Developing a Dipole Trap Laser for the Purpose of Cold and Ultra-Cold Molecule Production

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by
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Abstract

This thesis discusses the development of a laser to optically trap ultra-cold atoms and molecules. A strong laser can be used create a dipole trap, offering many advantages over other trapping methods. With the goal of creating molecules molecules via photo-association or the Feshbach resonances and subsequently trapping them, a defunct 1064nm Nd:YAG laser has been extensively repaired and refurbished. This laser is capable of outputting more than 5 Watts of power using a single mode beam characterized with a Gaussian profile. The photo-association method was also tested and a PA resonance of 12,569.49 cm^{-1} was successfully tested for the production of ^{87}Rb diamers.

1 Introduction

1.1 Motivations and applications

The creation and trapping of ultra-cooled molecules is pertinent to a wide number of research areas in physics and chemistry. Yet unobserved phenomena, such as the quantum behavior of a dipole gas and the different natures of chemical reactions with fermions and bosons at low temperatures, command a great deal of curiosity. Also, ultra-cold molecules possess a very small deBroglie wavelength. This would allow for very high certainty in cold matter spectroscopy measurements. Beyond that a degenerate Fermi gas could assist with a subtler probing of matter-wave phenomena. [1]

1.2 Methods of cold molecule production

It is not feasible to directly cool molecules to the nanoKelvin regime. Atoms can be made cold in a magneto-optical trap (figure 1), or MOT, through Doppler cooling. Atoms in this trap can reach temperatures below 100 miroKelvin and move with mean velocities between 1 cm/s and 1 mm/s. Unfortunately this approach is exclusive to atoms. Molecules cannot even be caught in the MOT. It is feasible to encourage two already-cold atoms to bond. At present this is accomplished in one of two ways: photo-association or Feshbach resonance.

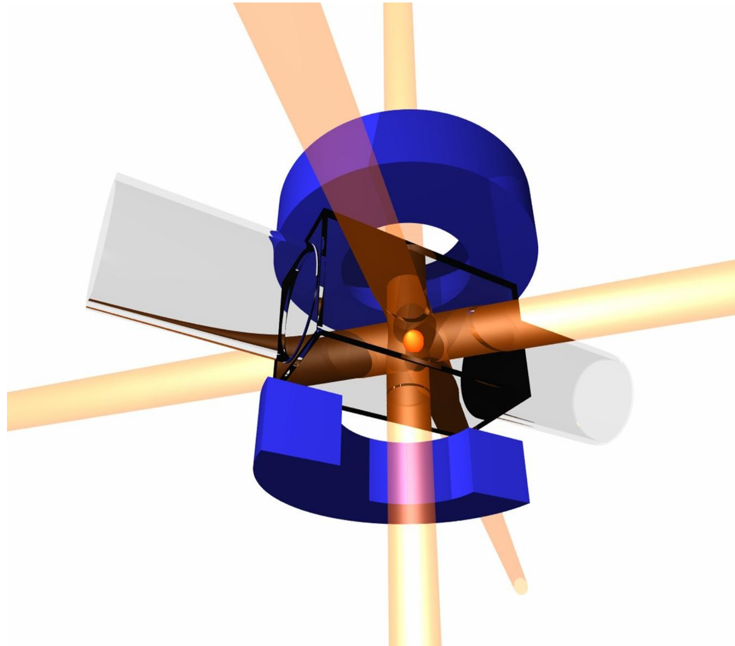

Fig. 1: The basic set up of a MOT. The orange beams of laser light slow down atoms, producing a greater effect the further atoms go towards the edges of the cell thanks go a magnetic field generated by the blue current-carrying coils.

1.2 Photo-association

Photo-association (PA) was first reliably demonstrated by Miller, Cline, and Heinzen[2] in 1993 with ^{85}Rb. Miller *et al.* pointed a tunable laser at their super-cooled atom trap and noted the creation of molecules as they scanned frequency space. This research has continued[3],[4] in recent years with different molecules. PA frequencies exists for a variety of atomic pairs and in some case care must be taken to not activate a PA frequency, such as when setting up a dipole laser trap.

Photo-association takes place as two atoms closely approach one another with a small impact parameter. Occasionally when they are near enough a photon can excite one of the atoms. The combined atoms inhabit an excited molecular bound state. As the atoms continue to approach one another they will decay into another molecular potential with a negative binding energy, as shown in figure 2. The pair will remain bonded until excited with enough energy to break apart. There are several resonant frequencies at which photo-association is possible due to the wealth of molecular states available. Calculating these resonances can be tedious but one can also scan across a multitude of laser frequencies ω_L to find the possible PA frequencies. For each different tuning there will be a corresponding spike in molecule production. Unfortunately, photo-association does not provide a perfect sample of molecules as the resulting molecules, even after initial de-excitation, can be in any of a number of possible quantum states shown by the lines in figure 2.

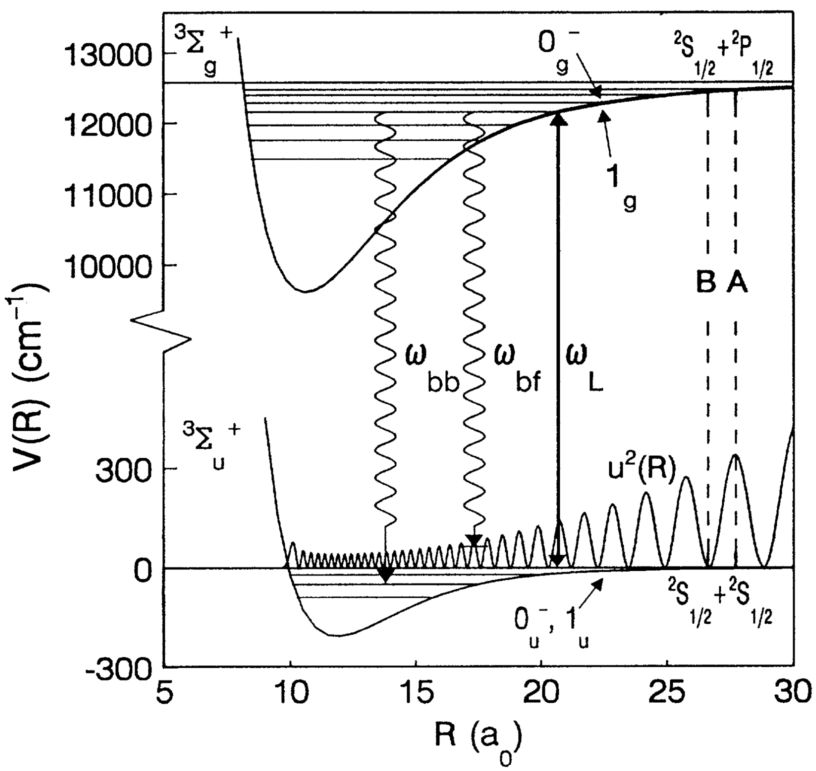

Fig. 2: This graph shows the energy levels for a PA resonance of 85-Rb. The potential (y-axis) is graphed against the inter-nuclear separation. The atom will not readily and spontaneously de-excite to the lower energy levels unless it is excited above its ground state to the raised potential. Figure taken from reference 3.

In November, 2011 the MOT apparatus was prepared to cool and trap atoms to be turned into molecules. A titanium-sapphire laser scanned near a frequency of 12,569 cm^{-1}, noted by Jelassi *et al.*[5] as a good place to start looking for PA frequencies of ^{87}Rb. Molecule production was surmised from a sudden significant drop in the trapped atom count. Checking again with a more detailed scan gave a rough by decisive graph of atom loss near the PA frequency. As shown in figure 3, the line fell somewhere between 12,569.48 and 12,659.50 cm^{-1}.

In the data from J.D. Miller *et al.* it is apparent that there is an expected PA frequency right near 12,569.49 cm^{-1}. This supports the interpretation that figure 3 depicts atom trap loss due to photo-association. The corresponding wavelength in nanometers is about 796 nm. The wavelength of any effective dipole trap should be far from any photo-association frequency to avoid unintended side effects. This is doubly important for the Feshbach resonance, or it would mix the states of the newly created molecules. Fortunately the dipole trap laser operates at 1064nm, or 9398 cm^{-1}.

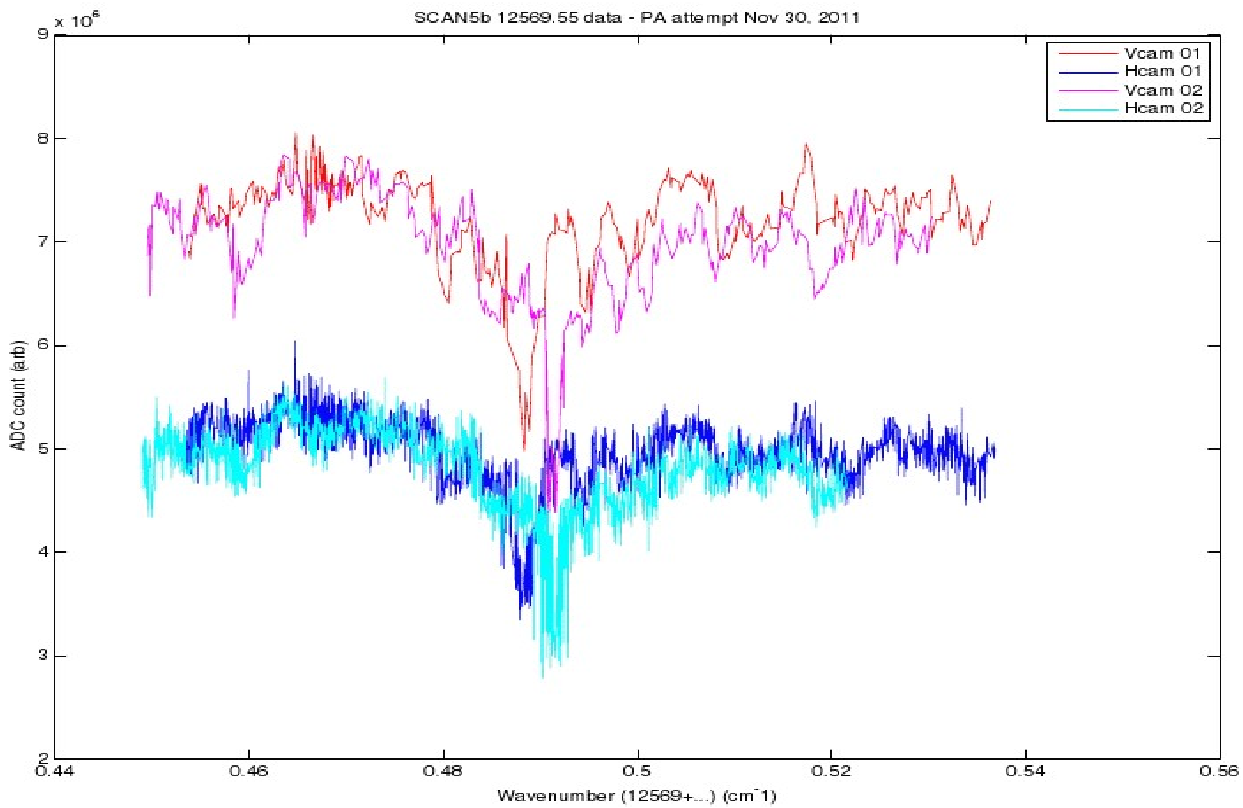

Fig. 3: Plots from two camera angles for two different data runs. As one can estimate just from this graph, we were able to get between 30% to 50% atom trap loss, clearly indicating the formation of molecules. Top are vertical camera counts and bottom are horizontal camera counts. Source: analysis and plotting by Megan Ivory.

1.3 Observing cold atoms and molecule production

Atoms in cold matter spectroscopy can be imaged by observing the scattering of a low intensity laser. If the laser frequency is nearly resonant with the atoms' energy levels some light will be absorbed and re-emitted. The amount of light being scattered can be graphed to give an impression of the atomic concentration (figure 4). More atoms will scatter more light, which is picked up by cameras stationed outside the MOT. In this way the concentration in a vacuum cell can be imaged in three dimensions with two cameras and a single laser. Molecules have different energy levels, and cannot be imaged by the same laser. Further, the complex nature of excitation levels in molecules make it all but impossible.

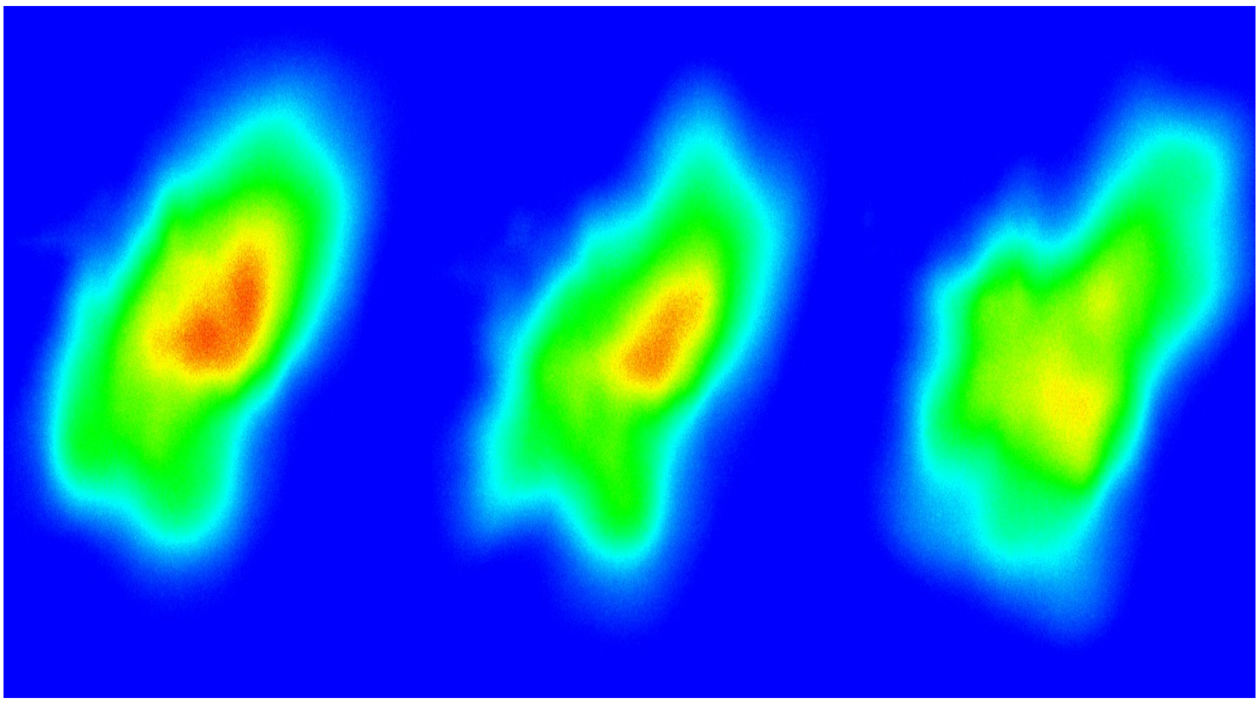

Fig. 4: Three separate pictures of the same group of atoms in a MOT at different stages of PA testing. From left to right note most to least concentration. Source: screen capture 11/30/2011.

Molecules can instead be imaged by using negative space. With all things held equal, a sudden dip in the atom count of a cell undergoing photo-association or Feshbach spectroscopy would indicate that molecules have been produced, lowering the atom count. In this way one can surmise an approximate (and relative) concentration of molecular states when observing a sample of super-cooled atoms. This method was used by Miller *et. al*[2] in their study and to infer the molecules being created when the data was taken for figure 3.

1.4 Feshbach Resonance

The Feshbach resonances manifest as discontinuities in the scattering length between two atoms as a function of a strong, semi-static (slowly changing) magnetic field. The discontinuities can run infinitely negative or infinitely positive depending on the atoms involved and the strength of the magnetic field. These interactions are evidenced best when the atoms are all very close together and moving very slowly. Such restrictions are why something very confining like a dipole trap is ideal for exploiting these resonances.

The approximation for the scattering length near a Feshbach resonance is:[6]

$$a_{sc} = a_{bg}\left(1 - \frac{\gamma}{B - B_0}\right) \tag{1}$$

This equation approximates the scattering length for two atoms with a background scattering rate a_{bg} at a divergent Feshbach resonance with magnetic field strength B_0 and a resonance linewidth of γ, all constant. 'B' is the extant magnetic field experienced by the particle. It is apparent (figure 5) that as the magnetic field approaches B_0 that the scattering length will approach a discontinuity. There can be an infinite well, an infinite hill, or a divergence, as shown. . In practice these divergences can increase scattering length, decrease it, or change depending on which direction the magnetic field is (slowly) changing from. If the scattering length is sufficiently decreased the atoms will experience a net attractive force and eventually bond.

Feshbach spectroscopy is much more efficient than Photo-association. Molecules formed at through Feshbach resonance spectroscopy end up all inhabiting the same molecular bound state, reducing the potential noise in following experiments. PA also runs the risk of re-exciting molecules into different states while a molecule produced at one of these magnetic resonances no longer experiences the effective force that created them. Feshbach spectroscopy has already been used to produce hetero-nuclear covalent bound states of rubidium and potassium.[7],[8].

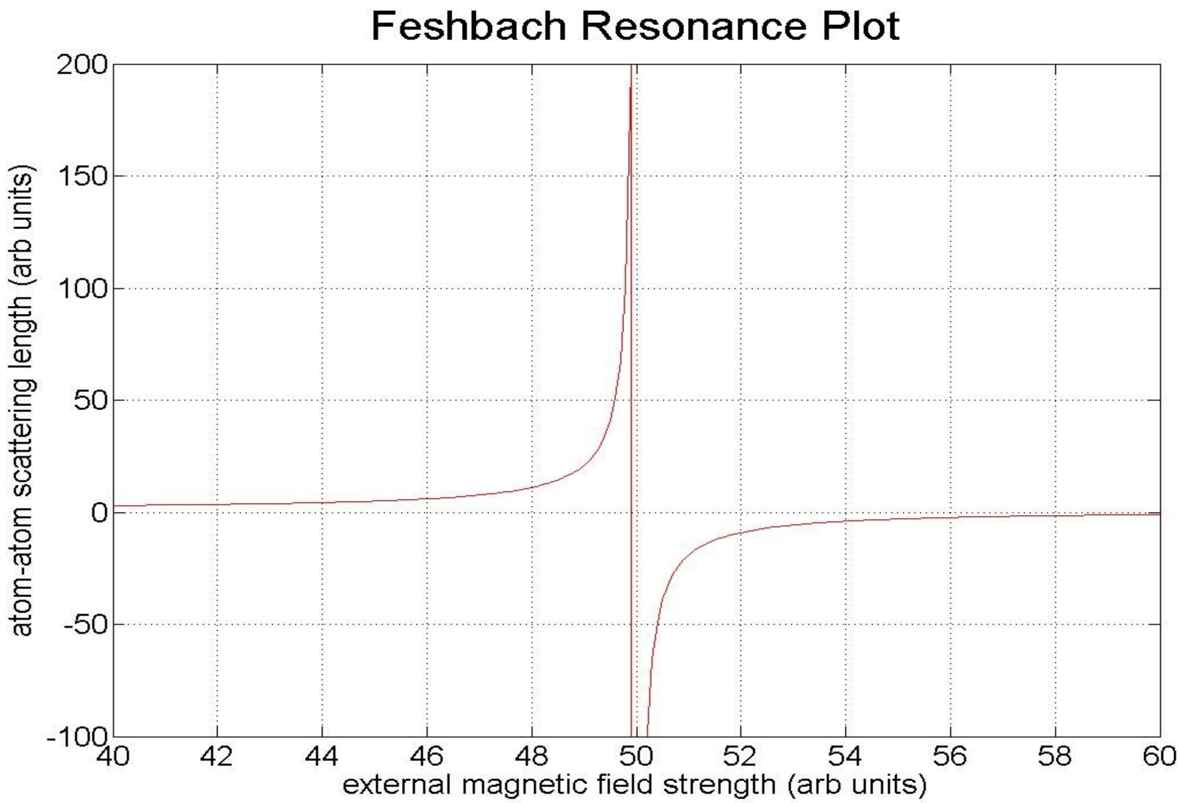

Fig. 5: Sample plot of scattering length versus magnetic field, arbitrary units, using Equation 1. As the external field strength is lowered from a value greater than 50 the atoms will be pushed together until they are forced into a bound state. Using equation 1 the parameters for this plot are $a_{bg} = 1$, $B_0 = 50$, and $\gamma \sim 10$.

2 Optical Dipole traps

In a semi-classical approximation, atoms and molecules have orbitals of electrons arranged in negatively charged shells. These shells usually orient themselves about a nucleus of equal charge in such a manner that the net electric field around an atom is zero. When a static external electric field is applied a shell will orient itself such that atom or molecule is now polarized in parallel with the electric field. Relative any electric field the atom will experience a potential.

The oscillating electric field of a polarized laser can both polarize a particle and subject it to a potential. This potential can be a hill or a well depending on the difference between the frequency of the light and a frequency inherent to the particles. By focusing such a laser it is possible to create a potential trap for most any polarizable particle. The potential equation for such a set-up is:

The potential energy formula for an atomic dipole trap is given by:

$$U_{\text{dip}}(\vec{r}) = \frac{\hbar\Gamma}{8}\frac{\Gamma}{\delta}\frac{I(\vec{r})}{I_{\text{sat}}} \tag{2}$$

This is the equation for the potential energy of a dipole in an oscillating electric field of intensity I(r) in the approximation of a two-level atom. Γ is a photon scattering rate related to the lifetime of the excited state. High amounts of scattering mean large losses of the trapped particles. is the frequency term of this primary atomic or molecular transition. δ, in radians per second, is the detuning between the resonant transition frequency ω_0 and the frequency of the laser light. If the laser is 'red-detuned', $\delta<0$, and the potential equation describes a well. This means that for a red-detuned laser of high intensity the particles will all be pulled in towards the center of the potential. Rubidium and potassium have resonant frequencies near 800 nm. Instinctively it looks to be best to pick a laser with a very small detuning to vastly increase the trap depth. Unfortunately in that limit another process becomes dominant. When the trapping laser is close to an atomic resonance photons will be scattered in amounts increasing with $1/\delta^2$, heating the atoms. It is preferable to look for a high-power laser with a large detuning.

3 The dipole trap laser

The Spectra Physics Model 3800 laser (figure 6) is a very powerful laser system. It is designed to emit a 10 Watt beam of 1064nm light. The laser is powered by a krypton arc lamp which pumps a Neodymium-doped Ytterbium-Aluminum-Garnet (Nd:YAG) crystal rod to emit light at the preferred frequency. The lamp itself is started from a series of internal capacitors which all must charge up fully before lamp ignition is possible. Once operable the laser is close to ideal for dipole trapping rubidium and potassium atoms and their associated diamers.

Fig. 6: The laser cavity. The lamp and rod are encased in the central box.

3.1 Installation

The laser was received on loan from Professor Charles Sukenik at Old Dominion University in late Summer 2011. Professor Sukenik had been unable to get the laser to work and offered to lend it in exchange or repairs. The power supply is capable of running in two configurations. The simpler configuration used 3-phase electrical service rated at 208V AC and 30A. Though powered, the laser required much time and effort before it was operational

3.1.1 Water service

The laser is serviced by two separate water cooling systems. An isolated supply o distilled water is used for the internal water cooling. It is used because distilled water conducts electricity poorly and will not draw current from the . Deionized water is not ideal because of its corrosive properties. There is still a de-ionizing filter on the rear of the power supply to deal with unwanted particulate. The original filter had not been replaced in some years and a new part was tracked down to be installed in its place.

This internal water supply container can only hold 7 gallons of distilled water. This supply draws heat from the lamp chamber raising its temperature. The heat is not dissipated quickly enough on its own to provide efficient cooling and the lamp could overheat, causing lamp failure. A secondary set of water pipes uses water or coolant from an external source, such as a city water supply or a dedicated chiller, to cool the internal water. This supply needs to have a low enough temperature and a high enough flow rate to draw away more heat than the lamp puts out. This precarious balance was difficult to maintain during the initial stages of laser installation and operation. In current operations it is still a limiting factor on laser power due to the constraint placed on laser lamp current.

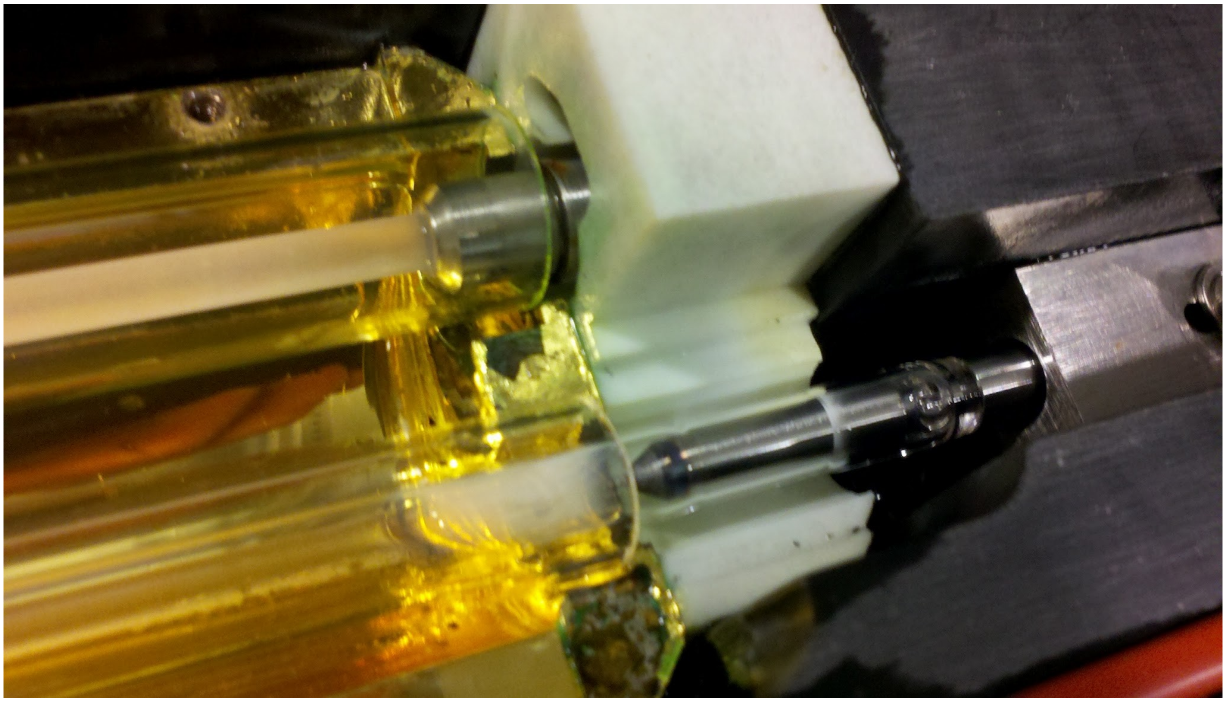

Fig. 7: A close look at one end of the lamp chamber. Note the discoloration where the gold plating has been worn away. The greenish tint of the white block is discoloration from the previous algae infestation.

3.1.2 Cleaning

Inspection immediately revealed an infestation of algae within the lamp chamber that left every square centimeter contaminated in some amount. This alone could prohibit lasing as the presence of algae will reduce the reflectivity of the chamber surface. The algae was cleared away with a prepared solution of hydrochloric acid. This was applied delicately with cotton balls and q-tips. Afflicted spots were then rinsed with distilled water and dried with lens tissue. Algae was discovered and cleaned from a few more locations over the course of installation, but there has been no noted increase since preliminary laser operation (non-lasing) was in full swing.

3.2 Pre-lasing procedure and problems

Several issues prevented lasing once the power supply was operating properly. The severity of these ranges from minor complications to critical obstacles. Some of the most prominent predicaments and their eventual solutions are listed here:

3.2.1 Lamp overheating

Upon initial operation the accompanying lamps would frequently heat up and cause the laser system to shut itself off with the "Water Temp" LED lit up.The lamps supplied with the laser were not rated to operate at 25 amps. Coupled with some other issues this led to the internal water supply overheating before the whole system could fully warm up during test runs. New lamps were purchased which reduced, but did not eliminate, the overheating issues.

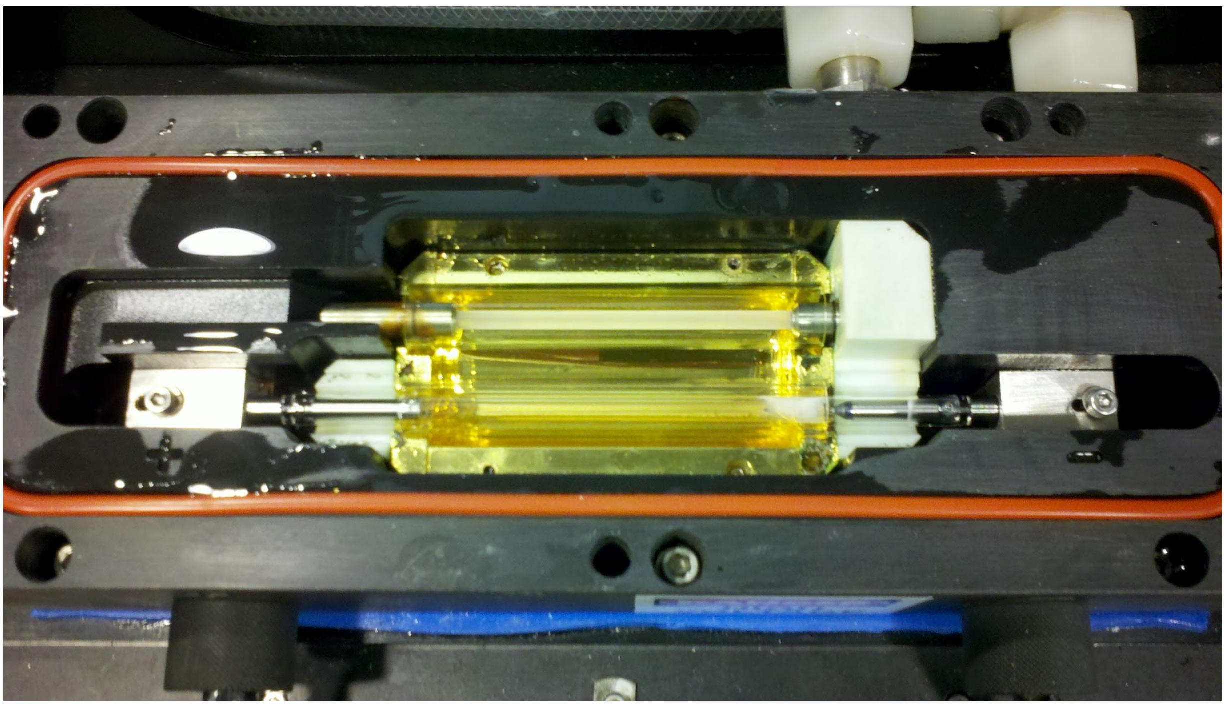

Fig. 8: The interior of the lamp chamber. The discoloration on the right side of the lamp (bottom) occurs in most lamps. With the broken lamps the discoloration was so severe that the glass was scorched due to increasing amounts of heat being absorbed.

3.2.2 Water cooling failures

The water cooling continue to fail, if less often, and more solutions were explored. A second water filter referenced in the laser's manual was cleaned out. This small filter caught particles before they entered the internal water pump. The few tiny pieces of broken glass and other particulate found were not sufficient to explain the low water flow rate. Eventually a similar filter, not referenced in the manual, was found tucked behind some piping inside the supply. This filter was coated in algae and in dire need of cleaning. With these two fixed the internal water loop should be free of flow issues.

The external cooling supply provided more difficulties. The temperature of this water is generally just below room temperature. This is not nearly ideal for cooling down the internal water supply, motivating the usage of a dedicated water chiller. That experiment was brief and unfruitful. The laser put out more heat than the chiller could remove and the chiller would quickly fail due to high water temperature. The laser's internal water circulation failed soon after if the lamp was not immediately shut off.

Originally the external water supply from the building ran through a medium-sized particle filter. With the failure of the chiller it was decided to attempt using the building water without the filter. There were no specific constraints set on the content of the external coolant aside from its temperature, differential pressure, and flow rate. The filter was not a necessary precaution and turned out to reduce the flow rate significantly. Now the laser power supply was able to run at a stable temperature for over an hour in a low power setting without shutting down. When the current of the lamp was increased to the suggested minimum operating current of 25 amps the laser would still occasionally turn itself off. Continuous operation was eventually made possible after removing the power supply's side panels and blowing air around the internal water supply tank with an external fan. Recently the external tubing was replaced with a wider hose to increase flow and possibly alleviate the cooling issue even further.

3.2.3 Other fixes and replacements

Several other parts of the laser had to be replaced in part or entirely:

- The ammeter on the front of the supply was getting stuck giving incorrect current values. This was circumvented with an external device until a new ammeter dial was installed.

- There are two glass tubes inside the reflection chamber. One protects the lamp and one protects the YAG crystal rod. This 'rod flow tube' was fractured upon the laser's arrival. During one of the early overheating episodes the tube was cracked and later broke.
- The laser comes with beam tubes to ensure stable operation in environments with dust or other floating particles. An air pump was set up to pressurize the tubes when they were installed to prevent anything from interfering with the beam path.
- Various pieces of ancillary equipment related to the power service or the external cooling were defective and replaced for safety reasons.

3.2.4 Alignment

The laser was aligned by retroflecting a He-Ne laser beam through the front opening of the laser head. Once the initial alignment procedure was done the laser was aligned using the visible light leaving the lamp chamber. Lasing was achieved in February 2012 during this alignment phase. Various tweaks followed to optimize the beam power. Twice the entire process had to be restarted due to unforeseen complications. Eventually the beam tubes were installed and an aperture was put in place to reduce beam spread and noise.

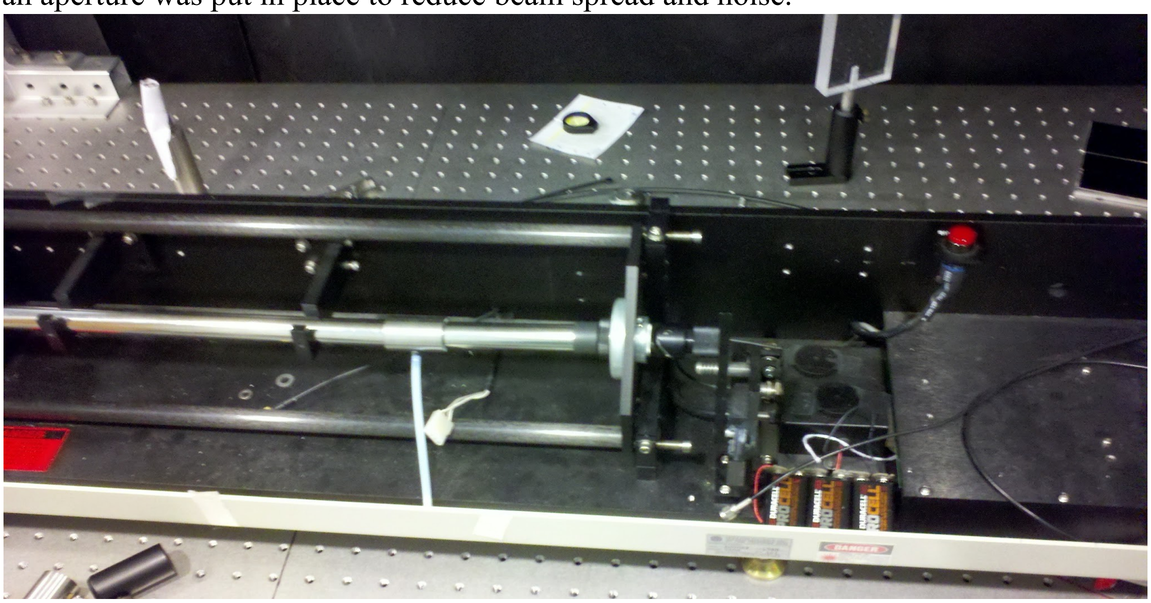

Fig. 9: The output coupler after the beam tubes have been put in place. The red button is the emergency shutter button (another switch exists on the front power supply panel).

3.3 Efficiency and beam integrity

Once capable of stable operation the beam needed to be checked for regularity. Initial checks on the beam polarization and frequency modes yielded positive results. The beam is vertically polarized and emits 1064nm light. This is of particular importance there are PA frequencies close to 1064nm for the relevant particles we are testing. The beam is also fairly stable and not subject to significant noise or any overt signals causing intensity fluctuations.

3.4 Spatial mode analysis

There are various aperture sizes available to install in the laser cavity. These range from 1.5 mm to 0.7 mm in diameter. A smaller aperture is associated with a better beam profile but at lower power. Laser power can also be regulated by lamp current, which itself is regulated by cooling capacity, as previously discussed. Initially the 1.0mm aperture was used due to stable output and good power. When the beam's profile was spread out with a lens (figure 10), the result shows a beam concentrated near its center with a roughly exponential drop-off near its edges. To be certain of the right profile shape a more detailed test was necessary.

Fig. 10: Image taken using the above set-up. The lens spreads out the beam to make internal structure more visible. Even after multiple reflections the beam is powerful enough to saturate the camera.

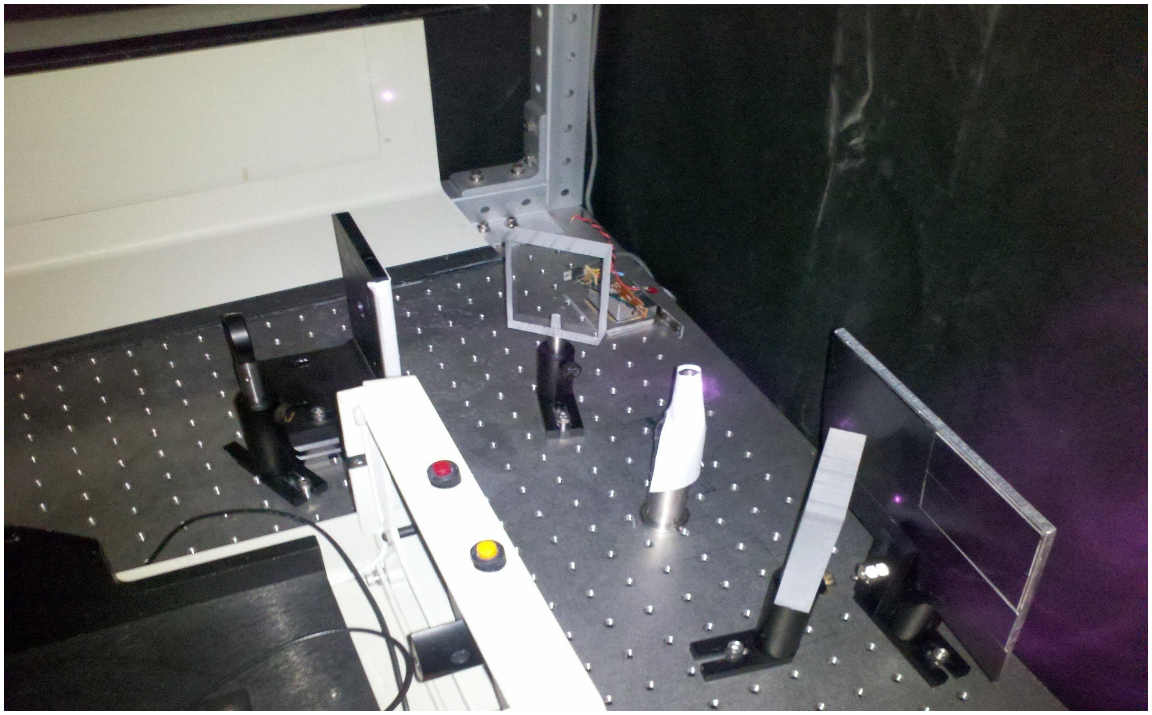

Fig. 11: Simple optical set-up to obtain information on the beam. The two plexiglass plates reflect the laser through a lens on the left.

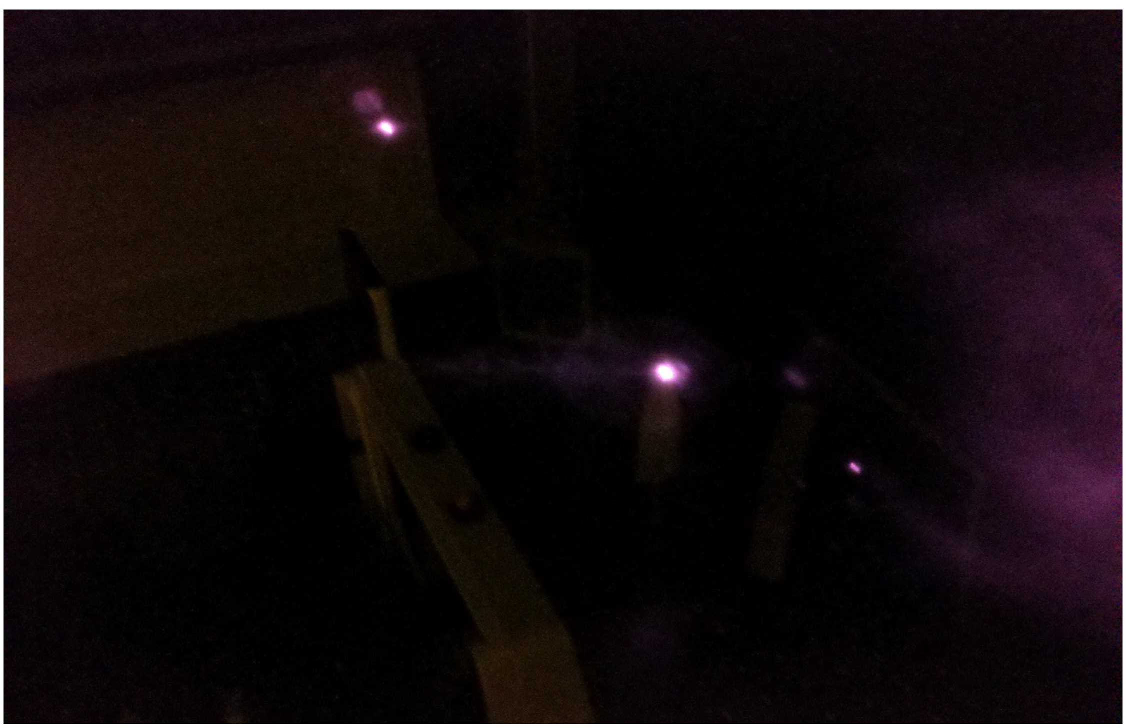

Fig. 12: The same picture as above, but without a flash. The spots where the laser light is blocked or directed to are much more easy to see.

Initial analysis gave more positive results. In figure 14 the beam profile is compared with the data expected from a flat top intensity distribution for a beam of equal power and area of incidence. This data was taken by using a razor blade attached to a horizontal translation stage and slowly moving it across the beam path. The distances were marked and the power observed as razor blade blocked off more and more of the beam path. This measurement is not perfect due to the geometry of a laser beam's incident surface area (a circle) but would pick out discrepancies of a more severe nature.

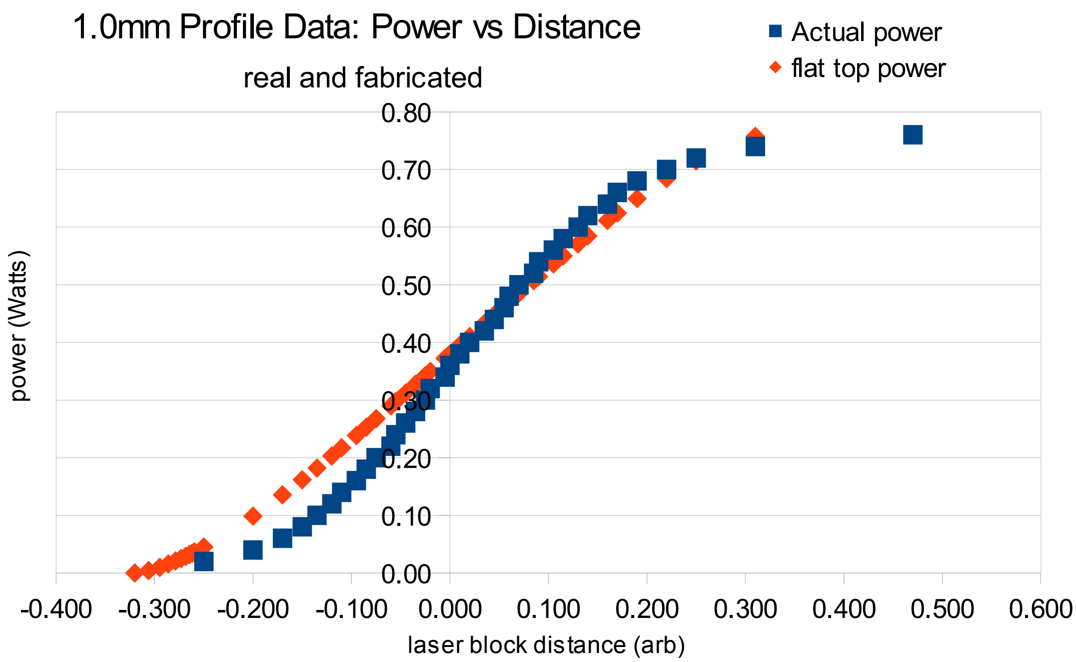

Fig. 13: The change in power as a vertical block is moved across the beam shows promise. Potentially integration would yield a fully Gaussian beam profile.

The beam profile was then directly taken using a pinhole over the power meter on top of the horizontal translation stage. The pinhole has a constant area and therefore can accurately measure the intensity of the light at any given point for comparison with any other point. This revealed that the beam was not, in fact, purely Gaussian in nature (figures 15 and 16). The incident beam had two distinct peaks. Each peak might have been Gaussian but it was difficult to isolate either. Eventually the larger peak was isolated but the resulting beam was much weaker.

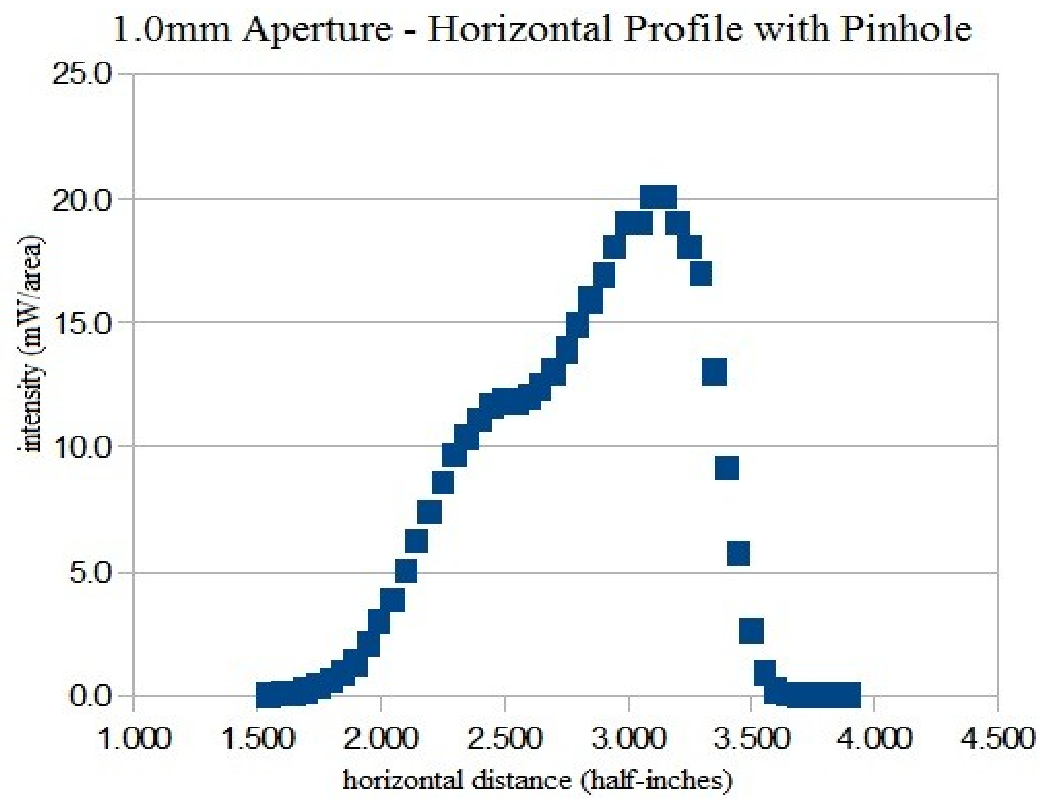

Fig. 14: Horizontal beam distribution using the pinhole. Note the two separate peaks.

With a much tweaking the above discrepancy could be almost completely resolved. The mirror and aperture positions could be changed to remove either peak but the result was a vastly decreased output power. The intensity distribution along the vertical axis was also unknown. The pinhole test was refined to aid in fully describing the laser beam's profile.

The power meter with pinhole and put onto a translation stage and readings from the meter were compared with horizontal displacement of the translation stage. A voltage divider with a linear potentiometer attached to the horizontal translation stage could take quick readings of the x-coordinate measured as a voltage. The y-axis was measured manually with a vertical translation stage placed atop the horizontal translation stage. The X coordinate and the pinhole power were measured with an oscilloscope. A graph was taken at each of twenty to thirty chosen y-coordinates. Each graph was given an associated y-coordinate and these were combined to give a plot in two dimensions of the laser's intensity profile (figure 15). The horizontal stage was difficult to use at first due to the heavy weight upon it and this maybe have contributed to a small discrepancy in the data below. However this does not affect the overall result.

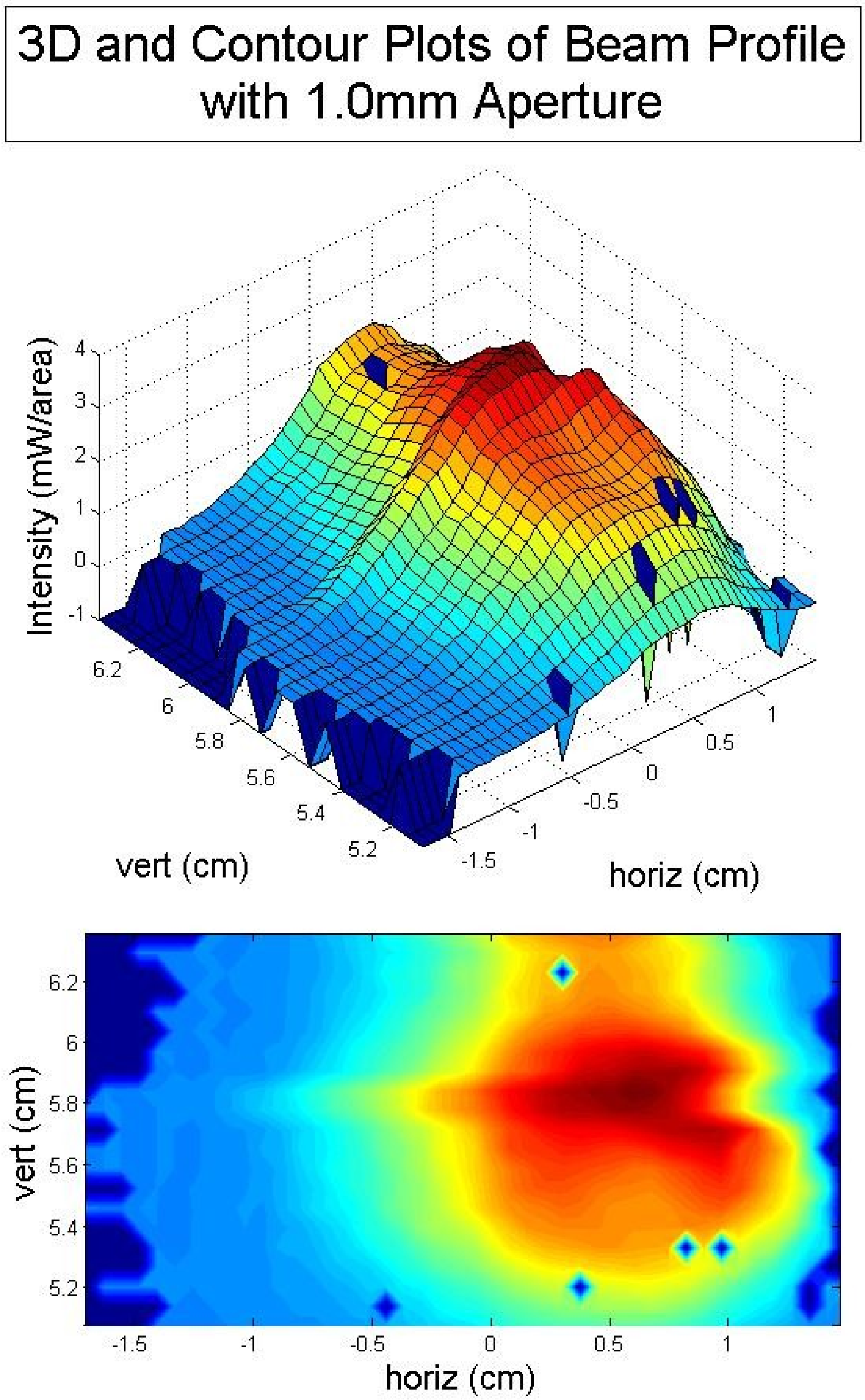

Fig. 15: The beam with the 10mm aperture was obviously not uniform in either dimension. The skewed data points near y=5.8cm may be an artifact of the data capturing, not of the laser itself.

The plausibility of using the 1.0mm aperture was ruled out. In its place the 0.9mm aperture was tried instead. The results were much improved, as figure 16 shows.

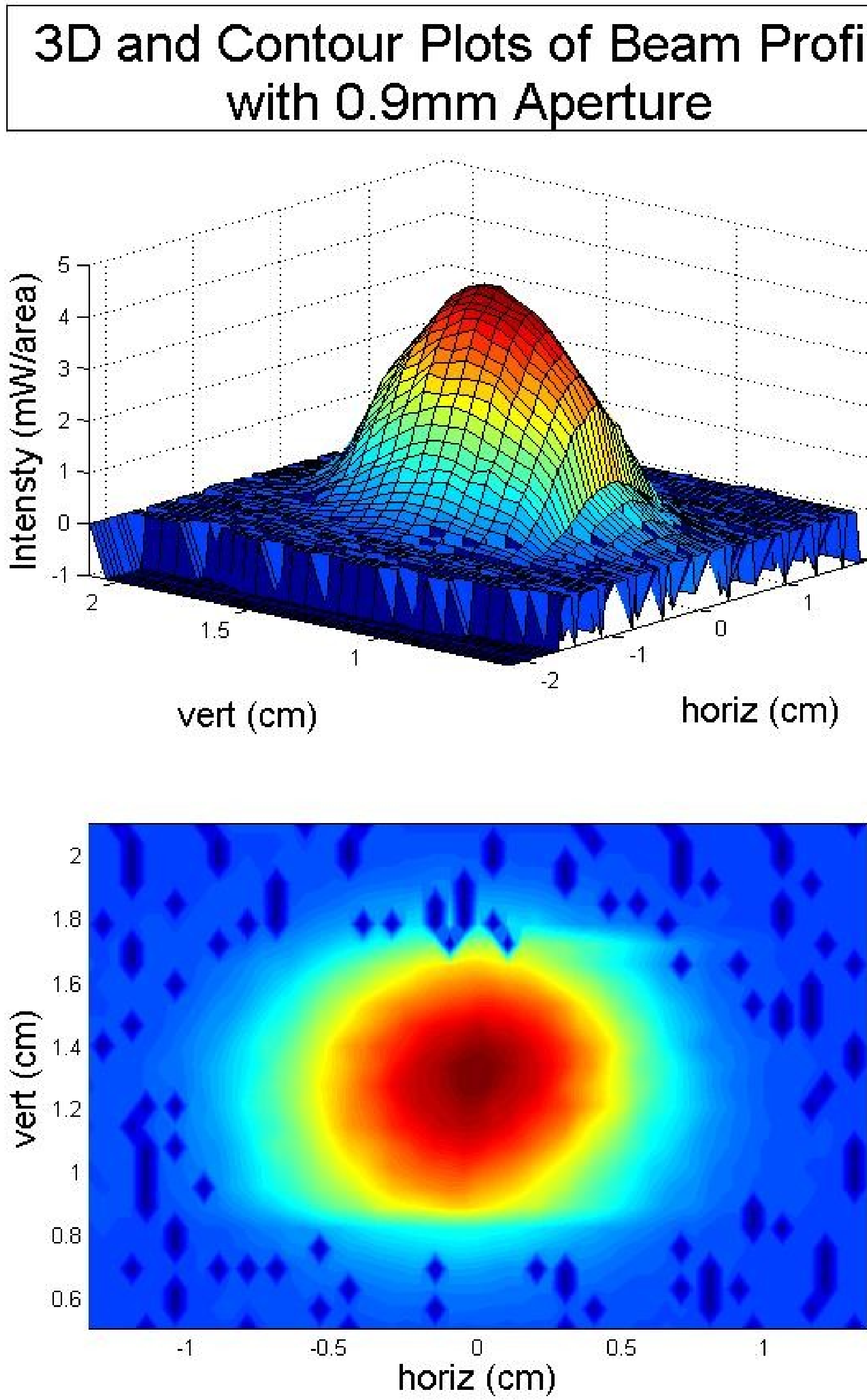

Fig. 16: The beam profile with the 0.9mm aperture installed in the lasing cavity.

For the sake of clarity it is important to note that there were missing values in the data sets graphed above. The nature of the data capture method precluded taking data at regular intervals along the horizontal axis. The oscilloscope could not provide sets of discrete points to accompany each graph and instead the data points were inferred from the graphs using the third party software Engauge[9]. The python script that amalgamated the data contained a smoothing algorithm to increase clarity but some horizontal values were not shared across all sets. The missing points were given values of -1 so they can be easily discerned from actual data when graphed.

4 Outlook

Very few tests remain before the Mode 3800 can be placed and readied for operation as a dipole trap. Currently the laser can operate with an output 5 Watts at a current of 25 amps. With improved methods of external cooling may be possible to run at higher current. I expect it to be possible to get 8 Watts of power and potentially more, providing for an excellent dipole trap. There is little to stop the dipole laser trap from seeing operation in the near future. With a molecule production method already verified there should be no doubts about seeing cold molecules produced and trapped within the coming months.

APPENDIX A

Chase, Brian

Spectra Physics Model 3800

Nd:YAG 1064nm Laser

A quick-reference sheet for daily operation.

Powering-up:

- Turn ON power at breaker box (flip switch up)
- CB-1 breaker switch ON (flip switch up)
- Turn key one-eighth clockwise
- An button should light up on power supply face

Water supply:

- Turn on lab water to laser power supply
  - Supply handle turned down
  - Return handle turned up
- Turn key one-eighth clockwise further
  - This will start the internal water pump
  - Expect some sputtering, may have to repeat multiple times
- Keep mindful of all connections for possible new leaks

Lamp ignition:

- On front of power supply make sure that:
  - Shutter switch is set to 'closed'
  - Current knob turned fully counter-clockwise
  - Supply is running in 'current mode' (NOT 'light mode')
- With pump running smoothly press 'Power On' button (green)
  - LED should turn off
  - Lamp Start light (white) should start to glow
- Press 'Lamp Start' for lamp ignition

    - LED should turn off
    - Should be able to hear lamp running inside reflection chamber
- Wait 10 minutes for supply to warm up, then set current to ~25A
- Wait another 30 minutes – current will rise by ~0.5A-1A
- If another current is desired, set knob and give more time to warm up

Lasing: only proceed once supply is warmed up

- Make sure that beam path is not endangering anything
- Wear laser safety goggles good at 1064nm
- Open the intra-cavity shutter
- Proceed with experimenting cautiously
    - Keep internal water below 39 degrees Celsius
    - Current may continue to rise past 30-minute window, be prepared to lower if necessary

Turning the laser off:

- Press 'OFF' button, *DO NOT TURN KEY*
- Allow at least 2 minutes for circulating water to further cool lamp chamber
- Now turn key to 'OFF' position.
- Turn off external water, CB1, anything else.

Troubleshooting:

LED doesn't light up when key turned to 'on' position

- Check that power supply cable is plugged in
- Check that breaker switches are all set to 'on' positions.
- Press all breaker switches on rear panel of supply to reset them, if necessary
- Last resort:
    - Open up electronics casing in power supply
    - Locate circuit board with colored LEDs near the front-right of box
    - Switch on circuit breakers and check for an LED to light up
    - If no LEDs light up the cables may be in wrong order
        - With both breakers off, try switching two leads in plug and try again
        - If this still fails check manual for further information

Water pump doesn't start

- Air bubbles in piping can cause pump to stop running – may need to stop and restart pump several times before continuous pumping can occur
- Water level can also be too high, which keeps pump from starting
- Check LED lights on front of supply when pump fails to work.
  - Low water resistivity – replace distilled water or replace DI filter
  - Low water level – check back of supply for water level between marked lines
  - Water Temp – water temperature is too high.
  - Doors – cover is off and safety switch is not bypassed (yellow key near rear reflector)

Water pump shuts itself off

- If possible restart pump manually (hold key to 'pump start') for a minute or two so lamp can cool off.
- Can occur if water level falls too low or water temp is too high. Check front panel of power supply for relevant LED warning light.

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