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# External Beam Alignment System for Quantitative Proton Induced Gamma-ray Emission (PIGE) Spectroscopy

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# External Beam Alignment System for Quantitative Proton Induced Gamma-ray Emission (PIGE) Spectroscopy

*By*

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## Abstract

OTTENS, ELIAS External Beam Alignment System for Proton Induced Gamma-ray Emission (PIGE)

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The effects of pollution on the ecosystem are paramount in our society, permeating air, soil, and drinking water. One contaminant of concern is per- and polyfluoroalkyl substances (PFAS), also referred to as "forever chemicals", which contains fluorine (F), a potentially harmful element to humans. To investigate pollution in the environment, it is necessary to make accurate measurements of the distribution and concentrations of these PFAS chemicals. To do this, soil samples are collected and analyzed using Particle Induced Gamma-ray Emission (PIGE) via the Union College Ion Beam Analysis Laboratory's (UCIBAL) particle accelerator. A 2.2 MeV proton beam comes into contact with a sample and that sample emits gamma-rays which allows for the identification of elements, specifically fluorine. To get an accurate concentration of fluorine in any particular sample, the charge incident on the sample and the solid angle between the target and detector is needed. The charge is measured via a Faraday cup, however accuracy of the solid angle requires a precision target system to align the proton beam, sample, and detector. An Ultimaker 3D printer was utilized for the construction of the alignment system with designs made in AutoDesk 360. We will highlight the design considerations, including dimensions, thought process, failures and successes, of a new target system built to enable fluorine concentration measurements.

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# Chapter 1

# Problem Statement

Pollution is effecting every facet of the environment and as technology continues to develop, new potential and dangerous pollutants are created. These pollutants are ever-present, infiltrating air, soil and water supplies. One contaminant of concern are per- and polyfluoroalkyl substances (PFAS), also referred to as "forever chemicals", which contain fluorine (F), a potentially harmful element to humans. PFAS substances are used in products such as non-stick cookware, fast food wrappers, fire extinguishers, and more [1]. PFAS substances are being found in local drinking supplies including in Poestenkill, NY, which was reported on August 4, 2021. The Poestenkill, NY outbreak was so serious it forced a local middle school to use bottled water only [5]. They are not alone in recent outbreaks of PFAS chemicals discovered in drinking water in the New York capital region, they join Hoosick Falls [4], Hyde Park [3], and Poughkeepsie [2] who have all had outbreaks in the past 5 years. Fluorine is one element that makes up PFAS chemicals which the Environmental Protection Agency (EPA) has set standards for acceptable levels in drinking water at 2.0 mg/L. Fluorine presents potentially harmful consequences for humans, such as fluorosis which affects teeth, making them discolored and weakened, and bones, causing stiffness and joint pain. PFAS is especially harmful in the environment because it does not breakdown easily due to strong

covalent bonds of fluorine with oxygen. Small quantities of fluorine are good for things like strengthening the enamel on teeth, but too much exposure can be dangerous which makes it critical to detect, quantify the concentration levels, and monitor the spread of fluorine in the environment.

To detect and ultimately make fluorine concentration measurements we use Proton Induced Gamma-ray Emission (PIGE) spectroscopy. PIGE is a form of nuclear reaction analysis that produces $\gamma$-rays from elements, like fluorine, which we detect with our Germanium detector. At present we are only capable of using the data to determine the presence of fluorine in samples. In order to calculate the concentration of elements, like fluorine, in a sample we use forumla 1.1 where $f_m$ is the mass fraction of the element which can be converted into parts per million (concentration). The target system used in the setup of the experiment gets factored into $\epsilon_{abs}$, which is the absolute efficiency of the detector. This is the part of the equation that currently has the largest source of uncertainty due to the rudimentary instruments depicted in Figure 1.1.

$$f_m = \frac{Y(E) \cdot A}{\epsilon_{abs}(E_\gamma) \cdot \frac{Q}{e} \cdot f_i \cdot N_{av} \cdot \int_0^{E_0} \sigma(E)/S_m(E)dE} \tag{1.1}$$

The absolute efficiency of the detector is dependent on the solid angle of the system shown in equation 1.2; where $r$ is the radius of the detector and $R$ is the distance from the target to the detector. The current target system is not held at a fix location above the detector which makes the measurement of $R$ highly uncertain, because the clamp that holds the target above the detector is susceptible to shifting from light contact.

$$\Omega = \frac{\pi r^2}{R^2} \tag{1.2}$$

Equation 1.3 shows the absolute efficiency as a function of the solid angle of the target

system, where $\epsilon_{rel}$ is the relative efficiency of the detector.

$$\epsilon_{abs} = \epsilon_{rel} \cdot \Omega \tag{1.3}$$

Making concentration measurements are only possible when the target system is has reliable measurements with minimal uncertainty to satisfy equation 1.1. The current target system is the primary factor limiting the ability to make concentration measurements, so a better target system needs to be developed with precision to minimize the uncertainty in the solid angle.

## 1.1 Current Target System

The particle accelerator currently has an antiquated target system to collect data on the number of $\gamma$-rays versus their energy for PIGE analysis. The physical structure makes it difficult to replicate exact angles and distances away from the sample while maintaining a center position with the samples and the detector (Figure 1.1). In PIGE analysis an ion beam is emitted externally onto a sample, typically, in the form of a pellet. Upon impact with the ion beam, the nucleus goes into an excited state and expels energy in the form of gamma rays ($\gamma$-rays) to move out of the excited energy state. Information pertaining to the energy and quantity of $\gamma$-ray's emitted is detected with a Canberra model GC1017 Germanium - Lithium Detector. This information is then used to determine whether or not certain elements, like fluorine, are present in a sample taken.

The current setup, shown in Figure 1.1, relies on a metal clamp, assumed to be fixed at a 45°angle to the ion beam, roughly centered above the detector. The metal clamp can be twisted on its axis with minimal force thus shifting the incident angle of the target, requiring calibration every time it is operated. Samples (in the form of pellets) are fixed onto a standard 75mm $\times$ 25mm (3" $\times$ 1") glass slide three at a time via double sided tape.Because

there are three pellets on a slide this requires the slide to be moved perpendicular to the beam within the clamp so that each sample is centered with the external beam. The pellets themselves are not all the same height which requires a realignment of the system to hit the center of the pellet. Adjusting the clamp and/or the detector is an imperfect process that led to off center hits of the pellets. Failure to hit the center of the sample reflects poorly on the target system and can lead to wasted time re-running the sample.

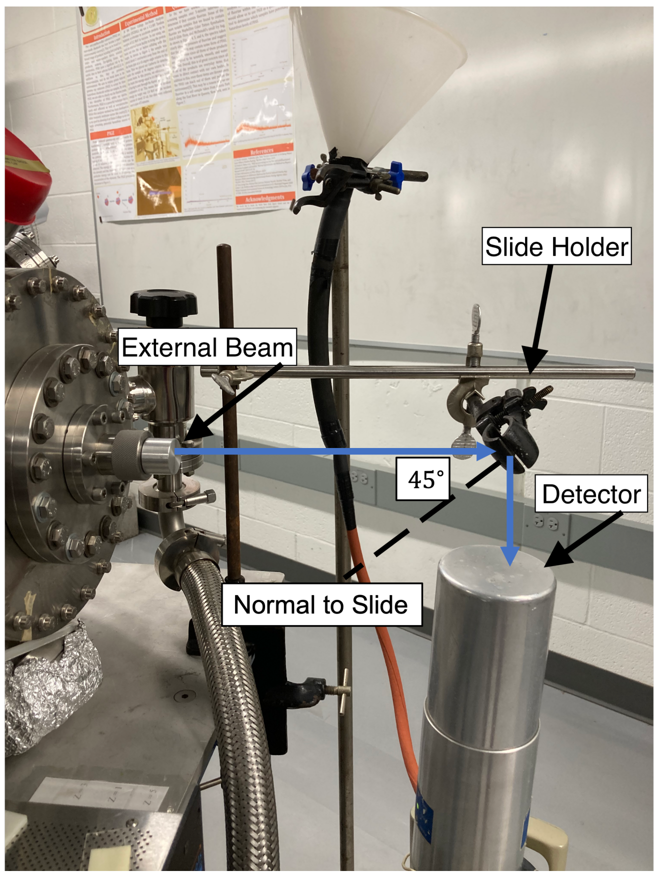


Figure 1.1: The current target system used for PIGE analysis. The Slide Holder is assumed to be at a 45° angle relative to the External Beam and centered over the Detector.

The Germanium detector has a diameter of 45mm (1.771”) which is covered by a 76.2 mm (3”) diameter aluminum casing. There are two suspected actions that are believed to be causing the background data. One reason is that the casing is larger than the detector, $\gamma$-rays are emitted at an angle where they partially hit the surface of the detector showing up as background data. The second is due to bremsstrahlung radiation from the deflection

of charged particles passing through the nuclei of the sample. An example of this is shown in Figure 1.2 where Union College Ion Beam Analysis Laboratory (UCIBAL) research group evaluated a sample from mayballine makeup on July 23, 2019. They were screening for fluorine at energy peaks 110keV and 197keV which can be seen in Figure 1.2 although the background data clouds the peaks. For low energy $\gamma$-rays and for low counts of gamma-rays, it is crucial that background data gets diminished to accentuate the desired peaks.

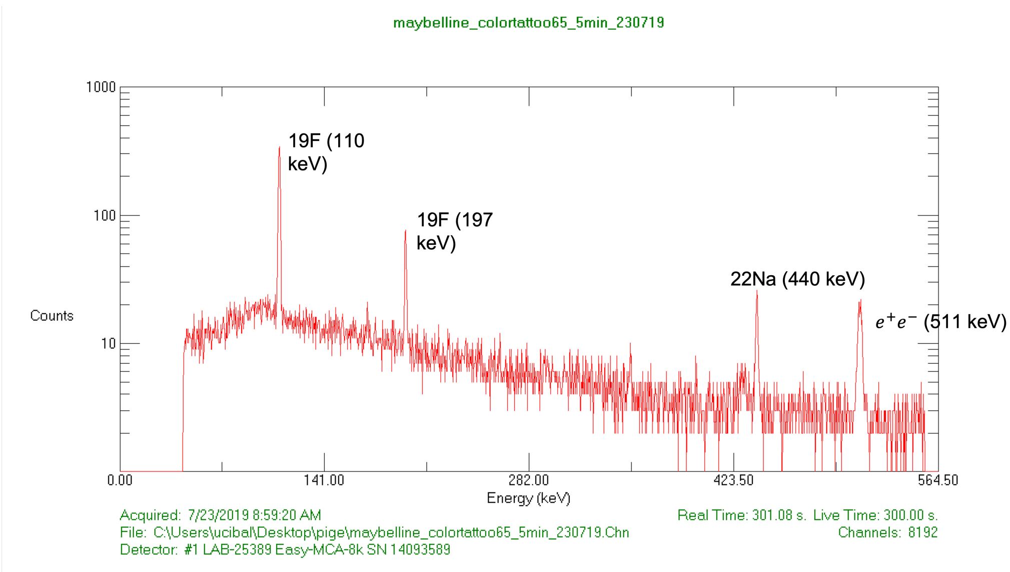


Figure 1.2: Energy graph of maybelline makeup product from July 23, 2019. The data was taken for 5 minutes before stoppage.

One of the ways to limit the background data collected is to have a high $Z$ collimator over the detector that, by the photoelectric effect, absorbs unwanted $\gamma$-rays. Figure 1.3 shows how a collimator reduces the exposure area of incident rays over the surface area of the detector. In this case a collimator would be placed over the detector with a hole in the middle of it to limit the total number of $\gamma$-rays detected, attenuating the low energy $\gamma$-rays. The reason lead is good at attenuating gamma-rays is because it has a high atomic number (Z) and most of the photons that come into contact with it get photoelectrically absorbed. A similar element with high-Z is Tungsten which is often used as a radiation shield as well.

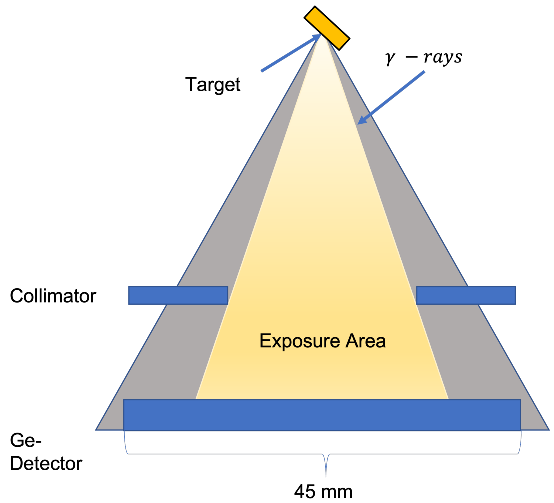


Figure 1.3: Digital drawing on how a collimator reduces the detected area of the gamma rays emitted.

There is an abundance of lead slabs in the UCIBAL which makes it the most accessible material to attenuate miss hitting $\gamma$-rays, which contributes to background data. Originally, we wanted to attenuate the intensity of the low energy $\gamma$-rays by one half. To determine the appropriate thickness, we used equation 1.4.

$$\frac{S_0}{2} = S = S_0 e^{-\mu x} \tag{1.4}$$

Where $S_0$ is the intensity of the $\gamma$-rays, which we want to cut in half, $\mu$ is the X-ray absorption coefficient for lead. We used the 200keV attenuation coefficient for lead, because the background data we want to reduce has energy 200keV or lower. To solve for the thickness of lead needed to attenuate half of the $\gamma$-rays,

$$\frac{ln(2)}{\mu} = x \tag{1.5}$$

$$\frac{0.693}{14058\text{cm}^{-1}} = 4.8 \times 10^{-5}\text{cm} = 1.89 \times 10^{-5}\text{"}$$

This tells us that the thickness of lead needed to attenuate low energy is $1.89 \times 10^{-5}$" which

is very small. We chose a 3.000" × 3.000" square slab of lead with a thickness of 3.22mm (0.127"), because it would attenuate significantly more than half of the low energy $\gamma$-rays. We tested this theory by taking data from three readioactive elements that produce $\gamma$-rays, once without the lead underneath it and once with it. Figure 1.4 shows the setup used for Barium-133, Cesium-137 and Sodium-22; data was taken for one minute and put into a count versus energy graph. Figure 1.5 shows the count versus energy for Barium-133 where the $\gamma$-rays with energy less than 200keV were attenuated by as much as 10 times. Figures 1.6 and 1.7 show how the thicker lead attenuates higher energy $\gamma$-rays. The lead still reduces the overall count of the detected $\gamma$-rays, but not as significantly as the low energy ones.


Figure 1.4: Left: Top down image of the setup used to see how much a 0.127" thick lead slap would attenuate gamma-rays. Right: Side view of the same setup.

In testing to see the effectiveness of the lead there were a few key findings beyond the overall reduction of $\gamma$-rays detected. The first finding, which is most prominent in Figure 1.5, is that the lead attenuated all of the $\gamma$-rays emitted at 81 keV. The next finding is that the lead in all cases emits a low energy X-Ray at 74.96keV and 81.93keV into the background. When incident photons interact with the lead an inner shell electron gets kicked out which

gets replaced by an outer shell electron which releases X-rays characteristic to lead. This is something to keep note of in future studies with the lead collimator, but it should not interfere with the intended data from fluorine which peaks at 110keV and 197keV. Thus, the use of a 0.127" lead collimator is appropriate for attenuating $\gamma$-rays.

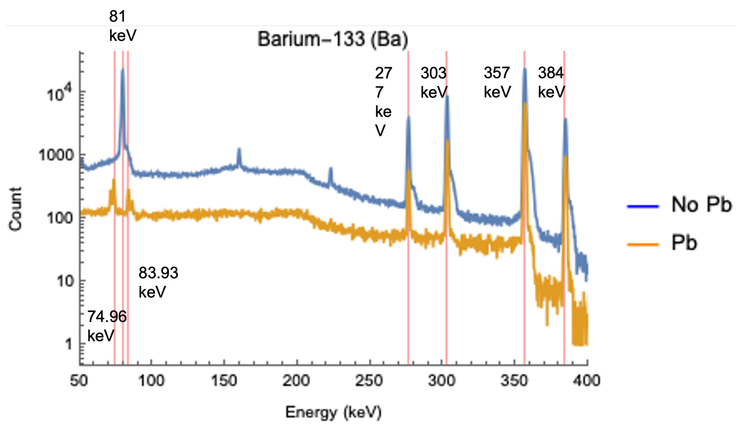


Figure 1.5: A $\gamma$-ray intensity versus energy plot for for Barium-133, with each of its energy peaks marked. The experiment was run twice, once with a 0.127" lead slab on top of the detector and once without.

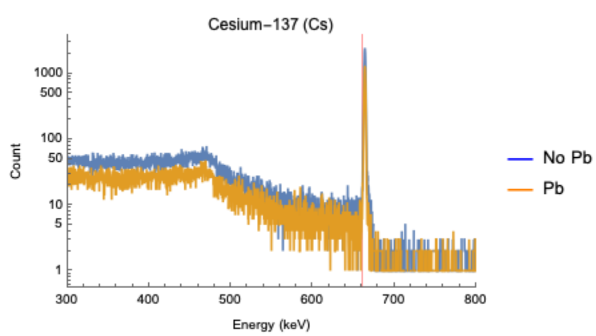


Figure 1.6: A $\gamma$-ray intensity versus energy plot for Cesium-137, with each of its energy peaks marked. The experiment was run twice, once with a 0.127" lead slab on top of the detector and once without.

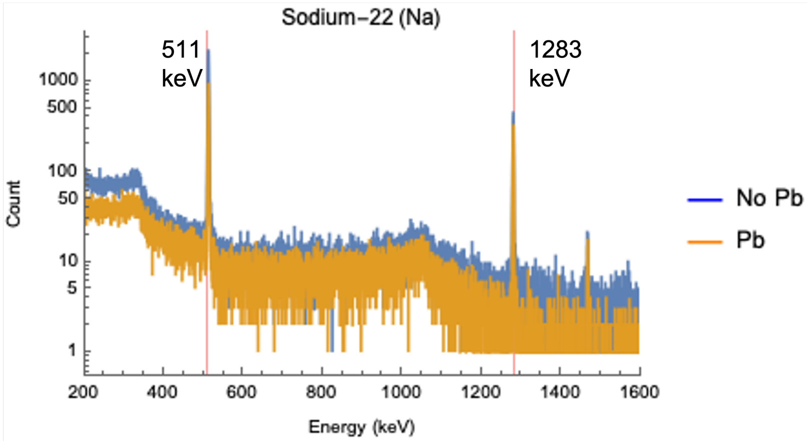


Figure 1.7: A $\gamma$-ray intensity versus energy count plot for Sodium-22, with each of its energy peaks marked. The experiment was run twice, once with a 0.127" lead slab on top of the detector and once without.

# Chapter 2

# Design Considerations

Making quantitative measurements of fluorine is possible with equation 1.1, which relies on the accuracy of the target system. The uncertainty of the target system needs to be reduced for equation 1.1 to yield accurate results. To design a new target system there were some key questions that needed to be answered before drawing any prototypes: What should we include? How big or small should it be? Are there material limitations? Should it be all one piece or separate? There were specific considerations that were kept in mind when designing the new target system, these include:

- Fixed height between target and detector
- Target to be fixed at a 45° angle to the external proton beam
- Alignment of the external proton beam with center of target, sample and the detector
- A space for a lead collimator that can be interchanged

The first consideration is what material should be used. The only constraint, aside of cost, was that anything that touches the external beam pipe cannot be a conductive material so as to not ground the ion beam charge. Grounding the charge across the beam would interfere with the measurement of the charge of the beam, a crucial part of fluorine concentration

measurements. To make sure that no part of the new system could ground the charge, and keep the cost of production low, the decision was made to 3D print the new target system with a non-conductive material.

Since we are printing it, we decided to design and construct the alignment system as multiple pieces that could be assembled post production. To do this we split the problem up into 3 parts: Base, Wall, and Slide Holder.

The initial concept for the system had two structures, one for alignment and holding of samples and another structure that would rotate the slide to create different incident angles with the external beam. This idea was scraped, because there was no reason to have samples held at any angle other than 45°. Therefore, the new target system would be made as one connected piece.

Multiple decisions were considered and evaluated during the process of creating the a new target system. The design process will be explained in the subsequent chapters, starting with a conceptual prototype that was, ultimately, never built, but led to the eventual final design.

# Chapter 3

# Conceptual Prototype

The new target system has to reduce the uncertainty present in the concentration measurements. This meant that the designs needed to fix the height from the detector to the target and the alignment of the sample with the detector and external beam. The new target system should also be modular allowing for new and different sized collimators to be used, while not interfering with any of the fixed designs.

Since the target system is going to be constructed as one piece, the most sturdy place to mount it will be off of the detector. Using the detector as the central build point helps with the alignment of the center of the detector and provides the most area to distribute the weight of the system over.

## 3.1 Base

Construction of the base - the piece that will hold the collimator and connect to the $\gamma$-ray detector- was first. Since the base will hold the collimator there would need to be an imprint to fit the 0.127" lead slab while the lower part of the base structure needs to fit on the cylindrical detector. The lead slab we chose is a 3.000" $\times$ 3.000" $\times$ 0.127" square, so

making the top of the base square would be an easy design choice even though the detector itself is a cylinder. The reason for leaving it a square is to avoid any unnecessary safety hazards that come with cutting and trimming a lead slab. Since the detector is a cylinder, the base should be cylindrical to slide right over the detector. To provide the base with a firm attachment to the detector, four perpendicular slits should be made in the cylinder part of the base so that a hose clamp can tighten around the base and detector (Figure 3.1). The slits provide flexibility to the cylindrical part of the base, acting is small flexible flaps, that allow for more variation of sizing.

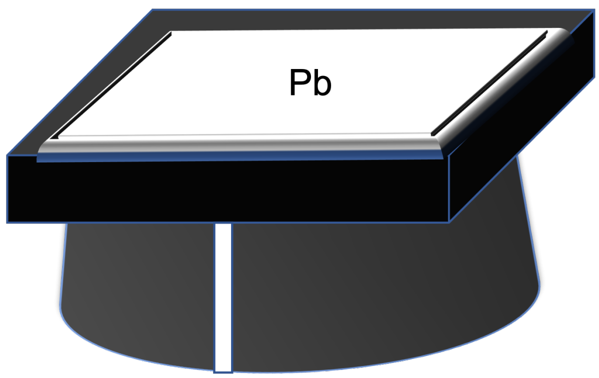


Figure 3.1: Schematic design made in PowerPoint, of the first base structure with a square top and cylindrical bottom.

## 3.2 Slide Holder

To connect the base to the target we needed to design a slide holder for samples, which would be held at a 45°angle to the beam and centered with both the detector and the external beam. The design required precision to not interfere with how the $\gamma$-rays are emitted from the sample. The amount of space available for contact to hold the slide in place was also taken into consideration. Double sided tape is used to hold the samples on to the slide and has a width of 0.660” leaving 0.166” on both the top and bottom free for contact with a the slide holder (assuming the tape has been placed in the center of the slide). Using a different material to adhere samples to the slide was considered, but ultimately not needed because

the space left over from the tape is more than enough room to satisfy the slide holder needs. Keeping this in mind, the slide holder was sketched as a hollowed out rectangle with two rails to support the top and bottom of the slide (Figure 3.2). While no dimensions were thought of for the slide holder at this time, it was noted that the slide holder should have a length less than 3.000" to allow for the user to easily guide the slide through the device. The shorter length slide holder would mean that part of the slide is always sticking out of the device which can be pulled or pushed for easy passage through the rails. We also needed to be sure that the slide holder could fit all 3 targets without falling out of the holder.

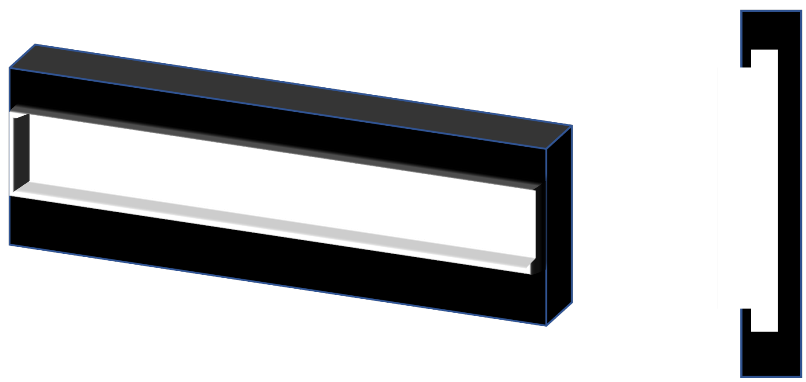

Figure 3.2: Left: Digital model of the first slide holder. It is hollow through the middle with rails on the top and bottom to hold the slide. Right: Profile view of the slide holder showing how the rails hold the slide. This would be fixed at a 45°angle to the beam.

Next we need to connect the slide holder to the base structure. To facilitate this, a wall would be built as support while also aligning the target at the same height as the external beam. The wall will be attached to the base via an extension to the square piece of the base that will hold the collimator to provide support.

## 3.3 Alignment System

The final aspect of the design was to find a way to center the external beam with the sample. One way to do this could be to have a sleeve with a diameter the same as the external beam pipe physically attach the slide holder to the beam pipe to hold center alignment

(Figure 3.3). The sleeve would be attached above the slide holder in such a way that the external beam is in the center of the slide. In doing so, the type of material would need to be non-conductive to prevent grounding of the beam pipe and target.

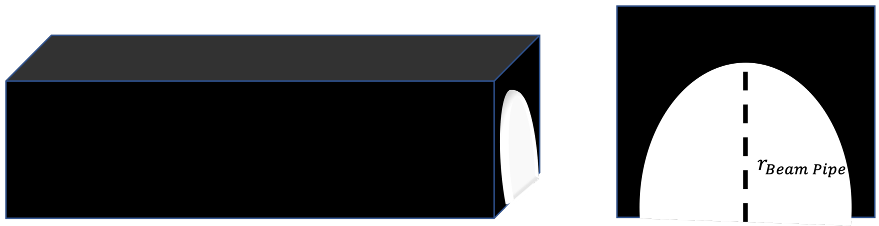


Figure 3.3: Schematic drawing on the left is a side view of the centering device that would be fitted onto the external beam pipe. The digital model on the right is a front view of the centering device.

The centering device would be the final piece of the closed target system that held all the components (the base, wall, and slide holder) fixed in place. Because the centering device would lay around the external beam pipe, it would be nearly impossible to not be aligned with the center of the sample.

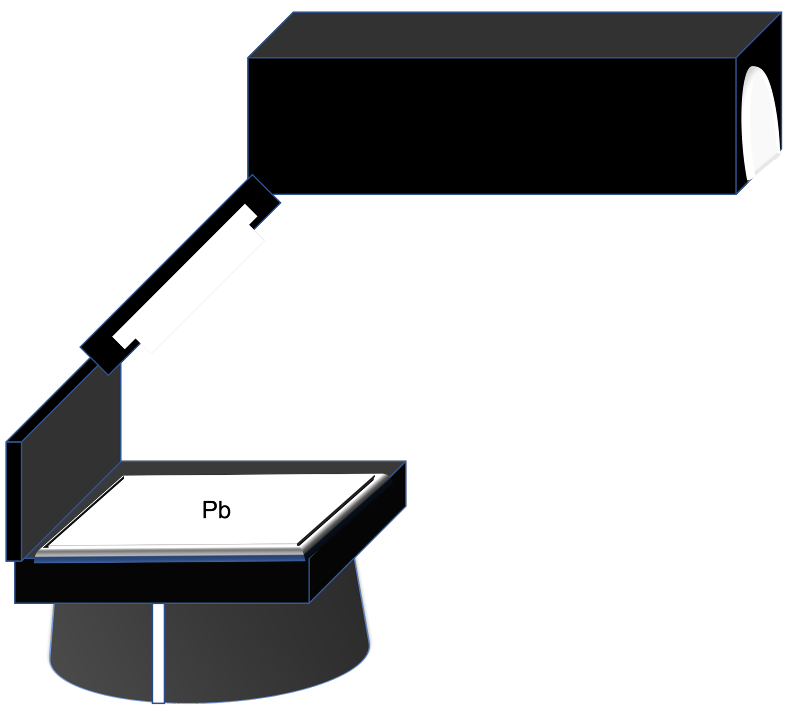


Figure 3.4: A complete schematic of the first design for the target system.

Each of these components, when put together, completes the first design of the target system as depicted in Figure 3.4. This design incorporates solutions for all the problems that have been previously mentioned. However, this design never made it to the production stage, because of some key flaws.

## 3.4 Prototype Flaws

The complete conceptual prototype is displayed in Figure 3.4. One of the biggest problems with the centering device, in its current form, is that it is not aligned with the center of the sample on the slide holder. If the centering device has a diameter equivalent to the diameter of the external beam pipe the external beam would be above the center of the slide holder. Figure 3.4 shows that the bottom of the centering device (also the location of the external beam) is aligned above the the slide holder, which would lead to the external beam missing the intended target. One of the ways to solve the problem would be to make the diameter of the centering device smaller which would lower the location of the slide holder in relation to the beam. This solution was considered, however the overall design of the centering piece is already bulky for its intended purpose and there is small surface contact between the slide holder and centering device which could lead to breakage (Figure 3.4). Also, it is supported by the beam pipe which we did not want, because the weight on the beam pipe could lead to vacuum breaks. The whole top apparatus would have to be completely re-designed.

The next key issue was the wall's connection with the slide holder and the alignment of the center of the sample with the detector. As seen in Figure 3.4, the slide holder rests on top of the wall with no material supporting the slide holder from the back. The slide holder was initially thought to be hollow through the middle, so the wall would only be able to support it from the bottom. This made the contact point between the two pieces weak, because of the small area of contact between them.

This design is overall very rigid in its construction with out being modular in the key

centering/alignment pieces and the points of contact are minimal leaving it susceptible to breakage. There are parts of this design that would carry over, with minor adjustments, to the finished product and some of the other components would be transferred as well.

The first design for the target system was a conceptual prototype that was never printed, nor put into AutoDesk360. For this reason, there were no dimensions seriously considered for this design, only the structure itself.

# Chapter 4

# Final Design

From the flaws of the prototype, it laid a good starting point to creating a new target system for quantitative PIGE. The drawings of the final target system took place by hand with pen and paper and eventually were drawn in AutoDesk360, a 3D modeling computer program. Starting from the prototype laid out in the previous chapter, the final system addresses the previously stated flaws, which include:

- Centering device alignment with sample
- Bulky centering device
- Centering device attachment to slide holder
- Slide holder attachment to wall
- Modularity of the system

All of these flaws are interconnected and required a holistic approach to re-design the centering device, parts of the slide holder, parts of the base and the wall. Since the target system was going to be 3D printed, the designs had to be altered to account for the printing process. To 3D print the system we used an Ultimaker model 5S 3D printer. The choice to partition the designs into 3 separate and combinable parts was made. This allowed for

more modular parts and more flexibility to spot errors in the printing process. Since each part would be printed separately, it was easy to re-print parts if they came out wrong or were not measured correctly. One of the things that had to be considered is the size of the printer needle 0.400mm (0.015") which meant that there was a margin of error of about ±0.015". Knowing this, the measurements for each part would be adjusted to compensate. The components, being 3D printed as separate pieces, will have to be designed to fit into one another post production. Adding another layer to the design considerations of the target system.

Re-designing the centering device so that it is not bulky and aligned with the center of the sample in the slide holder was not a long process, because of the utilization of a previous design consideration. Alternatively to the centering device laid out in section 3.3, a different method of aligning the external beam with the slide holder was to have two rods come out of the side of the slide holder so that they were parallel with the external beam pipe: one rod on each side of the pipe. This idea would have fixed the slide holder between the two parallel rods in the middle of the external beam pipe. However, it was quickly discovered that it could be done with just one rod placed on top of the slide holder that would extend all the way to the base the external beam pipe. The reason that one rod can accurately do the job of aligning the external beam pipe with the center of the slide holder is basic geometry. The distance from the base of the external beam pipe to where the slide holder is positioned is 12" with the diameter of the external beam being 0.255". Using a rod of diameter 0.250", extended along the top of the external beam pipe, would accurately show where the external beam would be hitting on the slide holder. This can be shown by using principles of trigonometry, specifically the tangent function, and the setup in Figure 4.1.

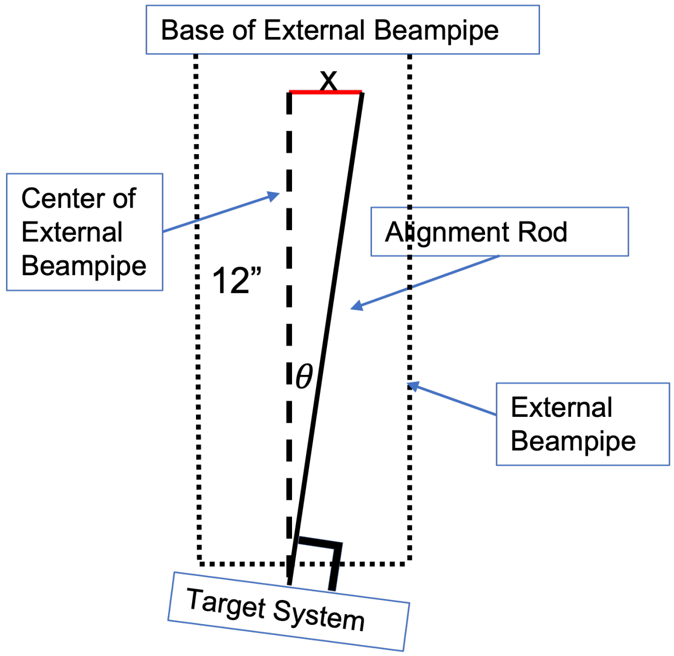


Figure 4.1: Top down view of, potential, miss alignment of the rod extended from the target system to the base of the external beam.

For example, if the rod were to be $\theta = 1^\circ$ miss aligned with the center of the external beam pipe the distance of miss alignment would be 0.209”, since (12”) $\tan(1^\circ) = 0.209$”, which can easily be seen with the naked eye. Going even smaller than that, if the rod is $\theta = 1^\circ$ miss aligned with the center of the external beam pipe the external beam would be off center by 0.020”, which can still be noticed but wouldn't be significant enough to miss the target completely. For reference, a sheet of standard 8” $\times$ 11.5” paper has a thickness of 0.004”, so a $0.1^\circ$ miss alignment would be equivalent to $5\times$ the thickness of a piece of paper.

One rod can accurately make the alignments necessary with less bulk than the previous alignment method. To securely attach the rod above the slide holder, the wall of the system has to have a considerable area (which will be outlined in following sections). Since the wall is connected to the base, the re-design process started with the base.

## 4.1 Base Design

The previous base structure, modeled in Figure 3.1, was largely kept the same with some minor adjustments. To attach the wall with the base structure, the design utilizes a tongue and snap connection method requiring one piece to have a negative space and the other to have a tongue with a small triangular retainer wall to hold the pieces together once snapped in.

We decided to make the base rectangular in shape to account for both the 3.000" × 3.000" × 0.127" collimator and extra area necessary for the snap connection with the wall. As shown in Figure 4.2, the base has a width of 3.500" providing 0.250" of support material on three sides of the collimator, a length of 4.500", and depth of 1.000". Accounting for potential printing error (±0.015") with the 3D printer, the imprint of the collimator has a square outline of 3.010" × 3.010"; after printing the actual dimensions of the imprint was 2.996" × 2.996". Although the actual printed result is smaller than initially intended, the lead was trimmed to fit the dimensions of the imprint. The printed base has real dimensions 4.485" × 3.499" which is within the margin or error expected (±0.015").

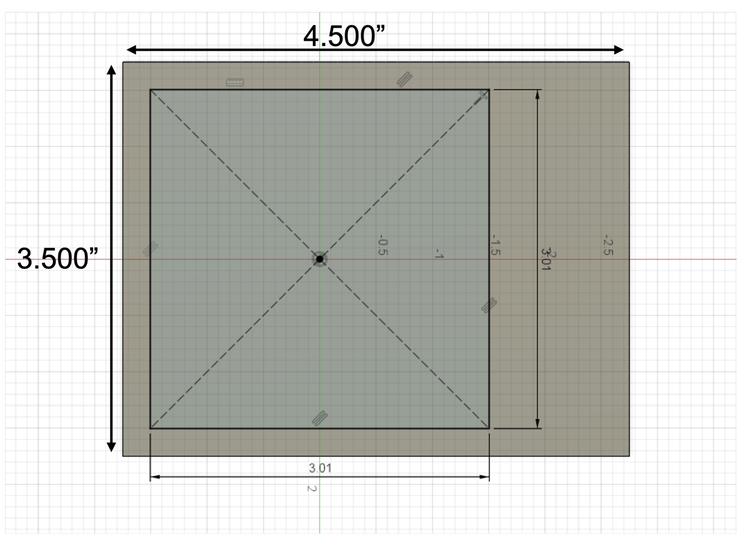


Figure 4.2: Top view from AutoDesk360 of the 3.500" × 4.500" rectangular base as well as the 3.010" × 3.010" imprint outline for the collimator.

The depth of the imprint, shown in Figure 4.3, is designed to be 0.200". Making the depth of the imprint thicker than the thickness of the lead was intentionally done, not just to account for potential printing error, but to allow for the use of thicker slabs of lead if greater $\gamma$-ray attenuation was desired. The thicker lead would be able to attenuate more gamma rays, lowering the background data better. When printed, the actual depth of the collimator imprint was 0.341" which provides even more room for thicker slabs of lead to be used in the future.

The lead slab needed to have a hole cut into the middle of it in order to become a collimator. There were a few factors that went into deciding on the diameter of the hole in the center of the collimator. The first issue in deciding the diameter was focused on the unknown depth at which the detector was placed within the detector casing. This is important, because the background $\gamma$-rays that the collimator is supposed to attenuate are created when the $\gamma$-rays hit the detector at an angle and then exit the side wall of the casing. The gray lines in Figure 1.3 shows gamma-rays hitting the detector at an angle that creates background data. An added problem is the unknown dimensions of the emitted $\gamma$-rays from the source to the detector. Not knowing the dimensions of the emitted rays nor where the detector is in the casing makes it difficult to choose a diameter for the collimator. If the diameter is too large, then the detector is still receiving data from the gamma-rays improperly passing through it and the background data has not been reduced. If the diameter is too small, then there would been a significant reduction in number of rays detected, increasing data collection time. The decision to make the diameter 25mm (0.984") was made based off of one piece of known data. The factory specifications of the Germanium detector said that the "distance from the window" was 5mm (0.195"). Taking the assumption that the window was at the top of the casing, a diameter of 0.984" would attenuate the unwanted information while leaving the desired data. To make the cut out, the lead was put into a milling machine which cut the desired diameter completely through the center of the 0.127" slab of lead.

The base also features 4 slits (0.828" × 0.020") perpendicular to each other, shown in Figure 4.3, providing flexibility to the fit of the base onto the detector. The slits allow the cylindrical sections to bend more easily than a completely solid base, so that if there is error in the printing size the cylinder part of the base can expand over the detector. Conversely, to mitigate the base fitting loosely on the detector a hose clamp will be attached, squeezing the slits together making a tight connection. The hose clamp can be loosened and tightened at the discretion of the user. To prevent the hose clamp from falling down the detector a rail was designed into the base (Figure 4.3) for the clamp to rest on when it is laying unfastened. The rail, as shown in Figure 4.3, completely wraps around the cylindrical base, excluding the slit areas, with a height of 0.125" and a thickness of 0.071". The overall height of the cylindrical base was chosen to accommodate for the height of the four perpendicular slits. The slits needed to have a considerable height in order to be effective at their purpose, so the height of the cylinder needed to reflect that. Therefore, a height of 1.250" was selected, as it provides enough room above where the slit ends to attach the rectangular upper region of the base.

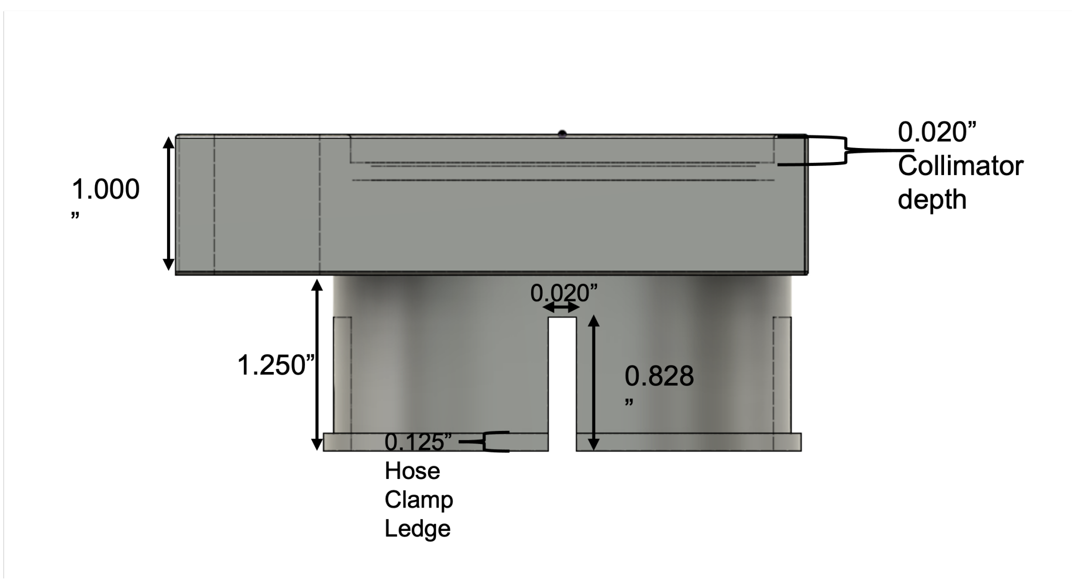


Figure 4.3: Side view of the base, designed in AutoDesk360, showing the depth of the collimator imprint, hose clamp rail, four perpendicular slits and the thickness of the base.

In Figure 4.2 the rectangular base has an extra one inch of length after the imprint of the collimator ends to account for the area needed to create the negative space for the connection of the wall with the base. In Figure 4.4, the negative space outlined in blue for the connection point between the wall and the base is 2.500" × 0.750". The area of the negative space is large enough for stable contact between the base and wall. The negative space was made smaller than the existing area to provide a ledge for the wall to sit on once it is snapped together. The design leaves 0.195" between the collimator imprint and the negative space and 0.250" between the negative space and the back of the rectangular base. The depth of the cut hole is 1.000", so that it goes straight through.

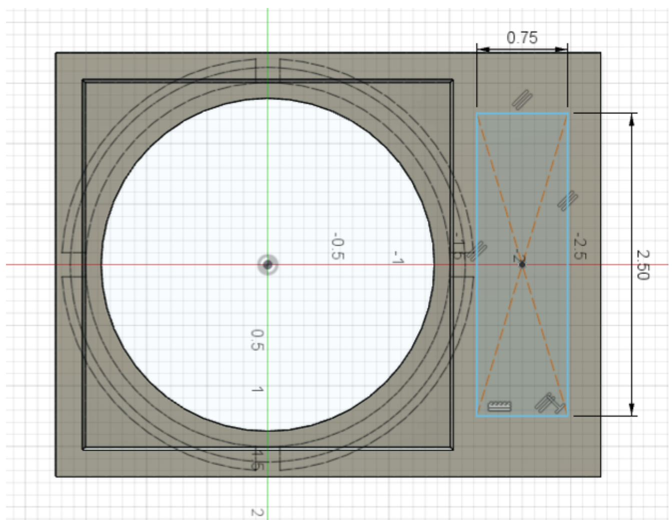


Figure 4.4: Top view of the rectangular base from AutoDesk360 showing the outline of the 0.750" × 2.500" hole necessary for the snap connection with the wall.

When printed, the negative space had a real length and width of 2.493" and 0.741" respectfully, which still falls within the range of expected error. The distance between the collimator imprint and the negative space, since both actual measurements came out shorter, is 0.292". In designing the wall, and eventually the slide holder, the parts would be measured based on the corresponding structures 'real' measurements. This means that the dimensions of the wall's tongue, that will fit through the negative space in the base, will be based on the actual measurements from the printed structure and not the intended measurements put

into AutoDesk360.

## 4.2 Wall & Alignment Rod Holder Design

The design of a more fortified wall is important for structural integrity of the system as well as securing the slide holder. The alignment system to center the external beam with the target will be designed to be fixed on top of the wall. Some of the considerations for the design of the wall include:

- Connecting the wall and the base
- Supporting the alignment rod on the wall
- Putting the alignment rod at the right height to hit the base of the external beam
- Supporting the slide holder
- Create a negative space to attach the slide holder

The wall has two sections that are joined together, the tongue which fits through the base and holds the base and wall together, and the upper wall which supports both the alignment rod and has a negative space for the slide holder to be attached. Starting with the tongue, the dimensions of the tongue are based on the real dimensions of the negative space in the printed base. The negative space after printing came out to be 2.493” × 0.741”. In order for the tongue to fit through the negative space, it had to be designed smaller but not so small that the tongue does not snap together. The tongue has rectangular dimensions of 2.466” × 0.731” as shown in Figure 4.5. To fit tightly together, a reduction of 0.010” was made in the width and 0.030” in length.

When the tongue goes through the negative space, it should have a mechanism that hooks onto the bottom of the base to secure the attachment. The design that accomplished this task was a triangular retainer along both lips of the tongue (Figure 4.6). The two triangular

retainer walls (one along each length) have a width of 0.030" and length of 0.100", providing support by hooking onto the bottom of the base once the tongue is pushed through the negative space and the tongue expands out. Although the two retainer walls width added with the width of the rectangular part of the tongue would make the total width 2.526", the tongue is able to fit through the hole due to a triangular area cut through the entire length of the tongue, shown in Figure 4.6. The triangular cut out spans the whole 2.466" length of the tongue and allows for the tongue to be pinched together when passing through the negative space. The base of the triangular cut out, as shown in Figure 4.6, is 0.399" which is the equivalent distance the tongue could bend, barring the material used in construction. Thus, when the retainer walls exit the bottom of the negative space, they expand out and hook on creating a tight, secure, attachment.

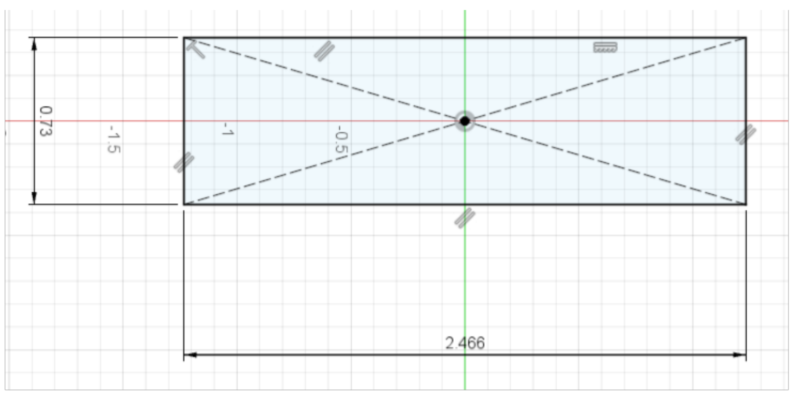


Figure 4.5: Dimensions for the tongue of the wall. The tongue is used to connect the wall to the base. The dimensions of the tongue (2.466" × 0.731").

After printing, the tongue has a real width, including the retaining walls, of 2.473" and the retaining walls had a real width of 0.025" each. The real width of the triangular hole is 0.342", which is more than the expected variation. However, since the thickness of the tongue, retaining wall width and other measurements were also off, this added up to a big difference in the triangular gap. This was not cause for concern, because there was still enough of a gap for the tongue to compress and have the retainer walls to fit through the negative space of the base.

A critical measurement of building the tongue-snap connection system is the length of the tongue that will pass through the hole of the base. The first thing to note is the depth of the hole the tongue is going into; after printing, the base has a real depth of 0.994". In order for the retaining walls to hook onto the bottom of the base, they will need to completely pass through the negative space. Thus, the length of the tongue needs to account for the height of the retainer walls (0.100") and the 'real' depth of the base. For the tongue to fit perfectly through the negative space in the base with the retainer wall completely passing through the bottom, the length of the tongue would need to be 1.094". The dimension used in the design of the tongue was 1.095", giving only 0.001" of room for error. The reason for such a tight dimensional measurement is based on two reasons. The first being that the printer usually prints small, so while the tongue will most likely be smaller than expected, so will the retainer walls which means it should still pass through. Secondly, the top of the wall should have little to no room in between it and the base, so that the upper section rests flat on the base. When the wall was printed, the tongue fit perfectly through the negative space in the base with the retaining walls hooking onto the underside of the base and the upper section laying flat on top of the base, as desired.

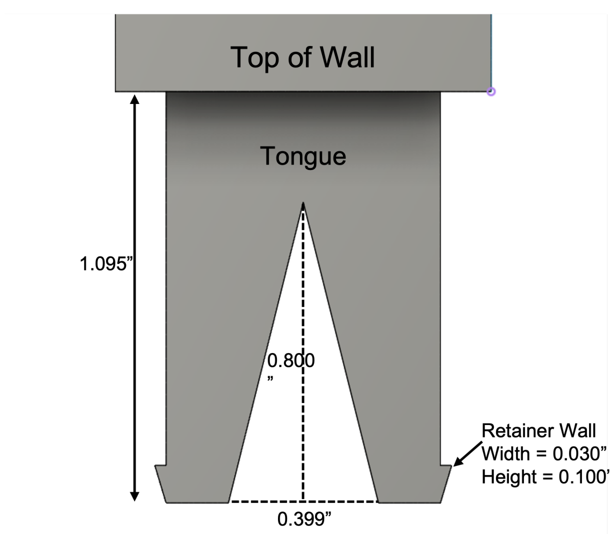


Figure 4.6: Back view of the tongue for the wall designed in AutoDesk360.

Once the tongue was designed, the top of the wall needed to be laid out. The dimensions of the top of the wall, shown in Figure 4.7, are 3.000" × 1.000". The length of the top of the wall aligns it with the width of the collimator imprint. The width, is wide enough to sit on top of the base, but not to extend out into the collimator imprint either. The dimensions of the base being larger was also a design choice to have the edges of the wall line up with the edges of the collimator imprint. This gave the whole structure a uniformitity that is pleasant to the eye. When printed, the real dimensions of the wall came to be 2.996" × 0.990", which is in the expected margin of error.

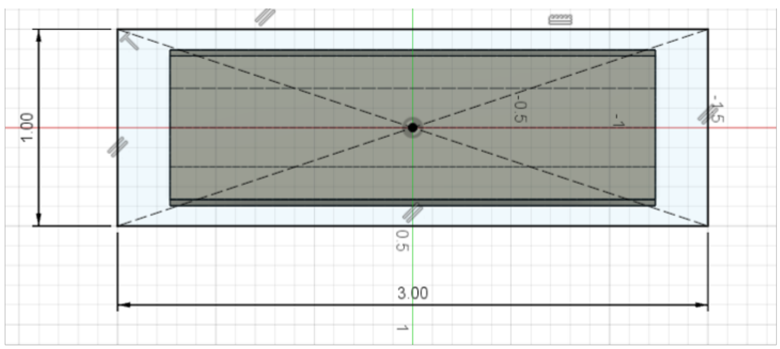


Figure 4.7: Dimensional layout of the top of the wall as created in AutoDesk360.

Determining the height of the wall is a crucial step to give the target system accuracy, because the height between detector and sample is one of the necessary measurements to make fluorine concentration measurements. The slide holder will be attached to the wall, using the same tongue connection method that was used for the wall and base. The height of the wall, specifically the negative space that will be cut out of the wall, will put the slide holder on the same plane as the external beam pipe. The distance between the detector and the center of the external beam pipe is 2.560". Thus, the center of the slide holder should be at that point. This created a center point during the build of the walls upper section. Everything about the upper section needed to be aligned with this measurement to satisfy one of the goals of the system. Determining how high up the negative space in wall should be required the dimensions of the negative space to be made first. To secure safe attachment

of the slide holder to the wall the dimensions of the negative space in the wall, as shown in Figure 4.8, was made to be 2.000” × 0.625”. The reason for these dimensions was simple. The length of a slide is 3.000” and the slide holder will have a length smaller than that as previously discussed. So, to have the dimensions of the upper part of the slide holder bigger than the tongue while having enough area to ensure a secure point of contact, the dimensions of 2.000” × 0.625” was determined. The height from the bottom of the wall to the center of the negative space is 2.415” (Figure 4.8). The reason that the height is only 2.4145”, is due to a ledge built into the cylindrical part of the base, whose thickness is 0.145”. The ledge provides a snug fit between the top of the detector and the bottom of the base. So, for the center of the slide holder to be at 2.560”, the thickness of the ledge needed to be accounted for leaving the height of the negative space to be 2.415”.

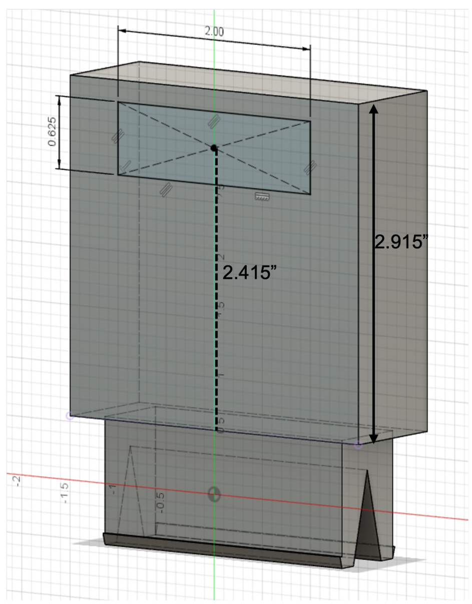


Figure 4.8: AutoDesk360 image of the top of the wall, including dimensions of the slide holder and total height.

Given the size of the negative space and the height needed to be aligned with the center of the external beam pipe, the top of the wall was given a total height of 2.915”. Enough material was left above the negative space for the tongue of the slide holder so that when the two were connected the wall would not break. The extra room above the negative space

was also necessary to provide support for the alignment rod structure that will be built on top of it. In the actual print of the wall the height came out taller than expected at 2.937” shifting the center of the external beam from the center of the negative space by 0.022”, which factors into the construction of the slide holder.

The last part of the wall is the alignment rod holder which will be joined at the top of the wall. The alignment rod holder has two parts to it, the rectangle where the rod rests and two support arches on either side, shown in Figure 4.9. The dimensions of the rectangle are 1.000” $\times$ 1.000” $\times$ 1.600”. The rod, whose diameter is 0.250” and aligned with the center of the wall, sits 0.750” from the top of the wall. This takes into consideration the height necessary to hit the back of the external beam pipe without coming into contact with the screws on the scattering chamber (shown in Figure 1.1). To fasten the rod in place threaded inserts were put on each side of the rod that can be loosened, to move the rod, and tighten to fix the rod. The threaded inserts have a diameter of 0.285” and a length of 0.350” and are made out of metal. In deciding the dimensions of the alignment rod holder, there needed to be considerable area on all sides around the threaded inserts to account for their installation process. If there was not enough material, the force required to install the threaded inserts would crack the structure. Therefore, there is extra space above, below and to both sides of the threaded inserts. The support arches on both sides of the rectangle act as extra material to support the top structure and a stylistic choice. When looking at the alignment rod holder, the arches provide a smooth visual transition from the rod to the rest of the wall.

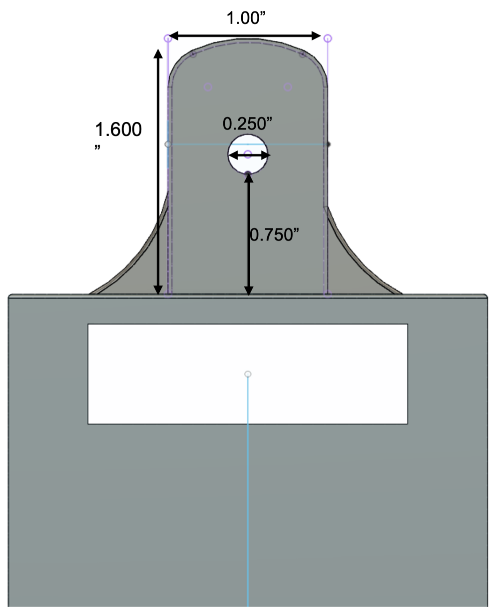


Figure 4.9: Dimensions of the alignment rod holder from AutoDesk360.

The tongue, wall and alignment rod holder are all one piece that were printed together. When the structure was printed, the alignment rod holder had a real width equivalent to the width of the wall 0.990”, a real length of 1.001”, and a real height of 1.585”. The threaded inserts were installed with no cracking on either side and the alignment rod easily passes through the center hole going down the mid line of the wall.

## 4.3 Slide Holder

The slide holder is attached to the wall using the same tongue and snap method that was used to connect the wall and base. To ensure that the tongue fits firmly in the wall’s negative space the design uses the ’real’ dimensions of the wall. Building the slide holder’s tongue is the same process as the wall’s tongue. The dimensions of the tongue need to be just barely smaller than the true dimensions of the negative space in order to have a tight fit. Like the wall, this tongue will have a triangular retainer wall on each long edge to hook onto the backside of the wall. The negative space on the wall has real dimensions of 1.968” $\times$ 0.620”; removing 0.010” in each direction provides enough space for the tongue to pass through.

This makes the dimensions of the tongue 1.958" $\times$ 0.610", which does not include the width of the retainer walls. The side view of the tongue, shown in Figure 4.10, shows the height and width of the retainer walls to be 0.100" $\times$ 0.045", respectively. The walls are able to fit through the negative space, despite the extra width, because of the triangular gap that cuts through the middle of the tongue (Figure 4.10). The triangle allows the tongue to squeeze together passing the retainer walls through the opening and eventually snap out when the retainer walls exit the back of the wall. Going off of the real width of the wall (0.990"), a tongue of length 1.099" will pass completely pass through the negative space and have the retainer walls hook onto back. When printed, the tongue did exactly what it was designed to do securely attaching the slide holder to the wall.

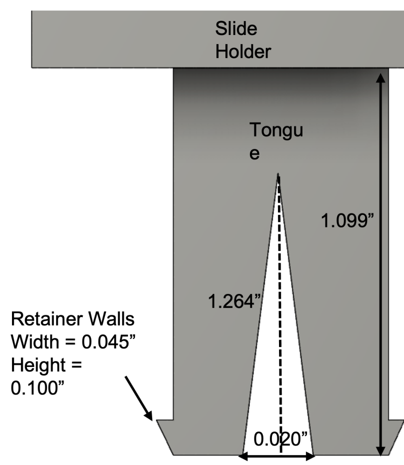


Figure 4.10: Side view of the tongue as designed in AutoDesk 360, showing the dimensions of the retainer walls, triangular gap and total height.

Previously, it was noted that the wall has a real height taller than expected which moved the alignment of the external beam lower than the center of the negative space on the wall. Taking that into consideration, the center of the top section of the slide holder was set 0.022" lower than previously anticipated. The dimensions of the the top section are shown in Figure 4.11, with total dimensions 2.500" $\times$ 1.562". Since the standard optic slide (used for holding samples) has a length of 3.000", the extra 0.500" lets the user easily push or pull the slide

through the slide holder while still leaving enough room for the slide to remain in place (and not fall out of the holder) as the user puts all 3 targets in front of the external beam.

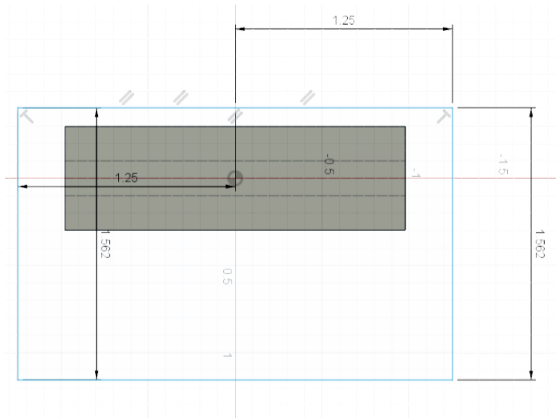


Figure 4.11: Dimension of the the top section of the slide holder, taken from AutoDesk360.

The height of the slide holder is a significant measurement that aligns the sample with the detector. The distance from the front of the wall to the center of the collimator is 1.582", which is where the center of the sample (which is angled at 45°) needs to be. To be precise throughout the construction of the slide holder, a reference line of length 1.506" was placed at at the exact point where the sample should be set. It is shorter than the distance to the center of the collimator, because the average height of a sample is 0.080" accounting for the extra distance to the center of the collimator. Setting the initial height of the slide holder to 1.975" gave enough space to make a 45° cut across the surface so that the middle of the slide holder was at the appropriate 1.506" (shown in Figure 4.13).

The initial length of the slide holder held no significance, besides being large enough to fit the width of the slide (1.000") with area to spare. Figure 4.12 is the outline for the slide on the angled surface of the slide holder. Width of the outline for the slide is 1.100" so that when the rails are attached for the slide to fit on there is enough room for it to move freely.

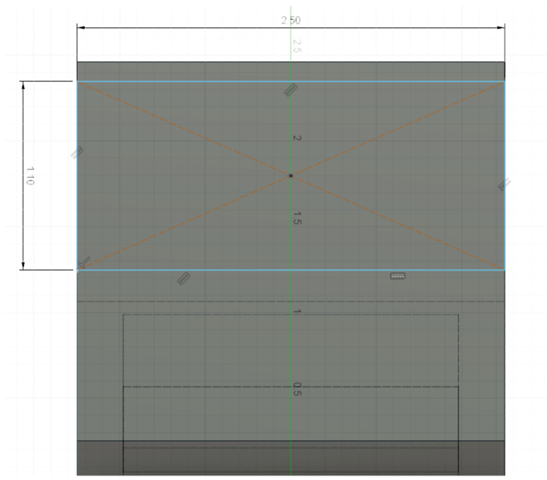

Figure 4.12: Outline of where the slide will sit on the angled surface of the slide holder.

Once the height and center location of the slide was set, the last thing to do was to design a way for the slide to easily glide through the structure. Using rails on the top and bottom of the slide maximize the exposed surface area of the slide to the external beam. It was noted earlier that samples are attached onto slides using double sided tape that, if put in the middle of the slide, leaves 0.166" of available contact area above and below the tape. The goal for designing the depths of the rails was to minimize the contact area between the slide and slide holder while also having a stable connection. Given the margin of error that the Ultimaker 3D printer had been showing, a depth of 0.063" (Figure 4.13), was reasonable to hold the slide and be printed accurately. The slides, including the samples and tape, are very light which allowed for such a small depth for the rails. The width of the standard optic slide is 0.040", so giving extra room for the ease of placing the slide into the rails and any potential error in printing, a width of 0.050" was allotted in the designs (Figure 4.13).

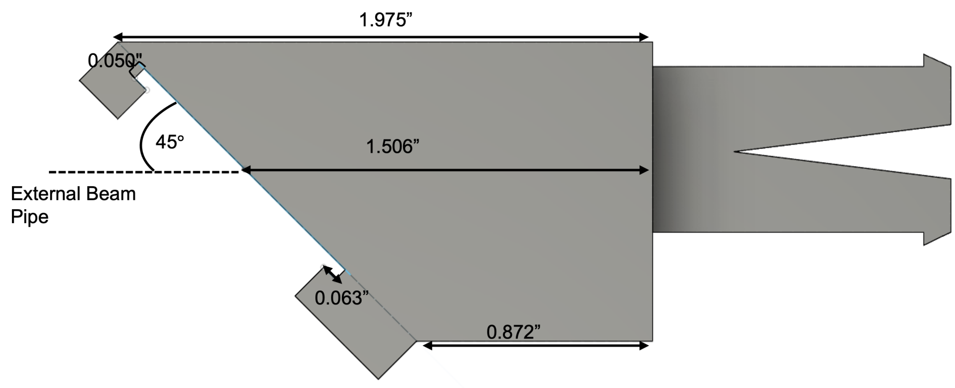


Figure 4.13: Horizontal view of the slide holder including all the dimensions of the top section of the slide holder. The horizontal view is how it will be attached to the wall.

When the slide holder was actually printed, the tongue fit perfectly into the negative space of the wall with both retainer walls hooking onto the back of it, as desired. The adjustments made to align the external beam pipe with the center of the sample came out as planned. The distance from the wall to the middle of the slide holder had a real length of 1.508”, only 0.002” off of the design. The width of the slide holder was 2.509” and the distance from top to bottom came out to be 1.099”. The slide passes through the rails as intended, with minimal effort needed by the user to push it all the way through. The precision necessary to build an accurate slide holder came to fruition, the slide is directly over the center of the collimator and aligned with the external beam.

# Chapter 5

# Construction

All of the designs made in AutoDesk360, outlined above, lead to the creation of the new alignment system (Figure 5.1). Printing the designs using an Ultimaker 3D printer presented the choice of what material to use to make the system. The choice was between normal poly lactic acid (PLA) and tough poly lactic acid (Tough PLA). Normal PLA is a biodegradable polymer that is ideal for prototyping 3D models, because of its reliability, low shrinkage factor and the ability to be printed at low temperatures. Tough PLA has all the same qualities as normal PLA, but there are extra additives to the plastic that make it stronger than normal PLA.

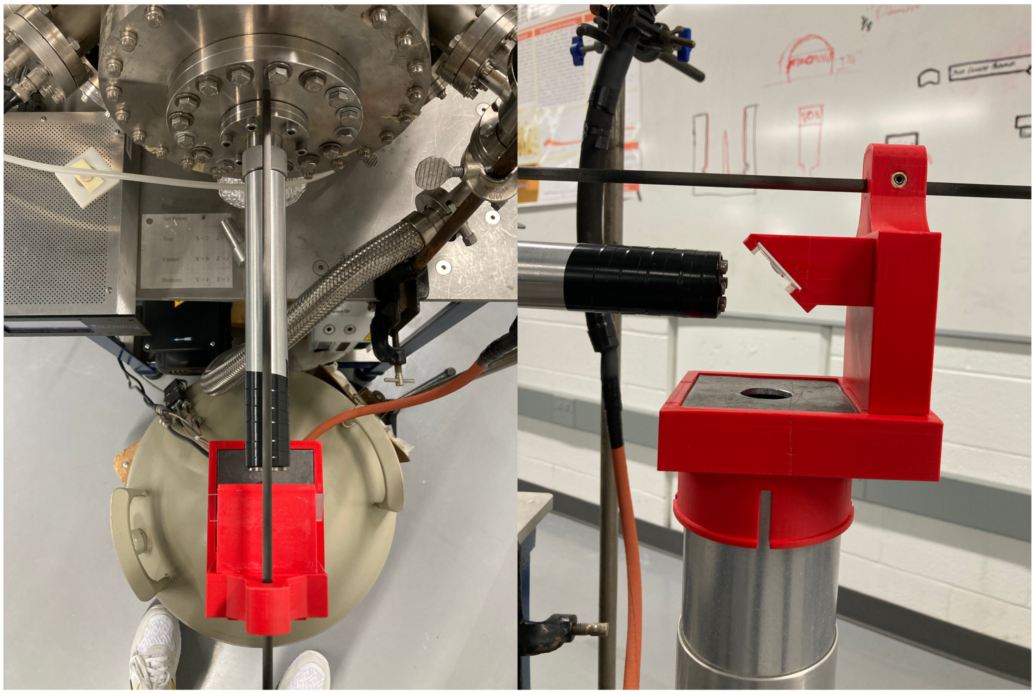

Figure 5.1: Left: Top view from the back of the final structure showing the alignment rod that goes to the base of the external beam pipe. Right: Side view of the complete system.

The base was printed in both normal PLA and Tough PLA, but due to printing process management a complete structure was only built using Tough PLA adding durability to the structure. To 3D print an object, there are typically two materials used, the material the object will be built out of and poly vinyl alcohol (PVA). PVA is used by the 3D printer to support parts of the object that are susceptible to breaking (thin walls, intricate parts, etc.) during the printing process, as well as providing filler support where there is supposed to be small gaps (places like the rails on the slide holder, the triangle cut out in the tongue and the retainer walls on the tongues). PVA is typically a clear substance and once the object is printed it dissolves in soapy water. All of the parts were washed to remove any PVA after printing. When printing with normal PLA, the PVA did not support the walls and intricate parts of the system well, leading to several miss prints. The reason was never determined, but had to do with how the printer was calibrated. However, when printing with the Tough PLA there were no issues of the sort, the PVA did its job correctly and the pieces were

printed smoothly.

Each component (base, wall, slide holder) are completely solid which made the print time inordinately long for some pieces. If the pieces were hollowed out, it would require less material and take less time, but as previously mentioned the system had to be sturdy. The print time for the base was two whole days (48 hrs) with another additional half day for the printed object to soak in soapy water. The print time for the wall was one and half days (36 hrs) with the additional half day soak. Finally, the slide holder only took a half day to print (12 hrs) with an additional half day of soak time. This totals five and half days of complete print and soak time for the system to be made. It is a very easy process to 3D print, but is time consuming.

The advantage of printing each part individually is that if one of the pieces breaks or wears out, only that part has to be replaced and not the whole system. The system was designed to be modular in as many aspects as possible. Each tongue and snap connection point can be removed and replaced with another object that fits in the same negative space. The imprint for the collimator was intentionally made deeper than the slab of lead currently used to allow for different thickness of lead and different sized collimators. The current collimator diameter is 0.984" and since the lead is not permanently fastened to the base, it can be removed and replaced with collimators of different sizes. This is what separates the final design from the conceptual prototype. This layout has the ability to adapt to new problems should they arise and is replaceable.

## 5.1 Cost

When building anything, cost efficiency is important to consider. The materials used to build the alignment system are all owned by the Union College Physics & Astronomy Department, meaning there is no third party charge involved. With that being said, the material still costs money to use. A spool of Ultimaker Tough PLA costs $49.95 for 96 m of

material with a diameter of 2.85mm. This makes the price per volume at about \$0.05/cm$^3$ or \$0.81/in$^3$. The three components, excluding the lead slab, have a total volume of 24.083 cubic inches. This makes the estimated cost of 3D printing the whole alignment system \$19.50. The value that the system adds to the research being done, surely out weighs the cost of production.

The current price for a 12" $\times$ 12" $\times$ 0.250" sheet of 99.9% pure lead on Amazon.com is \$89.00. That makes the price per cubic inch of lead \$2.47. The dimensions of the lead slab used in the system currently is 3.000" $\times$ 3.000" $\times$ 0.127" which makes the total volume 1.143 in$^3$. So, the cost of replacing just the slab of lead would be \$2.82, bringing the total cost of replacement of the system to \$22.32. However, buying lead is typically done in sheets, which means that the cost of replacement for the lead would be \$89.00, plus the internal cost to cut the correct dimensions out of the sheet.

# Chapter 6

# Conclusion

Pollution continues to spread to communities all across the United States effecting the basic functions of human life, like eating and drinking. Being able to detect and quantify the pollution that we come into contact with is important for remediation of a contaminated area. One of the contaminants that has been spreading in water supplies is PFAS, a potentially dangerous chemical to humans. Fluorine is one of the elements in PFAS and because of its strong covalent bond with oxygen, it has made PFAS deemed a ”forever chemical”. Detection of these chemicals in samples can be made through PIGE analysis using a particle accelerator. However, to get a concentration of fluorine, in any particular sample, a formula dependent on the target system is used. The old target system laid out in Chapter 1, is the source of the largest uncertainty in that equation which prohibits reliable concentration measurements from being made. Thus, a new target system needed to be designed. This new system would fix the distance between the target and detector, fix the angle at which the sample is held at, reduce background data, and center the sample with both the detector and external beam pipe. This new design lowers the uncertainty in the concentration equation allowing researchers the ability to both detect and quanitfy PFAS in samples.

The design and build of the final alignment system met the goals initially set out. The

solid angle between the sample and detector is now known, via the dimensions of the alignment system. It is now not an assumption that samples will be held at a 45° angle relative to the external beam, but assured knowledge. The system aids in the alignment of the external beam and sample to minimize the chances of missing the target completely and finally the collimator attenuates background data making energy peaks more noticeable during data analysis. Each aspect of the new target system was designed with the purpose of making quantitative PIGE measurements, in particular fluorine concentration measurements and will be used during future research projects.

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