LOCKING MULTIPLE LASERS TO A SINGLE REFERENCE CAVITY

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One of the biggest unsolved problems in modern physics is the excess amount of matter compared to antimatter that exists in the universe. Charge parity (CP) symmetry violation could explain this imbalance, but there are not enough sources of CP violation to explain the size of the imbalance we observe. The nuclear magnetic quadrupole moment (nMQM) experiment at ODU seeks to perform precision measurements on Lutetium ions to look for sources of CP symmetry violation beyond what has been found in high-energy particle physics experiments. This experiment requires multiple lasers for laser-cooling and atomic state manipulation, which we must lock to a reference cavity. Locking multiple lasers to a single cavity can result in unwanted correlations between the lasers as thermal effects cause their feedback loops to interfere. For this project, we will lock multiple lasers to one cavity and characterize and then mitigate the amount of interference in this system.

Acknowledgements

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1. BACKGROUND AND MOTIVATION FOR EXPERIMENT

In 1967 Andrei Sakharov provided an explanation for the asymmetry of matter and antimatter in the universe, and the key requirement was CP symmetry violation [1]. The Standard Model of particle physics contains a small amount of CP symmetry violation but not nearly enough to account for the large imbalance we observe in the universe. In order to explain the large imbalance, we need to find sources of CP symmetry violation in hypothetical new particles or interactions outside of the Standard Model. The best way to look for these new particles is to measure their small residual effects in atomic physics precision measurements. The nuclear magnetic quadrupole moment (nMQM) experiment at ODU is searching for new sources of CP symmetry violation in lutetium hydroxide molecular ions, which are uniquely sensitive to new physics due to the highly deformed nature of the lutetium nucleus [2]. The interaction between the nMQM and the electrons produce a shift in the energies of the electrons, which we can measure using standard techniques in atomic physics [2]. Such measurements require incredibly precise and stable lasers, however. Standard "out of the box" lasers do not possess narrow enough linewidths to drive the transitions needed to perform these kinds of measurements. Laser frequencies also drift over time due to a number of different factors. One way to resolve both of these issues is to lock the laser to an external optical cavity with a fixed length. This way, the laser light exiting the cavity will be precisely the right frequency as well as precisely the right linewidth.

2. LASER COOLING AND TRAPPING OF LUTETIUM IONS

In order to study and perform measurements on ions, their energy must be reduced in order to minimize thermal vibrations and effects; therefore, the ions must be trapped and then subsequently cooled. Laser cooling requires very precise control over the laser frequency, hence why a high-finesse Fabry-Perot cavity is necessary. This chapter shall discuss the physical mechanisms of ion trapping and laser cooling, as well as how those mechanisms apply to the Lu^+ ion.

2.1. Ion Trapping

The process of ion trapping is much more straightforward than the trapping of neutral atoms, which is a much more involved process. Because ions are charged, they exhibit very strong Coulomb interactions, which are much stronger than the dipole interactions that are used to trap neutral atoms. This means that ions are very responsive to electric fields, which makes them easier to trap (they generally have deeper trap depths than neutral atoms, and hence can be trapped at higher energies). In general, ions will feel a force on the order of 10^8 times greater than a neutral atom [3]. There are two main types of ion traps: the Penning trap and the Paul trap. This experiment uses a linear Paul trap, so we will only discuss the physics of the Paul trap. The linear Paul trap consists of four electrodes (shown in Figure 1), and produces a quadrupolar potential along the center of the trap (also known as the trap axis) [Leibfried]. It is for this reason that the trap is known as a linear trap: the stable region is along the trap axis. With the proper RF voltages applied to the electrode, an ion can be trapped anywhere along the trap axis. The nice thing about ion traps is unlike neutral atoms, the ions do not have to be laser cooled to be trapped. The ions can be laser cooled using the same methods as neutral atom cooling, but can be cooled while they are trapped. The mechanisms of laser cooling will be discussed next.

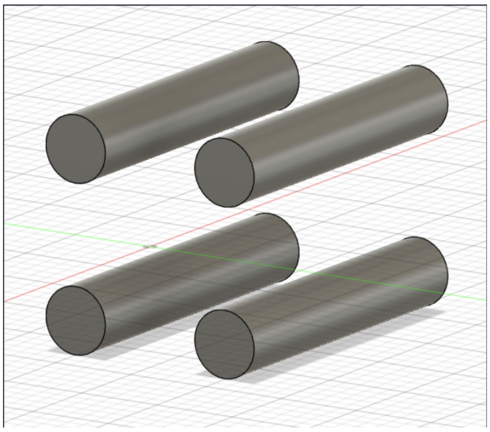

FIG. 1: Common configuration for a linear Paul trap

2.2. Laser Cooling Techniques

Once the ions are trapped, laser cooling techiques can be applied to lower the thermal energy of the ions to a low enough temperature that precision measurements can be performed. One common laser cooling technique that will be discussed here is Doppler Cooling. Laser cooling harnesses the momentum-carrying nature of light. The basic idea is that the photons from the laser gives the atom a momentum “kick” in the direction opposite its motion, thereby slowing it down. The “kick” comes from the atom absorbing the photon, which excites the electrons in the atom into a higher energy state. When these electrons relax, they emit photons in random directions. If enough of these kicks occur, the absorption and scattering of photons have a net slowing effect on the atom. This is called the *scattering force*, and is the product of the photon momentum and the scattering rate [3]. The scattering rate is given by the equation

$$R_{scatt} = \frac{\Gamma}{2} \frac{\Omega^2/2}{\delta^2 + \Omega^2/2 + \Gamma^2/4} \tag{1}$$

If the photon momentum is $\hbar k$, then the scattering force is

$$F_{scatt} = \hbar k \frac{\Gamma}{2} \frac{I/I_{sat}}{1 + I/I_{sat} + 4\delta^2/\Gamma^2} \tag{2}$$

where Γ is the spontaneous emission rate, Ω is the Rabi frequency, and δ is the detuning from the resonant transition frequency. This force can be used in Doppler cooling to cool an atom using counter-propagating laser beams. If the laser is detuned slightly below the resonant transition frequency, the doppler shift will cause atoms going towards the laser to experience the correct frequency and therefore will experience the maximum scattering force. For ions, the counter-propagating beams are not necessary since the ion is trapped and already moving in a stable orbit: the motion of the ion can be used to cause the Doppler shift, so only one beam is needed to cool. This drastically reduces the cooling scheme needed to laser cool ions. For our Lu^+ ion, we will use the 3_1^D to

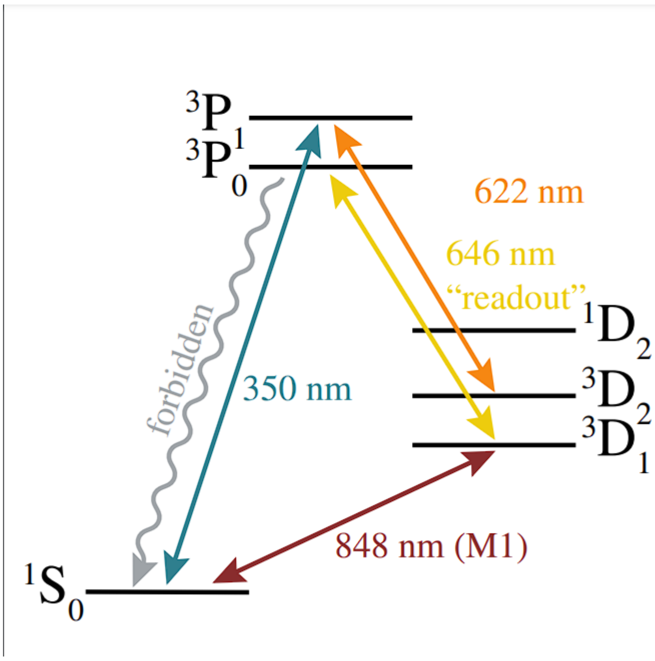

FIG. 2: Transition diagram for Lu^+ ion

State	Linewidth (1/s)	Lifetime (s)
$^3D_1$	5.14E-6	1.95E5
$^3D_2$	4.19E-2	20.9
$^3P_1$	1.05E7	35.7 (ns)
$^3P_0$	1.64E7	61.0 (ns)

FIG. 3: Transiton linewidths and state lifetimes for Lu^+, taken from [Paez]

3_0^P 646 nm transition as our cooling transition (Figure 2). The other transitions being driven are state manipulation (848 nm) and repump (350 nm and 622 nm) transitions.

3. FABRY PEROT CAVITIES

The Fabry-Perot (FP) cavity is central to the work done in this thesis. For this reason, it is worth dedicating a chapter to a detailed explanation of how they work. An FP cavity consists of two (usually flat) high-reflectivity mirrors separated by a gap of length d. If one of the mirrors is able to be moved, the cavity is called an interferometer [4]. If both mirrors are fixed, the cavity is called an FP etalon [4]. The latter case is true for this paper: both cavity mirrors are held in a fixed position by an Ultra-Low Expansion (ULE) glass cylinder (Figure 4).

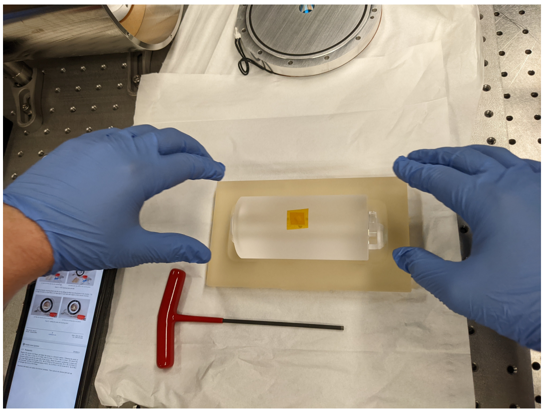

FIG. 4: Physical Fabry Perot Cavity

3.1. Interference Patterns

In order to truly understand how an FP cavity works, a working intuition for optical interference effects must first be obtained. This section of this chapter will serve as a brief overview of optical interference. Interference is a phenomenon that occurs in wave theory when two or more waves (these can be sound waves, electromagnetic waves, wave functions, etc) interact. From now on only electromagnetic waves will be discussed.

3.2. Interference of Two Electric Fields

Suppose we have two linearly polarized plane waves, $\vec{E_1}$ and $\vec{E_2}$. When these waves interact, invoking the superposition principle we can now find the total electric field at a point $\vec{r}$ at time t:

$$\vec{E}(\vec{r},t) = \vec{E_1}(\vec{r},t) + \vec{E_2}(\vec{r},t) \tag{3}$$

where

$$\vec{E_1}(\vec{r},t) = \vec{E_{01}}\cos(\vec{k_1}\cdot\vec{r} - \omega t + \epsilon_1) \tag{4}$$

and

$$\vec{E_2}(\vec{r},t) = \vec{E_{02}}\cos(\vec{k_2}\cdot\vec{r} - \omega t + \epsilon_2) \tag{5}$$

Now, since our plane waves in this case happen to be light waves, the very high oscillating frequency makes it difficult to directly measure the fields directly [4]. So instead, we can use irradiance which is easily measured by photo-sensitive devices. From Hecht, we know that irradiance is given by $I = \epsilon\nu\langle\vec{E}^2\rangle$. For the purposes of this discussion, the constants can be dropped since we are only going to be talking about irradiances in the same medium [4]. We can find the total irradiance by invoking the superpostion principle: we let $\vec{E} = \vec{E_1} + \vec{E_2}$. So the irradiance now becomes:

$$I = \langle(\vec{E_1} + \vec{E_2})^2\rangle \tag{6}$$

Carrying out the squaring operation and separating each time average gives the following:

$$I = \langle\vec{E_1}^2\rangle + \langle\vec{E_2}^2\rangle + 2\langle\vec{E_1}\cdot\vec{E_2}\rangle \tag{7}$$

From this we can then denote the following terms:

$$I_1 = \langle\vec{E_1}^2\rangle \tag{8}$$

$$I_2 = \langle\vec{E_2}^2\rangle \tag{9}$$

$$I_{12} = 2\langle\vec{E_1}\cdot\vec{E_2}\rangle \tag{10}$$

Where I_1 is the irradiance contribution of E_1, I_2 the contribution of E_2, and I_{12} is due to the interference between E_1 and E_2. Terms (8), (9), and (10) are all time averages of their respective fields over a given time interval T. Recall that the time average of a function is given as:

$$\langle f(t)\rangle = \frac{1}{T}\int_t^{t+T} f(t')dt' \tag{11}$$

In order to find the interference term, we must first do a little bit of math. We must first write the dot product in (10) in a way that is easier to work with:

$$\vec{E_1}\cdot\vec{E_2} = \vec{E_{01}}\cdot\vec{E_{02}}\cos(\vec{k_1}\cdot\vec{r} - \omega * t + \epsilon_1)\cos(\vec{k_2}\cdot\vec{r} - \omega * t + \epsilon_2) \tag{12}$$

Making use of some of the product trig identities, we can re-write (10) as the following:

$$\vec{E_1}\cdot\vec{E_2} = \frac{\vec{E_{01}}\cdot\vec{E_{02}}}{2}[\cos(\vec{k_1}\cdot\vec{r} + \vec{k_2}\cdot\vec{r} - 2\omega t + \epsilon_1 + \epsilon_2) + \cos(\vec{k_1}\cdot\vec{r} - \vec{k_2}\cdot\vec{r} + \tag{13}$$

Making use of yet another trig identity (one of the sum and difference identities), we can write (13) in a format that allows us to easily take the time average in order to find the interference term:

$$\vec{E_1}\cdot\vec{E_2} = \frac{\vec{E_{01}}\cdot\vec{E_{02}}}{2}[\cos(\vec{k_1}\cdot\vec{r} + \vec{k_2}\cdot\vec{r} + \epsilon_1 + \epsilon_2)\cos(\tag{14}$$

$$+\sin(\vec{k_1}\cdot\vec{r} + \vec{k_2}\cdot\vec{r} + \epsilon_1 + \epsilon_2)\sin(-2\omega t) + \cos(\vec{k_1}\cdot\vec{r} - \vec{k_2}\cdot\vec{r} + \epsilon_1 \tag{15}$$

The two time dependent terms, when averaged over an interval of one period ($T = 2\pi/\omega$), average to zero. This leaves:

$$\vec{E_1}\cdot\vec{E_2} = \frac{\vec{E_{01}}\cdot\vec{E_{02}}}{2}\cos(\vec{k_1}\cdot\vec{r} - \vec{k_2}\cdot\vec{r} + \epsilon_1 - \epsilon_2) \tag{16}$$

Therefore the interference term I_{12} is:

$$I_{12} = 2\langle\vec{E_1}\cdot\vec{E_2}\rangle = \vec{E_{01}}\cdot\vec{E_{02}}\cos(\vec{k_1}\cdot\vec{r} - \vec{k_2}\cdot\vec{r} + \epsilon_1 - \epsilon_2) \tag{17}$$

For simplicity, the phase difference due to the combined path length and the initial phase difference terms in the previous equation be called δ, so that the interference term now becomes:

$$I_{12} = E_{01}E_{02}\cos(\delta) \tag{18}$$

It is also assumed that E_{01} and E_{02} are parallel for simplicity. We can also use the other time field time averages to get I_{12} in terms of irradiance instead of electric fields. From (8) and (9), we know that $I_1 = \frac{E_{01}^2}{2}$ and $I_2 = \frac{E_{02}^2}{2}$ so we can re-write (18) as:

$$I_{12} = 2\sqrt{I_1 I_2}\cos(\delta) \tag{19}$$

So the total irradiance I can be written as:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\delta) \tag{20}$$

Maximum irradiance occurs when $\cos(\delta) = 1$, and minimum irradiance occurs when $\cos(\delta) = 0$. This is the basic relationship that arises when two light waves, such as lasers, interact. One important thing to note is that the two beams will only interfere strongly if they do not have a significant frequency difference [4].

3.3. Fabry Perot Etalons

Now that we have seen a detailed treatment of two beam interference, we can now look at how Fabry-Perot (FP) etalons work. Now instead of two beams, we have multiple beams (ie read: more than two) interfering with each other. A detailed analysis like we saw in section 3.2 is beyond the scope of this paper, but we can use the results of mumtiple beam interference analysis to describe how FP etalons work. FP etalons work by using very high reflectivity mirrors to bounce light inside of the cavity: if the light is the correct wavelenth, then each reflected beam will constructively interfere. Eventually, there is enough power build up inside the cavity that a measurable amount of light is allowed to escape from one end of the cavity. The wavelengths that will constructively interfere are given by interval multiples of the Free Spectral Range (FSR) of the cavity:

$$FSR = \frac{c}{2L} \tag{21}$$

For our cavity, which has a length of 100 mm, the FSR is about 1.5 GHz. So for every 1.5 GHz, there is a laser frequency that can be transmitted by the cavity. Another very important cavity parameter is the *Finesse* of the cavity. The finesse is essentially a measure of the quality of the cavity: the higher the finesse, the narrower the transmitted lights linewidth will be. Finesse is directly related to the reflectivities of the cavity mirrors:

$$Finesse = \frac{\pi\sqrt{R}}{1-R} \tag{22}$$

Using the data from Figure 22, we can calculate the Finesse for each wavelength: $Finesse_{646} = 13048.7$, $Finesse_{848} = 1410453.5$, $Finesse_{1050} = 14149.1$. We can see that 848 nm will have the narrowest linewidth, since the cavity has very high finesse at 848 nm.

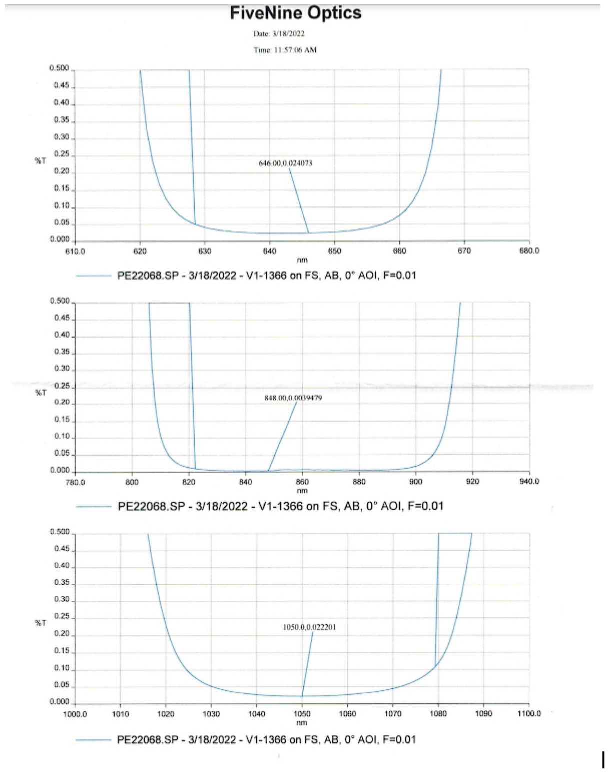

FIG. 5: Reflectivity data from Fine Nine Optics at 646nm, 848 nm, and 1050 nm

4. EXPERIMENTAL SETUP AND METHODS

4.1. Vacuum Housing and Associated Hardware

The heart of the experiment, the cavity, is housed in a cylindrical vacuum housing (VH). The VH is a double-walled, thermally insulated apparatus in the center of which the cavity sits. The cavity is seated on four Viton balls that sit inside the glass holder. The glass holder, with the cavity on top, sits inside the VH (Figure 6). The laser light is able to pass through the cavity via two windows, one on each end of the VH. The light passes through the exterior window, through the interior window, and then through the cavity. On one end of the VH, there is a tee that extends out from the bottom of the VH. Attached to one end of this tee is a valve that is used to connect the VH to a turbomolecular pump or a leak checker. The other end of the tee is attached to a 7 kV ion pump. Initial pumpdown of the VH is accomplished by attaching a turbomolecular pump to the end of the tee with the valve. Pumping down with the turbo is done over the course of 48 hours to ensure that a minimal amount of particulates are stirred up inside the VH, and that a very good base vacuum has been established. A Pfeiffer HiCube pumping station (combo roughing and turbopump) was used to achieve the initial vacuum. After the intial vacuum was reached, the ion pump was turned on.

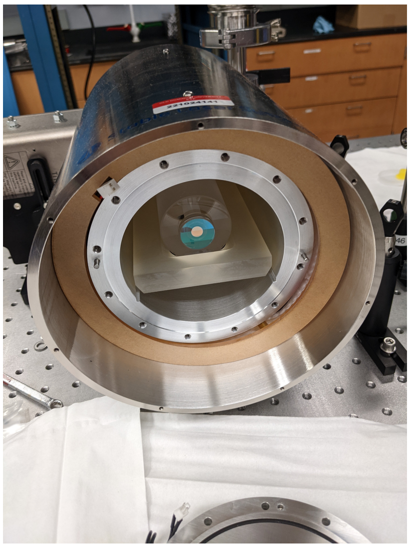

FIG. 6: Cavity seated inside the vacuum housing

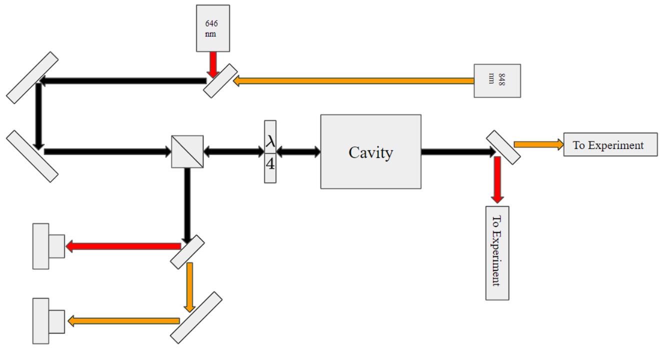

FIG. 7: Schematic of experimental setup

4.2. Optics

This setup is currently designed for two lasers: a third laser may be added later, pending the success of simultaneously locking two lasers (Figure 7). The lasers currently set up are the 646 nm Lu^+ cooling laser (red arrow), and the 848 nm state manipulation laser (orange arrow). Each laser is launched from the 99% end of a 99:1 fiber splitter; the light from the 1% end is sent to a wavemeter. The now free-space beams are combined using a dichroic mirror that reflects 646 nm light but allows 848 nm light to pass through. Beam overlap is accomplished by using two steering mirrors to steer the 848 nm beam before it passes through the dichroic. The idea is to align the 646 nm beam such that it is able to pass through the cavity, and then overlap the 848 nm beam on top of the 646 nm beam. This way, the 848 nm beam is automatically aligned once it is overlapped with the 646 nm beam. The overlapped beams are then reflected off of two steering mirrors that steer the beams onto the cavity axis. These two steering mirrors are only adjusted during the initial alignment of the 646 nm beam; they are not touched when overlapping the beams. The overlapped beam is then sent through a polarizing beamsplitter cube, with part of the beam going to the cavity and the other part going to a beam dump. The beam headed to the cavity then passes through a quarter-wave plate before heading into the cavity. After exiting the cavity, the transmitted beam is split into its constituent wavelengths and sent to the experiment. During the process of locking to the cavity (described in Chapter 4 of this thesis), light is reflected off of the cavity mirror when the beam is not in resonance with the cavity. The reflected beam is then sent to another dichroic mirror to be split and then each constituent beam is sent to its own photodetector. The photodetector provides the signal that is used during the PDH locking process.

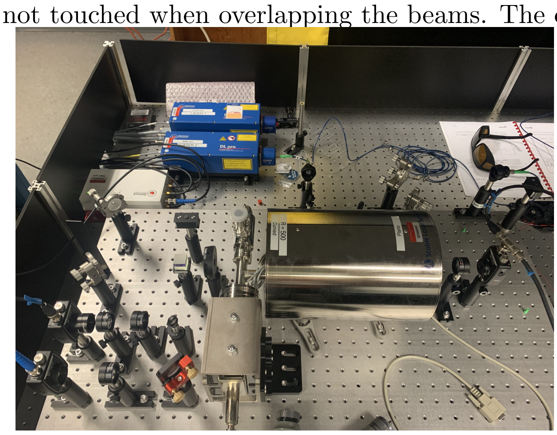

FIG. 8: Cavity with VH and associated optics

5. RESULTS AND CONCLUSIONS

Over the course of the year, we were able to get the cavity and all of the associated optics set up (Figure 8). Unfortunately, during routine operations we found that are pressure in the VH was not optimal during a leak test. We then had to send the VH back to the manufacturer to resolve the issue, so we lost about two months of time to work on the experiment. Recently, we got the VH back and have the cavity under vacuum and in operation again so work can resume. We are currently in the process of locking the 848 nm laser to the cavity, since this will be the hardest wavelength to lock due to the extremely narrow linewidth caused by the high cavity finesse at 848 nm. One of the issues we forsee with locking multiple lasers to the cavity is thermal length changes caused by circulating power inside of the cavity, so we are in the process of developing code to model the cavity length changes. Overall, considerable progress has been made on this project and our potential results seem to be very promising.

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