Construction of a Far-Off Resonance Optical Dipole Trap

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Introduction

Superfluid helium and its properties have interested scientist for many years. However studies of superfluid helium were frustrated by the fact that the superfluid occurs in a strongly interacting liquid. Nearly eighty years ago F. London suggested that superfluid liquid helium can be described as a Bose-Einstien condensate (BEC), distorted by the presence of strong interatomic forces [1]. Not long after this, it became clear that an interacting but dilute BEC gas could be used as means to study this phenomenon in liquid helium. Studying an interacting BEC has a distinct advantage over the liquid state, since the interactions in the liquid are much harder to understand theoretically. Only very recently, with the experimental realization of a weakly interacting BEC in 1995 by Eric Cornell and Carl Wieman, has made studying a strongly interacting BEC as a proxy for liquid Helium become feasible.

The experiment I have been involved in at the University of Colorado and JILA, is aimed at understanding the properties of superfluid liquid Helium, by studying a strongly interacting BEC gas of Rubidium atoms. In this experiment, the interactions between the atoms in a dilute Bose-condensed gas of ^{85}Rb can be tuned by applying a magnetic field to the condensate. By applying a magnetic field, one can tune the scattering length of the ^{85}Rb atoms via a Feshbach resonance.

When the magnetic field is turned on the atoms interact with each other and the condensate expands rapidly. Two beam Bragg spectroscopy is used to measure the interactions in the gas. In Bragg spectroscopy, two lasers with slightly different frequencies are shined on the BEC gas. As shown in Figure 1, one of the photons promotes atoms into an excited state and the second photon causes stimulated emission into the second beam. As a result the atom receives a momentum kick in the direction of the first beam corresponding to the difference in energy of the two photons. The upshot of probing the system in this way is that, if atoms are promoted out of the original BEC and the difference in frequencies of the two Bragg beams is known, the interactions between the atoms in the condensate can be measured by subtracting the energy of the photons from the kinetic energy of a two photon recoil. This energy which is due to atomic interactions and related to the magnetic field induced scattering length, is given by the equation [2]:

Figure 1: Diagram of two beam Bragg spectroscopy. The atoms receive a momentum kick determined by the difference in frequency of the two beams.

$$\hbar\omega(k) - \frac{\hbar^2 k^2}{2m} = \frac{4\pi\hbar^2 na}{m}$$

Here, is the momentum of the excitation, is the mass of the atom, is the density of the condensate, and $\hbar\omega(k)$ is the energy

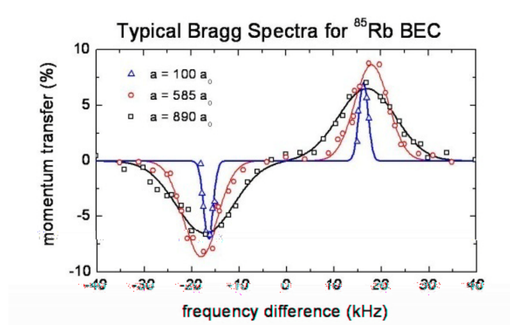


Figure 2: Typical bragg spectra for a ^{85}Rb BEC with varying scattering lengths. Note that as scattering length is increased peaks are much broader. (Papp and Pino, 2008)

required to promote an atom from the condensate. Figure 2 shows a typical Bragg spectra for different scattering lengths. The difference in frequency, the detuning, at which the largest response in the condensate occurs, corresponds to the energy of interactions in the condensate for a given magnetic field.

Unfortunately, as evidenced by studying liquid Helium, turning up interactions between the atoms in the condensate comes with a cost: that is, the interactions between the atoms cause the condensate to disperse rapidly. As the condensate expands, the density of gas decreases accordingly. As the condensate becomes less dense (and thus the atoms are farther apart), the gas move into the free particle, or non-interacting regime again (which is exactly the regime we are not trying to study). In addition since the interaction energy is dependent on density, it is important to measure the interaction energy where the gas is at a constant density. During the expansion, the condensate can only be considered to have constant density over very short timescales, thus the interrogation time for the experiment is limited by how quickly the gas expands. Ultimately, the timescales for expansion of the condensate depend on the trap frequency. From Heisenberg's uncertainty principle we know that the uncertainty in a measurement of energy is related time it takes to measure that energy by:

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$$

where ΔE is the uncertainty in energy and is the uncertainty in time. Since the Bragg experiments must be performed over a very short time there is an inherent uncertainty in the energy (and thus frequency) of the energy required to promote an atom out of the condensate. The result of this uncertainty can be seen in Figure 2 as the broadening of the spectral peaks. So for larger scattering lengths, which results in faster expansion of the gas, the interaction energy is less well known. One can imagine that for very large scattering lengths, where interactions are similar to those in superfluid Helium, interaction energies would be very difficult to measure. In order to measure interaction energies at higher scattering lengths, better resolution of Bragg peaks is necessary which means longer interrogation times are needed.

So how can the experiments be performed over longer times without large fluctuations in the condensate density? At this point it is necessary to describe how the condensate is held in place while experiments are performed. During experiments, the condensate is held in an optical dipole trap (this will be explained in further detail later, since the optical trap is the focus of my summer project). An optical dipole trap consists simply of a laser beam in which the atoms are trapped in a certain location by an electric dipole potential. For now, it suffices to say, that the atoms tend toward areas of high beam intensity. The intensity of the trap beam, as shown in Figure 3, is given by a gaussian, so atoms tend toward the center of the beam in both the radial and axial direction. More importantly, the rate at which atoms moves around in the trap and ultimately the rate at which the condensate expands is set by the trap frequency which is a function both of the trap depth and of the radius of the trap beam. The trap frequency, f, which is defined by the confining potential and the atoms which are confined, and in the radial and axial direction are given by:

$$f_r(w) = \frac{1}{2\pi}\sqrt{\frac{-4 \cdot U(w)}{w^2 m_{Rb}}}$$

and

$$f_z(w) = \frac{1}{2\pi}\sqrt{\frac{-4\cdot U(w)}{z_R^2 m_{Rb}}}$$

respectively. Here U is the trap potential w is the beam waist, and m is the mass of the atoms in the trap. For the current trap the ratio of the two trap frequencies $=\frac{130\ Hz}{3\ Hz}$. When the interactions are turned on the atoms respond by expanding on timescales set by the trap frequency. The result is that the condensate expands much more rapidly in the radial direction than in the axial direction. It is this radial expansion rate that defines the experiment time. In order to run experiments for longer times, as discussed above, the trap frequency in the radial direction must be lowered so that the condensate density changes over a longer period of time after the interactions are turned on.

One way to relax the primary trap in the radial direction without a loss in the overall density, is to confine the atoms further in the axial direction. This can be accomplished by installing a second optical trap perpendicular to original trap and then increasing the width of the original trap. Since the atoms will be confined to a smaller region in the axial direction, they can be confined to a larger region in the radial direction without changing the original density of the condensate. The addition of a second trap and the adjustment to the primary trap will result in a more spherical condensate geometry. A more spherical condensate will expand more slowly in the radial direction (the rate limiting direction with the current geometry) than a cigar shaped condensate. Since the condensate will expand more slowly, Bragg experiments can be performed for longer times which will produce better frequency resolution, especially at higher scattering lengths. My summer project was to construct the secondary trap and install the trap in the experiment. The physics of the optical trap is discussed below.

Physics of the FORT

A Far-Off Resonance Trap (FORT) is a purely optical trap used in confining cold atoms to a given region, and is composed simply of a stable, high intensity laser beam used to produce a trapping potential. It is important that the trap meet certain experimental conditions. First, since evaporative cooling will be conducted in the trap, the trap laser must have an adjustable peak intensity which can be easily controlled. In addition, since experiments will be performed while the atoms are confined in the trap, the trap laser must not interfere with the state of the condensate. These conditions are met by using a feedback loop to control the intensity of the laser (the “servo”, which will be discussed later) and by using a wavelength which is far removed from the absorption resonance of the atoms being confined in the trap (hence “Far-Off Resonance). Since the wavelength of the trap light is nowhere near resonance, incident light on the atoms will not case scattering of photons. The scattering of photons leads to the generation of heat which would move atoms out of the condensate state. The wavelength chosen for this particular trap is 1090 nm since this wavelength is well above the absorption resonance of ^{85}Rb.

As stated before an optical trap simply uses a laser which is used to produce a trapping potential defined by the AC Stark effect. The Stark effect refers to the act of inducing a dipole moment with an external electric field. The energy of an atom with a dipole moment **p**, is given by the equation:

$$U = -\boldsymbol{p}\cdot\boldsymbol{E}$$

where **E** is the electric field, and U is the energy of the dipole. In addition, the magnitude of dipole moment of the atom is proportional to the electric field with proportionality constant α, so:

$$\boldsymbol{p} = \alpha \boldsymbol{E}$$

In the case of an optical dipole trap the field is provided by a laser (the AC Stark effect refers to the fact that the field oscillates in time). Since the intensity, I of the laser is proportional to the square of the electric field, and the trapping potential is proportional to the square of the field, the potential must also be proportional to the intensity:

$$U \propto -E^2 \propto -I$$

Here the negative sign is important, because it indicates that the lowest potential energy in the region is at the highest intensity of the laser.

The intensity and thus the trapping potential of the trap are defined by the intensity of the beam which is a gaussian described by the equation:

$$I(r,z) = \frac{2P}{\pi[w(z)]^2} e^{-2r^2/[w(z)]^2}$$

Here, w(z) is the beam waist along the axial direction, P is the power of the beam, r is the radial coordinate and z is the axial coordinate. The beam waist as a function of z, is given as:

$$w(z) = w_o \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

where is the beam waist at the focus, z is the axial coordinate and is the Raylegh range which is defined as:

$$z_R = \frac{\pi w_o^2}{\lambda}$$

For this particular trap with we have chosen a beam waist (or radius) of w_o ~ 200 µm. This size corresponds to an order of magnitude increase in trap width in the radial direction. A plot showing the intensity of the beam and the corresponding confining potential is given in Figure 3.

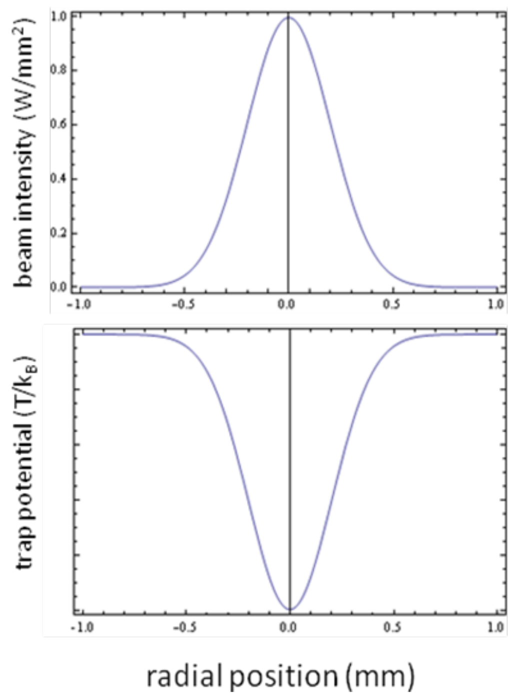


Figure 3: Intensity and corresponding potential of a 1W, 1090 nm Gaussian beam as a function of radial position in the beam. Here the intensity of the beam corresponds exactly to the graph shown however the trap potential is only proportional to plot which accounts for the absence of magnitude.

Atoms confined in the trap will be cooled by evaporative cooling. That is, the potential of the trap will be lowered over time so that atoms with kinetic energy higher than the trapping potential will escape and only the coldest atoms will be left in the trap. It is these atoms that the Bragg scattering experiments will be conducted on.

FORT Overview

The optical trap consists mainly of two components: the optics which control the size and location of the beam and the electronics which control its' intensity (and thus the trapping potential). A Diagram of all the components of the trap is shown below, in Figure 4. Both the trap optics and electronics are discussed in detail below.

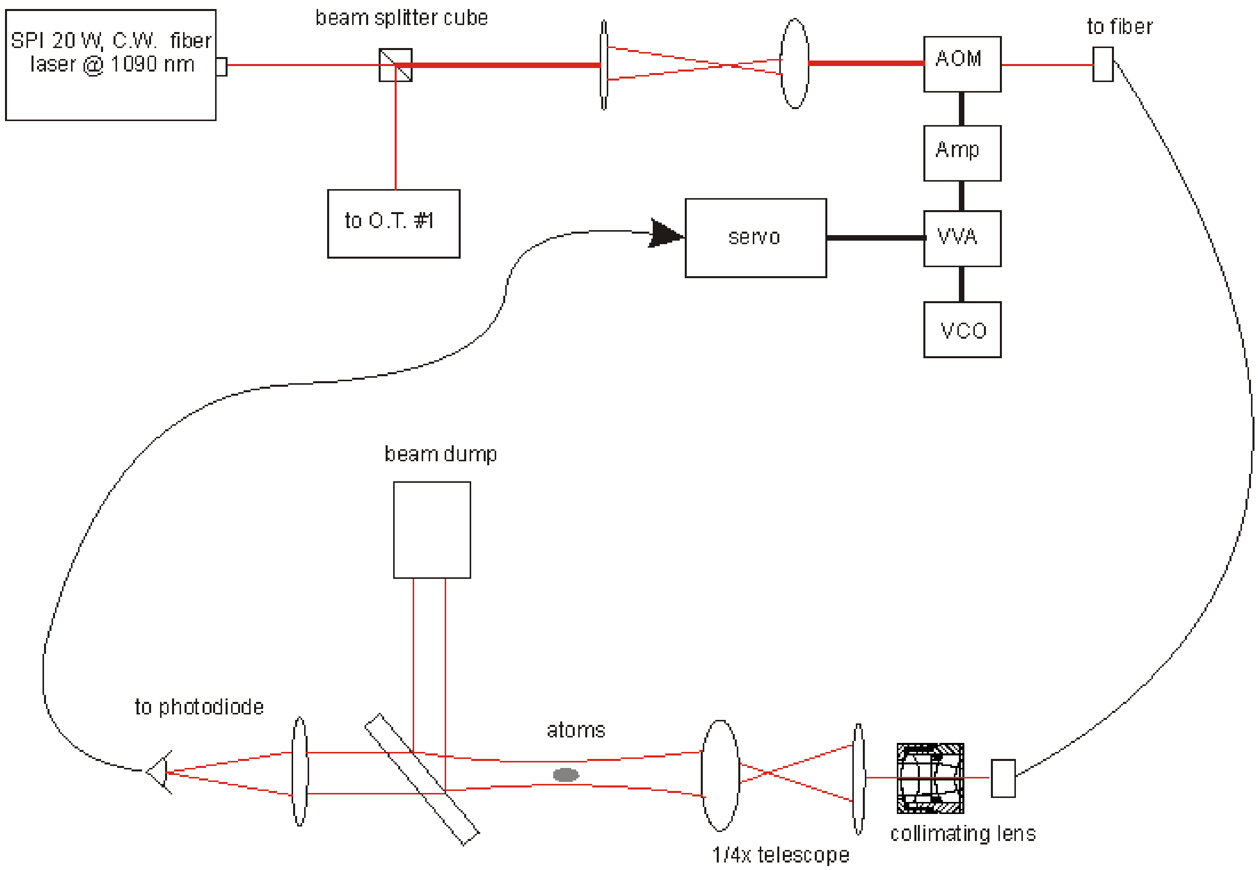


Figure 4: Diagram of entire trap showing intensity and size control components. One important aspect of the trap is that the trap electronics and optics are physically removed from each other. The laser is transported from the intensity control elements to the trap optics via a polarization maintaining optical fiber.

FORT Optics

As stated above the trap optics are designed to control the size (and shape) of the beam as well as its position. The laser source for the optical trap is a SPI 20 W, continuous wave fiber laser with a wavelength of λ = 1090 nm. The beam is sent through an Acousto-Optical Modulator (AOM) which controls the amount of power seen by the atoms (the function of the AOM is discussed later in a section describing the FORT electronics). In order to transfer the light from its source to the trap the laser is coupled to an Oz Optics polarization maintaining optical fiber. When the beam exist the fiber it can be considered a point source. In order to make use of this light the the beam is then collimated at the output of the fiber by a CVI GLC002 multi-element collimating lens AR coated for 1090 nm. At the output of the collimator the beam waist is around 1300 µm. The beam is then focused to ¼ its original size by a telescope composed of 25 cm and 8 cm AR coated achromats so that the beam is the desired size when it reaches the atoms. After the beam passes through the telescope the waist is approximately 200 µm, which is the desired size at the atoms. Directly before and after the beam passes through the telescope it is reflected by two Thorlabs dielectric mirrors coated for 1090 nm. The mirrors are held by two mirror mounts with actuating micrometers. The purpose of reflecting the light off of mirrors is to have control over the location of the beam at the atoms. Finally, before hitting the atoms, the beam passes through a long wave pass dichroic mirror. At the atoms, the optical trap beam path overlaps the imaging beam path so a dichroic mirror is used to separate out the image beam from the trap beam after it passes through the atoms. A diagram of the trap optics is given in Figure 5 (and a photograph of the completed trap optics is given in the appendix in Figure 11). After the trap beam passes through the atoms it is reflected off a CVI dichroic short wave pass mirror. The dichroic is used to separate the trap beam from the image beam on the other side of the atoms so it can be used as feedback. The beam then hits an uncoated wedge which passes close to 95% of the light. The light that passes through the wedge is then sent to a dump since only a small portion of the power is needed for feedback. The reflected portion of the beam is sent to a photodiode by way of another dielectric mirror. The photodiode converts the power left in the reflected beam into a voltage which is sent to the servo for feedback on the power of the trap laser.

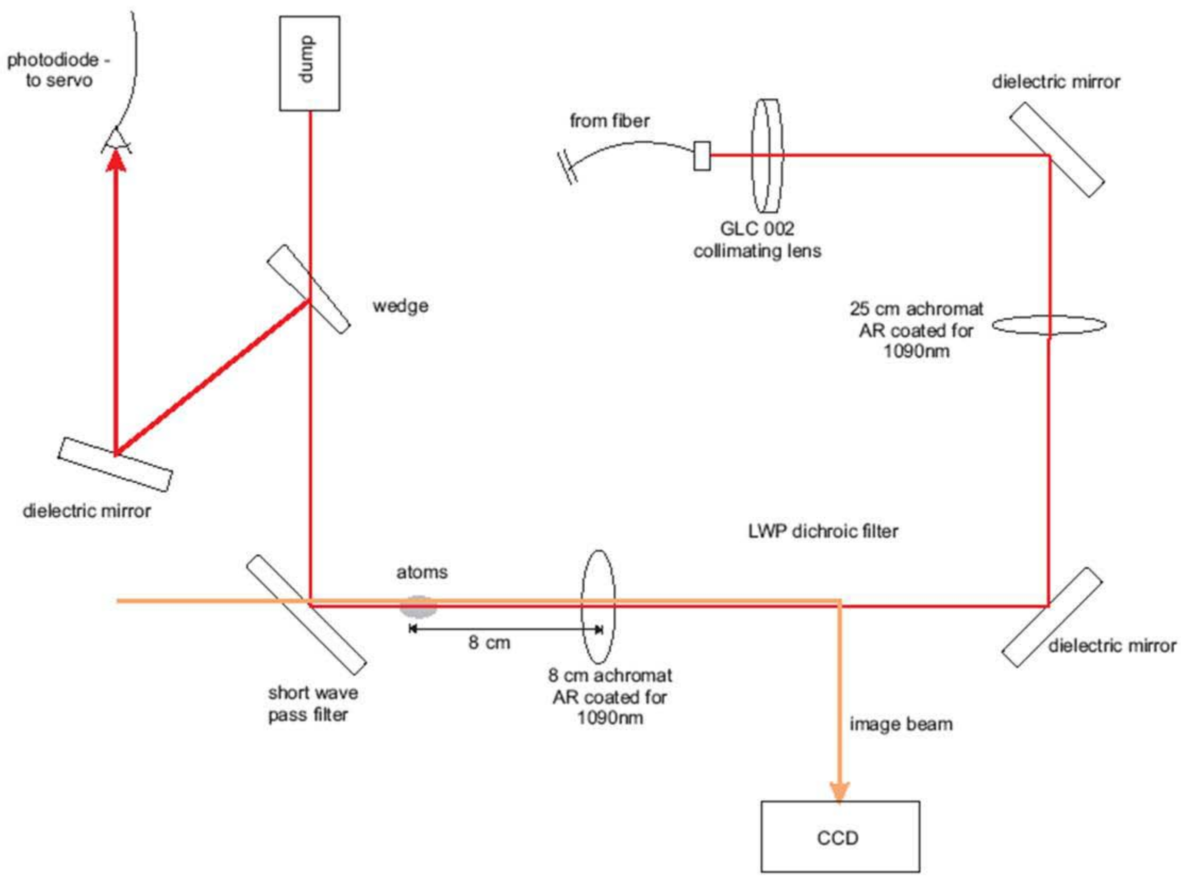


Figure 5: Diagram of trap optics. The two most important components are the 1/4x telescope composed of the two achromats which are used to achieve the desired beam size at the atoms and the two dielectric mirrors which allow the beam to be positioned directly onto the atoms.

Figure 6 gives an image and profile of the beam at the position of the atoms. As designed the beam profile at the atoms is very close to a perfect Gaussian with a waist of ~200 µm.

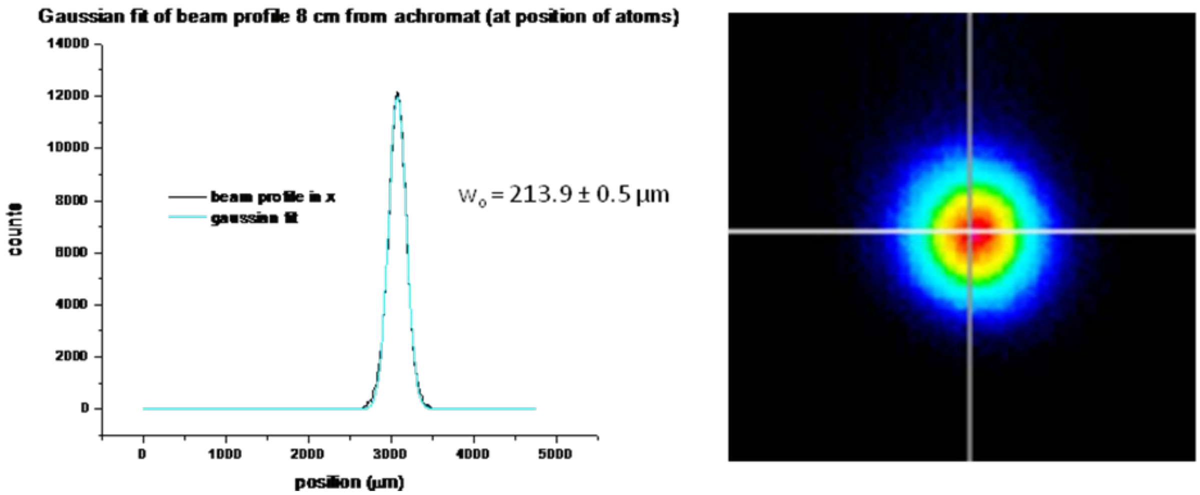


Figure 6: Intensity profile of the trap beam taken by a CCD camera at the position of the atoms. The beam is fit to a Gaussian. The fit gives a 1/e^2 half width of 213.9 microns which corresponds to a beam with a diameter of around 420 microns (almost exactly an order of magnitude larger than the primary trap diameter).

FORT Electronics

In order to have a stable and easily manipulated trap potential, an electronic intensity control system is used. The intensity of the trap beam is controlled by a feedback loop which is composed of a series of electronics as shown in Figures 4 and 7. The two main components of the electronic control system are the servo and the Acousto-Optical Modulator or AOM. The servo outputs an electronic control signal which is determined by the difference between a control voltage from a computer and a voltage from the photodiode which corresponds to the intensity in the beam[1]. The AOM translates the servo output voltage into a change in beam intensity. The elements of the intensity control loop are described below.

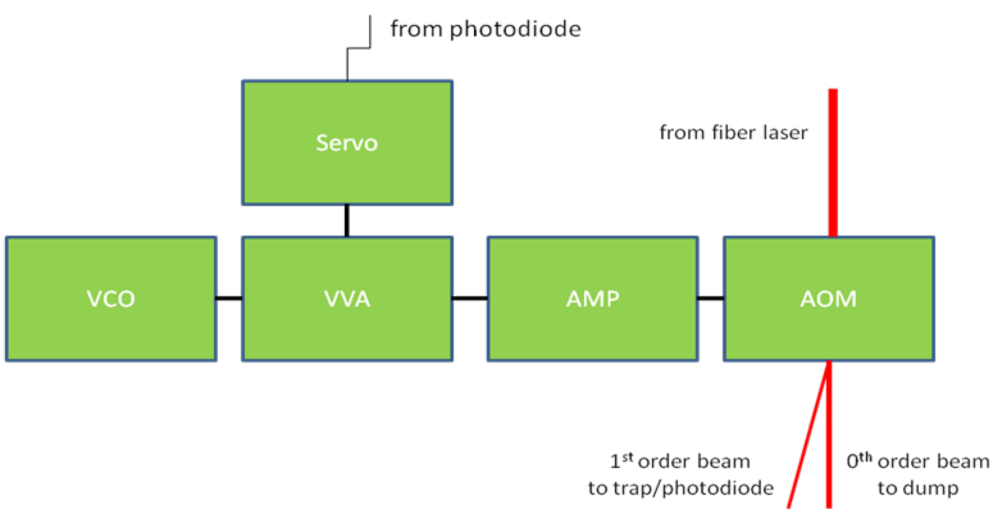


Figure 7: Diagram of the intensity control electronics. The diagram shows the AOM which splits an incedent beam into multiple diffracted orders.

[1] The photodiode actually outputs a voltage proportional to the power of the beam. However, since the power of the beam is given by the intensity times the area of the beam, P = IA, as long as the entire beam hits the detector the output voltage will also be proportional to the beam intensity.

The Photodiode

The photodiode used in my trap is a Thorlabs PDA36A adjustable gain photodetector. The photodiode outputs a DC voltage as a function of the power incident on the diode. The photodiode output voltage increases linearly as a function of the power of the trap beam at the atoms with a slope of m = 0.95±0.01 as shown to the right in Figure 8.

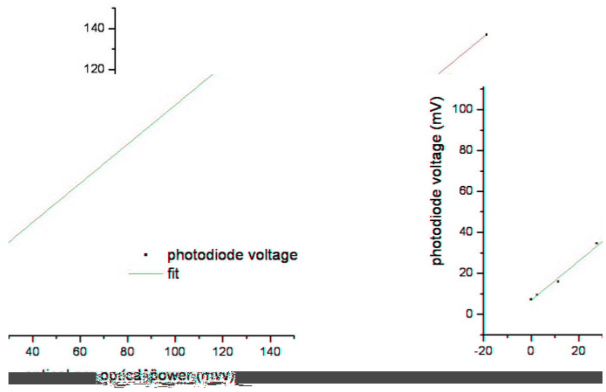


Figure 8: Calibration of output voltage as a function of optical trap power for the photodiode used in the trap.

The Voltage Controlled Oscillator

The purpose of the voltage controlled oscillator or VCO is to provide a tunable amplitude AC voltage with a tunable frequency of oscillation. The AOM, which is one of the main components in the beam intensity control, operates on an 80 MHz AC voltage. For this particular system the VCO is tuned to output an 80 MHz AC voltage at a specified amplitude. The VCO can be turned on or off by an external TTL signal from the computer. A diagram of the VCO is given in the appendix in Figure 12.

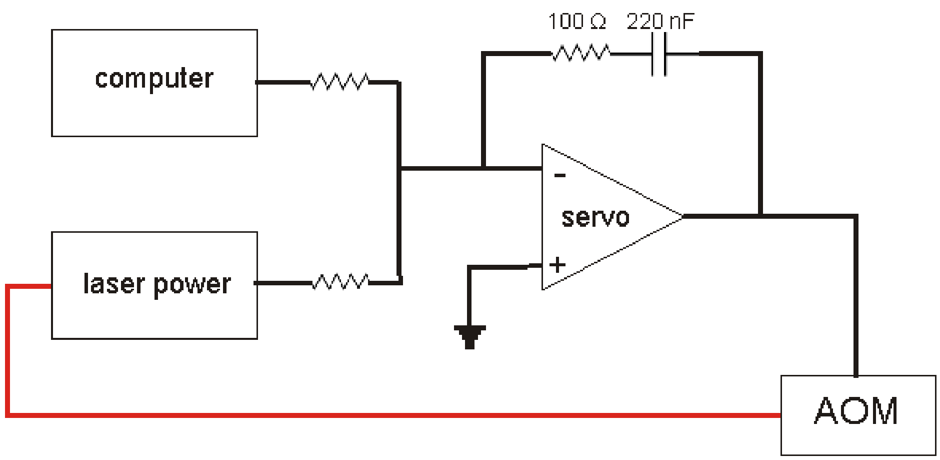
The Voltage Variable Attenuator and the Amplifier

For this trap we use a MiniCircuits ZX73-2500M+ Voltage Variable Attenuator (VVA). The purpose of the variable attenuator is vary the amplitude of the drive voltage for the AOM. The VVA takes two inputs, the DC output voltage from the servo and the 80 MHz output voltage from the VCO. The VVA attenuates 80 MHz driver voltage for the AOM by varying amounts depending on the DC input it receives from the servo. In this way the VVA is responsible for converting the DC servo voltage into a AC voltage which can be “understood” by the AOM. The output voltage from the VVA is then sent to an amplifier and finally to the AOM. The amplifier simply outputs the signal from the VVA with a 29 dB gain. The higher power signal from the amplifier is sent directly to the AOM.

The AOM

The Acousto-Optical Modulator or AOM is responsible for converting the electronic control signal from the servo (and subsequent signal modification elements) into a change in beam intensity. The AOM is composed of a crystal and a piezoelectric transducer. If an AC voltage is applied to the transducer it expands and contracts, striking the side of the crystal as it does so. As the transducer strikes the crystal it set up a standing sound wave in the crystal which results in compressed and expanded regions in the crystal. These regions define an effective diffraction grating in the crystal which is controlled by the intensity of the AC signal applied to the transducer.

When a laser is shined through the crystal, the result is a series of diffracted beams with differing intensities[2]. The intensities of the diffracted beams can be controlled by varying the power to the transducer since this amplitude of oscillations of the transducer determines the “sharpness” of the diffraction grating. For this trap the first order beam is used to trap the atoms.



$$\tau_{servo} = RC = 100\ \Omega * 220\ \text{nF} = 22\ \mu\text{s}$$

Figure 9: Diagram of servo feedback loop. The feedback integrator on the servo op-amp set the speed at which the servo will respond to changes in laser power.

The Servo

The servomechanism or “servo” controls the amplitude of the driver voltage sent to the AOM. Although in reality the servo involves several important electronic components (used to stabilize inputs and add multiple inputs as well as for varying the servo gain), the functional part of the servo is accomplished by a single OP27-GP low-noise operational amplifier. A diagram of the functional servo is given in Figure 9 (and a full circuit diagram is given in Figure 13 in the Appendix). As shown in Figure 9, the non-inverting input of the servo is grounded. The inverting input of the servo corresponds to the sum of the control voltage from a computer and the output voltage from the photodiode. For a negative control voltage, -V, the servo op-amp will send as much voltage as necessary to the AOM (which controls the beam intensity and thus the photodiode output voltage) such that the voltage from the photodiode, V, equals the negative of the control voltage from the computer to ensure that both inputs of the servo op-amp are at 0 V. So for example, if the photodiode output voltage were greater than the absolute value of the control voltage, the servo would decrease its output voltage, thereby decreasing the power of the trap beam, until the input from the photodiode was equal and opposite of the control voltage from the computer. Depending on the speed of the servo (which is determined by the feedback integrator in the op-amp), the servo can over correct for differences in the input which leads to “ringing” in the servo. “Ringing” refers to the photodiode input oscillating around, but never reaching, the control voltage from the computer. However, by choosing the correct components servo, these oscillations will be damped and the photodiode voltage will match the input voltage after a certain

[2] In addition to the diffracted order beams, the original beam always passes through the crystal regardless of whether the transducer sees a control voltage or not. The zero order beam, however, is sent to a beam dump and serves no further purpose in the trap.

period of time. As long as these oscillations are damped out on a timescale smaller than the speed the servo is expected to respond at, the oscillations can be ignored. For this particular servo, a time constant of 22 μs was chosen, as shown in Fig. 9. A plot of the response of the servo to a square pulse is given in Figure 10 below.

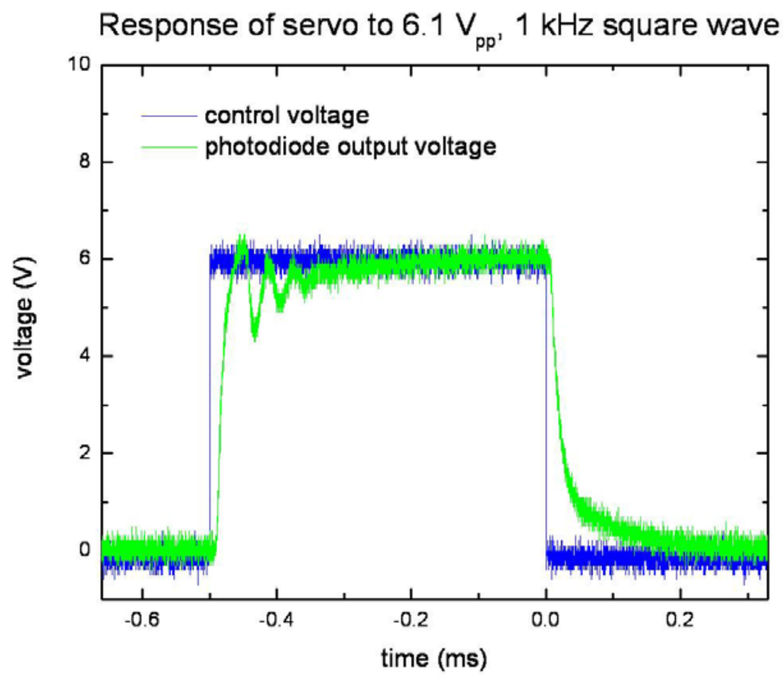


Figure 10: Scope trace of the output voltage of the photodiode in response to a 6V, 1 kHz pulse. Since the photodiode output voltage is proportional to the optical power of the trap laser, the plot shows that changing the input voltage to the servo effects the power in the laser. The electronic gain in the servo is set up so that the photodiode voltage will match the input voltage. Note that the oscillations in the photodiode voltage (and thus the laser power) are damped by the servo on a timescale much smaller than the experiment is performed over.

Conclusion/Future Work

As described above, both the beam width and beam intensity control elements of the servo, have been constructed and tested. The width of the beam at the position of the atoms is 213 ± 0.5 μm which is sufficiently close to the desired width. The trap has been installed into the experiment and shown in Figure 16 in the appendix, which is an image of the completed trap. Scope traces of the control voltage and the photodiode output voltage show that the beam intensity control elements work as expected.

Unfortunately, due to time constraints, we were not able to show that the secondary trap has helped to change the final condensate geometry. We believe that this is simply a matter of aligning the secondary trap onto the primary trap. Although not the simplest of procedures, due to the current trap setup, the secondary trap should be aligned in the very near future. Once the trap beam is aligned properly on the atoms, the atoms in trap will be confined to a smaller region in the axial direction, which will allow the primary trap to be relaxed in the radial direction. Relaxing the primary trap in the radial direction will allow for more constant condensate densities during experiments which was the original goal of installing the second trap.

In order to align the secondary trap onto the atoms, for the time being, the optical trap beam with be replaced with a beam which is resonant with the atoms. In order to hit atoms with resonant light the dichroic mirror, which reflects short wavelength light, will be replaced with a beam splitter cube which will allow short wavelengths to pass through the science cell and hit the atoms. The beam will then be aligned by imaging the absorption of the resonant beam by the atoms. Once the resonant beam is aligned, the optical trap beam and the dichroic mirror will be swapped back into their original configuration. At this point the trap should be approximately aligned with the primary trap beam. At this point, only small adjustments will be needed to align the two beams completely on the atoms.

Appendix

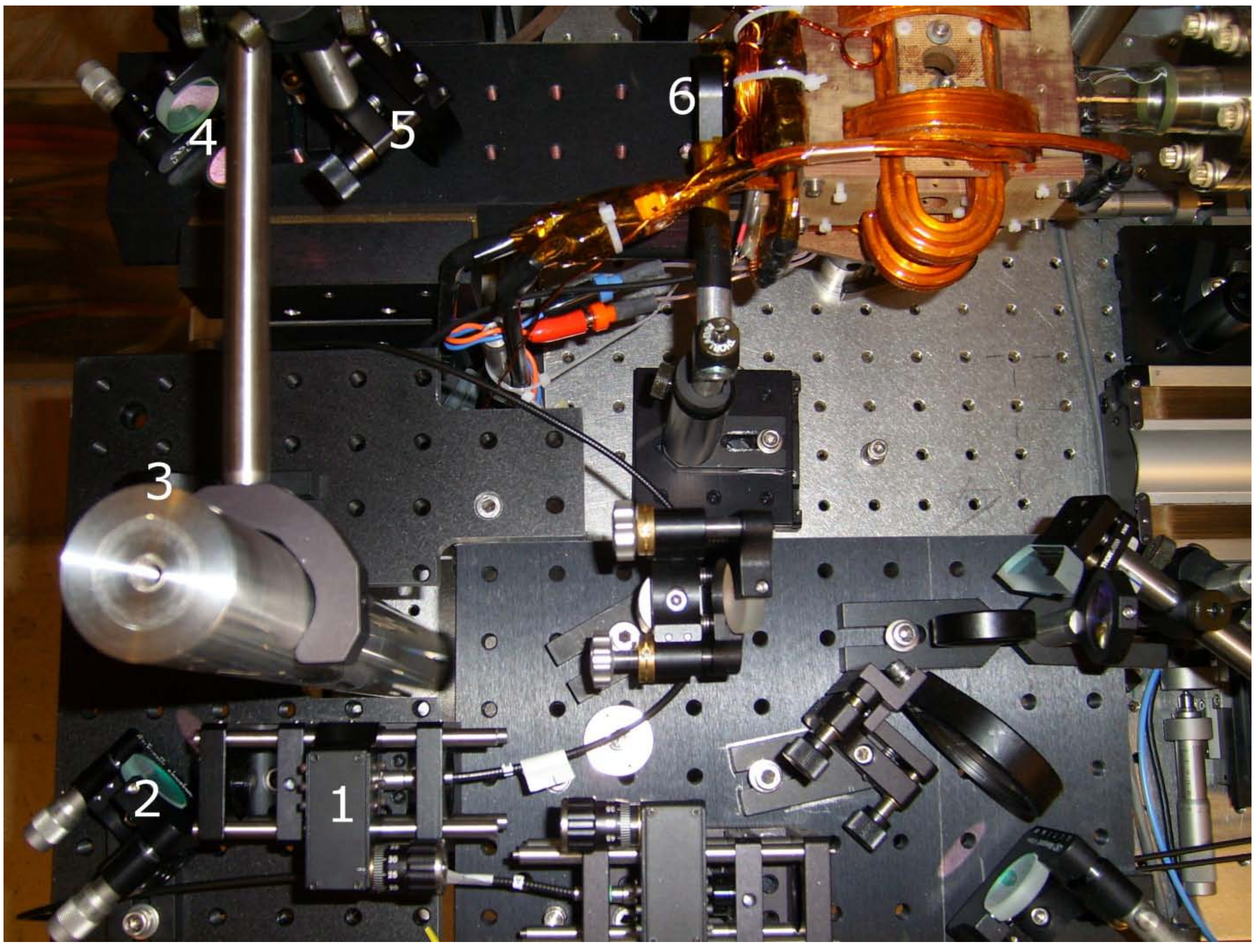


Figure 11: Image of trap optics installed on science table. Main components of the trap are labeled with white numbers coresponding to: 1. High power fiber and collimating lens 2. First dielectric mirror 3. CVI 25 cm achromat AR coated for 1090 nm 4. Second dielectric mirror 5. CVI Long wave pass dichroic mirror 6. CVI 8 cm achromat AR coated for 1090 nm.

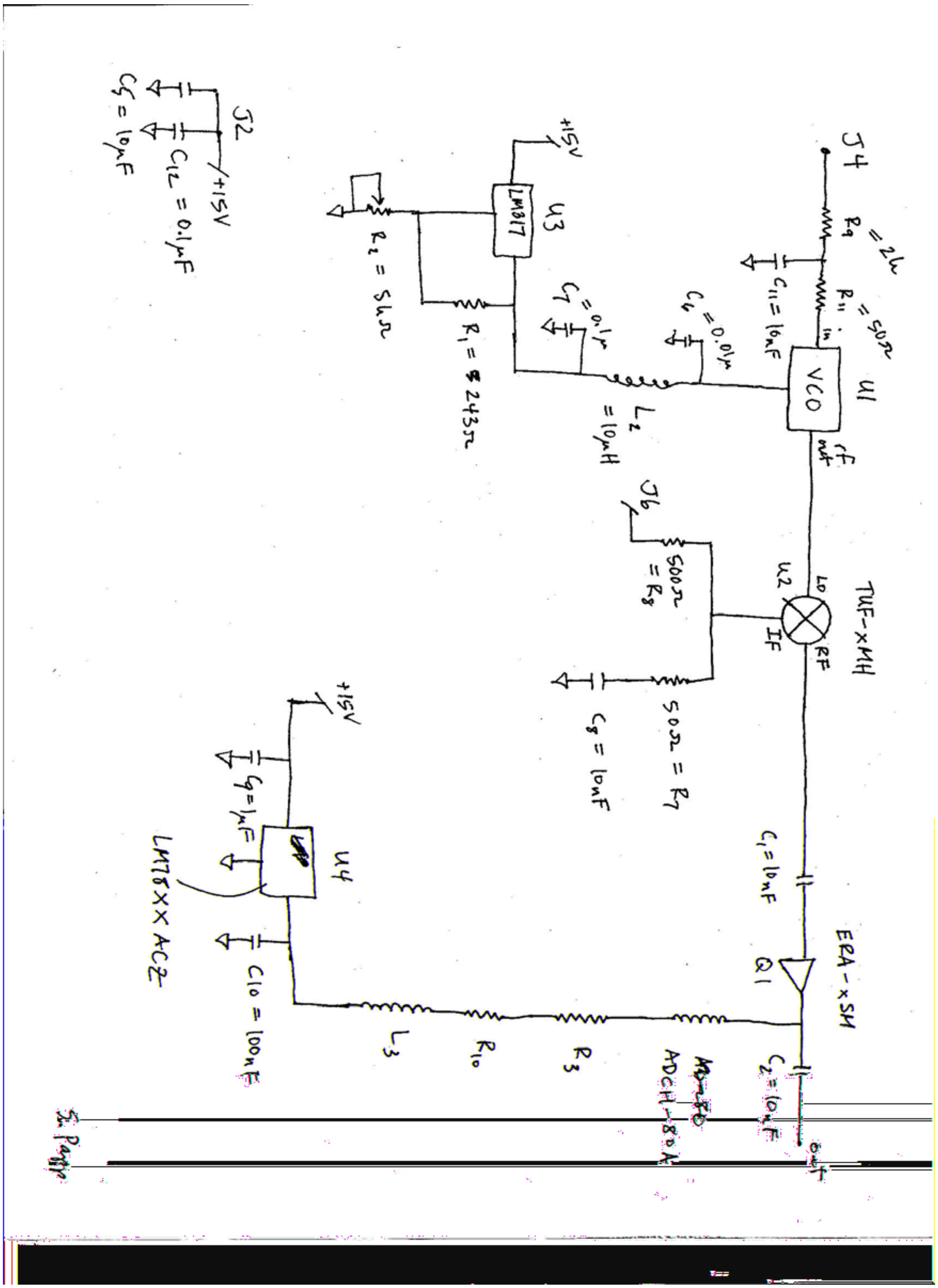


Figure 12: Circuit diagram of VCO draw by Scott Papp.

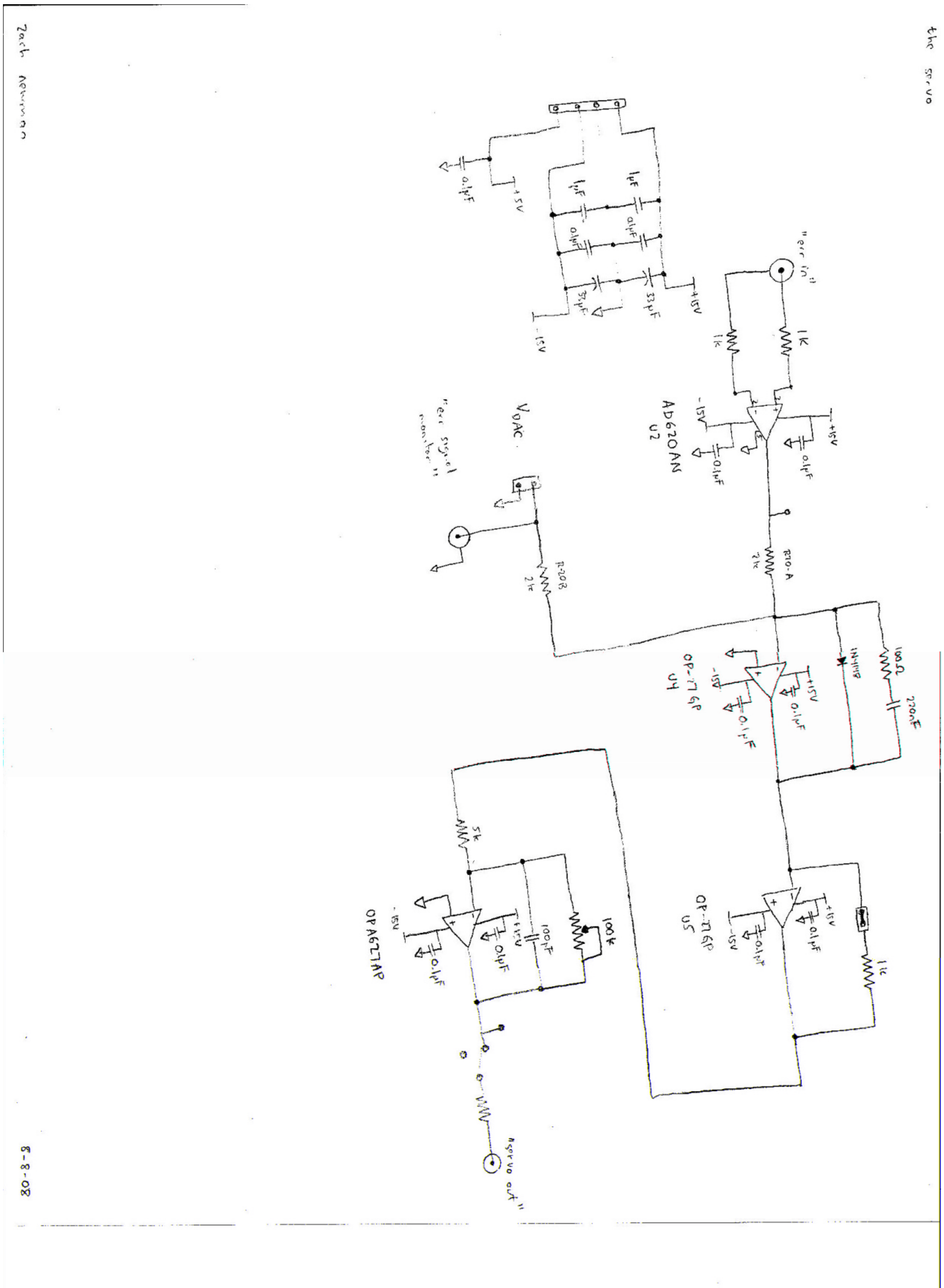


Figure 13: Complete circuit diagram for the servo.

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