A bulb.

![Figure 17: The power supply](image)

7.3 Subtractor

The idea of the subtractor circuit (Figure 18) was to mimic the operation of a differential photodiode, with the intent being to eliminate any residual laser intensity noise or Doppler-related distortion from the spectroscopic signal. The circuit accepts two photodiode signals \(V_1\) and \(V_2\) with the output being computed as \(V_{out} = G_{out}(G_1V_1 - V_2)\) for \(G_1, G_{out} \in [1, 10]\).

8 The Electronics Fiasco

The following section documents the series of electronic successes and failures associated with generating an error signal from the spectroscopy signal.

8.1 Lock Box

From the point of view of speed, the Lock Box provided what appeared to be the quickest route to a locked laser system. With the ability to both internally

\[^6\]I neglected to include an LED to indicate whether the box is on or off. One can check this by feeling the vibrations the unit produces.
generate an error signal and produce the necessary feedback signals, the possibility of the box providing a quick solution was simply too good to ignore. Dithering with a 0.5V signal at 100kHz, an error signal was generated as shown in Figure 19. A low bandwidth lock utilizing piezo feedback was also done, and the laser did indeed appear to be locked.

Throughout the preceding, the phase adjustment knob, the purpose of which was to modify the phase of the input reference signal, was non-functional. This didn’t seem to pose a problem for generating an error signal, so not much at-
tention was paid to it. However, events quickly took a turn for the worse. One
day during routine use, it appeared that the generated "error" signal was inde-
dependent of whether the reference signal on or off. The "error signal" displayed
was simply a highly distorted version of the original photodiode signal.

With the help of Alan and Jason, an afternoon was spent in the belly of the
beast investigating the apparent problem. After miserably hunting through
over-engineered circuit diagrams and testing voltages, no problem could be
found. When the box was restored to service and tested, the phase adjust-
ment knob had repaired itself and what appeared to be an error signal was
again generated. Sure enough though, the Lock Box giveth and the Lock Box
taketh away, and the entire slew of problems returned shortly.

The Lock Box has proven itself to be an unreliable piece of equipment, and
as Jason put it, a black hole of time and energy. It has since been placed on the
back shelf of the BEC lab.

8.2 Lock-In Amplifier

Common sense dictated that an attempt should be made to generate an er-
ror signal with the lock-in amplifier for comparison with the Lock Box. Again
dithering with a 0.5V signal at 100kHz, such a signal was generated, as shown
in Figure 20.

![Error Signal from Lock-in Amplifier](image)

Figure 20: Averaged error signal obtained from the lock-in amplifier. Photodi-
ode signal is AC coupled.

After the calamitous failure of the Lock Box, the lock-in amp was reinstated
for duty so that, at the very least, an error signal could be generated. However,
in an almost flawless archetype of Murphy’s law, troubled waters lay ahead.
Over several days the amplifier displayed increasingly unusual behavior such as becoming unresponsive to all user inputs. Sometimes the lights just wouldn’t come on, other times all of the lights would come on; in either case, the device would not respond. This would often occur in the middle of normal operation. The lock-in amplifier has thus also proven itself to be unreliable.

9 An In-House Solution

Dave had, previous to the discussed failures, purchased a mixer from Mini-Circuits in hopes of pursuing an alternative locking scheme. With the twin error-signal-generating titans subdued, Dave sprung into action, quickly designing and building an integral control circuit (Figure 21b) for piezo feedback and making the necessary adjustments for feeding the reference and photodiode signals to the mixer (Figure 21a). This approach has since proved successful both in generating an error signal and in creating a piezo feedback lock. Since I am for the most part unfamiliar with the specifics of what has been done here, I must defer the reader to Dave for additional information.

10 Conclusions, Comments, and Future Work

In the interest of clarity when considering the large number of small topics considered, this section is broken into individual bullets, with conclusions and comments being given for each.

Toptica DC110 and DL110

The Toptica DC110 control rack has been used to adjust the DL110 frequency to the desired range, and the appropriate modifications have been made to allow
for piezo feedback via the DCB110 analog input. Feedforward was used liberally in achieving a mode-hop free tuning range, and for the case of feedback control, an external ramp must be used to scan the piezo. The 405nm diode has shown signs of degradation including an increased threshold current and poor beam shape. I am not aware of any settings that must be adjusted to accommodate current feedback (the input BNC is on the far right of Figure 6), but one should of course consult the appropriate manual before attempting any such control.

**Cavity**

The finesse of the cavity was found to be roughly 500, with a corresponding transmission linewidth of 2.8MHz. Any future cavity intended to be a serious reference for reducing the laser linewidth will require a more robust construction including compensation for thermal and vibration related disturbances.

**Vapour Cell**

The current vapour cell has been a completely functional atomic reference during its use. The two problems associated with it are loss due to the microscope-slide end windows, and the possibility of pushing the temperature inside the cell too high and destroying the heater wire. In the future, use of the custom 14cm vapour cell would presumably allow a similar signal quality to be obtained while running at a lower temperature, thereby alleviating any concerns regarding heat.

**AOMs, AOM Drivers, and AOM Driver Boxes**

Two AOMs, along with their respective support equipment, have been set up and are operational. Neither AOM is rated for 405nm, and it is thus unsurprising that the diffraction efficiency has not as of yet been made to exceed 65%. Care should be taken when adjusting the AM output on the Driver Boxes to ensure that the voltage the driver itself receives does not exceed 1V. Adjustment of the maximum RF output power of the drivers was not pursued. A power supply was built to accommodate these devices, and is functioning properly.

Driver Box 3 is not operational. For trouble shooting, I would first recommend that the troubleshooter confirm that all resistor values used are correct, and that none of the components appear to have been burnt due to shorts. If this is the case, then I would proceed with ensuring all crimp-wire connections are secure, that the potentiometers and switches are functioning properly, and that there is no visible degradation of the circuit pathways themselves. Finally, ensure that all op-amps and voltage regulators are functioning properly. A full parts list can be found in the appropriately labeled yellow packing envelope, or, failing that, in my lab book.
Spectroscopy
The hyperfine structure of $^{39}$K was resolved. The Doppler broadening resulting from the transition from each hyperfine ground state was found to have a width of approximately 1.8GHz, with the hyperfine transitions themselves having widths on the order of 12MHz.

The optical set-up shown in Figure 13 does not include the pick-off for use in the subtractor circuit, or the additional 210MHz AOM in cat’s-eye which feeds to a fibre-optic connection. The addition of these elements has reduced the amount of power reaching the sat-spec setup, and therefore, in the interest of signal quality, care should be taken to ensure that saturation is achieved.

Subtractor Circuit
A subtractor circuit has been built to function as a make-shift differential photodiode. When tested, the circuit worked, but may require additional noise filtering for the low signal levels produced by the photodiodes.

Inoperative Electronics
Both the Lock-in amplifier and the Lock Box are inoperative. Unless repairs are made, I would strongly suggest avoiding both pieces of equipment. I am sure that I would not be making a bold statement by proposing that in the future, bulky devices such as the Lock Box should be avoided in favour of more simple, homemade solutions.

Locking
David McKay has created a homemade mixing and locking system, which has indeed shown promise as a permanent method for locking. The system does not currently incorporate current feedback, and is thus vulnerable to high frequency disturbances.

References

