Determining the beam waist and other parameters in an optical set up to detect solar chameleons

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Abstract

The chameleon field is a hypothetical scalar field that is coupled to matter. Though it has not been detected yet, the chameleon field is a possible dark energy candidate. The KWISP detector is an optical set up designed to maximize sensitivity to detect solar chameleons. In order to maximize the effectiveness of the optical set up, knowledge of the optical parameters of the optical elements is necessary. Assuming the laser can be modeled as a gaussian beam, we determined beam waist to be $3.26 \pm .03$m of a 532nm laser that will be used in the KWISP (kinetic WISP detection) setup as well as the optimal locations for lenses so that the radius of curvature of the laser will be 5cm and 100cm at the Fabry-Perot (FP) optical resonator.

1 Introduction

The lambda cold dark matter (ΛCDM) model is the standard model of cosmology describing the history of our universe. While it is in agreement with current astronomical and astrophysical observations, there is still no explanation for where Λ, the dark energy term, comes from. One possible mechanism is the chameleon mechanism, a light scalar field that is coupled to matter and can drive the accelerated expansion of the universe. The field is coupled to the surrounding matter density, so that the expansion energy increases with lower local matter density. This explains how the universe is expanding at an accelerated rate, since the more it expands, the lower the local matter density of the universe becomes, increasing the expansion energy of the field. [1]

The coupling to matter also renders an effective mass to the field, which is dependent on the local matter density. Because of this, chameleons can be reflected off a dense medium if their effective mass becomes greater than their total energy. This allows them to be detected on earth by measuring the momentum transfer from the chameleon particles to an opto-mechanical force/pressure sensor. This is the goal of the KWISP sensor. [1]

Chameleons can mix with photons in regions with strong magnetic fields, which makes the sun an ideal source of chameleons. By mounting the KWISP detector on the CAST (CERN Axion Solar Telescope) experiment which is searching for Axions created in the sun, the KWISP detector can probe uncharted chameleon parameter space.[1]

In order to detect chameleons, very sensitive equipment is needed. KWISP utilizes a membrane-based opto-mechanical sensor to achieve the desired sensitivities. The system operates by using a FP optical resonator with a membrane placed inside. The membrane will reflect chameleon particles because the chameleon effective mass will become greater than their total energy in the membrane. This reflection causes a displacement in the membrane, and this can be detected optically. By placing the membrane inside the FP resonator at an electric field node, the sensitivity is greatly enhanced, since the finesse of the resonator acts as a gain factor in the sensitivity. By placing the membrane at the node of the FP resonator, it will not disturb the normal modes of the resonator. However, if the membrane experiences a displacement, it will couple the mechanical modes of the membrane to the TEM modes of the cavity, which detunes the mode proper frequencies. This detuning is dependent on the membrane position along the cavity axis, and once the setup has been calibrated with regards to the detuning curve, it can be used to detect mechanical displacements in the membrane, and therefore the force acting on the membrane. [1]

2 Determining the Beam Waist

The beam waist can be determined by measuring the width of the beam at various points along the propagation axis. To measure the width of the beam at a specific point, we measured the power spectrum of the beam using an adjustable slit. By measuring the amount of power that enters through the slit at different slit widths, we can reconstruct the gaussian beam profile at any point along the path of propagation.

2.1 Experiment

Our set up consisted of a FireFly 532nm green laser, an adjustable slit, and a power meter. Additionally, in order to increase the optical path length of the laser before reaching the power meter, we used a filter, which reflects 90 percent of incoming light, as a mirror. In the first leg of the set up, we had our laser pointed at our filter. The laser beam was then reflected at a right angle at the power meter along the second leg of the set up. The slit was placed with a vertical orientation along 10 points in the optical path and centered on the beam. We placed it in 5 locations along the first leg and 5 locations along the second leg. At each location we started with a completely closed slit and opened it in increments of 0.2 mm until it was 4.0 mm wide. The error in all slit widths is 0.05 mm. The power was recorded at each slit width. Our recorded errors were fluctuations in the values that the power meter displayed. The distances from the laser at which we placed the slit are as follows:

Table 1: Distance of slit from laser along beam propagation path [$\pm$.01 cm]

1st leg [cm]	14.25	26.90	39.40	56.60	69.00
2nd leg [cm]	86.25	93.90	106.10	118.80	133.75

2.2 Data Analysis

The adjustable slit we used was not calibrated so that a recorded 0.0 mm width opening corresponded to the completely closed slit. It wasn't until the slit was recorded to be -0.4 mm that we were sure that no light was passing through the slit. We used this measurement as a measure of the background, so to adjust for background light, the power measured at a width of -0.4 mm was subtracted from the rest of the data points in the set, and the point at -0.4 mm was then discarded. After this procedure, our data started at -0.2 mm, and we did not perform any other adjustments to the data because in our fit we added a translational parameter which would account for our slit-width value starting at a negative number. This translational parameter also will not affect the width parameter of the fit, which is what we are interested in.

To find the width of the laser at the various points along the beam propagation path, we fit the data points to the following function:

$$A * Erf(\frac{\sqrt{2} * (x - x_0)}{w})$$

Where Erf is the error function, A is the amplitude, x is the slit width, x_0 accounts for the fact that the slit may not be perfectly centered on the beam and the translational parameter mentioned above, and w is the width of the beam at that point. The error function is used because it is the integral of a gaussian from 0 to x, and it is where the factor of $\sqrt{2}$ comes from inside the error function. However, as we open our slit, because it is centered on the laser, we have the total power of a gaussian from -x to x. To account for this we divided all of our slit width values by 2. Our data was then fit using scipy's non-linear least square function and the width values and errors were recorded. In the fit, we ignored the errors in the slit width. See Figure 1 for examples of fits.

The corresponding values for the beam widths that we recovered from the fits can be found in Tables 2 and 3. They are also plotted in Figure 2

Table 2: Beam Width Values 1st Leg

Distances [cm]	14.25	26.90	39.40	56.60	69.00
Width [mm]	$1.050 \pm .003$	$0.993 \pm .003$	$0.978 \pm .003$	$0.967 \pm .003$	$0.937 \pm .003$

Table 3: Beam Width Values 2nd Leg

Distances [cm]	86.25	93.90	106.10	118.80	133.75
Width [mm]	$1.114 \pm .005$	$1.089 \pm .008$	$1.125 \pm .013$	$1.115 \pm .012$	$0.995 \pm .011$

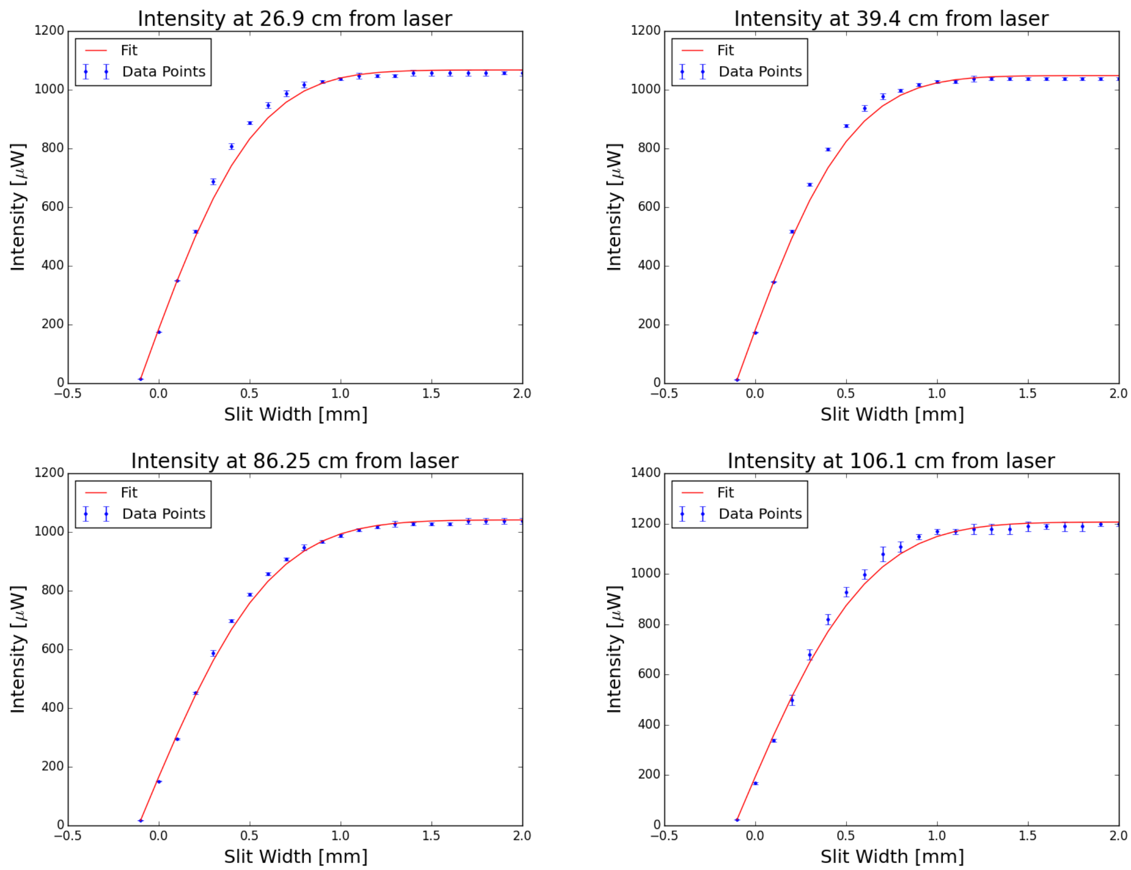

Figure 1: Here the examples of our fits for the error function at various distances from the laser. Notice that the slit width values only reach 2 mm. This is because we had divided all values by 2, as mentioned above.

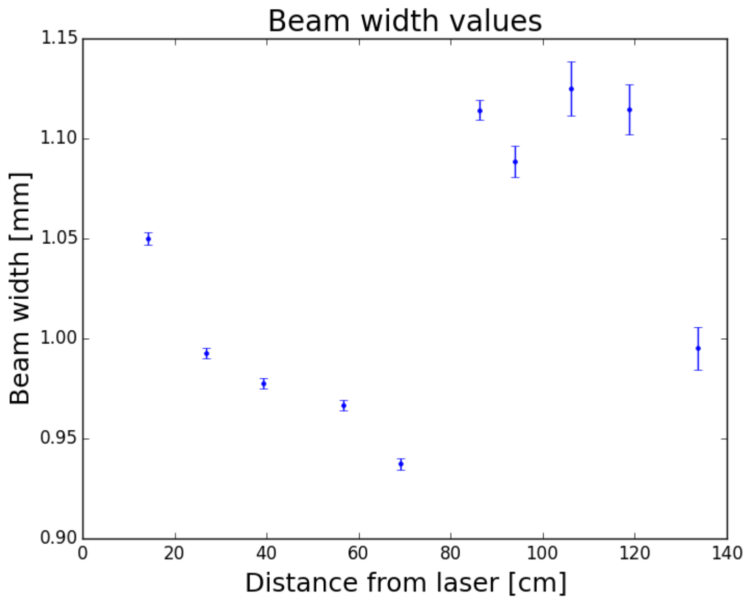

Figure 2: There is a discontinuity between the first five points and the second five points. These groups correspond to points taken in the first leg of the optical set up and the second leg respectively.

From the derived beam width values we see that there is a discontinuity between data points taken in the first leg and the second leg of the set up. Our first thought was that the power stability of the laser may cause this. However, the firefly laser is supposed to reach power stability after 7 minutes, and since our data taking lasted roughly 2 hours, the power stability fluctuation after the laser is turned on should not have affected our results [2]. Another possible cause may be that there was ambient light affecting our power reading, so we added a pinhole in front of the power detector to limit the amount of ambient light entering the power receiver. Again, this did not affect our results so we ruled that explanation out. The last explanation we came up with is that our filter, which we are using as a mirror is not perfectly flat. This would change the radius of curvature and beam waist after the laser was reflected off the mirror. We were unable to verify this hypothesis, so in order to avoid the strange affect causing the data in our second leg to be different, we calculated the beam waist only using the points from the first leg.

To calculate the beam waist, we fit the first five beam width points to the following gaussian beam formula:

$$w(z) = w_0\sqrt{1 + \left(\frac{z-a}{z_r}\right)^2} \tag{1}$$

$$z_r = \frac{\pi w_0^2}{\lambda} \tag{2}$$

Here $w(z)$ is the beam width at some distance, z, along the beam propagation axis, w_0 is the size of the beam waist, a is the distance to the beam waist, z_r is the Rayleigh range, and λ is the wavelength of the laser. Fitting our points with a non-linear least square function we obtained a value of:

$$3.58 \pm .40m$$

This is the distance from the laser to the beam waist. Again we ignored the error in the position of the slit and only accounted for the error in the beam width values in our fit.

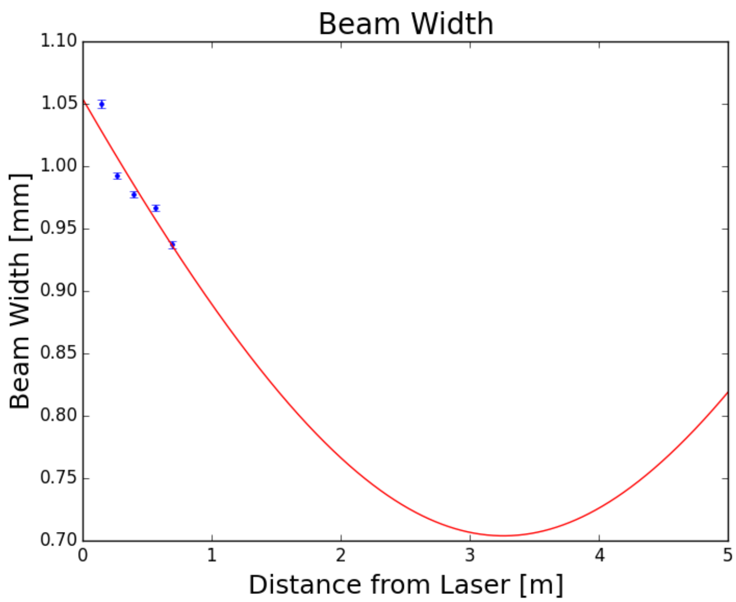

Figure 3: The fit to the first five data points of the 1st leg. The beam waist is located at the minimum of the curve.

3 Analysis with the New Mirror

To avoid any phenomena that our filter was contributing to our data taking, we replaced the filter with an actual mirror. Following the same technique detailed above, the beam profile was measured at 10 different points along the beam propagation path. With the mirror we hoped there would not be a discontinuity between the first leg of our set up and the second. The beam width at the 10 points can be seen in Figure 4. With the new set of data, there was no obvious jump between the first and second leg, confirming our hypothesis that the filter is adding some phenomena that changes the beam profile after it passes through the filter. However, there were two outlier points. When fit, the points taken 47.15 cm from the laser and 94.45 cm from the laser fell more than 5 standard deviations from the fit. After eliminating these two points from our fit, the data was then fit again using a non-linear least square function as shown in Figure 5. Again, only the error in the beam width values were taken into account while fitting. The resulting beam waist is a distance of:

$$3.25 \pm .03m$$

This result has a smaller error due to the use of more points, and it also falls within one standard deviation of our previous result.

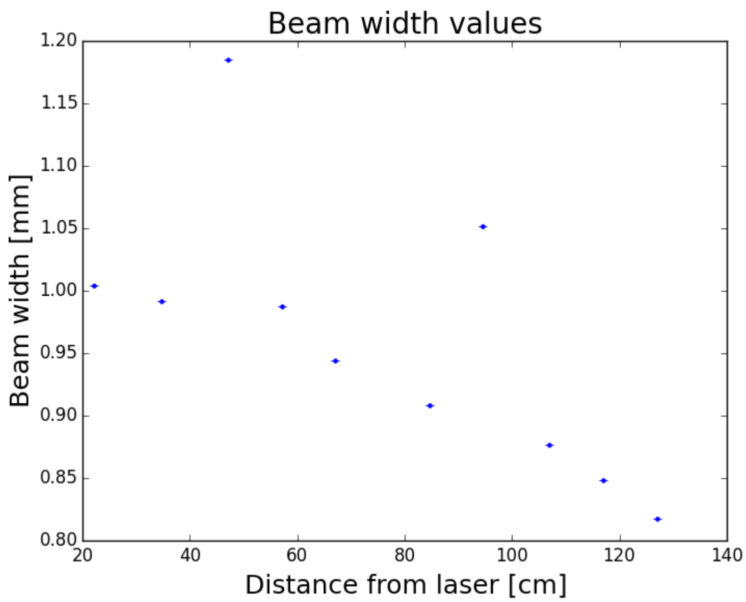

Figure 4: The 10 beam width points calculated while using a mirror instead of a filter as an optical steering mirror. Notice the outlier points (the 3rd and 7th points from the left).

One way we decided to improve our measurement was to increase the optical path length. This is because the beam width should decrease in size before reaching the location of the beam waist and increase in size afterwards. With the data we have, we are only able to capture points where the beam width is decreasing, so by increasing the optical path length we can get more data near the actual beam waist. This was accomplished by using three steering mirrors to propagate the beam around the optical table. Again 10 points were taken, and the beam width was calculated using the same method as above. Our data can be seen in Figure 6. Again there were two outlier points at 197.15 cm and at 294.50 cm which were greater than 5 standard deviations from the fit when the 10 data points were fit. After removing those two points, the remaining 8 points were fit using a non-linear least square fit, and only the error in beam widths was accounted for in the fit. The resulting fit can be seen in Figure 7. With the new fit, we calculated the beam waist to be at a distance of:

$$3.28 \pm .05m$$

Again this result falls within the standard deviation of the previous two results.

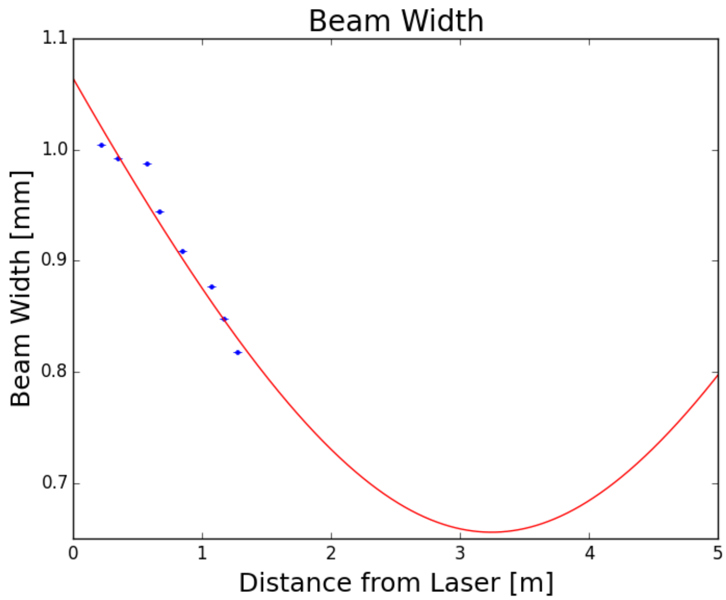

Figure 5: The remaining 8 points were fit to determine the location of the beam waist.

Taking the weighted mean and variance of the three results (using the first 5 points in the optical set up with the filter as a steering mirror, the set up replacing the filter with a mirror, and the longer set up utilizing 3 mirrors to extend the optical path), we achieved a final weighted value of:

$$3.26 \pm .03m$$

4 Lense Locations

4.1 Experiment

The platform from which the optimal lens locations was determined is a software called reZonator. It is a beam propagation simulator that outputs specific parameters according to the specific optical system that is set up. In our case, we had to determine the optimal lens positions along the optical set up shown in Figure 8. The goal was to achieve a 5cm radius of curvature (ROC) and 100cm radius of curvature at the cavity, preferably using only one lens, but using two lenses if necessary.

After simulating multiple configurations, it was found that a 5 cm radius of curvature at the cavity can be achieved with only one convergent lens, but a radius of 100 cm needed a divergent then a convergent lens. A sample reZonator configuration for the two lens set up can be seen in Figure 9

Additionally, we took into consideration the fact that we would not want any lenses in the first segment AB (see Figure 8) because there would be other optical components there.

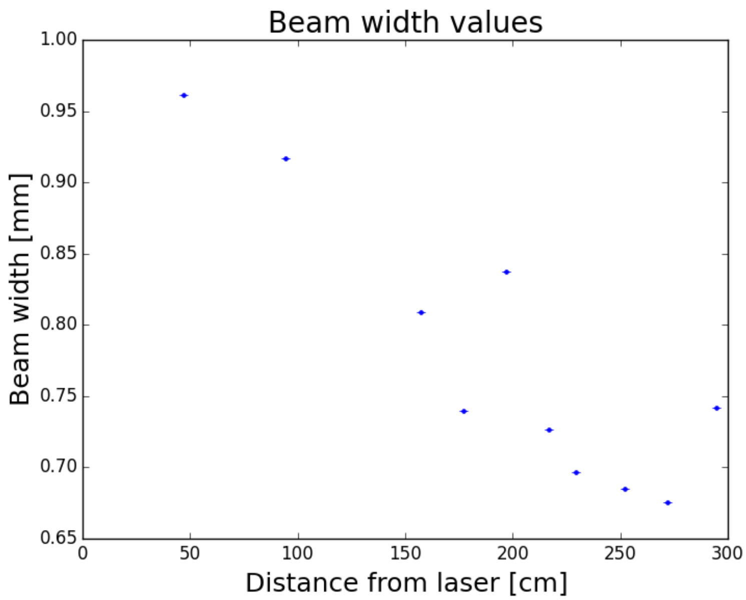

Figure 6: The 10 beam width points that were calculated using a longer optical path. Again there was no discontinuity between the subsequent legs, however the 5th and 10th points show outlier behavior.

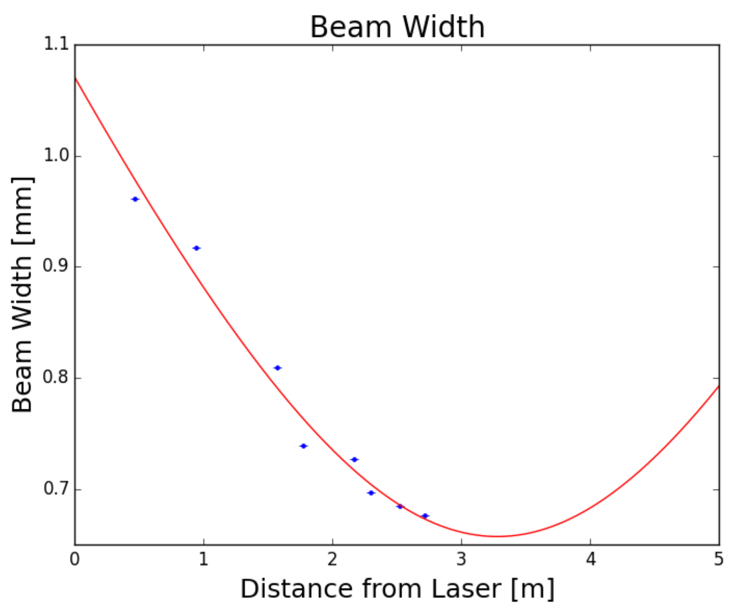

Figure 7: The 8 points were fit. Our points are able to probe the behavior closer to the beam waist, but our optical set up was not long enough to probe the behavior at the beam waist and afterwards when the beam width increases.

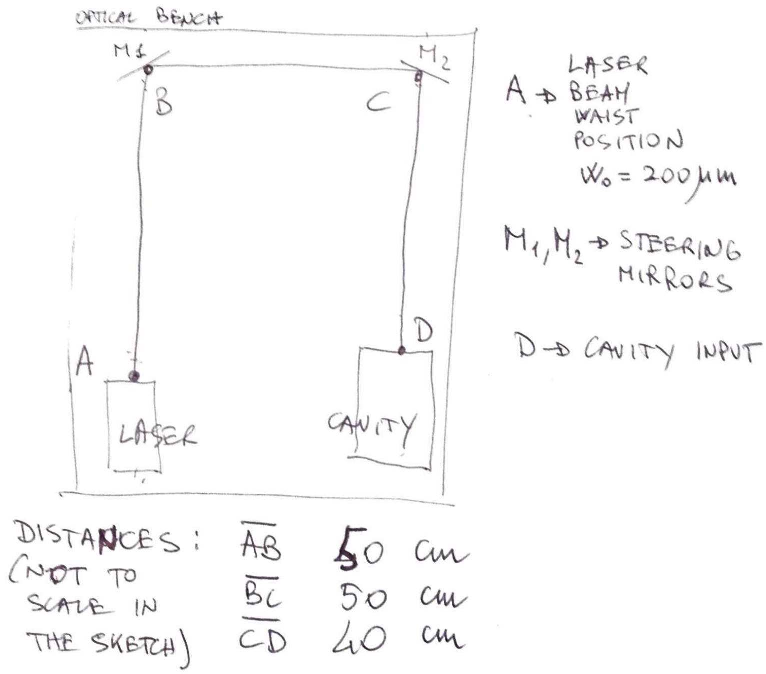

Figure 8: The optical set up we had to recreate on reZonator. The goal was to achieve radii of curvature of the laser beam of 5 cm and 100cm at point D (the FP Cavity) after placing lenses in segments AB, BC, or CD. The one thing that is not accurate with the picture is A is not the position of the beam waist. We had used a beam waist distance of 243 cm from A. We used 243 cm because that was the value we had originally calculated as the beam waist distance before we performed the analysis above to get a value of 326 cm. However, running reZonator with both values did not change the radius of curvature values by more than 1 percent, so our analysis with a distance of 243 cm is still reasonable.

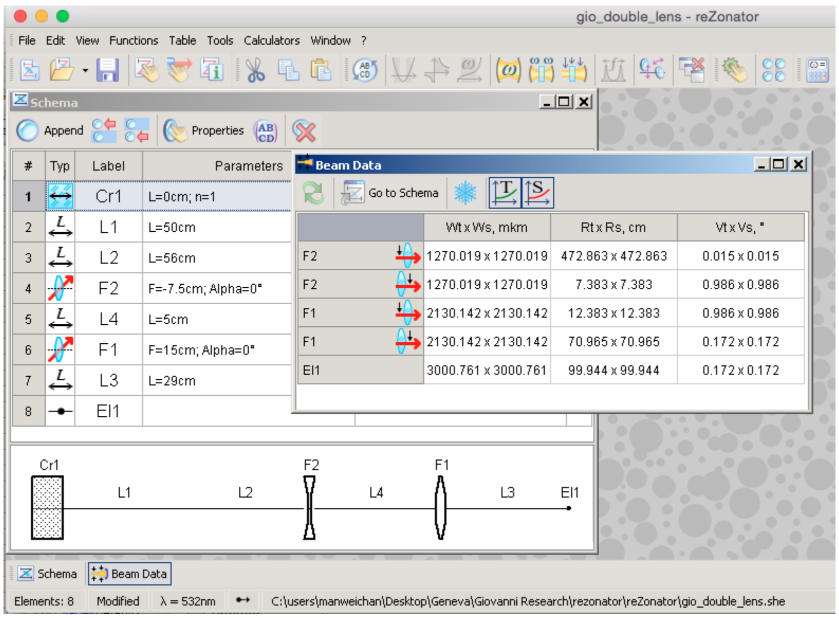

Figure 9: Here is the computer interface for the two lens reZonator set up. We simulated a 532 nm laser, with a beam waist at a distance of 243 cm from the start of the set up, and a waist size of 0.65 mm. In the window in the back you can see the elements we used in the simulation (Cr1, L1, L2, etc.). The important element is El1 which represents the cavity. In the foreground window, the beam parameters are shown at the elements. The important column is Rt x Rs, cm which represents the radius of curvature. As one can see, the radius of curvature at El1 is 99.944 cm, which is close to our desired value of 100 cm.

We also took into account the commonly available lenses produced by ThorLabs, as well as other optical equipment that can be provided by ThorLabs to make the final decision of the most optimal lenses and positions. Our results can be seen in Tables 4 and 5.

Table 4: Optimal set up for 5 cm ROC at Cavity (1 convergent lens)

Focal Length (FL) [cm]	Distance of Lens From Cavity [cm]	ROC at Cavity [cm]
20.0	26.0	5.195
15	20.5	5.039

Table 5: Optimal set up for 100 cm ROC at Cavity (divergent (A) then convergent (B) lenses). FL is the Focal Lengnth, A is the divergent lens, B is the convergent lens, DBL is the distance between the lenses.

FL of A [cm]	FL of B [cm]	DBL [cm]	Distance: 2nd Lens to Cavity [cm]	ROC at Cavity [cm]
-10.0	20.0	5.0	44.0	100.759
-7.5	20.0	5.0	68.0	100.463
-7.5	15.0	5.0	29.0	99.944

5 To Do

To fully understand the behavior of the beam, we can increase the optical path length of our set up so that we can take data points after the beam waist to confirm the location of the beam waist. We also have to re run the reZonator simulator with the distance of 3.26 m to the beam waist instead of 2.43 m. Once the simulations have been run again, we can then measure the radius of curvature at different points along the optical set up and see if the parameters match the ones output by reZonator. This is especially important once the lenses are placed in the set up.

References

[1] Baum, S. et al. Detecting solar chameleons through radiation pressure, arXiv:1409.3852v1 [astro-ph.IM] 12 Sep 2014.

[2] FireFly Green Laser Data Sheet, Global Laser, http://docs-europe.electrocomponents.com/webdocs/0966/0900766b80966e28.pdf.