ALL AROUND ATTA

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ABSTRACT

Single atom trap trace analysis is important for both its contributions to the XENON project and other applications, such as radiokrypton dating. ATTA is able to experiment on a sample and accurately identify contamination to the parts per trillion level. This summer, I was able to contribute to the ATTA experiment. My contributions consisted of creating and automating a data analysis code and designing and building a pressure valve automation attachment.

1 INTRODUCTION

ATTA stands for Atom Trap Trace Analysis and it is a system that can trap and detect single atoms. One of its strengths is that it will only trap the atoms that we are interested in. The ATTA project was started at Columbia University because the XENON group needed a way to know how many Krypton atoms were in their liquid Xenon. At the time the project began, ATTA was the only method selective and sensitive enough for the level of Krypton being searched for. For XENON1T, the ^{85}Kr to Xe contamination must be on the order of one Krypton atom in every 10^{23} Xenon atoms [1]. ATTA traps ^{84}Kr since it is the most abundant isotope and we know its relation to ^{85}Kr– which is about 1.5×10^{-11} [1]. This means that the sensitivity level we need for ^{84}Kr is a part per trillion.

The ATTA experiment's importance extends beyond its usefulness to the XENON project and into radiometric dating. It is the only method that can perform radiokrypton and radioargon dating that is not extremely expensive [2]. Element dating with these radioisotopes is important for two main reasons. The first is that there is an age range that only radioargon can date [3]. The other reason is that, as noble gases, the only interference a sample experiences is from elements in their surroundings radioactively decaying into Krypton or Argon. This means that even if there are other elements that can date an age range, radiokrypton and radioargon are desirable radioisotopes since they are immune to chemical reactions [3].

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2 EXPERIMENTAL SYSTEM

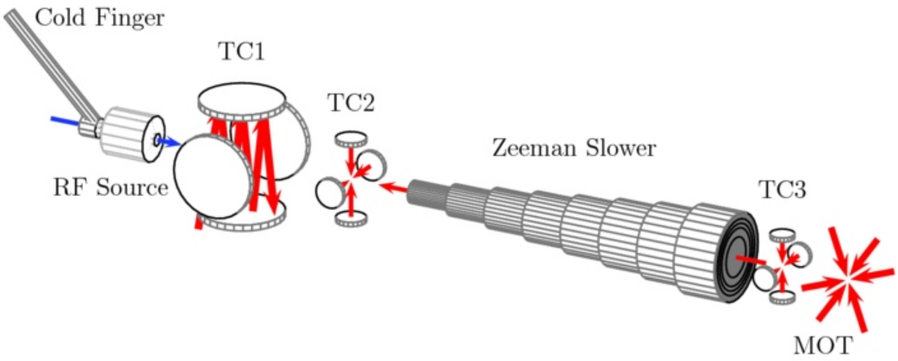


Figure 1: This is a diagram of the ATTA system at Columbia University. It shows the setup of how the atoms pass through a plasma created by the RF source, are slowed by the transverse cooling stage and Zeeman slower and then captured in the MOT. Image from: [1]

2.1 RF Source

Xenon expands from a reservoir into the radio frequency (RF) source. The RF signal creates a plasma discharge that the gas goes through. As the gas flows through the plasma, it is excited into a metastable state. This occurs via inelastic collisions with electrons and ions [1]. An RF discharge source is necessary for the experiment because the Krypton needs to be in a metastable state. If the Krypton were not in a metastable state, our laser sources would need to be in the deep ultraviolet to be able to slow the atoms down [1]. With the Krypton in the metastable state, we are able to use semiconductor lasers in the near infrared for the transverse cooling and trapping.

2.2 Transverse Cooling

After exiting the RF source, the atoms go through a stage of transverse cooling. Transverse cooling, also known as optical molasses, is a process in which lasers collimate the beam of atoms and increase the forward flux of atoms [1]. The frequency of the lasers are tuned so that all non-forward components of movement interact with the lasers and are killed off. This reduction in transverse movement is what increases the forward flux and is important to the experiment since the magneto-optical trap only catches atoms that are moving straight forward.

2.3 Zeeman Slower

The atoms enter the Zeeman slower following transverse cooling. The laser coming opposite the atomic beam is detuned to the frequency of the atomic transition of the atoms going 250 m/s at the entrance of the Zeeman slower [4]. The atoms that are not going that fast do not interact with the laser until farther into the Zeeman slower. This ensures that absorption and spontaneous emission occurs, lowering the atoms' velocities so that the atoms all exit the Zeeman slower with the same velocity. Since the resonance of the transition is over a narrow line width, any relative motion–such as the velocity of an atom lowering–takes the atom out of resonance. The Zeeman slower accounts for this with the increasing magnetic field of the solenoid. The magnetic field displaces the energy level of the atomic transition so that the laser frequency is still resonant [4].

2.4 Magneto-Optical Trap

When the atoms leave the Zeeman slower and enter the magneto-optical trap, they are moving at tens of meters per second. The magneto-optical trap (MOT) is made of three pairs of counter-propagating laser beams tuned near the resonant frequency and a quadrupole magnetic field. The magnetic field is zero at the center of the trap so that once the atom is there, it is unaffected by the detuned lasers. Elsewhere, the magnetic field displaces the energy levels of the atom so that when it is not in the center of the trap, it is resonant with the laser that will direct it back towards the center [4].

2.5 Detection

The main concern when detecting an atom is reducing background fluorescence. The detection setup, shown in Figure 2 on the following page, is all enclosed and the inner walls of the vacuum chamber are painted black.

The first three lenses capture the image in the MOT. The 27.0 mm aperture in front of the bandpass reduces the background fluorescence due to stray reflections. Light from the trapped

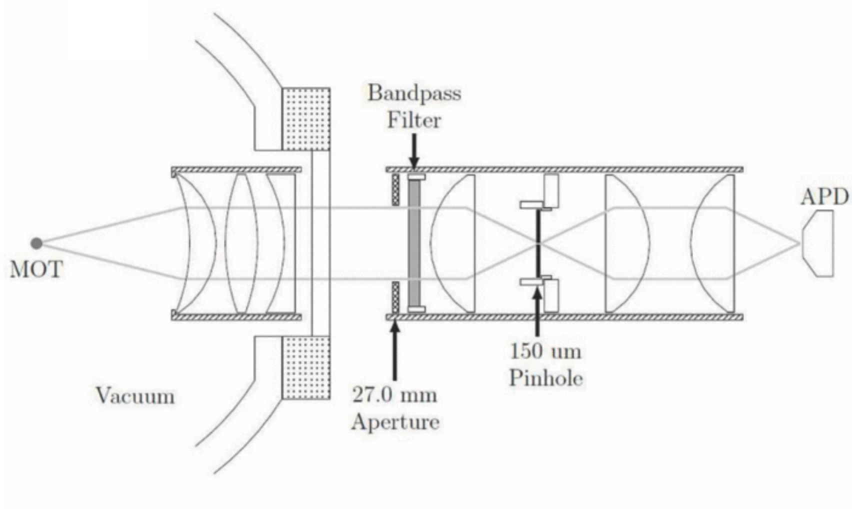


Figure 2: The detection setup used to reduce background light and detect the fluorescence of the trapped atoms. Image from: [1]

atoms that is captured in the blocked out area would not be imaged onto the small APD active area anyway due to optical abberations. The bandpass filter remove ambient light. The next lens focuses the image into the pin hole. Spatial filtering with the pinhole is done in order to detect only the fluorescence of the MOT image. The following lenses capture and focus the fluorescence onto the active region of the APD. [5]

2.6 Avalanche Photodiode

An avalanche photodiode (APD) is what detects the single photons trapped in the MOT. The APD needs to be sensitive to single photons since the contamination levels that we are looking at are in parts per trillion, which means that there is almost never more than one atom, if any, in the trap. The APD amplifies the signal so that it is large enough to be read in by the computer. The APD does this by increasing the electrons per photon. The process consists of converting the photon detection to an electronic TTL pulse, expanding the TTL pulse and then converting the TTL pulse to a voltage signal [4]. The signal is then read by the computer program and recorded in counts per second.

3 MY CONTRIBUTIONS

3.1 Data Analysis

The data that is read into the computer from the APD is the number of photons per second (plotted as fluorescence in kilohertz) and the time in seconds. Using just this raw data, it is feasible to determine the number of atoms of Krypton in the Xenon sample. However, this can be time consuming if the contamination is high and the criteria for what constitutes a peak needs to be determined. My first project was to perform data analysis on the raw data and then automate the analysis as much as possible. Performing an analysis on the data is useful because it leads to consistent classification of peaks. Automating the data analysis process serves the purpose of saving time during future trials.

3.1.1 *Backgrounds*

Despite the efforts to enclose and insulate the detection system, there is still a substantial amount of background photons that are picked up by the APD. This background fluorescence stems mostly from one of three sources. The main source of background noise is due to internal reflections, such as reflections off of dust that gets into the system and the walls of the MOT housing. This background source is the cause of the high values–around and above 100kHz–of the fluorescence, which can be observed in Figure 3 on the next page. Another origin of the background noise is variation in temperature and humidity within the lab. The laser alignment drifts with changes in temperature and/or humidity. This drifting affects the background that the APD picks up; leading to the sinusoidal appearance of the baseline fluorescence. The last of the three major origins of background photons is laser noise and accounts for a majority of the short term fluctuations in the signal.

I used the R Programming Language to reduce and analyze the data. The first step in this process was to reduce the background as much as possible. I fit a line to the data and then plotted it to see how well it followed the background noise. This line is shown in blue in Figure 3 on the following page, added onto the plot of the original data. This process was somewhat difficult as I had trouble creating a fit line that was not strictly graphical, but also consisted of the set of data

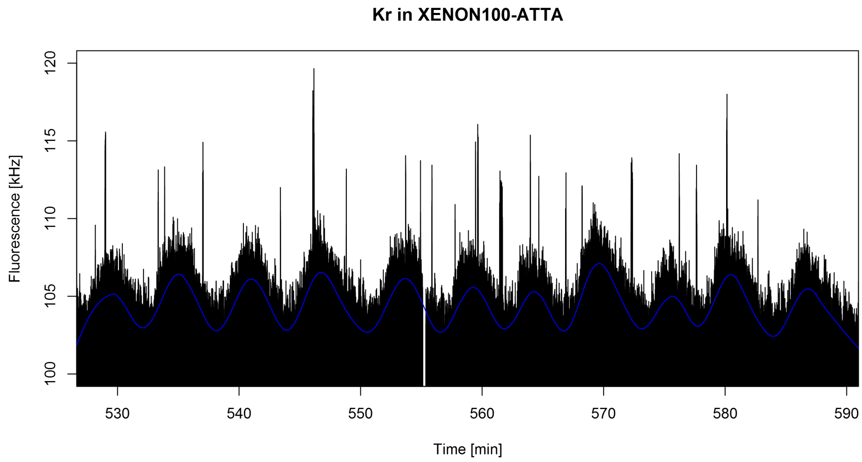


Figure 3: An hour of the data plotted with a fit line.

points that made up the line. Once this was accomplished, I subtracted the fluorescence values of the fit line data set from the original fluorescence, which resulted in the plot Figure 4.

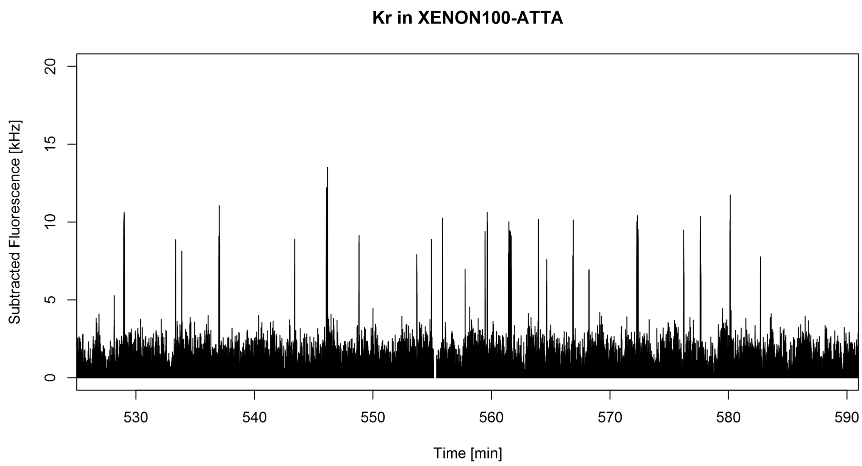


Figure 4: A plot of an hour of the data after the backgrounds have been subtracted.

3.1.2 *Peak Identification*

With this background reduced data, I began the process of correctly identifying the peaks. This turned out to be a rather arduous task as I found that a simple criteria requiring two consecutive points be above a threshold fluorescence did not catch all of the peaks and tended to split peaks up too much. In order to solve this problem, I colored the points that were picked as peaks blue and the points that were part of peaks but had been missed red. Then I began trying to find the criteria that best caught all of each peak and zooming in on the sections where red signified points had been missed. It did not take long for me to tire of seeing red within my plots; especially since I would start out looking at a plot that spanned a similar range as the plots in the figures just above to analyzing plots spanning less than a minute of data, as shown by two examples in Figure 5.

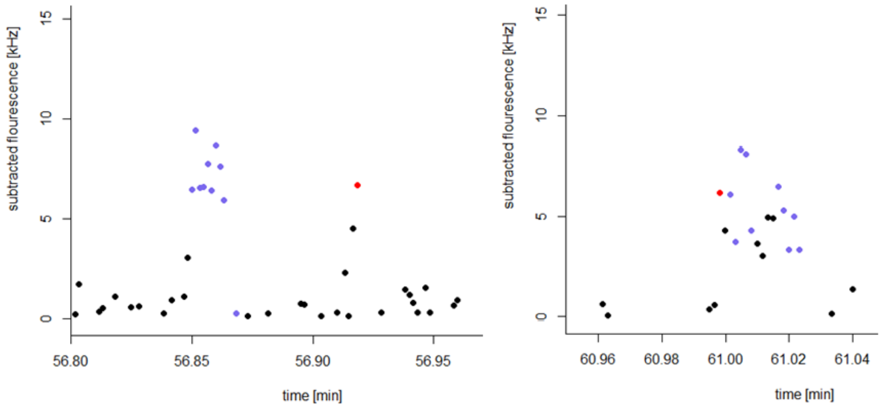


Figure 5: Two plots that exemplify the plots I used to analyze the different peak identification methods. The red dots indicate peaks or parts of peaks that the method did not catch. I continued trying different methods until I generated plots that did not contain any red points.

After looking through many a plot, I was able to determine criteria that caught all of the points in the peaks and was consistent in its identification. The final criteria for identifying peaks are as follows:

- Peak begins when two points above the threshold (5 kHz in our case) occur within two points of each other
- Peak ends when four consecutive points are below the threshold
- Single points above 7 kHz are peaks
- The period of the peak begins when the first point is above the threshold and ends at the last point above the threshold

Using this criteria, I was able to determine the number of peaks in a trial and their lifetime. Plots of this are shown in Figure 6 on the next page and Figure 7 on page 10. Having the peaks correctly and consistently identified is very important as the number of peaks correspond to the number of Krypton atoms trapped, i.e. the number of Krypton atoms in the sample. Translating the number of peaks into the number of Krypton atoms is done by counting the peaks identified and then seeing which Gaussian peak they correspond to in the histogram along the side of Figure 6.

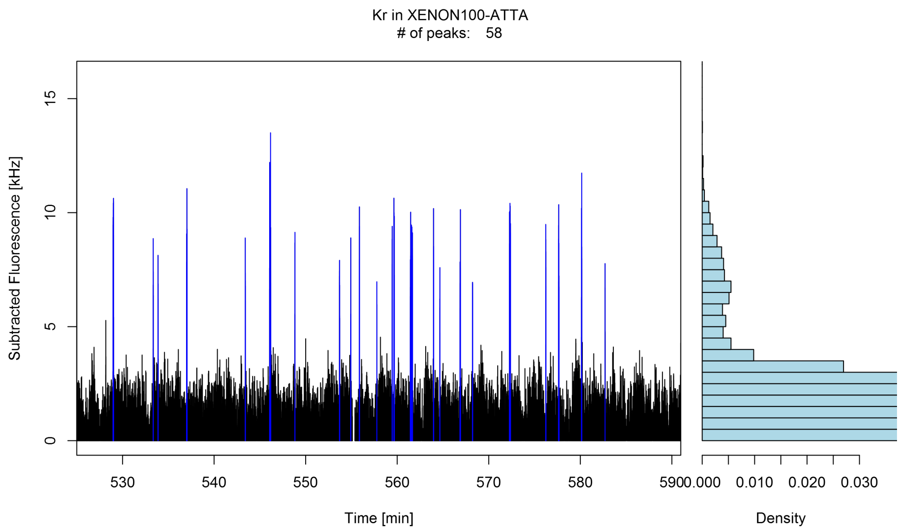


Figure 6: Plot of the subtracted fluorescence with the peaks highlighted in blue. Along the side of the plot is a histogram of the peaks that can be used to determine how many atoms were in the trap during a peak. The plot of the subtracted fluorescence is only over half of the time of the trial, while the histogram and number of peaks found are over the whole trial.

The first Gaussian peak in the histogram is at the baseline fluorescence, so this corresponds to zero atoms. The second Gaussian peak is the average fluorescence for a single atom. Any peaks within this Gaussian correspond to a single atom trapped. If there were a third Gaussian peak in the histogram, it would correspond to two atoms being trapped at once. So in the case of Figure 6, all of the peaks correspond to a single atom meaning that there were 58 Krypton atoms within the sample that I analyzed. Having a histogram of the periods of the peaks can be used to find the average lifetime of a Krypton atom in the trap. This is done by fitting an exponential curve to it and then extracting the lifetime from the function of the exponential decay. The lifetime is useful for seeing how well the MOT is performing.

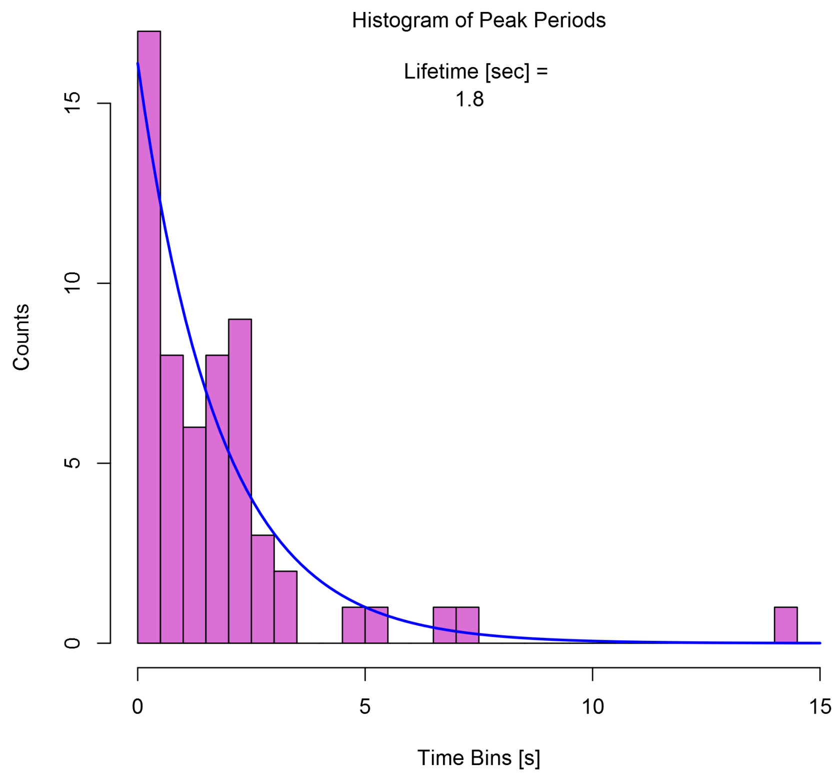


Figure 7: Histogram of the peak periods with an exponential curve fit to it.

3.2 Pressure Valve Automation

The second project that I worked on this summer was the automation of the valve connecting the gas reservoir and the RF source. This valve that controls the gas flow from the reservoir into the RF source needs to be adjusted during the experiment as the pressure in the reservoir changes to keep the gas flow constant. The Xenon consumption rate needs to stay constant so that the plasma in the RF source stays on and to keep the rate of metastable Krypton produced constant since that keeps the detection at its most efficient. As the valve needs to be continuously adjusted during each measurement, finding a way to automate it instead of turning it by hand is favorable.

AUTOMATION The adjustment will be automated by attaching a stepper motor to the reservoir valve. The stepper motor will turn the valve based on what it reads in from a pressure sensor monitoring the reservoir. We needed a way to attach and hold the stepper motor to the reservoir valve and keep it steady. Another aspect of the stepper motor is that it has a high torque, which means that it needs to be in a stiff holder.

3D PRINTING There was one main obstacle in attaching the stepper motor to the valve; which was that the reservoir is sometimes baked. So the attachment had to be something that could be baked and that the stepper motor could be easily disconnected from or the apparatus as a whole needed to be easily removed from the valve. That left two options: machining it or 3D printing it. While machining it would make it rigid and able to be baked, it is also the more expensive and time consuming route and is very unforgiving of slight deviations from exact specifications. 3D printing, however, took less time and money to make, did not need everything to fit into exact specifications and prototypes could be quickly reprinted if small changes were needed in the design–this is known as rapid prototyping. For these reasons, we decided that 3D printing would be the better choice even if it meant that we had to get more creative in the design to compensate for it being slightly less stable.

3.2.1 *Design Process*

The first step in my design process was to analyze the original holder that had been made for the stepper motor. Through this analysis, I was able to identify the problems that caused it to be unsuitable and figure out what would need to be changed to prevent them. The two main problems that I identified in the original attachment were that the apparatus as a whole did not fit well together and that it was not strong enough. This was shown by how it was not steady when the motor ran and part of it broke, which just led to it being more unstable. The root of these problems was that the type and placement of the connections allowed the attachment to be too flexible. To counteract these problems, I made the connecting pieces thicker and had the top and base connect at two points instead of one central connection. I created my design using SolidWorks, which is a 3D CAD software. It allows you to sketch and simulate component designs, as well as assemble them together to create whole apparatuses.

After finishing my initial design, I met with the Emerging Technologies Coordinator, Jeffrey Lancaster, to discuss my design and the possibility of getting it 3D printed. Jeffrey made some good suggestions on how to improve my design; the main one being that the top and base be connected by threaded rods instead of creating connecting pieces in each part to be 3D printed. Taking his considerations into account, I refined my design, which is shown is Figure 8.

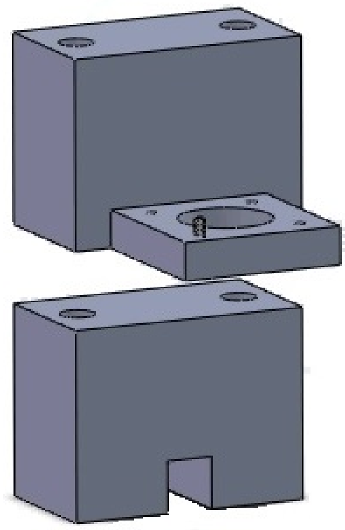
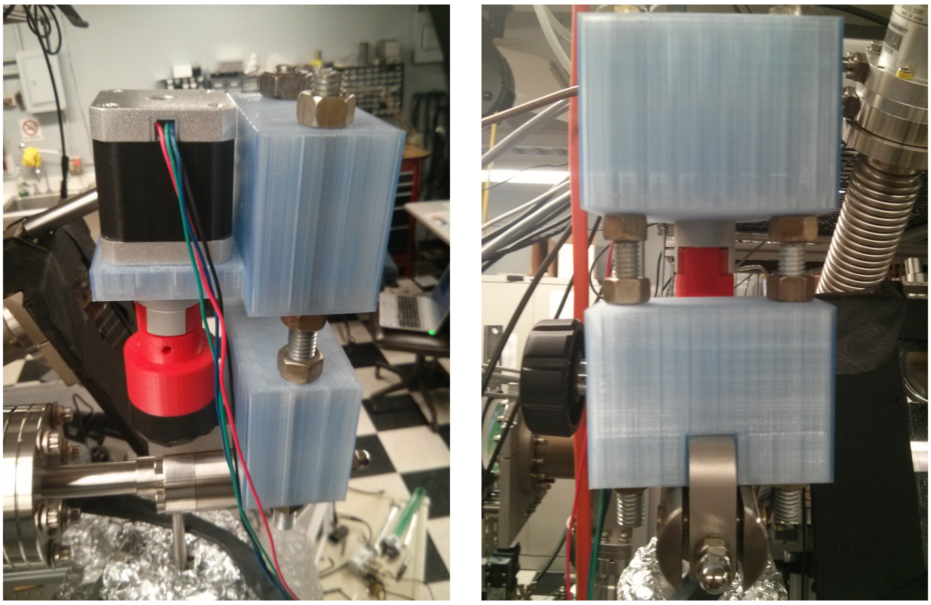


Figure 8: 3D SolidWorks image of my design for the pressure valve automation apparatus.

3.2.2 *Prototype*

I was able to have the prototype of my design printed before the end of the program. Luckily, none of the pieces needed to be reprinted. I attached the stepper motor and the threaded rods to the components and then fitted the apparatus to the valve. Images of this are in Figure 9 on the following page.

Some adjustments to the programming of the stepper motor were necessary to increase its torque and lower the step size. With these changes in place, I found that the attachment was stable. Going forward, code needs to be written to read in the pressure from the pressure sensor and automate the necessary adjustment.



(a) Side View of Pressure Valve Automation

(b) Front View of Pressure Valve Automation

Figure 9: Front and side view of the 3D printed apparatus attached to the ATTA experiment.

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